Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

# A pathway to understanding running-related injuries

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A thesis submitted for the award of Doctor of Philosophy (PhD)

August 2024

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**Declaration**

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Doctor of Philosophy is entirely my own work, and that I have exercised reasonable care to ensure that the work is original, and does not, to the best of my knowledge, breach any law of copyright, and has not been taken from the work others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: Aisling Lacey (candidate) Student ID: 16301251 Date: 28/08/2024

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Miscellaneous

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**List of abbreviations**

ADLs: Activities of daily living

AB: Dr. Aoife Burke

AL: Aisling Lacey

BMI: Body mass index

CGT: Constructivist grounded theory

DOMS: Delayed onset muscle soreness

ECSS: European College of Sport Science

EW: Dr. Enda Whyte

F: Female

FIFA: Federation of International Football Association

GPS: Global positioning system

GT: Grounded theory

HCP: Healthcare professional

HS: Hard shoe

ICF: International Classification of Functioning, Disability and Health

IMU: Inertial measurement unit

IOC: International Olympic Committee

IP: Interpretative phenomenology

IPP: Injury prevention practice

KM: Prof. Kieran Moran

M: Male

MCS: Motion control shoe

NR: Not reported

NRFS: Non-rearfoot strike

OSTRC: Oslo Sports Trauma Research Centre

OSTRC-H: Oslo Sports Trauma Research Centre – Health questionnaire

OSTRC-O: Oslo Sports Trauma Research Centre – Overuse injury questionnaire

PPI: Public and Patient Involvement

PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses scoping review

PROM: Patient Reported Outcome Measure

Pulse Ox: Pulse oximetry

Q angle: Quadriceps angle

QoL: Quality of life

RCT: Randomized controlled trial

RFS: Rearfoot strike

RISC: Running Injury Surveillance Centre

RRI: Running-related injury

RRP: Running-related pain

RTA: Reflexive thematic analysis

RTÉ: Radió Teilifís Éireann

SD: Dr. Sarah Dillon

SFI: Science Foundation Ireland

SOC: Dr. Siobhán O'Connor

SOK: Dr. Sinéad O'Keeffe

$SPO_2$: Oxygen saturation

SfS: Soft shoe

SS: Standard shoe

TAM: Technology Acceptance Model

TL: Time-loss

TR: Training reduction

TRIPP: Translating Research into Injury Prevention Practice

UTAUT: Unified Theory of Acceptance and Use of Technology

$VO_2max$: Maximal oxygen consumption

XC: Cross-country

**Philosophical positioning**

When considering the methodology and findings of this thesis, it is important to consider my own background, experiences and philosophical position. This may be particularly salient in Chapters 5-7, when I am conducting, analysing and interpreting qualitative data obtained from recreational runners.

Philosophical positioning stems from ontology, as the study of being (what exists for people to know), and from epistemology, as the study of knowledge (how knowledge is created and what is possible to know) (Moon and Blackman, 2014). From the knowledge I acquired during my undergraduate degree (BSc. Athletic Therapy and Training), my continued clinical practice (as a Certified Athletic Therapist) working with runners, my lifetime playing sport and participating in physical activity, my own personal experiences of injury and pain, and the views of my supervisors, I had developed a positivist outlook. Over the course of my PhD, however, my philosophical position has developed, and the subsequent interpretations made throughout this PhD will have been influenced by my own experiences. Subsequently, it is important to acknowledge that I view myself as a pragmatic researcher. I recognise that there are many different ways of interpreting the world and undertaking research, and believe that no single stance can provide a complete understanding (Poucher *et al.*, 2020). I appreciate that positivism and interpretivism are two mutually exclusive paradigms about the nature and source of knowledge, and that the research questions are the most crucial determinants of the research philosophy. Pragmatists, therefore, link the choice of approach directly to the purpose and nature of the research's aim(s) (Creswell and Creswell, 2018). To ensure methodological coherence, researchers must demonstrate that the approach taken is optimal for addressing their research question(s), aligning with their philosophical position (Poucher *et al.*, 2020). In line with this, I believe that research should be practical and generate meaningful impact, and with various approaches to research, should be dependent on addressing the research question.

**Abstract**

***Name:*** **Aisling Lacey**

***Title:*** **A pathway to understanding running-related injuries**

Running-related injuries (RRIs) insidiously develop from repetitive micro-traumatic loading, eventually exceeding tissue integrity. With fluctuating and cyclic signs and symptoms, clearly identifying when 'injury' has occurred is challenging. This challenge has resulted in conflicting and inconsistent foundational RRI epidemiological evidence (i.e., injury rates and risk factors). Without establishing this evidence, injury prevention cannot advance. The fundamental way 'injury' has been considered, not reflective of its true developmental nature, is possibly contributing to the unclear evidence, and adapting how RRIs are captured may be required. This may be achieved with a large-scale, prospective study, monitoring multiple potential risk factors, across the entire injury development process. Wearable technologies offer an elegant solution to capturing and analysing the extent of data required. However, several challenges interfere with this approach: understanding 'injury' and the RRI development process, ensuring runners' engagement with technology, and ensuring runners can be recruited and retained in such a study. The overall aim of this thesis is to explore factors important for the development of an extensive surveillance system for RRIs, using a smartphone app and wearable device(s), to target the fundamental aspects of epidemiological research that appear to be limiting RRI prevention.

The results of this thesis have been informed by reviewing the literature regarding defining and measuring RRI severity, and capturing qualitative data from runners to understand their lived experience of injury, their perceptions of wearable technologies for preventing injuries, and their willingness to participate in research. Inconsistent approaches, not reflective of the RRI development process experienced by runners, have been employed to capture RRIs to date. An alternative approach, ensuring lower severity injuries are recognised, is needed to better establish the foundational evidence necessary to advance RRI prevention. Runners appear willing to engage with wearable technologies and to adhere with research requirements to aid the advancement of RRI prevention.

# 1. Chapter 1: Overall introduction to thesis

## 1.1. Background and rationale

Despite its popularity (Hulteen *et al.*, 2017) and vast physical (Pedisic *et al.*, 2020) and mental health benefits (Oswald *et al.*, 2020), running is associated with a high rate of injury (Hollander *et al.*, 2021; Kakouris, Yener and Fong, 2021), with recent figures demonstrating that one in every two recreational runners sustain an injury annually (Burke *et al.*, 2023; Dillon *et al.*, 2023), or every 1000km (Nielsen *et al.*, 2024). Indeed, Irish runners have been found to be one of the most frequently injured populations globally (Nielsen *et al.*, 2024). Running-related injuries (RRIs) are clearly problematic because of their frequency (Hollander *et al.*, 2021; Kakouris, Yener and Fong, 2021), negative physical consequences (Hespanhol Junior, van Mechelen and Verhagen, 2017), resultant time-loss from running (van der Worp *et al.*, 2015), associated mental health issues (Maschke *et al.*, 2022), social consequences (Sleeswijk Visser *et al.*, 2021), and financial cost (Hespanhol Junior, van Mechelen and Verhagen, 2017). Therefore, it is in the interest of millions worldwide to reduce and prevent the likelihood of RRIs.

From a biomechanical perspective, injuries are caused by high loads relative to tissue integrity (Bertelsen *et al.*, 2017), manifesting when these loads (both internal and external) exceed the tissues' adaptive capabilities (Davis and Gruber, 2019; Paquette *et al.*, 2020). In running, these loads are typically micro-traumatic being repeatedly applied over prolonged periods (Bertelsen *et al.*, 2017), resulting in the majority of RRIs being 'overuse' (Hreljac, 2004). Insidious physiological tissue damage occurs, accompanied by often fluctuating, albeit progressively worsening, signs and symptoms of injury (Bertelsen *et al.*, 2017), in the midst of runners' attempts to continue running (Clarsen, Myklebust and Bahr, 2013). They differ from 'acute injuries' in that they lack a single causative event (Hreljac, 2004; Bahr, 2009; Saragiotto *et al.*, 2014). This makes their identification, capture and monitoring challenging for researchers, clinicians, coaches, and runners themselves, because it is difficult to determine when 'injury' occurs (Clarsen, Myklebust and Bahr, 2013) and what factors relate to it.

Multiple factors have been suggested to relate to RRIs, such as previous injury (van der Worp *et al.*, 2015; Burke *et al.*, 2023; Dillon *et al.*, 2023), training behaviour (van der Worp *et al.*, 2015; Burke *et al.*, 2023), sex (Messier *et al.*, 2018; Dempster, Dutheil and Ugbolue, 2021), age (van der Worp *et al.*, 2015), and running technique (Willwacher *et al.*, 2022; Burke *et al.*, 2023). However, despite clear theoretical biomechanical relationships between suggested risk factors and the onset of RRIs, evidence to date is largely conflicting, inconsistent and inconclusive (Ceyssens *et al.*, 2019; Fredette *et al.*, 2022; Peterson *et al.*, 2022; Correia *et al.*, 2024). This is somewhat surprising as running is a relatively simple sport, in that, there are typically no sudden changes of direction or pace (e.g., rugby, soccer), there are no large ranges of motion (e.g., tennis serve, kicking), and there are often no other individuals to come into contact with (e.g., tackling in team sports). Therefore, in theory, risk factors for RRIs should be better understood, and the ability to predict and reduce their likelihood should be more advanced. Possibly, this slow progression of injury prevention research may be due to methodological weaknesses, including: (i) retrospective data collection (Vannatta, Heinert and Kernozek, 2020; Willwacher *et al.*, 2022; Burke *et al.*, 2023), (ii) a lack of monitoring internal and external loading (Soligard *et al.*, 2016), (iii) a focus on capturing single risk factors (when RRIs are multifactorial [Bertelsen *et al.*, 2017]) (Bredeweg *et al.*, 2013; Davis, Bowser and Mullineaux, 2016; Messier *et al.*, 2018), (iv) the use of one-off assessments (despite constantly changing injury susceptibility and predisposition [Meeuwisse *et al.*, 2007]), (v) capturing data in laboratory environments (which is not reflective of 'natural' running) (Benson *et al.*, 2018; Burke *et al.*, 2023), and (vi) a focus on defining and recording injuries by criteria, with high thresholds not representative of their overuse nature (Clarsen, Myklebust and Bahr, 2013; Yamato *et al.*, 2015). To target these weaknesses, a possible approach is to develop a surveillance system which continually captures and monitors all possible factors that may influence high loading and tissue integrity (i.e., the biomechanical model of injury [Hreljac, 2004]) (Neal *et al.*, 2024). An appropriately designed smartphone application (app) could be an elegant solution, allowing for run-by-run capture of sensed data (e.g., biomechanical and training-related data) and runner-reported subjective data (e.g., sleep, recovery, menstruation) in runners' natural environments. This system should also capture injuries across their entire development process, using a holistic approach to monitor all possible consequences of injury.

There appear to be several challenges in designing such a surveillance system and conducting this type of research: (i) ensuring accurate and complete capture of the full extent of the RRI development process, (ii) ensuring runners engage with wearable technologies to collect this frequent and extensive data, and (iii) ensuring the recruitment and retention of runners into prospective research, where involvement is likely onerous. This thesis employs a mixed-methods approach, reflecting my pragmatic position, exploring both *what* has been done and *how* research could potentially evolve, in the pursuit of understanding RRIs. In terms of the first challenge, a critical step in understanding RRIs is appropriately defining them. Despite their overuse nature, gradual symptom development, and runners' common behaviour to continue to run with injury, RRIs are defined by high threshold criteria, largely relying on time-loss to determine injury onset (Yamato *et al.*, 2015). This is problematic because less severe injuries that do not cause time-loss, but are associated with sub-clinical pathologies (interfering with running, but not preventing it) are not being recorded (Clarsen, Myklebust and Bahr, 2013). It is important that these injuries are captured to examine their relationship with 'typical' RRIs (i.e., those that *do* cause time-loss), how they interact with other risk factors, and their role as potential risk factors themselves (Soligard *et al.*, 2016; Whalan, Lovell and Sampson, 2020).

To address the challenge of defining, capturing and reporting RRI data, it is important to understand what has been done previously. Just one previous review has been conducted on the definitions of RRIs (Yamato *et al.*, 2015), while no reviews have examined injury severity, or the surveillance methods employed. In addition, understanding runners' lived experiences of RRIs may allow for more appropriate examination of the less severe injuries; however, just three studies explore runners' perception of injury and its development process (Jelvegård *et al.*, 2016; Wickström *et al.*, 2019; Verhagen, Warsen and Silveira Bolling, 2021). While providing valuable information on the 'progressive' nature of injuries and recognising the 'complaint' level along the Injury Pathway model (Verhagen, Warsen and Silveira Bolling, 2021), a greater understanding of this process is required if researchers and clinicians are to better understand the multifactorial nature of RRIs, their risk factors, and means of prevention.

With regard to the second challenge, while convenience is one of the greatest advantages of smartphone app utilisation for research, and developments in wearable technologies have made it possible to prospectively and remotely collect extensive data (Clermont *et al.*, 2019; Malasinghe, Ramzan and Dahal, 2019), adherence can be low (Daniore, Nittas and Von Wyl, 2022). The majority of research investigating runners' use of technologies has focused on performance enhancement as the primary motivation (Vos *et al.*, 2016; Stragier, Vanden Abeele and De Marez, 2018; Feng and Agosto, 2019; Janssen *et al.*, 2020), with just one study examining runners' use of technology for preventing injury (Clermont *et al.*, 2019). Therefore, to enhance the adoption of these devices for injury prevention purposes, it is essential to understand runners' perceived barriers and facilitators to their use.

Finally, in relation to the third challenge, with intra- and inter-individual variability of RRI risk factors (Borresen and Lambert, 2009) and the high variability in running kinematics and kinetics (Bartlett, Wheat and Robins, 2007; Preatoni *et al.*, 2013), recruiting a sufficiently large sample size is required to represent these variabilities and ensure ecologically valid findings (Oliveira and Pirscoveanu, 2021). However, participant retention is a major challenge of prospective, longitudinal research (Mychasiuk and Benzies, 2012) and high attrition can occur as a consequence of the prolonged duration and onerous participant involvement (Davis, Broome and Cox, 2002; Teague *et al.*, 2018). Participant retention has also been found to be particularly problematic in research involving wearable technologies (Attig and Franke, 2020; Meekes, Ford and Stanmore, 2021). Therefore, to facilitate participant-friendly research, it is essential that the perceived barriers and facilitators to research recruitment and retention are identified. No studies appear to have addressed this in runners.

## 1.2. Overall aims of thesis

The overall aim of this thesis is **to explore factors important for the development of an extensive surveillance system for RRIs**, potentially using a smartphone app and wearable device(s), to target the fundamental aspects of epidemiological research that appear to be limiting the prevention of RRIs. This thesis addresses several research questions to explore this overall aim:

1. To **examine how RRIs have been defined and captured**,
2. To **investigate how RRI severity has been measured**,
3. To **explore runners' description and management of the injury development process**.
4. To **identify the barriers and facilitators to runners' use of wearable technologies for preventing injury,**
5. To **examine the barriers and facilitators to the recruitment and retention of recreational runners in prospective research**.

### 1.2.1. Chapter 3: Study 1: Definitions and surveillance methods of running-related injuries: A scoping review

The broad aim of this scoping review was to investigate the registration of RRIs in the literature. This was addressed primarily by examining how RRIs are defined, and secondly by investigating the methods of RRI surveillance. A systematic search was conducted for studies which investigated RRIs in adult running populations, providing a definition for a general RRI. Results were extracted and collated. This review (Chapter 3) has been published:

**Lacey, A**., Whyte, E., Dillon, S., O'Connor, S., Burke, A. and Moran, K. (2024) 'Definitions and surveillance methods of running-related injuries: A scoping review'. *European Journal of Sport Science*. DOI: 10.1002/ejsc.12123.

### 1.2.2. Chapter 4: Study 2: An investigation into the measurement of injury severity in running-related injury research: A scoping review

The primary aim of this scoping review was to investigate how injury severity is measured in RRI research by describing the injury severity scales used (in terms of the criteria for defining injury severity and the grading of injury severity), and examining to what extent these scales differ. A secondary aim was to examine if the way in which injury severity is measured influences the study outcomes (i.e., the rate of injury reported and the risk factors identified). A systematic search was conducted for studies which investigated RRIs in adult running populations, utilizing a measure of injury severity for general RRIs. Results were extracted and collated. This review (Chapter 4) has been published:

**Lacey, A**., Whyte, E., Burke, A., O'Connor, S., Dillon, S. and Moran, K. (2024) 'An investigation into the measurement of injury severity in running-related injury research: A scoping review', *Scandinavian Journal of Medicine and Science in Sports*. DOI: 10.1111/sms.14704.

### 1.2.3. Chapter 5: Study 3: The Running Injury Continuum: A qualitative examination of recreational runners' description and management of injury

The aim of this study was to examine recreational runners' description and management of the injury development process. To investigate this, a qualitative focus group study was carried out. Seven semi-structured, in-person, focus groups with male (n=13) and female (n=18) recreational runners took place. Focus groups were audio and video recorded, and transcribed verbatim. Transcripts were reflexively thematically analysed (Braun and Clarke, 2019), and multiple methods of trustworthiness were executed (McGannon *et al.,* 2018; Smith and McGannon, 2018; Sparkes and Smith, 2014; Tracy, 2010), and multiple methods of trustworthiness were executed. This paper (Chapter 5) has been published:

**Lacey, A**., Whyte, E., O'Keeffe, S., O'Connor, S., Burke, A. and Moran, K. (2023) 'The Running Injury Continuum: A qualitative examination of recreational runners' description and management of injury', *PLoS One*, 18(10), p. e0292369. DOI: 10.1371/journal.pone.0292369.

### 1.2.4. Chapter 6: Study 4: A qualitative examination of the factors affecting the adoption of injury focused wearable technologies in recreational runners

The aims of this study were to determine the metrics deemed important by runners for monitoring running-related injury risk, and identify the facilitators and barriers to their use of injury focused wearable technologies. To investigate this, a qualitative focus group study was carried out. Nine semi-structured focus groups with male (n=13) and female (n=14) recreational runners took place. Focus groups were audio and video recorded, and transcribed verbatim. Transcripts were reflexively thematically analysed (Braun and Clarke, 2019) and multiple methods of trustworthiness were executed (McGannon *et al.,* 2018; Smith and McGannon, 2018; Sparkes and Smith, 2014; Tracy, 2010). This paper (Chapter 6) has been published:

**Lacey, A**., Whyte, E., O'Keeffe, S., O'Connor, S. and Moran, K. (2022) 'A qualitative examination of the factors affecting the adoption of injury-focused wearable technologies in recreational runners', *PLoS One*, 17(7), p. e0265475. DOI: 10.1371/journal.pone.0265475.

### 1.2.5. Chapter 7: Study 5: Recruitment and retention of recreational runners in prospective injury research: A qualitative study

The aim of this study was to identify factors for facilitating the recruitment and retention of recreational runners in prospective, longitudinal running-related injury research involving running technologies. Twenty-seven male (n=13) and female (n=14) recreational runners participated across nine semi-structured focus groups. Focus groups were audio and video recorded and transcribed verbatim. A reflexive thematic analysis was undertaken (Braun and Clarke, 2019), and multiple methods of trustworthiness were executed (McGannon *et al.,* 2018; Smith and McGannon, 2018; Sparkes and Smith, 2014; Tracy, 2010). This paper (Chapter 7) has been published:

**Lacey, A**., Whyte, E., O'Keeffe, S., O'Connor, S. and Moran, K. (2023) 'Recruitment and retention of recreational runners in prospective injury research: A qualitative study', *International Journal of Qualitative Methods*, 22. DOI: 10.1177/16094069231178278.

### 1.3. Delimitations

This thesis is focused on the surveillance of *general* RRIs. With that, specific injuries (e.g., Achilles tendinopathy) were not typically examined through the review of literature, nor investigated in the subsequent studies contained in this thesis. General RRIs were considered for several reasons:

1. Due to the wide range of injuries (across anatomical locations and specific diagnoses) associated with running, and their common possible mechanisms (e.g., training behaviour), it is better to be able to identify patterns and underlying causes for multiple types of injuries (i.e., general RRIs) to develop preventions interventions which are more applicable and beneficial to a larger population. Furthermore, the practical implications for clinicians, runners and coaches may be more applicable.
2. For a holistic understanding of injury, it is important to consider that multiple injuries may occur simultaneously (e.g., Achilles tendinopathy and patellofemoral pain syndrome), and investigating general RRIs can enhance our understanding of these injuries' interactions and role as possible risk factors.
3. Inter-individuality between runners may predispose them to varying types of injuries (e.g., sex, age), and focusing on specific injuries may limit our understanding of the broader trends and risk factors across groups.

4. To develop a foundation for future research, we must first lay the groundwork on broad risk factors for general RRIs. More focused studies may follow when the fundamentals of RRIs are better understood.

In addition, there are numerous sub-groups of runners that potentially exist within the scope of 'recreational runners', each with varying perceptions, experiences, motivations for running, and risk factors for injury. Those who participated in the research outlined in this thesis were considered recreational runners as: those running at least once per week for at least six months (adapted from Mulvad *et al.*, 2018). It is important to consider the subsequent findings and implications in light of this.

# 2. Chapter 2: Review of literature

## 2.1. Introduction to the review of literature

The overall objective of this review of literature is to analyse the current literature relating to the development of a novel surveillance approach for RRIs, which for example, could be implemented with a smartphone application. This review of literature is divided into three sections. The first section focuses on the development of RRIs, examining injury epidemiology, definition of injury, injury severity measurement, surveillance methods, and the development process of RRIs. The second section examines running technologies, with a focus on the perceived barriers and facilitators to their use. The third section addresses participants' involvement in longitudinal injury research, focusing on enhancing the recruitment and retention of recreational runners.

## 2.2. The development of running-related injuries

### 2.2.1. Epidemiology of running-related injuries

Injury epidemiology concerns the distribution and determinants of injury among a specific population, with subsequent findings being applied to efforts to prevent or reduce the likelihood of such injuries (Petridou and Antonopoulos, 2017). Epidemiological studies can be broadly classified as either observational or experimental (Woodward, 2013; Munnangi and Boktor, 2023). Types of observational studies include cross-sectional, case control and cohort studies (Khan, Kumar and Chatterjee, 2014). Cross-sectional studies are most useful for describing injury epidemiology as they capture a 'snapshot' of the issue at a particular moment in time. However, they can be limited by associated recall bias as participants have to retrospectively recall whether risk factor exposure or onset of injury occurred first (Woodward, 2013). Case control studies compare cases (those with an injury) and controls (those without an injury) to determine the presence and role of risk factors between groups. While advantageous for the examination of rare cases, this type of study is unable to measure likelihood of injury (Woodward, 2013). Cohort studies investigate a specific population and their exposure to certain risk factors, measuring the outcome (i.e., injury) over a period of time. They represent the strongest design among observational research for the capture of injury rates and the investigation of risk factors (Song and Chung, 2010). In particular, prospective cohort studies, in which a population is followed over a prolonged period of time, can provide insight into confounding factors for the occurrence of injury (Woodward, 2013). However, this research is not without challenges, including the prolonged length of studies, high participant onus, and likely dropout (Teague *et al.*, 2018; Meekes, Ford and Stanmore, 2021).

Epidemiology is the foundation of injury prevention research (Van Mechelen, Hlobil and Kemper, 1992). In terms of RRIs, this foundational evidence is unclear, with large variances in rates of injury (Kakouris, Yener and Fong, 2021) and a lack of clarity on risk factors (Ceyssens *et al.*, 2019; van Poppel *et al.*, 2021; Peterson *et al.*, 2022), hampering the progress of injury prevention.

#### 2.2.1.1. Prevalence and incidence of running-related injuries

In contrast to the many positive physical and mental health benefits associated with regular running (Pedersen and Saltin, 2015; Pedisic *et al.*, 2020), running is also associated with injury (Lopes *et al.*, 2012; Kakouris, Yener and Fong, 2021). RRIs have been reported as figures of prevalence and incidence. In a 2020 consensus statement, the International Olympic Committee (IOC) suggested that incidence better represents acute injuries, while prevalence is more appropriate for overuse injuries (Bahr *et al.*, 2020). Prevalence refers to the proportion of a specific population who have an injury *at* a particular point in time (Noordzij *et al.*, 2010), but can be captured repeatedly to determine changes in prevalence over time (e.g., weekly), or widened to 'period prevalence' to represent the number of people who reported an injury during a longer time-frame (e.g., 1 year) (Bahr *et al.*, 2020). Prevalence is usually reported as a percentage, calculated using the following formula:

$$\text{Prevalence} = \frac{\text{Number of people with an injury at a certain point in time}}{\text{Total number of people in the population}}$$

(Noordzij *et al.*, 2010)

Incidence reflects the number of new cases of an injury *during* a particular time (Noordzij *et al.*, 2010), representing a 'rate' of injury (Bahr *et al.*, 2020). It can be expressed in multiple formats, including a cumulative rate (as a percentage), in terms of exposure time (e.g., per 1000 hours of running), or in terms of people at risk (e.g., per 1000 runners) (Noordzij *et al.*, 2010). Incidence can be calculated using the following formula:

$$\text{Incidence} = \frac{\text{Number of people who develop a new injury during a period of time}}{\text{Total number of people observed during that period of time}}$$

(Noordzij *et al.*, 2010)

In order to review the literature on RRI epidemiology (i.e., incidence, prevalence, and risk factors), a search for systematic reviews and/or meta-analyses examining the epidemiology of general musculoskeletal RRIs in adult runners was conducted. The PubMed database was searched using the following search string: "running-related" OR "running" AND "injur*" AND "epidemiologic*" OR "incidence" OR "prevalence" OR “rate” OR “risk” OR “risk factor*” on 13th March 2024, with findings limited to systematic reviews and/or meta-analyses. Out of a total of 202 search results, 24 were included in the current review of literature. Studies were not included if they: (i) did not investigate musculoskeletal RRIs, (ii) included other types of athletes (e.g., soccer players, triathletes), (iii) included child or adolescent participants, (iv) only included specific RRIs (e.g., Achilles tendinopathy), and (v) only included injuries to a specific anatomical location (e.g., knee injuries). An overview of included reviews is presented in Table 1.

Prevalence of RRIs ranged from 1.3-93.0% (Viljoen *et al.*, 2022), with average prevalence reported as 44.6% ± 18.4% (Kakouris, Yener and Fong, 2021) (Table 1). Incidence figures ranged between 3.2-84.9% (Kluitenberg *et al.*, 2015), with an average incidence of 40.2% ± 18.8% (Kakouris, Yener and Fong, 2021) reported. Incidence was also reported between 0.7-4,285 injuries/1000 hours of running (Viljoen *et al.*, 2021; Viljoen *et al.*, 2022), and 5.9-2762 injuries/1000 runners (Viljoen *et al.*, 2022) (Table 1).

Prevalence and incidence figures reported span a very large range, causing significant difficulty in interpreting findings, and their subsequent implications. Such variance may result from methodological differences across studies, including study designs, population samples, and follow up time (Kakouris, Yener and Fong, 2021). However, other possible reasons include: (i) variances in the definition of injury (Kluitenberg *et al.*, 2016), (ii) a lack of consideration for severity of injury (Bahr, Clarsen and Ekstrand, 2018), and (iii) variances in methods of injury surveillance (Clarsen, Myklebust and Bahr, 2013); aspects that will be addressed later (sections 2.2.2, 2.2.3 and 2.2.4, respectively).

Table 1. Epidemiology and aetiology of running-related injuries: A summary of systematic reviews

| **Review study** | | **Included studies** | **Population** | **Incidence** | **Prevalence** | **Strong evidence for risk factors for general RRIs** |
|---|---|---|---|---|---|---|
| **1** | (van Gent *et al.*, 2007) | 17 studies: 13 prospective cohort, 4 retrospective cohort.<br>From 1982-2004 | Recreational, 5km/10km, marathon/half marathon.<br>Number of participants NR | 19.4 - 79.3% | NR | Previous injury (4 studies)<br>Higher weekly training distance (>64km/week) (male only) (2 studies) |
| **2** | (Perkins, Hanney and Rothschild, 2014) | 23 studies: Type NR.<br>From 1999-2014 | NR | NR | NR | No strong evidence to support any risk factors |
| **3** | (Saragiotto *et al.*, 2014) | 11 studies: 11 prospective cohort.<br>From 1989-2012 | Novice, amateur, cross-country, recreational, marathon.<br>4,671 participants | NR | NR | Previous injury (in the last 12 months) (5 studies)<br>Weekly running distance (>64 km/week) (2 studies)<br>Weekly running frequency (no consistent frequency found) (2 studies)<br>Higher Q angle (2 studies) |
| **4** | (Gijon-Nogeuron and Fernandez-Villarejo, 2015) | 25 studies: 11 RCTs, 5 systematic reviews, 3 controlled laboratory, 2 analytical observation trials, 2 retrospective cohorts, 1 case-control study, 1 descriptive study.<br>From 1995-2013 | NR.<br>902 participants | NR | NR | No strong evidence to support any risk factors |
| **5** | (Kluitenberg *et al.*, 2015) | 86 studies: 51 prospective cohort, 24 retrospective, 5 cross- sectional, 6 RCTs.<br>From 1978-2014 | Recreational, novice, marathon, ultra-marathon, track (sprinters, middle- & long- distance runners).<br>Number of participants NR | 3.2%-84.9% | NR | NR |
| **6** | (van der Worp *et al.*, 2015) | 15 studies: 13 prospective cohort, 2 retrospective cohort.<br>From 1989-2012 | Novice, recreational, competitive.<br>Number of participants NR | Overall: 20.6-79.3%<br>Male: 25.0-79.5%<br>Female: 19.8-79.1% | NR | Previous injury (4 studies) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **7** | (Videbæk *et al.*, 2015) | 13 studies: 8 prospective cohort, 5 RCTs.<br>From 1987-2015 | Novice, recreational, ultra-marathon, track & field.<br>4,112 participants | 2.5-33.0/1000 hours | NR | NR |
| **8** | (Mann *et al.*, 2016) | 8 studies: 5 retrospective, 3 prospective.<br>From 2004-2015 | Novice, experienced, recreational.<br>580 participants | NR | NR | No strong evidence to support any risk factors. |
| **9** | (van der Worp, Vrielink and Bredeweg, 2016) | 18 studies: 16 case-control, 2 prospective cohort.<br>From 1991-2015 | NR.<br>1172 participants | NR | NR | Loading rate in those with a history of stress fractures and those with all RRI types (1 study) |
| **10** | (Damsted *et al.*, 2018) | 4 studies: 2 prospective, 1 RCT, 1 cross-sectional.<br>From 2008-2014 | Novice, leisure-time.<br>1,563 participants | NR | NR | No strong evidence to support any risk factors. |
| **11** | (Ceyssens *et al.*, 2019) | 16 studies: 16 prospective cohort.<br>From 2006-2018 | Novice, recreational, cross-country, experienced.<br>2,625 participants | NR | NR | No strong evidence to support any risk factors. |
| **12** | (Christopher *et al.*, 2019) | 7 studies: 7 prospective cohort.<br>From 2007-2016 | Novice, cross-country, track, recreational, high school.<br>1,181 participants | NR | NR | No strong evidence to support any risk factors. |
| **13** | (Anderson *et al.*, 2020) | 52 studies: Type NR.<br>From 2003-2019 | Competitive, recreational, experienced, middle- and long-distance, cross-country, active individuals, habitual RFS and NRFS runners.<br>1,393 participants | NR | NR | No strong evidence to support any risk factors. |
| **14** | (Vannatta, Heinert and Kernozek, 2020) | 13 studies: 13 prospective cohort.<br>From 2006-2018 | Recreational, collegiate cross- country, high school cross-country. | NR | NR | No strong evidence to support any risk factors. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 923 participants | | | |
| **15** | (Burke *et al.*, 2021) | 12 studies: 9 retrospective cohort, 3 prospective cohort. From 2008-2021 | Recreational, collegiate cross- country, competitive. 2,564 participants | NR | NR | No strong evidence to support any risk factors. |
| **16** | (Hollander *et al.*, 2021) | 38 studies: 37 prospective, 1 case-control. From 1983-2020 | Road runners, middle- and long-distance, cross-country, recreational, novice, competitive, elite. 35,689 participants | 20.8/100 female 20.4/100 male | NR | No strong evidence to support any risk factors. |
| **17** | (Kakouris, Yener and Fong, 2021) | 42 studies: 24 prospective cohort, 15 retrospective cohort, 3 cross-sectional. From 1974-2020 | Ultramarathon, marathon/half- marathon, middle- and long- distance, novice, recreational, amateur, competitive. Number of participants NR | 40.1±18.8% | 44.6±18.8% | NR |
| **18** | (van Poppel *et al.*, 2021) | 29 studies: 29 prospective cohort. From 1998-2018 | Short- and long- distance. 18,852 participants | NR | NR | No strong evidence to support any risk factors. |
| **19** | (Viljoen *et al.*, 2021) | 16 studies: 8 prospective, 8 cross- sectional. From 1990-2020 | Trail runners. 8,644 participants | 1.6-4285/1000 hours[1] | NR | NR |
| **20** | (Peterson *et al.*, 2022) | 30 studies: 30 prospective. From 1998-2021 | Cross-country, novice, competitive, recreational. 3,404 participants | 3.8-79.3% | NR | No strong evidence to support any risk factors. |
| **21** | (Fredette *et al.*, 2022) | 36 studies: 33 prospective cohort, 3 RCTs. From 1977-2020 | Novice, recreational, competitive, mixed ability. 23,047 participants | 26.2% (8.8-91.3%) | NR | No strong evidence to support any risk factors. |

[1] Injuries were recorded based on the definitions used in individual studies, many of which used self-report-, or medical encounter-based definitions

| | | | | | | |
|---|---|---|---|---|---|---|
| **22** | (Relph *et al.*, 2022) | 9 studies: 6 two-arm parallel RCTs, 3 three-armed parallel-group trials.<br>From 2011-2020 | Recreational, distance, endurance.<br>Number of participants NR | NR | NR | No strong evidence to support any risk factors. |
| **23** | (Viljoen *et al.*, 2022) | 13 studies: 7 observational, 2 prospective cohort, 2 retrospective, 2 cross-sectional.<br>From 2000-2021 | Trail runners.<br>9,763 participants | 0.7-61.2/1000 hours<br>5.9-2762.1/1000 runners[2] | 1.3-93.0% | No strong evidence to support any risk factors. |
| **24** | (Correia *et al.*, 2024) | Umbrella review: 13 systematic reviews.<br>From 2007-2023 | Novice, recreational, competitive, experienced.<br>Total number of participants NR | NR | NR | Critically low and low quality systematic reviews exhibit evidence for health & lifestyle factors (alcohol consumption, participation in other sports, previous injury), and training factors (increased race participation, marathon running, initiation into running, weekly running distance) to be related to RRI risk.<br>Insufficient evidence to conclusively identify biomechanical risk factors |

NR: not reported; RRI: running-related injury; Q-angle: quadriceps angle; RCT: randomized controlled trial; RFS: rearfoot strike; NRFS: non-rearfoot strike.

[2] Injuries were recorded based on the definitions used in individual studies, many of which used self-report-, or medical encounter-based definitions

#### 2.2.1.2. Models of injury aetiology

From a biomechanical perspective, injury occurs when excessive load is applied to a tissue beyond its integrity and adaptive capability (Hreljac, 2004; Edwards, 2018). These loads are either applied via a single macro-traumatic incident, in which the magnitude of this single load exceeds tissue integrity, or via repetitive micro-traumatic events, in which the accumulation of these loads exceed tissue integrity (Hreljac, 2004; Edwards, 2018). In running, the majority of injuries are overuse in nature (Lopes *et al.*, 2012), resulting from repetitive, micro-traumatic loads (Hreljac, 2004; Edwards, 2018).

There are a number of theoretical models depicting the aetiology of sports injuries, including: the stress-injury model (Andersen and Williams, 1988), biological adaptation through cycles of loading and recovery (Soligard *et al.*, 2016), the acute-chronic workload ratio (Gabbett, 2016), and the framework for stress-related, strain-related and overuse injury (Kalkhoven, Watsford and Impellizzeri, 2020). However, for the purpose of this review of literature, the evolution of the understanding of RRI aetiology will be described with four models: Meeuwisse *et al.'s* (2007) dynamic and recursive multifactorial model of injury (as it is one of the most cited), and the only three models specific to RRIs: Malisoux *et al.*'s (2015) conceptual RRIs, Bertelsen *et al.*'s (2017) framework for the causal mechanism of RRIs, and Hulme *et al.*'s (2017) Australian distance running system.

In 1994, Meeuwisse described a multifactorial model of general sports injury aetiology (Meeuwisse, 1994), later updating this model to better reflect its dynamic, recursive nature (Meeuwisse *et al.*, 2007) (Figure 1). This model describes how, initially, intrinsic risk factors (e.g., age, previous injury) alter an athlete’s predisposition to injury, while exposure to extrinsic risk factors (e.g., equipment, environment) alters their susceptibility. The ‘susceptible athlete’ is a point in the model where the intrinsic and extrinsic risk factors, and their interactions, accumulate. With non-injurious events, ‘no injury’ is the subsequent outcome; however, with the addition of an inciting event, ‘injury’ occurs

(Figure 1; Meeuwisse *et al.*, 2007). When injury occurs, requiring removal from activity, a phase of recovery and tissue adaptation (and/or maladaptation) unfolds, facilitating the athlete's re-entry into sport. However, the athlete now possesses a new set of intrinsic risk factors (e.g., previous injury), altering their predisposition to injury. This, in turn, may result in changes to the extrinsic risk factors (e.g., use of equipment), altering injury susceptibility at the next athletic exposure. In the case of 'no injury', training adaptations (and/or maladaptations) may still occur, altering injury predisposition and susceptibility. Therefore, even in the absence of injury, the risk of injury at each athletic exposure is constantly changing (Meeuwisse *et al.*, 2007). This model emphasises the need for the frequent capture of injury data, ideally at each athletic exposure.

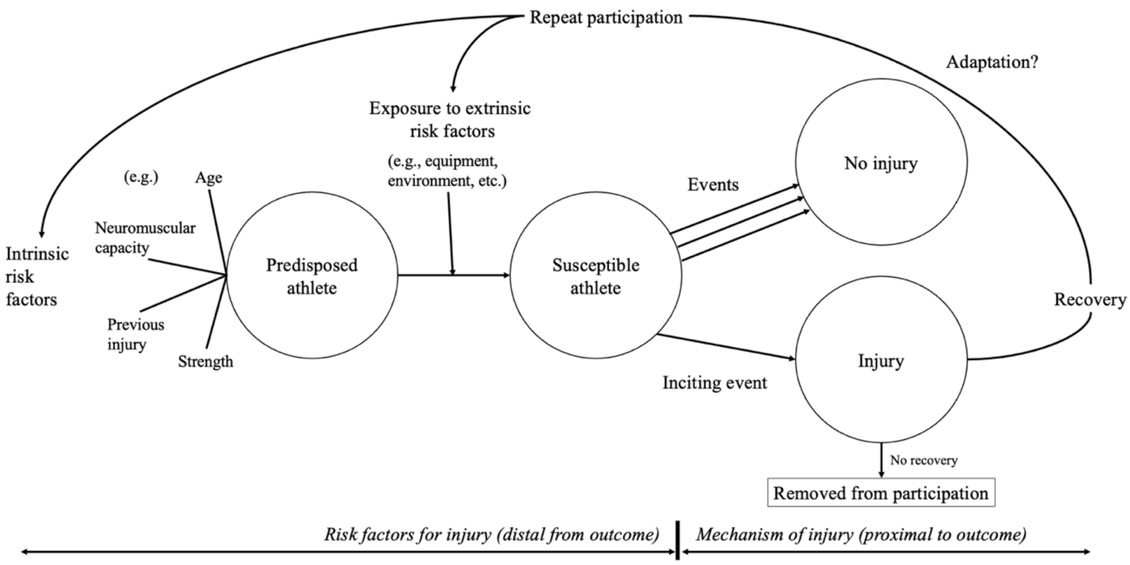



Figure 1. The dynamic, recursive model of etiology in sport injury (Meeuwisse *et al.*, 2007)

Malisoux *et al.*'s (2015) model of RRI aetiology considers training-related characteristics (e.g., weekly volume, session frequency) as the primary exposure of interest, based on the notion that RRIs cannot occur without exposure to running (Figure 2). Other factors which contribute to the predisposition and susceptibility to injury (i.e., non-training-related characteristics) are referred to as effect-measure modifiers. These factors affect tissues' capacity to tolerate loading before sustaining an injury. Testing this model with data collected from a prospective randomized controlled trial, the risk of injury was examined with regard to training-related characteristics in isolation (i.e., no effect-measure modifiers) (Malisoux *et al.*, 2015). Lower weekly running volume (<2 hours) and lower weekly session frequency (<2 session) displayed higher hazard ratios. The role of the effect-measure modifiers was then considered, in combination with the assumed primary risk factors (i.e., training-related factors). Identifying statistical significance, the authors concluded that two sub-populations were at a particularly high risk of RRI: those with a combined previous history of a RRI and who have a lower weekly running volume (<2 hours), and those with a combined low body mass index (BMI) (less than 25) and a lower weekly running volume (<2 hours) (Malisoux *et al.*, 2015). This model, and the subsequent significant findings, emphasizes the importance of taking a multifactorial approach to RRI investigation.

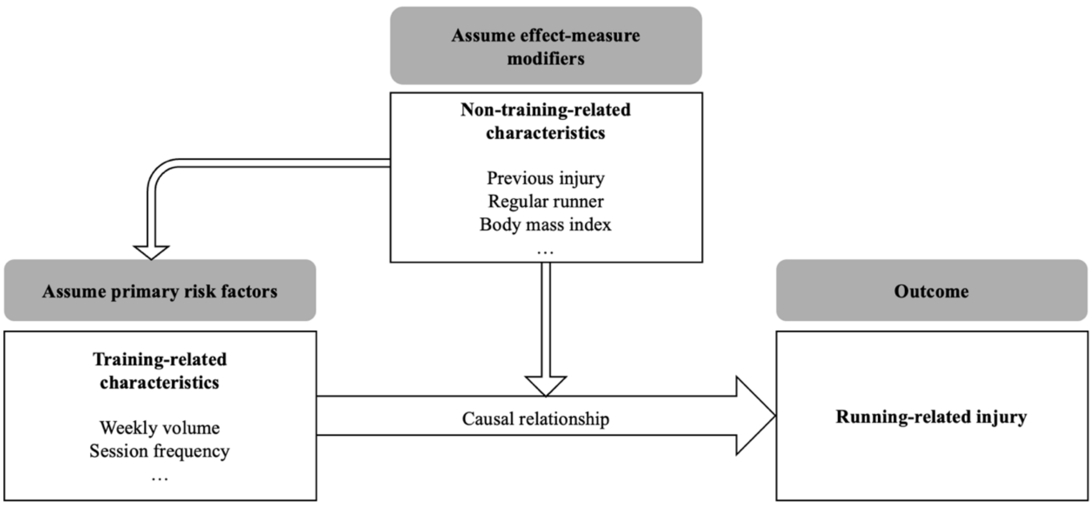



Figure 2. A conceptual model of the determinants of running-related injuries (Laurent Malisoux *et al.*, 2015)

Bertelsen and colleagues (2017) present a framework outlining the multifactorial nature specific to RRI onset (Figure 3), following recommendations made from an IOC consensus meeting regarding loading and injury risk (Soligard *et al.*, 2016). This model is novel in its presentation of the relationship between running participation and the cumulative structure-specific load. Four parts of this conceptual model are presented: (A) structure-specific capacity when entering a running session, (B) structure-specific cumulative load per running session, (C) reduction in the structure-specific capacity during a running session, and (D) exceeding the structure-specific capacity (Bertelsen *et al.*, 2017). Part A represents a tissue's capacity to tolerate loading during a single running session, drawing similarities to the intrinsic or predisposing factors seen in Meeuwisse *et al.*'s (2007) model, and the effect-measure modifiers in Malisoux *et al.*'s (2015) model. Part B considers the cumulative load as the sum of the number of strides taken per session, with load distribution and load magnitude per stride being of particular importance. This framework emphasizes that injury risk changes based on the dose-response relationship of loading/running practice (Bertelsen *et al.*, 2017). Part C represents the structures' reduction in load-capacity, determined by the combined input of Parts A and B. Part D represents when a structure's capacity to tolerate load is exceeded. Broadly speaking, this can occur either in a single session or over multiple running sessions. However, a specific injurious-session will exist, in which the multiple load repetitions (i.e., strides) will result in tissue failure (i.e., injury) (Bertelsen *et al.*, 2017).

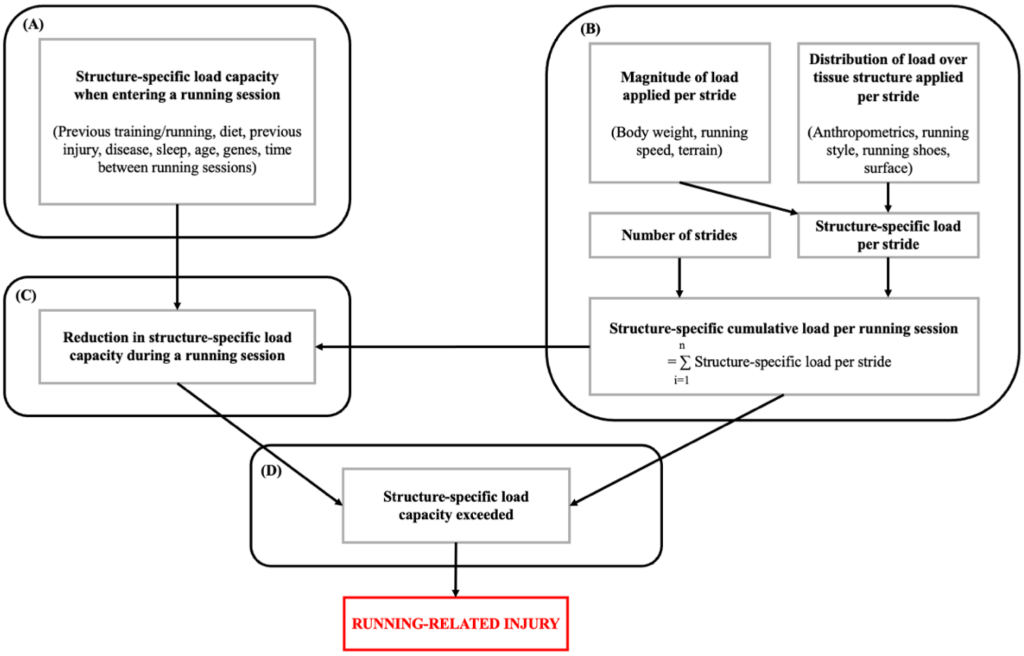



Figure 3. A conceptual model for the causal mechanism underpinning running-related injury within one single running session (Bertelsen *et al.*, 2017)

Finally, Hulme *et al.* (2017) present a complex systems model detailing the political, organisational, managerial and sociocultural processes that make up the intermediate pathways influencing runners' training-related and behavioural practices in the development of RRIs. Due to the extent of the entire 'complex systems model', only level five is described in the main body of this thesis (Figure 4). The full model of the Australian distance running system can be found in Appendix A1. This model considers the causal relationships between load-related and capacity-related exposures, and RRI development at an individual level. Adapted from Bertelsen *et al.*'s (2017) slightly earlier framework, there are two categories of factors that contribute to individual injury risk: external and environmental factors (which are load-related), and lifestyle factors (which are capacity-related). Only with exposure to running (number of strides), which consists of the balance between structure-specific load capacity and structure-specific cumulative load, does a RRI occur (Hulme *et al.*, 2017). Inclusive of the sociotechnical systems contexts (i.e., levels one to four of the complete model, [Appendix A1]), this appears to be the most comprehensive framework for conceptualising the entire system responsible for RRIs to date.

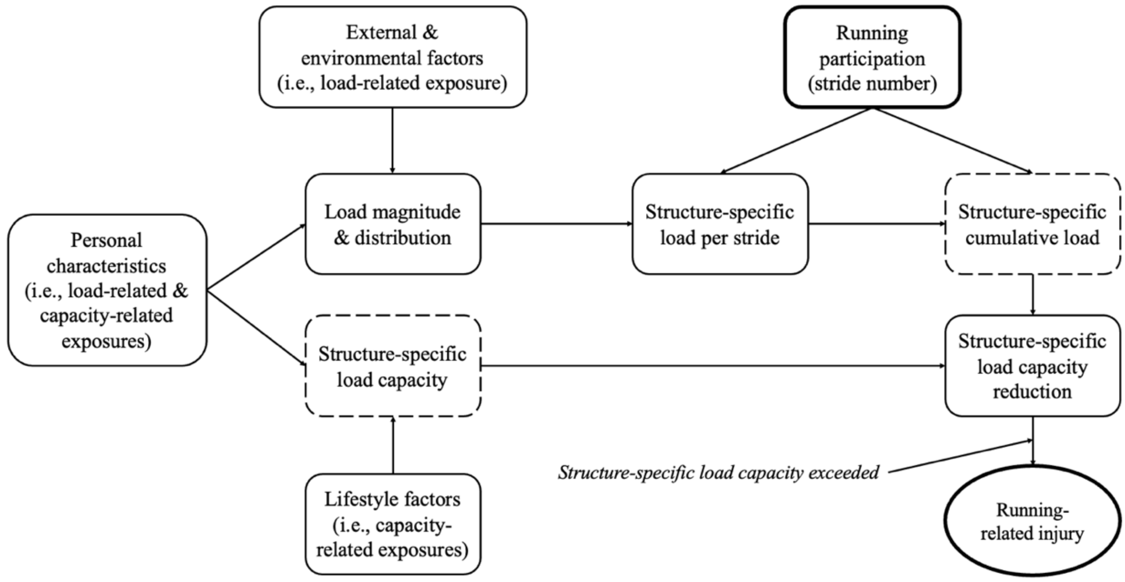
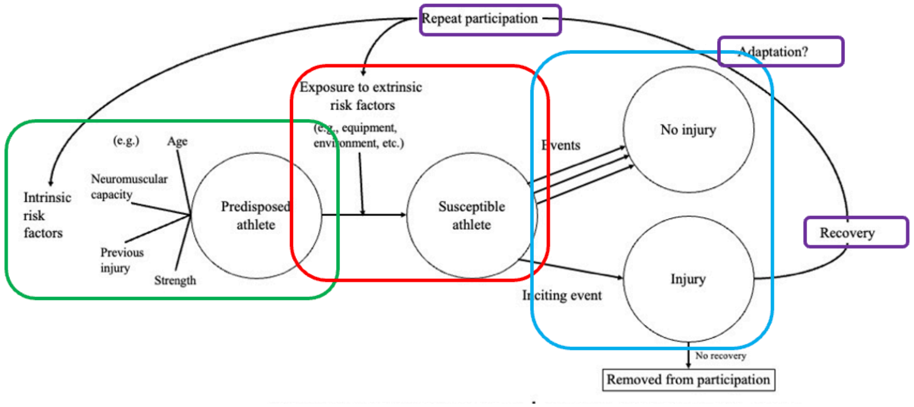
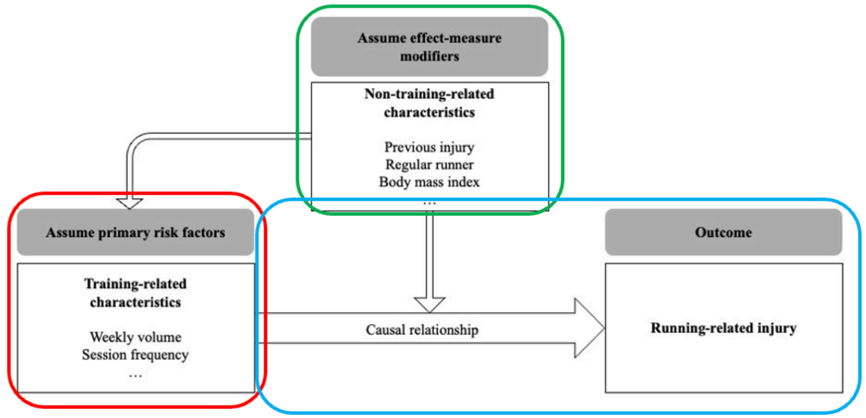



Figure 4. The relationship between structure-specific load capacity, structure-specific cumulative load, and running-related injury (as part of the Australian distance running system) (Hulme *et al.*, 2017)

Comparing these four models, three aspects appear consistent. Firstly, all models identify underlying, intrinsic risk factors that affect tissues' capacity to tolerate load (highlighted in green in Figure 5). While being the initial step in Meeuwisse *et al.'s* (2007) and Malisoux *et al.'s* (2015) models, this aspect occurs in sequence with Part B of Bertelsen *et al.'s* (2017) framework, and with the external and environmental factors in Hulme *et al.'s* (2017). Secondly, the importance of the dose-response relationship between loading/running practice and injury is emphasised by inclusion in all four models (highlighted by the red in Figure 5). This relationship is multidimensional, resulting from the careful balance between overloading and under-conditioning. Finally, all models recognise a process where load exceeds tissue integrity, resulting in a clear outcome of injury (highlighted in blue, Figure 5). There are also some differences of note. Firstly, only Meeuwisse *et al.'s* (2007) model of general sports injury depicts the cyclic nature associated with overuse injury development, with this aspect seemingly lacking from the latter three models (highlighted in purple, Figure 5). Secondly, Bertelsen *et al.* (2017) seem to take a novel approach with their consideration for *cumulative* structure-specific load, which Hulme *et al.* (2017) carry through in their model (highlighted in yellow, Figure 5).

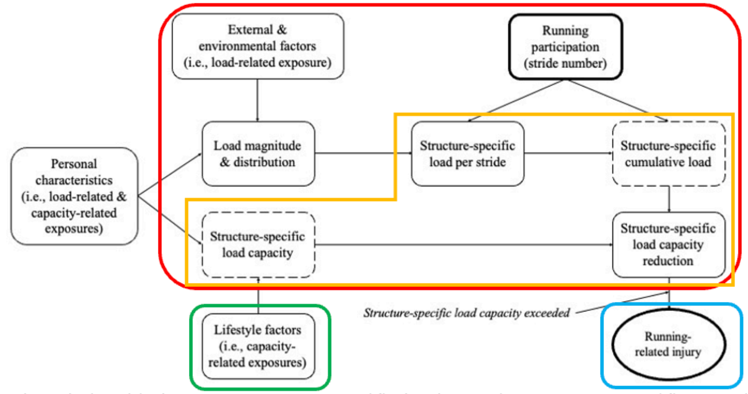



(i) The dynamic, recursive model of etiology in sport injury (Meeuwisse *et al.,* 2007)




(ii) A conceptual model of the determinants of running-related injuries (Malisoux *et al.,* 2015)


(iii) A conceptual framework for the causal mechanism underpinning running-related injury within one single running session (Bertelsen *et al.,* 2017)




(iv) The relationship between structure-specific load capacity, structure-specific cumulative load, and RRI (Hulme *et al.,* 2017)

Figure 5. Models of injury aetiology, with similarities and differences highlighted by coloured shapes

Strengths of each model should also be highlighted. Meeuwisse *et al.* (2007) seem to be one of the earliest to conceptualize the dynamic and cyclic nature of injury risk and injury outcome. Malisoux *et al.'s* (2015) model clearly demonstrates the need for considering training-related factors and effect-measure modifiers in combination for determining specific populations at-risk for injury. Bertelsen *et al.* (2017) and Hulme *et al.* (2017) demonstrate the importance of quantifying running exposure through cumulative structure-specific loading. There are also some limitations to consider. Firstly, Malisoux *et al.'s* (2015), Bertelsen *et al.* (2017) and Hulme *et al.* (2017) do not portray the cyclic, progressive nature of RRI onset, demonstrating only unidirectional pathway to injury. Secondly, all four models consider 'injury' as a dichotomous outcome, without any consideration for the potential role of varying levels of injury severity. Repeated 'events' (Meeuwisse *et al.*, 2007) that do not result in 'injury' (i.e., removal from activity), but do provoke a mechanism of tissue (mal)adaptation could be considered sub-levels of injury. Evidence for these sub-levels of injury is described in section 2.2.5. In addition, the possibility of individual perception of tissue damage/injury (and the associated consequences) is not taken into consideration with a dichotomous definition. Thirdly, these models focus on external loading as the primary extrinsic risk factor, seemingly not considering internal loading. While external loading refers to the physical work completed (e.g., running volume), internal loading refers to the physiological or perceived effort (e.g., heart rate, rate of perceived exertion); both being shown to contribute to injury risk (Gabbett, 2016; Impellizzeri, Marcora and Coutts, 2019). Fourthly, no model seems to draw sufficient attention to the psychosocial risk factors for injury, and how they may affect tissues' capacity to tolerate load, despite being previously shown to be related to overuse injuries (Timpka *et al.*, 2015; Martin *et al.*, 2021). Finally, while there is a suggestion of the influence of some demographic factors (e.g., age [Meeuwisse *et al.,* 2007]), further demographic characteristics may need to be considered (e.g., sex [Hollander *et al.,* 2021] or type of runner [van der Worp *et al.,* 2015]).

Since the ultimate aim of this thesis is to explore factors important for the development of a RRI surveillance system, through the use of a smartphone application (app), several important considerations can be made. Three of these relate to concepts highlighted in these models (points 1-3), while four are drawn from limitations (points 4-7).

1. With the cyclic, progressive nature of RRI development, the need for **prospective** research is clear.
2. With potential accuracy enhancements of capturing cumulative structure-specific load, and how risk of injury differs at each athletic exposure, the need for **frequent, run-by-run data capture** is emphasised.
3. Demonstrating the effectiveness of capturing extrinsic and intrinsic risk factors in combination, the need for investigating **multiple potential risk factors** is clear.
4. There is a need to consider **injury as a development process across varying 'levels of injury',** rather than a single (dichotomous), definable point.
5. Additionally monitoring measures of **internal load**, such as the rate of perceived exertion, is important, and possible via a smartphone application.
6. The **psychosocial risk factors** for injury should be considered given their role as potential risk factors.
7. Runner **demographics** (e.g., sex, type of runner) are important factors to consider, not only as potential risk factors, but as potential contributing factors to engagement with running technologies and research (discussed in later sections throughout this thesis).

#### 2.2.1.3. Risk factors for running-related injuries

These conceptual models of injury aetiology present the complex relationship between evolving intrinsic and extrinsic risk factors, running exposure, and injury onset (Meeuwisse *et al.*, 2007; Malisoux *et al.*, 2015; Bertelsen *et al.*, 2017, Hulme *et al.,* 2017). However, evidence to date in support of specific risk factors for RRIs is conflicting and unclear (Ceyssens *et al.*, 2019; Vannatta, Heinert and Kernozek, 2020; Correia *et al.*, 2024).

Reviewing systematic reviews which examined RRI aetiology, the possible risk factors for RRIs represent a range of exposures (Table 1). Four categories seem to dominate, however: biomechanical and musculoskeletal risk factors (e.g., loading rate, foot strike pattern, Q angle, excessive pronation), training-related risk factors (e.g., weekly training volume, weekly running frequency, type of footwear), previous injury, and demographic risk factors (e.g., sex, age) (Table 1).

Eleven reviews have concluded on biomechanical and musculoskeletal risk factors. While it makes theoretical sense that biomechanical and musculoskeletal factors influence risk of injury (due to how they can increase or decrease loading on the body) (Hreljac, 2004), reviews predominantly concluded that either evidence is conflicting and inconsistent (Ceyssens *et al.*, 2019; Vannatta, Heinert and Kernozek, 2020; Correia *et al.*, 2024), or non-supporting (Peterson *et al.*, 2022). Ground reaction forces, foot strike pattern, kinematic factors, kinetic factors, muscle strength and muscle flexibility have all been reviewed. In relation to ground reaction forces, single reviews have concluded that impact peak (the point of initial foot contact with the ground) and active peak (when the stand leg accepts full the body mass) (Vannatta, Heinert and Kernozek, 2020), and plantar pressure (Mann *et al.*, 2016) are not significant risk factors, while there is inconsistent evidence surrounding the relationship between loading rate and RRIs (van der Worp, Vrielink and Bredeweg, 2016; Vannatta, Heinert and Kernozek, 2020). In terms of foot strike pattern, there has been very low evidence (Burke *et al.*, 2021) or no association (Anderson *et al.*, 2020) to support its relationship with RRI risk. Overall, there seems to be no strong evidence to conclusively identify kinematic risk factors for RRIs (Gijon-Nogueron and Fernandez-Villarejo, 2015; Vannatta, Heinert and Kernozek, 2020), while the evidence supporting kinetic risk factors is conflicting and limited (Vannatta, Heinert and Kernozek, 2020). Just one review identified inadequate muscle stabilization as a risk factor for RRIs (Gijon-Nogueron and Fernandez-Villarejo, 2015), while another identified very low quality evidence for muscle strength and flexibility as a risk factor (Christopher *et al.*, 2019).

Nine reviews have concluded on training-related risk factors, with training errors, footwear, and surface/terrain being reported on. In terms of training errors, training load has received the most attention. High weekly mileage (>64km/week) was found to be associated with injury risk in one review (van Gent *et al.*, 2007), in contrast to another review which found medium to large associations with lower weekly mileage (<16km/week) and injury risk (Correia *et al.*, 2024). One review found consistent evidence that running frequency per week is not associated with injury risk (Viljoen *et al.*, 2022), while another concluded that there is conflicting evidence for training parameters and RRI risk (Fredette *et al.*, 2022). While evidence is conflicting, the relationship between training load and RRI risk should be carefully considered, as it is proposed as the necessary contributing factor in the reviewed models above (i.e., RRIs cannot occur with exposure to running) (Meeuwisse *et al.*, 2007; Malisoux *et al.*, 2015; Bertelsen *et al.*, 2017; Hulme *et al.*, 2017). In relation to footwear, there is no definitive association with RRI risk (Perkins, Hanney and Rothschild, 2014; van Poppel *et al.*, 2021; Relph *et al.*, 2022). Finally, with regard to surface and terrain, one review identified that regular training on asphalt was associated with injury risk (in trail runners) (Viljoen *et al.*, 2022), while another found low quality evidence that terrain is not a risk factor (van Poppel *et al.*, 2021).

Five reviews have reported previous injury as a consistent factor for increased risk of RRIs (van Gent *et al.*, 2007; Saragiotto *et al.*, 2014; van der Worp *et al.*, 2015; van der Worp, Vrielink and Bredeweg, 2016; van Poppel *et al.*, 2021; Correia *et al.*, 2024) (Table 1), making it the most consistently identified risk factor.

Finally, five reviews have investigated demographic risk factors, most frequently on sex and age. In terms of sex, evidence varies, with some reviews suggesting males are more at risk for RRIs (van Poppel *et al.*, 2021; Hollander *et al.*, 2021), while another concluded that there is consistent evidence to suggest sex is not associated with injury risk (Viljoen *et al.*, 2022). However, sex may be a risk factor for specific types of RRIs, with findings suggesting males are more at risk for Achilles and calf injuries, and females are more at risk for bone stress injuries (Hollander *et al.*, 2021). With regard to age, contrasting conclusions have been made, with van Poppel *et al.* (2021) suggesting there is moderate quality evidence that older age is a risk factor for RRIs, while Viljoen *et al.* (2022) concludes that there is consistent evidence suggesting age is not a risk factor. It seems there are mixed findings supporting demographic risk factors for RRIs.

As the first step in the prevention of injuries (Van Mechelen, Hlobil and Kemper, 1992), the establishment of RRI epidemiological and aetiological evidence is weak and unclear, with research possibly struggling to progress until this fundamental step is clarified. There may be several reasons for this: (i) retrospective study designs, which are often associated with recall bias (Rasmussen, Holtermann and Jørgensen, 2018), (ii) lab-based data collection, which is not reflective of a natural running environments (e.g., treadmill running or wearable multiple markers) (Kiernan *et al.*, 2018) and a possible influence of the Hawthorne effect (Jeon *et al.*, 2023), (iii) one-off assessments, which fail to capture the natural variation and changes in running technique over time (Benson *et al.*, 2018; Schlueter *et al.*, 2021), (iv) infrequent data capture (e.g., biweekly), which does not allow for monitoring of how injury risk differs at every athletic exposure (Meeuwisse *et al.*, 2007), (v) not capturing all possible contributing factors (e.g., psychosocial risk factors) (Ivarsson *et al.*, 2017), and (vi) a lack of monitoring both internal and external loading (Gabbett, 2016; Soligard *et al.*, 2016). With a large-scale prospective study, the use of wearable technologies (e.g., inertial sensors, GPS systems) and a smartphone app, which captures field-based, run-by-run data across all possible contributing risk factors, including elements of internal and external loading, it is possible that these limitations can be addressed.

Prior to conducting this type of research however, a further challenge appears to lie within how 'injury' is defined, captured and reported. The challenge of defining sports injuries has been reported on for decades (Finch, 1997), with a well-established understanding that variations in definitions create inconsistencies in rates of injuries reported (Kluitenberg *et al.*, 2016), and uncertainty in understanding injury risk factors (Ceyssens *et al.*, 2019; Vannatta, Heinert and Kernozek, 2020). The following sections of this review of literature address the definition, injury severity measurement, and surveillance methods of RRIs.

### 2.2.2. Definitions of running-related injuries

Possibly, the most fundamental question in injury epidemiological research is 'what is an injury?' With acute onset injuries, this question seems relatively straightforward to answer, as predominantly, they are associated with obvious mechanisms of injury and an almost immediate onset of signs and symptoms (Brukner *et al.*, 2017). RRIs are not as straightforward, and defining them is challenging because of their typical slow, progressive onset, the frequent lack of an obvious inciting event, runners' persistence to continue running through injury (Clarsen, Myklebust and Bahr, 2013), and possible variation in individual runners' perception of what constitutes an injury.

Consensus definitions enhance the comparison of findings across studies (Timpka *et al.*, 2014), and since 2006, there appear to be 12 consensus definitions published in soccer (Fuller *et al.*, 2006; Waldén *et al.*, 2023), cricket (Orchard *et al.*, 2005; 2016), rugby union (Fuller *et al.*, 2007), multisport events (Junge *et al.*, 2008), rugby league (King *et al.*, 2009), tennis (Pluim *et al.*, 2009), horse racing (Turner *et al.*, 2012), athletics (Timpka *et al.*, 2014), recreational running (Yamato, Saragiotto and Lopes, 2015), aquatic sports (Mountjoy *et al.*, 2016), mass-participation events (Schwellnus *et al.*, 2019), and badminton (Gijon-Nogueron *et al.*, 2022). The effectiveness of consensus definitions has possibly contributed to reductions in sport injury rates. Taking soccer as an example, following the publication of the inaugural consensus definition (Fuller *et al.*, 2006), the Federation of International Football Association (FIFA) injury prevention programme was developed (2006), contributing to reductions in injuries across multiple populations following its implementation (Thorborg *et al.*, 2017; Al Attar, 2021; Al Attar *et al.*, 2023).

To initiate the development of a consensus definition for RRIs, a systematic review aiming to examine the descriptors used to define injury was conducted in 2015 (Yamato *et al.*, 2015). Examining 48 studies, this review identified that chiefly, two criteria were used to define RRIs: the presence of a physical complaint (either injury or pain), and the need to interrupt training. Additionally in some studies, a third criterion (the use of medical attention) is referred to (Yamato *et al.*, 2015). This systematic review reported that, overall, the definition of RRIs was inconsistent, few studies capture severity of injury, and a consensus definition was essential (Yamato *et al.*, 2015). Following this review, a consensus meeting was organised to provide uniformity to injury surveillance research, and based upon recommendations, a standardised definition of a RRI was published, being defined as:

*running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration or training) for at least seven days or three consecutive scheduled training sessions, or that required the runner to consult a physician or other healthcare professional* (Yamato, Saragiotto and Lopes, 2015, p. 377).

Nearly ten years later however, there are still inconsistencies and conflicting findings in terms of RRI risk factors (Correia *et al.*, 2024) (section 2.2.1.3), there appears to be no evidence-based RRI prevention intervention published, and rates of RRIs are still high (Kakouris, Yener and Fong, 2021). Possibly, the slow progression of RRI prevention research may be due to the consensus definition not being adopted, and inconsistent definitions still being used (Correia *et al.*, 2024). However, another possible cause may lie within the fundamental way injury is defined. Indeed, reframing this may be required, and rather than considering 'injury' as a single, dichotomous entity, a more appropriate approach may be to view injury as a process. Capturing this view of injury can be facilitated with an appropriately designed surveillance tool, possibly via a smartphone app.

To explore this notion, an updated review of current RRI definitions is required. The criteria used to define injury, and their appropriateness in light of the true nature of RRI development, should be considered. Secondly, it should be investigated if the RRI consensus definition has been widely adopted. In order to examine these questions, an extensive scoping review was conducted as part of this thesis. The primary aim of this review was to investigate how RRIs are defined by examining: (i) the criteria used to define RRIs, and (ii) how the consensus definition has been adopted since publication. This study is presented in its full paper format in Chapter 3. In summary, the review found nine varieties of definition, with three primary criteria used: a physical description, an effect on training, and the requirement of medical intervention. In addition, the consensus definition of (Yamato, Saragiotto and Lopes, 2015; defined on page 66) seems to be used by only 40% of studies since its publication. There seems to be two key issues with RRI definitions used to date. Firstly, there are wide inconsistencies, and secondly, the appropriateness of definitions to capture the true nature and consequences of RRIs is questionable.

Considering the first issue, inconsistent definitions seem to contribute to two major problems: large variances in the rates of injury reported (section 2.2.1.1), and researchers' inability to compare findings across studies. In 2016, Kluitenberg *et al.* (2016) applied different definitions of injury to the same data set to determine if there was an effect on the rate of injury reported. Definitions were categorised into running-related pain (RRP), training-reduction (TR), and time-loss (TL), as well as day-long or week-long definitions. This resulted in six different definitions of injury: RRP-day, RRP-week, TR-day, TR-week, TL-day, and TL-week. Incidence proportions varied significantly, with the RRP-day definition eliciting the highest rate (58.0%), and the TL-week definition eliciting the lowest (7.5%). It was also noted that all day-long-based injuries were associated with higher incidence rates compared to week-long-based injuries. This implies that not only are the criteria important in defining injury, but the length of time associated with these criteria is also a crucial factor. In addition, significant differences were found between the definition of injury employed and the anatomical location of injuries. Injuries to the pelvis/sacrum/buttock region were mostly present with RRP-day definitions, calf injuries were most common with a TR-day definition, and knee injuries were most common with a TL-day definition (Kluitenberg *et al.*, 2016). The authors concluded that definition of injury has a major role on the incidence and anatomical location of RRIs reported (Kluitenberg *et al.*, 2016). With this, they advocate for consistency, not with definition of injury used, but with injury registration methods, suggesting that a continuous tool capable of monitoring both the development of overuse injuries and traditional time-loss injuries should be developed (Kluitenberg *et al.*, 2016). This study seems to be the only research specifically examining the effect of injury definition on RRI incidence rates, while there appears to be no study examining how the definition of injury may affect the risk factors identified; highlighting a clear gap in the RRI research.

In relation to the second issue regarding the appropriateness of definitions to capture the true nature and consequences of RRIs, there is a well-established argument that use of definition criteria with high thresholds do not capture the majority of overuse injuries (Bahr, 2009; Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2020). It is important to capture injuries which fall below these thresholds of (i) causing pain, (ii) prolonged, consecutive training restrictions or time-loss, and (iii) requiring medical attention) (Bahr, 2009; Clarsen, Myklebust and Bahr, 2013; Yamato *et al.*, 2015; Clarsen *et al.*, 2020). Not only can these lower level injuries provide a truer reflection of the rate of injury (Kluitenberg *et al.*, 2016), but it is possible that their presence contribute to a runners' risk of sustaining a more severe injury, either by interacting with other risk factors, or by being risk factors themselves (Soligard *et al.*, 2016; Whalan, Lovell and Sampson, 2020). Additionally, these lower level injuries may result in negative consequences (section 2.2.5.2) which should be monitored and addressed during rehabilitation. Once again, considering the fundamental questions of what an injury is, 'injury' could be considered to exist along a fluid and cyclic scale of varying consequences (e.g., tissue damage, physical sensation, effect on training), rather than as a single, definable outcome. This is supported by Verhagen, Warsen and Silveira Bolling's (2021) theoretical proposal of the Injury Pathway (discussed in section 2.2.5.1).

An important point to consider when defining injury is the challenge of differentiating between symptoms that mimic injury, but are merely indications of tissue adaptation (e.g., delayed onset muscle soreness), and those that are the genesis of injury (Gabbett, 2016;

Soligard *et al.*, 2016; Francis *et al.*, 2019). In a sport where overuse injuries dominate (Lopes *et al.*, 2012), this line is blurred. Indeed, athletes have reported that not all sporting pain is unwelcome (McNarry, Allen-Collinson and Evans, 2020), and a description of 'positive pain' has been associated with positive tissue adaptations, rather than injury (McNarry, Allen-Collinson and Evans, 2020; Tarr and Thomas, 2021; Hall, Rhodes and Papathomas, 2022). Defining injury is additionally complex as it is a subjective entity, with many factors influencing how it is perceived and managed, including subjective pain sensation (Raja *et al.*, 2020), psychological factors (e.g., mood) (van Wilgen and Verhagen, 2012), and previous experience (Vella *et al.*, 2022).

Potentially, the challenge of defining RRIs could be addressed with an appropriate surveillance system which does not assume 'injury' is a dichotomous entity. This could be achieved through continually monitoring internal and external loading in a user-friendly way, such as with a smartphone app. However, a further aspect of injury epidemiology also needs to be considered: injury severity.

### 2.2.3. Severity of running-related injuries

In addition to understanding the frequency of injuries (i.e., incidence/prevalence), capturing injury severity is a key part of the 'sequence of prevention' (Van Mechelen, Hlobil and Kemper, 1992) (Figure 6). Injury severity is important for several reasons. Firstly, Bahr, Clarsen and Ekstrand (2018) recommend combining the elements of incidence *and* severity to capture 'injury burden'[3], using this concept to prioritise injury prevention research. Secondly, it informs the allocation of management resources (Van Mechelen, 1997; Bahr, Clarsen and Ekstrand, 2018), and when monitored over time, can be used to assess the effectiveness of injury prevention or rehabilitation interventions

[3] Throughout this thesis, 'burden' will refer to the combination of injury incidence and severity as per Bahr, Clarsen and Ekstand's (2018) recommendations.

(Clarsen, Myklebust and Bahr, 2013; Bolling *et al.*, 2018). Finally, understanding injury severity is a key component of injury aetiology because different severities of injury may be associated with different risk factors (Soligard *et al.*, 2016). Indeed, lower severity injuries may themselves act as risk factors for the occurrence of higher severity injuries (Whalan, Lovell and Sampson, 2020).

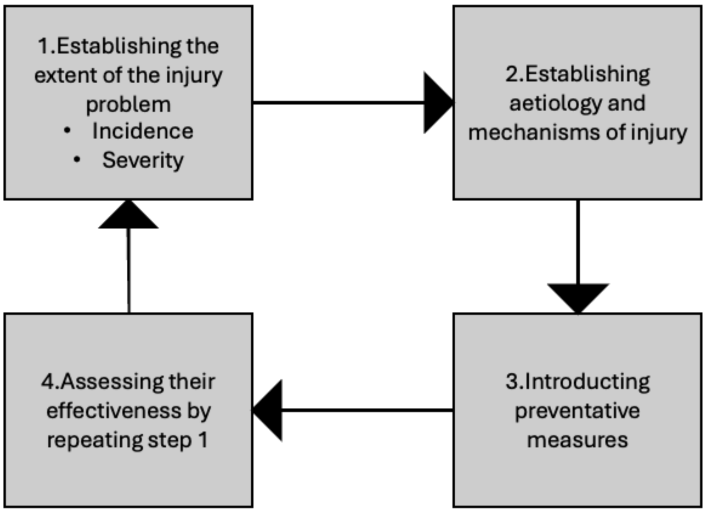



Figure 6. The ‘sequence of prevention’ of sports injuries (Van Mechelen, Hlobil and Kemper, 1992)

It has been suggested that injury severity be determined based on six closely related criteria: the nature of the injury (i.e., the diagnosed injury, e.g., strain, sprain or fracture), the duration and nature of treatment required, the sporting time lost, the working time lost, the permanent damage suffered, and the economic cost (Van Mechelen, Hlobil and Kemper, 1992; Van Mechelen, 1997). Previously, using the number of days lost from sport has been reported as the preferred method for determining injury severity (Clarsen, Myklebust and Bahr, 2013). Possibly for reasons of consistency, this approach has also been recommended in individual sports (Pluim *et al.*, 2009; Timpka *et al.*, 2014), and those more often associated with overuse injuries (Mountjoy *et al.*, 2016). However, in a similar vein to the definitions of injury (section 2.2.2), the appropriateness of time-loss, and its associated high threshold, to determine the severity of RRIs, should be carefully considered (Bahr, Clarsen and Ekstrand, 2018). In addition, only using time-loss captures just one potential consequence of injury, not recognising multiple other consequences that often occur (section 2.2.5.2).

In order to address the difficulty of defining overuse injuries and combat the limitations of using length of time-loss to measure their severity, researchers at the Oslo Sports Trauma Research Centre (OSTRC) developed a method of surveilling overuse injuries based on changes in athletes' symptoms, function, and sports performance (Clarsen, Myklebust and Bahr, 2013). The OSTRC overuse injury questionnaire (OSTRC-O) was derived from four primary recommendations (Bahr, 2009). Firstly, it was suggested that studies be prospective and capture continuous or frequent serial measurements of injury symptoms and function. Secondly, valid and sensitive scoring systems, completed directly by the athlete, should be used. These systems should capture other domains of impairment and disability caused by overuse injuries, rather than considering 'pain' as the main symptom. Thirdly, prevalence, over incidence, is considered a more appropriate measure of injury risk for overuse injuries. Finally, the duration of time-loss is not an appropriate measure of injury severity for overuse injuries, and instead, functional or performance limitations should be used (Clarsen, Myklebust and Bahr, 2013).

The development of the OSTRC questionnaires will be discussed in a later section (section 2.2.4). In terms of injury severity, this tool captures the extent to which injury affects four domains: (i) difficulty participating in training, (ii) alterations to training load, (iii) impaired performance, and (iv) pain. With repeated administration, changes in injury severity can be monitored overtime. Compared to the standard method of using length of time-loss, this approach clearly captures a more appropriate picture of the complete burden of overuse injuries, by representing multiple possible consequences of injury, more reflective of their progressive nature (Clarsen, Myklebust and Bahr, 2013). Following the publication of the OSTRC-O, a health problem version (OSTRC-H) was released (Clarsen *et al.*, 2014), and both tools were updated further in 2020 (Clarsen *et al.*, 2020). The publication of these tools has facilitated the capture of overuse injuries in research, providing a more appropriate account of their true consequences (Clarsen *et al.*, 2020). However, in relation to RRIs and their severity, two limitations can be considered. Firstly, some questions may be not appropriate when considering all populations of runners. The term 'performance' is not defined in the OSTRC-O and OSTRC-H questionnaires, firstly leaving this term open to interpretation by the responder, and secondly, it may not be applicable to all types of runner. For example, 'performance' could relate to achieving a specific time in a race, but for a recreational runner who does not consider competition or 'performance' an aspect of their running, this is not appropriate. As a second limitation, although these tools expand beyond solely using length of time-loss, there are additional consequences of injury that runners may experience which contribute to injury severity, and subsequently, the full picture of injury burden (Üstün *et al.*, 2003; Bahr, Clarsen and Ekstrand, 2018). For example, it is understood that injured athletes can experience a myriad of psychosocial responses to injury (Russell and Wiese-Bjornstal, 2015); however these consequences are not specified in the OSTRC tools.

Specific to RRI research, there appears to be no consensus recommendation for the measurement of the injury severity. Furthermore, despite its importance, there appears to be no review examining how the severity of RRIs is measured. Just one systematic review, which primarily examined the definitions of RRIs, briefly commented on the measurement of injury severity (Yamato *et al.*, 2015). However, as a tertiary aim, no investigation into this measurement, or analysis into the consistency across studies, was conducted (Yamato *et al.*, 2015). Furthermore, there seems to be no study examining how the measurement of injury severity may influence the incidence rate reported or the risk factors identified (i.e., the study outcomes). Yamato *et al.'s* (2015) previous review did identify however, that of the studies they reviewed for definition of injury, few actually captured injury severity. This highlights a clear gap in the RRI literature and suggests that injury severity may be an underused element of injury epidemiological research in running.

To address this, an extensive scoping review was conducted as part of this thesis. The primary aim of this review study was to investigate how the severity of RRIs is measured by (i) describing the injury severity scales used, and (ii) comparing to what extent these scales differ. A secondary aim was to examine if the way in which injury severity is measured influences study outcomes. This paper is presented in full in Chapter 4. However, in summary, the measurement of injury severity is inconsistent overall. Furthermore, few studies report the incidence rates per level of injury severity, while no studies report specific risk factors for varying levels of injury severity, making it difficult to determine whether injury severity measurement influences study outcomes.

The finding of this review (Study 2, Chapter 4) suggest several problems. Firstly, the issue of inconsistency does not allow for the comparison of findings across studies, limiting the advancement of injury prevention research. Secondly, few studies provide information on the incidence rate per severity level, and none provide information on risk factors per severity level. This lack of information may also be limiting the advancement of injury prevention research. Thirdly, it seems that RRI severity is solely determined by two primary criteria: the extent of the physical description (e.g., pain) and/or the effect on training. With several other consequences of injury evident (section 2.2.5.2), this is problematic, as these additional consequences may not be monitored or addressed during the injury development or rehabilitation processes. Therefore, the burden of RRIs is likely not fully understood. A potential solution lies within the design of an effective surveillance tool (e.g., via a smartphone app), which is capable of capturing varying severities of RRI, across numerous consequences. This tool could also identify rates of injury per severity level, as well as monitor any potential effect lower severity injuries have on the onset of higher severity injuries (and vice versa). In order to develop such a tool, it is important to firstly understand how RRIs have been captured to date.

### 2.2.4. Surveillance of running-related injuries

Injury surveillance relates to the standardised, routine, and ongoing collection of data which describes the occurrence of and risk factors for injury, and is crucial in order to monitor the effectiveness of injury reduction and prevention strategies (Finch, 1997). No previous review has been conducted examining the surveillance methods of RRIs.

Previous reviews have been conducted on the surveillance of injuries in various sports (e.g., football [Shaw *et al.*, 2017]), in various populations (e.g., young athletes [Goldberg *et al.*, 2007]), in specific injuries (e.g., concussion [Kerr *et al.*, 2017]), and in specific settings (e.g., within sports clubs and organisations [Ekegren, Gabbe and Finch, 2015]). However, most relevant to RRIs, only one review has reported on the surveillance methods of overuse injuries. Franco *et al.* (2021) conducted a systematic review and meta-analysis of the prevalence of overuse injuries in individual and team sports, and as a tertiary aim, reported on the methods of surveillance used. Out of 17 included studies, nine used the OSTRC-O, four used the OSTRC-H, identifying the OSTRC tools as the most commonly adopted tool for the surveillance of overuse injuries in sport. However, this review did not discuss or draw conclusions on the methods of injury surveillance of the included studies (Franco *et al.*, 2021).

The original OSTRC-O was developed by a group of sports physiotherapists, medical practitioners, sports injury epidemiologists, athletes, and experts in questionnaire design. Four consequences, deemed the most important to monitor, were used to record overuse injuries: (i) difficulty participating in training, (ii) alterations to training load, (iii) impaired performance, and (iv) pain (Clarsen, Myklebust and Bahr, 2013). Severity of injury is based on the extent to which these four consequences are affected, and with repeated and frequent administration, changes in injury severity can be monitored overtime. Each of the four consequences is scored from 0-25, with higher scores corresponding to higher injury severity. Questions 1 and 4 have four possible outcomes (being scored as 0-8-17-25), while Questions 2 and 3 have five (being scored as 0-6-13-19-25). Summing the responses to each of the four questions provides a total severity score from 0 (full participation without pain) to 100 (no participation at all, with severe pain) (Figure 7). If Questions 2 or 3 are scored 13 or higher, the injury is considered a 'substantial problem'

**OSTRC Questionnaire on Overuse Injuries for knee problems (OSTRC-O)**
Please answer all questions regardless of whether or not you have problems with your knees. Select the alternative that is most appropriate for you, and in the case that you are unsure, try to give an answer as best you can anyway.
The term 'knee problems' problems' refers to pain, ache, stiffness, swelling, instability/giving way, locking or other complaints to one or both knees.

**Question 1**
*Have you had any difficulties participating in normal training and competition due to knee problems during the past week?*
- Full participation without knee problems
- Full participation, but with knee problems
- Reduced participations due to knee problems
- Cannot participate due to knee problems

**Question 2**
*To what extent have you reduced your training volume due to knee problems during the past week?*
- No reduction
- To a minor extent
- To a moderate extent
- To a major extent
- Cannot participate at all

**Question 3**
*To what extent have knee problems affected your performance during the past week?*
- No effect
- To a minor extent
- To a moderate extent
- To a major extent
- Cannot participate at all

**Question 4**
*To what extent have you experienced knee pain related to your sport during the past week?*
- No pain
- Mild pain
- Moderate pain
- Severe pain

**Updated OSTRC Questionnaire on Overuse Injuries for knee problems (OSTRC-O2)**
Please answer all questions regardless of whether or not you have problems in your (insert anatomical location here, e.g., knees). Select the alternative that is most appropriate for you, and in the case that you are unsure, try to give an answer as best you can anyway.
The term '(location) problems' refers to (insert common symptoms or injury consequences here, e.g., pain, ache, stiffness, clicking/catching, swelling, instability/giving way, locking) or other complaints related to your (location).

**Question 1 – Participation**
*Have you had any difficulties participating in normal training and competition due to knee problems during the past 7 days?*
- Full participation without (location) problems
- Full participation, but with (location) problems
- Reduced participations due to (location) problems
- Could not participate due to (location) problems

**Question 2 – Modified training/competition**
*To what extent have you modified your training or competition due to (location) problems during the past 7 days?*
- No modification
- To a minor extent
- To a moderate extent
- To a major extent

**Question 3 - Performance**
*To what extent have (location) problems affected your performance during the past 7 days?*
- No effect
- To a minor extent
- To a moderate extent
- To a major extent

**Question 4 - Pain**
*To what extent have you experienced (location) pain related to your sport during the past 7 days?*
- No pain
- Mild pain
- Moderate pain
- Severe pain

**OSTRC Questionnaire on Health Problems (OSTRC-H)**
Please answer all questions regardless of whether or not you have experienced health problems in the past week. Select the alternative that is most appropriate for you, and in the case that you are unsure, try to give an answer as best you can anyway.
If you have several illness or injury problems, please refer to the one that has been your worst problem this week. You will have a change to register other problems at the end of the questionnaire.

**Question 1**
*Have you had any difficulties participating in normal training and competition due to injury, illness or other health problems during the past week?*
- Full participation without health problems
- Full participation, but with injury/illness
- Reduced participations due to injury/illness
- Cannot participate due to injury/illness

**Question 2**
*To what extent have you reduced your training volume due to injury, illness or other health problems during the past week?*
- No reduction
- To a minor extent
- To a moderate extent
- To a major extent
- Cannot participate at all

**Question 3**
*To what extent has injury, illness or other health problems affected your performance during the past week?*
- No effect
- To a minor extent
- To a moderate extent
- To a major extent
- Cannot participate at all

**Question 4**
*To what extent have you experienced symptoms/health complaints during the past week?*
- No symptoms/health complaints
- To a minor extent
- To a moderate extent
- To a severe extent

**Updated OSTRC Questionnaire on Health Problems (OSTRC-H2)**
Please answer all questions regardless of whether or not you have experienced health problems in the past week. Select the alternative that is most appropriate for you, and in the case that you are unsure, try to give an answer as best you can anyway.
A health problem is any condition that you consider to be a reduction in your normal state of full health, irrespective of its consequences on your sports participation or performance, or whether you have sough medical attention. This may include, but is not limited to, injury, illness, pain or mental health conditions.
If you have several health problems, please begin by recording your worst problem in the past 7 days. You will have a change to register other problems at the end of the questionnaire.

**Question 1 – Participation**
*Have you had any difficulties participating in normal training and competition due to injury, illness or other health problems during the past 7 days?*
- Full participation without health problems
- Full participation, but with a health problem
- Reduced participations due to a health problem
- Could not participate due to a health problem

**Question 2 – Modified training/performance**
*To what extent have you modified your training or competition due to injury, illness or other health problems during the past 7 days?*
- No modification
- To a minor extent
- To a moderate extent
- To a major extent

**Question 3 – Performance**
*To what extent has injury, illness or other health problems affected your performance during the past 7 days?*
- No effect
- To a minor extent
- To a moderate extent
- To a major extent

**Question 4**
*To what extent have you experienced symptoms/health complaints during the past 7 days?*
- No symptoms/health complaints
- To a minor extent
- To a moderate extent

Figure 7. Oslo Sports Trauma Research Centre questionnaires (updated versions highlighted in red text)

The validity of the OSTRC-O was assessed in the original publication, being tested against a 'standard' (i.e., time-loss, defined as prevention of full participation in training or competition) method of injury surveillance (Clarsen, Myklebust and Bahr, 2013). Athletes from multiple sports completed the questionnaire every week for 13 weeks, specific to three anatomical locations (shoulder, lower back and knee), regardless of whether or not they experienced problems in that location. Using the standard time-loss method, 103 time-loss injuries were recorded among 82 athletes. Sixty-one of these were overuse injuries, while 42 were acute. In contrast, using the novel OSTRC-O, 419 overuse conditions were recorded among 236 athletes. Seventeen percent of these involved minor pain with no consequences on training and performance, while 34% were considered substantial problems (Clarsen, Myklebust and Bahr, 2013). These findings demonstrate that the use of time-loss as a method of injury surveillance dramatically underestimates the true burden of overuse injuries in sport. This new approach monitors how overuse injuries and health problems progress, quantifying severity and capturing any changes over time, rather than employing the traditional dichotomous approach enforced by a time-loss definition (Clarsen, Myklebust and Bahr, 2013). There are several other strengths associated with this new method. Firstly, this approach takes into account multiple consequences of injury when determining injury severity, providing a more complete picture of the burden of injury sustained by athletes (Clarsen, Myklebust and Bahr, 2013; Bahr, Clarsen and Ekstrand, 2018). Secondly, identifying 'substantial problems' helps to filter out the more minor problems which may be more associated with response to training loads, which given the appropriate conditions, may lead to positive adaptations, rather than injury (Meeuwisse *et al.*, 2007). Thirdly, by capturing prevalence rather than incidence (in line with Bahr's recommendations [Bahr, 2009]), this approach reflects the proportion of athletes that could expect to be affected by overuse injuries at any given time point (Clarsen, Myklebust and Bahr, 2013). Finally, as this is a self-report tool, data is collected directly from the athlete, reducing the risk of bias from third party recorders (Bahr, 2009). There are also some limitations to this method that should be considered. Firstly, while expanding beyond length of time-loss in isolation, there are several other consequences of injury that athletes experience, not captured by this method (e.g., psychological consequences such as frustration) (section 2.2.5.2). Secondly, as this approach employs an ‘any physical complaint’ definition by default, there is a possibility that the consequences and symptoms associated with ‘normal’ responses to training load, and not necessarily injury, will be captured. However, as stated above, the identification of ‘substantial’ problems helps to minimize this. Thirdly, the validity of information is dependent on both frequent administration, increasing the onus on athletes and data recorders/analysts, and a high response rate. Both of these aspects pose a challenge for the recruitment and retention of participants; issues that will be addressed later in this thesis (section 2.4 and Chapter 7: Study 5). Fourthly, as the severity of injuries is represented on a scale from 0-100, many studies have analysed this scale as a continuous outcome variable (Clarsen *et al.*, 2020). However, being addressed in the updated publication (Clarsen *et al.*, 2020), due to the scoring breakdown differing between questions, this is actually not a true continuous outcome measure as it does not represent equidistance between possible outcomes. The authors concluded that it should therefore be considered an ordinal measure, with 25 possible outcomes, rather than 100 (Clarsen *et al.*, 2020). To rectify this, the updated versions possess a scoring system in which all questions have only four responses, all being weighted equally (0-8-17-25) (Figure 7).

The OSTRC tools have been widely adopted in both sports injury research and as clinical monitoring tools, enhancing the surveillance of overuse injuries (Clarsen *et al.*, 2020). However, the methods used for RRI surveillance are currently unknown, with no review investigating this topic. Furthermore, it is unclear whether the OSTRC tools have been adopted in RRI research. This highlights a clear gap in the RRI literature. To address this, a scoping review was conducted as part of this thesis. While the primary aim of this review paper was to investigate the definition of RRIs, a secondary aim was to investigate the surveillance methods of RRIs. This paper is presented in its full format in Chapter 3; however, in summary, there is no consistent method of injury surveillance utilised in RRI research. Clearly, there is a need for a standardised surveillance tool for RRIs addressing the following important considerations. Firstly, injury and injury severity must be viewed within the context of the specific sport (Bahr *et al.*, 2020; Clarsen *et al.*, 2020), in addition to the high subjectivity of individual athletes' perception of injury, injury severity, and their consequences (van Wilgen and Verhagen, 2012). This context specificity and subjectivity needs to be carefully considered when designing and implementing surveillance methods. Secondly, choosing an injury definition, severity measurement and surveillance method (taking runners' commitment requirement into consideration) needs to be balanced between (i) addressing a study's aims, and (ii) being consistent with other research. To date, this balance seems to be in favour of addressing study aims, evidenced by the inconsistencies across these three elements. However, if injury prevention research is to be advanced, re-establishing this balance needs to prevail. While it has been suggested that injury definition and severity measurement should be defined prior to the implementation of a surveillance tool (Van Mechelen, Hlobil and Kemper, 1992), a possible solution to re-establish this balance is the development of a single tool capable of capturing the full development process of RRIs, and monitoring injury severity across a wide scope of consequences, to which specific definitions and severity criteria can be applied post-hoc. In this way, consistent capture of injury data and its comparison across studies is possible (with researchers making raw injury data available), without being limited by methods driven by definitions or severity measurements. Once again, this type of approach can be facilitated by the development of an appropriate surveillance tool (via a smartphone app); however, in order to develop such a tool, a better understanding of the RRI development process, and its consequences, is required.

### 2.2.5. The development process of running-related injuries

In light of the insidious, progressive nature of RRI onset (Lopes *et al.*, 2012), this section will address three primary points. Firstly, it will discuss how a process of RRI development is likely, being made up of multiple ‘levels’ of injury. Secondly, it will examine the consequences of injury and how they might differ depending on the ‘level’ of injury. Finally, it will examine how runners’ lived experience may provide insight into this development process and its associated consequences.

#### 2.2.5.1. ‘Levels’ of running-related injuries

During the development of overuse injuries, it is possible that various ‘levels’ of injury likely exist. This is evident in various ways, but firstly from a physiological or biological perspective (i.e., the signs of injury). A consensus statement from the IOC discussed the complex relationship between loading and tissue damage, considering this to exist along a continuum (Soligard *et al.*, 2016) (Figure 8). This relationship must be carefully balanced between loading appropriately in order to cause positive adaptations to training and provoke performance enhancements, and loading inappropriately (or recovery insufficiently) and causing negative adaptations, resulting in tissue damage and possible injury (Soligard *et al.*, 2016). The Well-Being Continuum depicts nine levels, progressing from homeostasis as the initial level, to death as the most severe consequence (Figure 8). It indicates that, as load is applied to tissues, a sequential process from acute fatigue, through subclinical tissue damage, functional overreaching, non-functional overreaching, clinical symptoms, overtraining syndrome, time-loss injury or illness, and death, occurs. The same process, in the opposite direction, also unfolds when adequate recovery ensures tissues can adapt positively to the applied load. Considering the definition of a ‘continuum’, the end points are typically distinctively unique (i.e., homeostasis vs. death), while the adjacent levels can overlap (Soligard *et al.*, 2016). This makes it challenging to definitively determine the point of overuse injury onset as tissue damage improves and disimproves progressively.

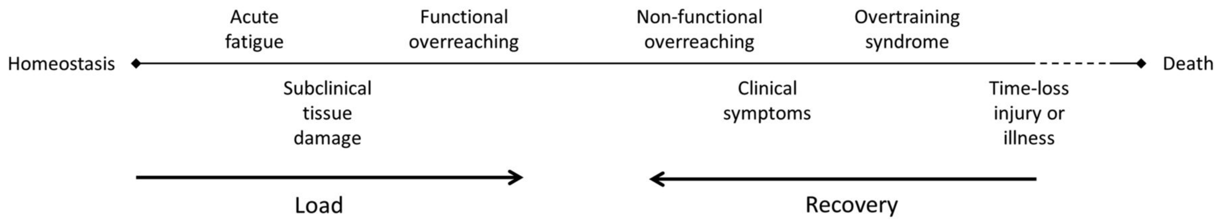



Figure 8. The Well-Being continuum (Fry, Morton and Keast, 1991; Soligard *et al.*, 2016)

Secondly, evidence for the existence of ‘levels’ of overuse injuries can be seen through their associated symptoms. Two primary consequences of injury seem to be referred to in research: the physical descriptions (i.e., pain) and the effect injury has on running (or the equivalent activity) (Yamato *et al.*, 2015). In terms of physical symptoms, overuse injuries may initially manifest as mild complaints, such as discomfort, but progressively worsen to cause more severe experiences of pain (Ostermann, Ridpath and Hanna, 2016), indicating multiple levels. In terms of the effect on running, the extent to which training is altered or disrupted is suggested to be relative to the severity of injury (Wiegand, Tandy and Silvernail, 2023), signifying various ‘levels’ of injury. Indeed, subclinical symptoms may often be present, without causing any alterations or disruptions to training, and it is only when an injury progresses to a more severe level, do these negative effects on training occur (Clarsen, Myklebust and Bahr, 2013). This is evidenced through the development of the OSTRC tools which monitor this progressive development of injury (Clarsen, Myklebust and Bahr, 2013).

Thirdly, it seems that runners themselves are aware of these progressive ‘levels’ of injury. Anecdotally among runners and those interested in RRIs, it is a common belief that levels of injury exist (e.g., niggles or twinges) (Runner’s World, 2022; Sellers, 2024). However, RRI research has been slow in exploring this, with just two studies investigating this from a runner’s perspective (Wickström *et al.*, 2019; Verhagen, Warsen and Silveira Bolling, 2021). Indeed, one study emphasises that “runners described injuries as the outcome of a process” (Verhagen, Warsen and Silveira Bolling, 2021, p. 4). These two studies are examined below in further detail.

Wickström *et al.* (2019) took a quantitative approach to investigate marathon and ultramarathon runners’ perceptions of overuse injury. Runners described overuse injuries as existing on a cyclic and chronic timeline, referring to “categories” of injury (Wickström *et al.*, 2019, p. 8), suggesting there are different levels of injury. This was further explored by Verhagen, Warsen and Silveira Bolling (2021), in which recreational runners described a three-level process of injury development from loading to complaint to injury. This process was coined the Injury Pathway (Figure 9) (Verhagen, Warsen and Silveira Bolling, 2021). This study seems to be the first to explicitly identify and name a level of injury that exists in the development process of RRIs: the ‘complaint’ level. As an extremely novel piece of research, and possibly the most influential paper to this thesis, this finding gives evidence-based recognition to common anecdotal perceptions of runners that levels of injury exist (Verhagen, Warsen and Silveira Bolling, 2021). Similar to the Well-Being Continuum (Soligard *et al.*, 2016) (Figure 8), progression along the Injury Pathway is facilitated by (over)loading and an inability to self-manage, while improvement is supported by self-regulation (Verhagen, Warsen and Silveira Bolling, 2021) (Figure 9). Although identifying a sub-level of injury, this study found that runners do not generally consider ‘complaints’ to be ‘injuries’, even when they feel the need to reduce their training load (e.g., distance, speed, or intensity) in order to manage them. It is only when attempts at self-regulation have failed and runners lose autonomy over their running practice, that they perceive themselves as injured  (Verhagen, Warsen and Silveira Bolling, 2021).

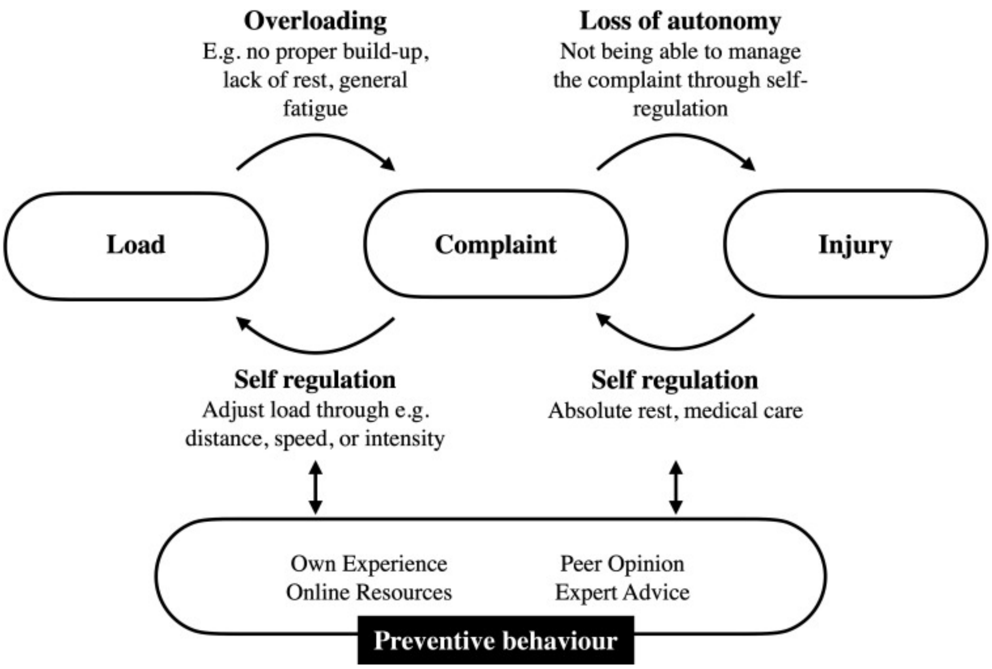



Figure 9. The Injury Pathway, as experiences by recreational runners (Verhagen, Warsen and Silveira Bolling, 2021)

In order to build on these studies, some limitations can be addressed. Firstly, findings are possibly only applicable to the relevant population samples that were studied: marathon and ultramarathon runners (Wickström *et al.*, 2019), and just one study examining recreational runners (Verhagen, Warsen and Silveira Bolling, 2021). With the high variability of perception of injury (van Wilgen and Verhagen, 2012), future research with different populations should be conducted. Secondly, although these studies have initiated the evidence in terms of identifying 'levels' of RRI development, there is uncertainty regarding exactly what these levels are, how runners describe them, or whether further 'levels' exist. This warrants further exploration.

Despite varying levels of injury being evident, definitions (section 2.2.2), severity measures (section 2.2.3) and surveillance methods (section 2.2.4) of RRIs do not seem to appropriately reflect their existence. An example scenario describing the importance of recognising varying levels of injury severity is as follows: a runner experiences symptoms of an injury (i.e., a 'complaint') at their knee. However, they continue to run, although now with an altered running technique in an attempt to offload the knee complaint. Subsequently, they go on to develop an 'injury' (as per the consensus definition) at their calf. If unaware of the knee complaint, we may fail to consider its potential impact as a risk factor for the development of the calf injury. Evidence to support this relationship has been shown in soccer research, in which the presence of non-time-loss injuries was significantly related to the onset of time-loss injuries within seven days (Whalan, Lovell and Sampson, 2020).

Considering how this may affect the development of an app-based surveillance tool, knowledge of the various 'levels' of injury will inform how they are captured. Additionally, it is also important to capture the consequences of RRIs to ensure the full extent of their burden is understood, and to ensure these consequences are addressed during injury management and rehabilitation.

#### 2.2.5.2. Consequences of running-related injuries

The consequences of injury are far reaching (Bahr *et al.*, 2020), causing negative physical outcomes (Hespanhol Junior, van Mechelen and Verhagen, 2017), negative impacts on running (van der Worp *et al.*, 2015), the requirement of various management strategies (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022), and psychological (Russell and Wiese-Bjornstal, 2015), social (Sleeswijk Visser *et al.*, 2021), and economic (Hespanhol Junior, van Mechelen and Verhagen, 2017) consequences. However, the 'physical' consequences of RRIs seem to be prioritised (i.e., pain, and impacted training) (sections 2.2.2 and 2.2.3), with a lack of recognition for the psychosocial consequences of injury. Furthermore, insight into these consequences across the entire injury development process, and whether they differ based on the ‘level’ of injury (section 2.2.5.1), seems to be lacking.

Firstly, consideration can be given to the negative physical consequences of RRIs. In the early 1990’s, Hoeberigs (1992) described that pain, as a characteristic of injury, is present from the earliest onset of injury, suggesting that negative physical outcomes represent the initial signal of the injury development process. A range of physical symptoms are associated with RRIs, including stiffness (e.g., with tendinopathies [Millar *et al.*, 2021]) and aching (e.g., patellofemoral pain syndrome [Glaviano *et al.*, 2022]). However, it seems that ‘pain’ is the most referred to/reported symptom, being: used in many definitions of injury and specified in the consensus definition (Yamato, Saragiotto and Lopes, 2015), frequently used to determine injury severity (Van Mechelen, Hlobil and Kemper, 1992), and specified in injury surveillance tools (Clarsen, Myklebust and Bahr, 2013). It is possible that symptoms of injury such as stiffness or discomfort, which may not be as severe as ‘pain’, are associated with early physiological tissue damage, representing earlier ‘levels’ of injury as seen in the Well-Being Continuum (Soligard *et al.*, 2016) (Figure 8), and the Injury Pathway (Verhagen, Warsen and Silveira Bolling, 2021) (Figure 9). However, as just one study has explicitly identified such a level (Verhagen, Warsen and Silveira Bolling, 2021), evidence is limited.

Secondly, a major consequence of injury is the negative impact they have on running (Van Mechelen, Hlobil and Kemper, 1992; Clarsen, Myklebust and Bahr, 2013; Yamato *et al.*, 2015). The extent of required training modification can be related to varying severities of injury, which in turn, may point towards varying levels of injury (section 2.2.5.1). This is evident when considering the ‘complaint’ level of the Injury Pathway (Verhagen, Warsen and Silveira Bolling, 2021) (Figure 9), in which adjustments in training load at an earlier level injury, or absolute rest from running at a later level injury, are required. It is unclear whether, prior to the point of time-loss or training reduction, other alterations to training occur that may indicate earlier levels of injury.

Thirdly, the requirement of management strategies can be considered a further consequence. These strategies can be referred to as runners' self-management of injury, or requiring external management (i.e., medical attention), with seeking medical attention typically being associated with more severe injuries (Van Mechelen, Hlobil and Kemper, 1992). Medical attention, as a management strategy, can be described in terms of the treatment modalities required (e.g., physical rehabilitation, drug therapies, therapeutic modalities, or surgery), the level of expertise necessary (e.g., an Athletic Therapist or Physiotherapist versus a specialist consultant), or the duration of time for which medical attention is needed. Each of these aspects may be associated with various levels of injury development; however, there is a lack of research detailing how medical attention is used depending on the 'level'. Medical attention is typically only sought by runners when progression of their 'complaint' demands it, and in cases where runners do not seek medical attention, self-management strategies are often used (Russell and Wiese-Bjornstal, 2015; Jelvegård *et al.*, 2016; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022). With early levels of injury development, runners often engage in self-diagnosis of their injury (Russell and Wiese-Bjornstal, 2015) and employ a self-regulation process to accommodate for 'complaints' (Russell and Wiese-Bjornstal, 2015; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022), trusting that these earlier levels of injury can be self-managed (Verhagen, Warsen and Silveira Bolling, 2021). Neglecting symptoms, continuing to train, and demonstrating 'magical thinking' in the hope their injury will resolve, runners eventually abstain from running when the injury progresses to a level of intolerable pain or loss of function (Jelvegård *et al.*, 2016). Examples of self-management strategies include alterations to training, completing stretching or strengthening exercises, and taking self-prescribed rest from running (Russell and Wiese-Bjornstal, 2015; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022). It has also been shown that runners seek other sources of advice when experiencing injury, from coaches, running peers, family or friends who are healthcare professionals, or the Internet (Russell and Wiese-Bjornstal, 2015; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022). Definitions, severity measurements and surveillance tools do not assess or measure this variety in management strategies, nor do we understand the extent to which they may differ depending on the level of injury.

Fourthly, the psychological consequences of the injury development process must be considered. There appear to be five key studies identifying a consistent chronology of negative emotions associated with the development of RRIs (Collinson, 2005; Clement, Arvinen-Barrow and Fetty, 2015; Russell and Wiese-Bjornstal, 2015; Hall, Rhodes and Papathomas, 2022; Festersen *et al.*, 2023). A recent meta-synthesis examined narrative reviews of injured ultra-runners (Hall, Rhodes and Papathomas, 2022), reporting that pain is often a central feature of injury, driving a "spectrum" of emotions in response. Feelings of frustration, seemingly due to ambiguity with diagnoses or prognoses, persistent symptoms, and perceptions of non-runners that overuse injuries are less severe than acute injuries (Collinson, 2005; Russell and Wiese-Bjornstal, 2015; Festersen *et al.*, 2023) are reported. Extensive feelings of fear in terms of not recovering, re-injury, diminished performance, and appearing weak have all been reported, many of which lead to catastrophic thinking (Russell and Wiese-Bjornstal, 2015). In addition, anxiety and disappointment (Collinson, 2005; Russell and Wiese-Bjornstal, 2015; Hall, Rhodes and Papathomas, 2022), general emotional distress (Russell and Wiese-Bjornstal, 2015), negative thoughts leading to negative emotions (Clement, Arvinen-Barrow and Fetty, 2015), and poor self-efficacy, changes in mood, feelings of failure, dissatisfaction, turmoil and loneliness, and poorer body image (Festersen *et al.*, 2023) have all been reported as injured runners are forced to confront the emotional response process that follows injury. However, the only study to explicitly identify an earlier level of injury reported that runners did not associate ‘complaints’ with ‘strong emotional manifestations’ (Verhagen, Warsen and Silveira Bolling, 2021). This is surprising as other consequences of injury (such as physical sensation) are clearly associated with escalating severities as levels of injury progress (i.e., rather than occurring only from the point of perceived ‘injury’). This warrants further investigation.

Finally, the social consequences of RRIs can also be considered, although research is limited (Festersen *et al.*, 2023). These include impacts on quality of life (QoL), activities of daily living (ADLs), and social relationships. Injured runners have reported significantly worse QoL compared to uninjured runners, with higher levels of injury severity associated with lower self-efficacy scores (Mihalko *et al.*, 2021). In terms of daily living, injuries have been reported by runners as “significant life events” (Jelvegård *et al.*, 2016, p. 3), with one in ten injured runners experiencing limitations in daily and household activities, or activities in work/school (Sleeswijk Visser *et al.*, 2021). Social relationships, such as those established through running groups or work, can also be negatively affected by injury. Associated with a high sense of community, runners can experience a loss of social connectivity when extracted from running, and if absenteeism from work occurs due to injury (either with physical symptoms or associated psychological stress), further reduced social interaction can occur (Festersen *et al.*, 2023). In contrast however, some runners have reported a positive outcome when not expected to participate in social running events due to injury (Festersen *et al.*, 2023). This highlights the subjectivity of the injury experience between individuals. Similar to the psychological consequences, there is minimal evidence describing these social consequences throughout the injury development process. Only one study has seemingly reported that ‘complaints’ cause ‘moderate consequences’ to daily life (Verhagen, Warsen and Silveira Bolling, 2021); however, as the sole study reporting this, further research is warranted.

RRI epidemiological research seems to be focused on capturing the ‘physical’ consequences of injury (i.e., pain and effect on running), with surveillance methods largely ignoring the psychosocial consequences experienced by runners. The International Classification of Functioning, Disability and Health (ICF) (as part of the World Health Organisation) suggests that injury is a complex phenomenon and must be viewed wholly as the interaction of ‘medical’ and ‘societal’ approaches in order to appropriately represent the full scope of consequences (Üstün *et al.*, 2003) (i.e., a biopsychosocial approach to injury). Ensuring a holistic approach to RRI surveillance is important to ensure that all consequences of injury are addressed in rehabilitation, and monitored to determine the effectiveness of injury prevention interventions (Üstün *et al.*, 2003). Furthermore, monitoring how consequences of injury vary based on the level of injury could provide additional insight into potential risk factors. Evidence for this can be seen by the cognitive appraisals (such as fear or denial) and behavioural responses (such as avoidance or overuse) to athletes dealing with overuse injury development (Timpka *et al.*, 2015). Once again, the design of an appropriate app-based surveillance tool could capture the subjectivity of these consequences, across the entire injury development process. However, there appears to be one further limitation to RRI research: a limited capture of runners’ opinions. If we are to truly understand the development of RRIs, the lived experience of those who are most affected by injury needs to be understood.

#### 2.2.5.3. Runners’ perceptions of injury

The sole consensus-based RRI surveillance method (i.e., the consensus definition) was developed through the opinions of researchers and medical professionals (Yamato, Saragiotto and Lopes, 2015), with the opinions of runners, who are possibly the most experienced with RRI epidemiology, seemingly overlooked. Not considering runners' lived experience may be a missing source of evidence, possibly limiting RRI epidemiological and aetiological research to date (van Wilgen and Verhagen, 2012). Furthermore, understanding how runners describe injury, and its development process, also seems to be lacking, with just three studies (Jelvegård *et al.*, 2016; Wickström *et al.*, 2019; Verhagen, Warsen and Silveira Bolling, 2021) seemingly reporting on this.

The first study took a qualitative approach to examine middle- and long-distance runners' perceptions of injury and illness, and how these translate to behaviour (Jelvegård *et al.*, 2016). While not reporting on runners' description of injury as a development process, this study details a process of cognitive appraisals and behaviours of how runners manage the injury development process (Figure 10). Runners typically take one of two approaches. With acute injuries or gradual onset injuries which have not been experienced previously, immediate training alterations are made. This decision process is termed 'self-monitoring activity pacing' and is often driven by fear of a serious injury. In contrast, when fearful thoughts can be avoided and runners feel that rest or training alterations are not necessary, they continue to run. Termed 'overactivity', this decision is associated with neglect and 'magical thinking'. However, runners describe how continuing to run will eventually lead to injury deterioration when they are often forced to stop running due to intolerable pain or strong advice from a medical professional (Jelvegård *et al.*, 2016).

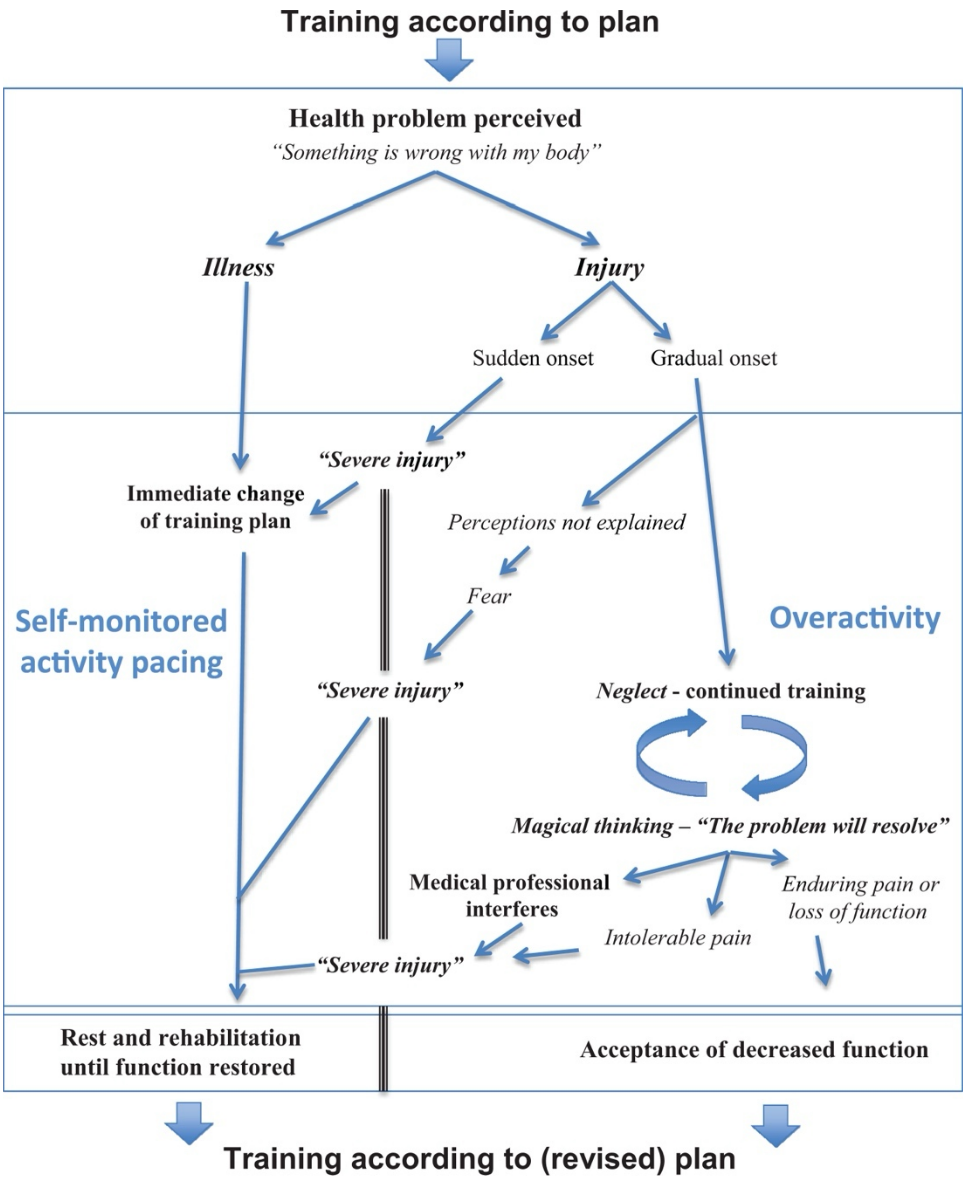



Figure 10. Overview of competitive runners' appraisals and behaviours related to health problems (Jelvegård *et al.*, 2016)

The second study took a quantitative approach to explore marathon and ultramarathon runners' perceptions of overuse injuries (Wickström *et al.*, 2019). The symptoms mainly associated with overuse injuries were pain, stiff muscles, stiff joints, and impaired physical ability. Runners understood overuse injuries as entities that were controllable, treatable, and comprehensible. To a lesser extent, they also associate overuse injuries with a timeline, representing a cyclic and chronic presentation of symptoms (Wickström *et al.*, 2019). Although not specifically examining the ‘development process’ of injury, this study identified that runners are aware of an injury ‘timeline’, and allude to the existence of various levels of injury, with the term ‘injury category’.

The third, and seemingly the only study to explicitly identify and name an early level of a RRI, took a qualitative approach to explore recreational runners’ perspectives, management, and prevention attempts of RRIs (Verhagen, Warsen and Silveira Bolling, 2021). Described above (section 2.2.5.1), the authors developed the three-level, bi-directional, ‘Injury Pathway’ (Figure 9), clearly detailing runners’ description of the progression of RRIs. Driven by overloading, runners associate the ‘complaint’ level with small pains or aches. They describe how ‘complaints’ are a normal part of running, not equating them with injuries, but describing how they can be managed by a self-regulated process of training modifications (e.g., reducing distance or speed of sessions) (Verhagen, Warsen and Silveira Bolling, 2021). The self-regulation process is influenced by runners’ competition schedule, competitive drive, personal goals, or daily personal life, and if successful, ‘complaints’ can improve. This process is supported by previous experience and information from peers, online resources, or experts. When attempts to self-regulate fail and ‘complaints’ overtake a runner’s autonomy in their training, they perceive themselves as injured. When injured, runners are forced to take absolute rest from running, with some also seeking medical advice (Verhagen, Warsen and Silveira Bolling, 2021). This paper provides the most explicit evidence for the existence of runners’ experience of various levels of injury development.

With just three studies exploring runners’ perception and description of injury, for the purpose of this review of literature, the views of other athletes were also considered (van Wilgen and Verhagen, 2012; Von Rosen *et al.*, 2018; Bolling *et al.*, 2019; Tarr and Thomas, 2021; Vella *et al.*, 2022). The beliefs of nine elite athletes and nine coaches regarding their description of overuse injuries were examined (van Wilgen and Verhagen, 2012). Athletes and coaches perceive overuse injuries to be extremely common and mainly describe them as a process, in which there is an imbalance between load and rest. Associated descriptions included pain and a slow progression, with somatic, psychological (behavioural and cognitive) and sociological factors being integrated. These findings show that athletes and coaches have a holistic view of overuse injuries (van Wilgen and Verhagen, 2012).

In a second study using a mixed-methods approach (prospective quantitative questionnaires and interviews), Von Rosen *et al.* (2018) examined the perceptions and experiences of injury suffered by adolescent elite athletes. Injury is perceived as a 'major threat' to young athletes' identities (Von Rosen *et al.*, 2018). Young athletes perceived personal and environmental factors, such as social support (or a lack thereof), coping strategies, and fear of re-injury, to influence the injury and recovery process. Prior to injury, pain is often perceived as a natural response to training, but when athletes gain the experience of injury, pain is learned from and recognised to be a sign of injury. Additionally, following injury, athletes report improvements in knowledge, prevention skills, motivation, and self-confidence (Von Rosen *et al.*, 2018).

In a third study, elite athletes', coaches' and physiotherapists' perceptions of sports injuries were examined in an interview-based study (Bolling *et al.*, 2019). Reduction in performance is used to define injury, while pain and altered training or competition schedules are perceived as subcomponents of injury, typically relating to injury severity. Athletes described pain as a normal part of training, with 'just pain' not being perceived as an 'injury'. The extent to which these consequences are experienced depends on personal or external factors, including individual pain tolerance, personal motivations, importance of competition, and previous experience (Bolling *et al.*, 2019).

Fourthly, in a qualitative study of 205 dancers, Tarr and Thomas (2021) explored perceptions of 'good' and 'bad' pain and injury. Most dancers experienced 'good' and ‘bad’ pain, with ‘bad’ pain being associated with injury. Dancers use three dimensions to distinguish between these pains: quantitative, qualitative, and a dimension of control. The quantitative dimension relates to the severity (typically exceeding 6-8 out of 10 for ‘bad’ pain), and duration (differing between individuals) of pain. While longer duration was perceived by some as more severe, in some cases, dancers reported suffering from chronic pain for years (especially in their lower backs), but never considered themselves injured. The qualitative dimension relates to anatomical structure and type of pain. Typically, muscle pain was perceived as ‘good’ pain, indicating hard work, while joint pain was more commonly associated with ‘bad’ pain and injury. Dancers described dull or chronic pain as being less problematic than sharp or acute pains. The dimension of control was suggested to be the most crucial element in determining whether pain was ‘good’ or ‘bad’. ‘Good’ pain was typically associated with an understandable cause, it was brought on by the dancer themselves (through training), or it could be tolerated; while ‘bad’ pain typically had an unexpected, acute onset. Dancers tended to ignore ‘good’ pain and not take it seriously, while they listened to ‘bad’ pain and reacted to it (Tarr and Thomas, 2021).

Age and experience also appear to influence perception and behaviour towards pain and injury, with dancers’ process of listening to their bodies appearing to waver (Tarr and Thomas, 2021). Young dancers describe being ‘socialised’ to pain, initially perceiving it as something serious, but as their careers progress, they practice ‘filtering’ pain, with ‘good’ being ignored as ‘noise’. With this process, they learn to only hear pain that is outside their normal range, with chronic, less serious pain often going unheard. With more experience, dancers tend to become more proactive about pain treatment and management, eventually redefining injury and pain to more carefully consider chronic, ‘niggling’ pains. The process through which dancers distinguish between ‘good’ and ‘bad’ pain is described as erratic, highly individual, and driven by experience (Tarr and Thomas, 2021). The long-term consequences of pain are often not considered by dancers, with an apparent acceptance that pain is a part of their dancing career. ‘Good’ pain is seen as a sign of improvement, with a perception that improvement cannot be achieved without pain. This is referred to as ‘intrinsically good pain’. A moral dimension also exists where dancers fear being labelled as lazy, akin to being injury-prone. This drives dancers’ behaviour to ignore pain, where they are apparently more concerned about *not* dancing through pain, than the consequences *of* dancing through pain. This is referred to as ‘extrinsically good pain’ (Tarr and Thomas, 2021). Overall, it appears that dancers’ descriptions of pain are individual and context-dependent, and often contradictory, highlighting the blurred line between ‘good pain’, ‘bad pain’, and injury.

Finally, national-level, professional soccer stakeholders’ perceptions of injury and injury management were explored (Vella *et al.*, 2022). Similar to above (Bolling *et al.*, 2019), players, coaches and healthcare professionals perceive injuries as pains which hinder performance, with pain, training modifications and time-loss acting as subcomponents, determining injury severity (Vella *et al.*, 2022). Players report never playing ‘pain-free’, with pain being considered ‘normal’ (Vella *et al.*, 2022). There are several contextual factors that determine injury perception and management, with a reported cultural norm of injury risk acceptance acting as a primary modulator for other situational, relation and individual factors. Unstable situational factors, including position within the team, national-team selection opportunities, and most importantly, match importance, will influence injury perception and management. Relations with the club, support staff and teammates, either increases or reduces pressure to play with injury. Personal factors such as motivation, team loyalty, risk taking behaviour and pain tolerance will influence perception and management of injury; however, these will be largely modulated by age and previous injury experience (Vella *et al.*, 2022).

Investigating runners' (and athletes') perceptions and experiences of injury is essential, not only to understand the range and extent of consequences suffered, but also to potentially improve injury surveillance and injury prevention interventions (Finch, 2006). In particular, qualitative methodologies which capture and interpret runners' lived experiences, may contribute to the development of surveillance tools which are more representative of the true nature of RRI development (Korstjens and Moser, 2017).

To summarise this review of literature thus far, the fundamentals of RRI epidemiology and aetiology appear to be ill-established, with several possible reasons being examined. Firstly, it is conceivable that 'injury' exists as a process or a fluid phenomenon, with sports medicine's 'black or white' dichotomous view of injury failing to consider the intermediate 'grey' that encompasses overuse injury development. Secondly, while research largely advocates for standardized and consistent definitions and surveillance systems (Bahr *et al.*, 2020), when runners' and athletes' lived experiences are considered, injury perception is clearly individual- and context-specific. These factors behave in an interactional manner, demonstrating dynamicity, fluidity, and complexity. Injury surveillance needs to embrace this complexity. Thirdly, runners clearly experience a range of biopsychosocial factors with injury development. While defining injury by pain and performance limitations may be applicable in an elite sport setting (Bolling *et al.*, 2019; Vella *et al.*, 2022), in populations where other goals dominate (e.g., recreational runners running to improve their overall health), this definition may not transfer. Ingraining this holistic approach into injury surveillance systems may enhance their value. Finally, it seems that researchers' opinions have been relied upon to develop RRI surveillance methods (i.e., the consensus definition [Yamato, Saragiotto and Lopes, 2015]), despite definitions possibly not aligning between various stakeholders involved (e.g., athletes', coaches and healthcare professionals). Understanding runners' lived experience of injury could lead to the development of a more applicable surveillance system, capable of capturing the injury development process as experienced by runners. Advancing RRI prevention research may be possible by monitoring and investigating the entirety of the injury development process, across all consequences and influential factors. As no single marker of an athlete's response to load consistently predicts maladaptation or injury (Soligard *et al.*, 2016), a multifactorial approach to injury surveillance is needed (Neal *et al.*, 2024). Frequent (run-by-run) data capture is also required to capture the constantly changing risk of injury at each athletic exposure (Meeuwisse *et al.*, 2007). The development of a comprehensive surveillance system is required. However, this extensive type of research can be associated with difficulties in terms of consistent, accurate, and valid data collection (Patel, Doku and Tennakoon, 2003; Oliveira and Pirscoveanu, 2021). Smart technologies offer a possible solution with their capacity to remotely (i.e. in-field) capture biomechanical, training-related, and patient-reported data (among other potential risk factors) (Neal *et al.*, 2024). In order to develop such a surveillance system, the use of running technologies must be investigated.

## 2.3. Running technologies

Smart technologies can be utilised to address the challenge of the extensive type of data collection necessary for investigating RRIs (as described throughout section 2.2). To understand how these technologies can be utilized in research and develop appropriate technologies for injury prevention, we must first understand runners' use of technologies. Therefore, the aim of this section is to understand the types and uses of running technologies, how runners use running technologies, and their perceived facilitators and barriers to technology usage.

### 2.3.1. Types and uses of running technologies

Smart technologies, otherwise known as smart devices, mobile devices, internet-of-things or smart things, are objects capable of communication and computation (Risteska Stojkoska and Trivodaliev, 2017). They have revolutionized the fields of healthcare (Tian *et al.*, 2019) and sports performance (De Fazio *et al.*, 2023), typically monitoring daily activity levels (e.g., steps), sleep patterns, heart rate and mood, to provide insight to the user, typically with the ultimate goal of living a healthier lifestyle (Cusack *et al.*, 2024). Running technologies are smart devices that are used by runners to capture running-related data, and can be mainly described as wearable devices and smartphone applications (apps).

Wearable devices are technologies that possess sensors to detect how the body is manoeuvring (Aroganam, Manivannan and Harrison, 2019). The process of collecting and analysing data is known as self-monitoring and is an important aspect of training, enabling runners to monitor their progress (Stragier, Vanden Abeele and De Marez, 2018). The collected data can be visualised, analysed, summarised, saved or shared with many commercially available platforms (Stragier, Vanden Abeele and De Marez, 2018). Wearable devices commonly used in running include motion sensors such as global positioning system (GPS) devices, inertial measurement units (IMUs), and instrumented insoles, and physiological sensors such as heart rate monitors and temperature sensors (Li *et al.*, 2016; Moore and Willy, 2019). GPS, found in many sports watches and smartphones, is used for navigation, and by capturing location and time information in real-time, devices can measure spatiotemporal metrics (e.g., distance, speed or pace) when running (Willy, 2018; Aroganam, Manivannan and Harrison, 2019). IMUs are made up of three types of sensors: (i) an accelerometer, which measures segmental acceleration (linear and gravitational accelerations), (ii) a gyroscope, which measures angular velocity, and (iii) a magnetometer, which measures orientation (Willy, 2018; Aroganam, Manivannan and Harrison, 2019). Together, these sensors can be used to capture running biomechanics, with foot pods being a commonly used IMU in running (Benson *et al.*, 2018). Heart rate monitors measure and display heart rate in real time and/or record it to be analysed later (Gajda *et al.*, 2024). Many sports watches are equipped with heart rate monitors, while separate (supposedly more accurate) devices can be worn in other locations (e.g., chest or arm based), and synced to other types of running data collected (Gajda *et al.*, 2024).

Smartphone apps are used to support the collection, storage, analysis and interpretation of data collected by wearable devices (Aroganam, Manivannan and Harrison, 2019). The smartphone carrying an app can be transformed into a sports device by being used directly when running, or alternatively, an app can be coupled with a separate wearable device to present, store and analyse running-related data. Sports watches appear to be the most popular type of running technology, followed by smartphone apps (Janssen *et al.*, 2017, 2020; Clermont *et al.*, 2019; Helsen *et al.*, 2022).

Running technologies are typically associated with two goals: to enhance running performance and/or reduce the likelihood of RRIs , with enhanced performance appearing to be the primary goal (section 2.3.2.2). They can be used for logging running sessions (Strohrmann *et al.*, 2013), setting and tracking running goals (Karahanoglu *et al.*, 2021), enhancing motivation (Karahanoglu *et al.*, 2021), and social connectivity (Spotswood, Shankar and Piwek, 2020). Multiple types of data can be collected, both during running to provide real-time feedback, and outside of running for more in-depth analysis and insight (Moore and Willy, 2019). During running, real-time external load (e.g., distance and pace), internal load (e.g., heart rate) and running technique (e.g., cadence) data can be collected. This data is immediately available to runners during their session, presenting opportunities for adaptation (e.g., changes in pace) or reassurance (e.g., that they are on-target) (Moore and Willy, 2019). Additional data is also collected during running, but typically not analysed until the session has finished (Moore and Willy, 2019). These include external load (e.g., total distance, average pace, or calories burned), internal load (e.g., average heart rate or rate of perceived exertion), running technique (e.g., average cadence or stride length), running kinematics (e.g., foot strike position), and geographical information (e.g., terrain). Outside of running sessions, data can also be collected to provide a wider picture of health and recovery. Data on sleep (e.g., duration or sleep cycles), nutrition (e.g., calories taken in), menstrual cycle (e.g., cycle tracking or symptoms), physical activity/inactivity (e.g., steps, standing time or sedentary time), psychological health (e.g., mood or stress), other training (e.g., strength training), overall health status/physical fitness (e.g., resting heart rate), and recovery status or readiness to train (e.g., body battery) are often captured. When this data is monitored overtime, it can provide insight into the training and recovery status of the user, helping them to achieve their goals (Karahanoglu *et al.*, 2021).

There is huge popularity in the use of running apps. Strava is the largest online social network for athletes (Franken, Bekhuis and Tolsma, 2023) and many well-known sports brands have launched their own apps (Cheng, Huang and Lai, 2022), with Adidas and Nike having over 50 million and 10 million downloads, respectively (Byun, Chiu and Won, 2023). To review popular running apps, various sources were used to identify them:

(i) evidence collected directly from runners (Janssen *et al.*, 2017; Karahanoglu *et al.*, 2021), (ii) a book chapter which conducted a systematic search of five apps stores for the most downloaded running apps available (Gute, Schlögl and Groth, 2022), and (iii) a search of the top grossing apps on Apple Store (Apple Inc., 2024) and Google Play (*Google Play*, 2024). Each of these apps were downloaded and reviewed to identify their included features, detailed in Table 2 below (note: only free versions of apps were reviewed). Popular pay-for apps such as Couch to 5K, WorkOutDoors and Run Tempo are also available.

Table 2. List of popular smartphone running apps and their associated features (as of 16th May 2024)

| **App features** | **Adidas Running** | **Garmin Connect** | **Map my Run (Under Armour)** | **Nike Run Club** | **Runkeeper (Asics)** | **Strava** | **Apple Fitness** | **FitBit** | **Runna** |
|---|---|---|---|---|---|---|---|---|---|
| *Run-specific metrics* | | | | | | | | | |
| Basic running metrics (e.g., distance, pace, speed) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| GPS/Route information (e.g., location, elevation, weather) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Heart rate (e.g., average, maximum) | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ |
| Perceived exertion/feeling | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| Training effect (aerobic/anaerobic) | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Running technique (e.g., cadence, strike length) | ✗ | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ | ✓ | ✗ |
| Power output | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ | ✗ |
| Nutrition/Hydration (e.g., sweat loss, calories burned) | ✗ | ✓ | ✗ | ✓ | ✗ | ✗ | ✓ | ✓ | ✗ |
| *Out-of-run analyses* | | | | | | | | | |
| Sleep monitoring | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| Menstrual cycle tracking | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| Daily activity (e.g., steps, floors climbed, calories burned) | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ |
| Stress level | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| Heart rate, breathing rate | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✓ | ✓ | ✗ |
| Body battery/Recovery status | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Training status (estimated $VO_2$max, training load) | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ | ✗ |
| Nutrition/Hydration | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| Pulse Ox/$SpO_2$ | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| Weight tracking | ✗ | ✓ | ✗ | ✗ | ✗ | ✗ | ✗ | ✓ | ✗ |
| *Coaching plans/Motivation enhancement* | | | | | | | | | |
| Coaching plans | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ |
| Goal tracking | ✓ | ✗ | ✓ | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ |
| Motivation (challenges, badges) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✗ |
| *Other features* | | | | | | | | | |
| Feedback during run (e.g., distance ran, average pace) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Compatibility with wearable device | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Requirement to carry smartphone | ✓ | ✗ | ✓ | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ |
| Social interaction with other users | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Information articles/Blog posts | ✓ | ✗ | ✗ | ✓ | ✓ | ✗ | ✓ | ✗ | ✓ |
| Monitor footwear/gear | ✓ | ✓ | ✗ | ✓ | ✓ | ✓ | ✗ | ✗ | ✓ |

$VO_2$ max: maximal oxygen consumption; pulse Ox: pulse oximetry; $SpO_2$: peripheral oxygen saturation

### 2.3.2. Runners' use of running technologies

Running technologies range in use from 28% (Janssen *et al.*, 2020) to 95% (Karahanoglu *et al.*, 2021) but appear to be popular among the majority, with 74% (Clermont *et al.*, 2019), 75% (Pobiruchin *et al.*, 2017), and 86% (Janssen *et al.*, 2017) of runners using at least one device. There appears to be a trend towards these devices being considered a 'need' rather than a 'want' (Aroganam, Manivannan and Harrison, 2019), perhaps stimulated by the current era in which society often values 'success' in terms of quantifiable metrics (e.g., the fastest or the longest run) (Aroganam, Manivannan and Harrison, 2019). Technology acceptance is a pivotal factor in the success or failure of a new technology (Davis, 1989); however, the use and non-use of technologies are not categorical and binary things (i.e., meaning people can change their behaviour) (Mertala and Palsa, 2024). Therefore, prior to developing an injury-focused running technology, it is important to understand individuals' behaviour with technologies in order to optimize their adoption.

#### 2.3.2.1. Technology usage models

Several models describe individuals' behaviours towards technology usage (Nadal, Sas and Doherty, 2020); however, two models in particular appear to have found widespread adoption in health care and sports research (Ammenwerth, 2019; Guo, 2022): the Technology Acceptance Model (TAM) (Davis, 1989) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh *et al.*, 2003).

The TAM was developed in the late 1980's to better understand users' acceptance and use of technologies, in order to improve technology design (Davis, 1989; Davis, Bagozzi and Warshaw, 1989). It consists of two key constructs: perceived usefulness and perceived ease of use. Perceived usefulness refers to the degree to which a person believes that using a particular system will be effective at achieving the associated goal, while perceived ease of use refers to the degree to which a person believes that the system will be user-friendly and free of effort (Davis, 1989; Davis, Bagozzi and Warshaw, 1989; Ammenwerth, 2019) (Figure 11). These constructs influence a user's 'attitude towards using', which is a determinant of the behavioural intention to use, which results in actual use (Davis, 1989; Davis, Bagozzi and Warshaw, 1989; Ammenwerth, 2019). The TAM is one of the most commonly used models for understanding technology usage behaviour (Marangunić and Granić, 2015; Cho, Chi and Chiu, 2020; Yau and Hsiao, 2022).

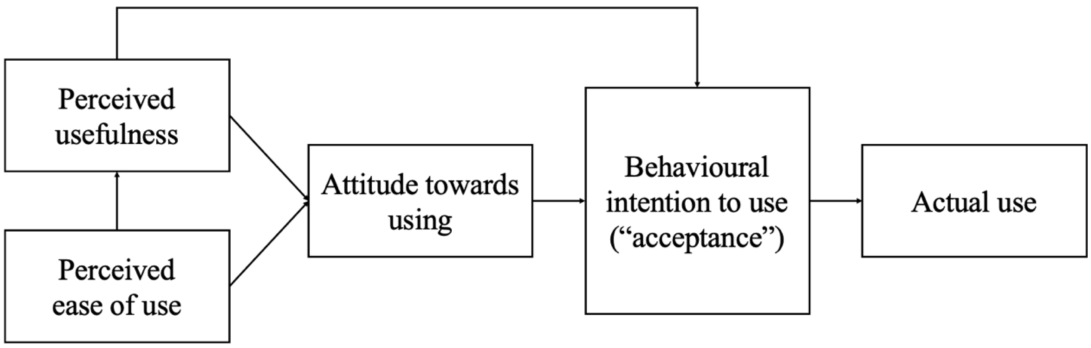



Figure 11. Technology Acceptance Model (Davis, 1989; Davis, Bagozzi and Warshaw, 1989)

The UTAUT was developed in 2003, based on an analysis and comparison of eight previous models (Venkatesh *et al.*, 2003). Its development was aimed at synthesizing current technology acceptance models into one unified model, to assess the likelihood of success for new technologies, and understand the drivers of acceptance (Venkatesh *et al.*, 2003; Ammenwerth, 2019). The UTAUT describes four key constructs: performance expectancy, effort expectancy, social influence, and facilitating conditions (Venkatesh *et al.*, 2003; Ammenwerth, 2019) (Figure 12). Performance expectancy, which corresponds to perceived usefulness in the TAM, is related to the users' perception that the technology will be useful for its intended purpose. Effort expectancy, which corresponds to perceived ease of use in the TAM, is related to the users' perception that the technology will be user-friendly. Social influence is related to the user's perception of other people's beliefs on their use of the technology. Facilitating conditions are the extent to which a user believes organisational and technical infrastructures are in place to support their use of the technology. Gender, age, experience and voluntariness are moderators of the four constructs, together impacting on behavioural intention to use and actual usage behaviour (Venkatesh *et al.*, 2003; Ammenwerth, 2019).

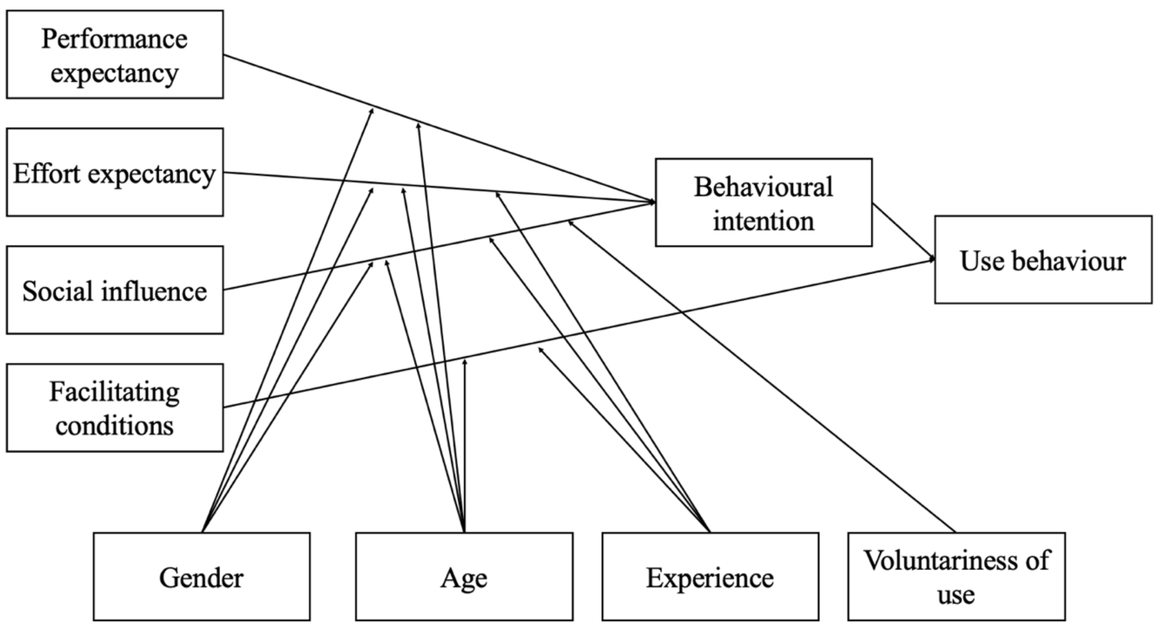



Figure 12. Unified Theory of Acceptance and Use of Technology (Venkatesh *et al.*, 2003)

Based on these two models, it appears that the perceived usefulness and ease of use of devices will largely determine individuals' technology use, acting as facilitators and barriers. These perceptions are subjective however, and it is important to consider that they may be influenced by individual characteristics and the social contexts within which they are deployed (Canhoto and Arp, 2017).

#### 2.3.2.2. Facilitators and barriers of running technology use

Perceived usefulness (TAM, [Davis, 1989]) or performance expectancy (UTAUT, [Venkatesh *et al.*, 2003]), and perceived ease of use (TAM, [Davis, 1989]) or effort expectancy (UTAUT, [Venkatesh *et al.*, 2003]) appear to act as both facilitators and barriers to runners' use of technology. For perceived usefulness or performance expectancy, there appear to be three aspects to consider: the data collected, how this data is used, and why running is monitored. Firstly, in terms of data collected, runners appear to be most interested in capturing basic running metrics including distance, duration and speed of sessions (Janssen *et al.*, 2020; Helsen *et al.*, 2022), with secondary metrics including heart rate and cadence also being reported as important (Janssen *et al.*, 2020). Secondly, in terms of how this data is used, reviewing sessions afterwards (Janssen *et al.*, 2020; Karahanoglu *et al.*, 2021), monitoring progress overtime (Janssen *et al.*, 2020), adapting training (Clermont *et al.*, 2019; Janssen *et al.*, 2020), or stay on target during sessions (Karahanoglu *et al.*, 2021) were reported as facilitators. As a barrier however, non-users reported perceived freedom when not using running technologies. Mertala and Palsa (2024) found that runners often enjoy being in nature, with using technology detracting from this, while 34% of non-users in Janssen *et al.'s* (2020) study reported that running with technology had no added value. Thirdly, in relation to why runners use running technologies, enhanced performance appears to be the primary motivator, with tracking and documenting training frequently identified (Pobiruchin *et al.*, 2017; Rönnby *et al.*, 2018; Clermont *et al.*, 2019; Janssen *et al.*, 2020; Karahanoglu *et al.*, 2021). This tracking is in relation to optimizing training (Pobiruchin *et al.*, 2017; Rönnby *et al.*, 2018), receiving insights into achievements (Clermont *et al.*, 2019; Karahanoglu *et al.*, 2021), and supporting running goals (Clermont *et al.*, 2019; Karahanoglu *et al.*, 2021). Other motivators include enhancing motivation to run (Clermont *et al.*, 2019; Janssen *et al.*, 2020; Karahanoglu *et al.*, 2021), monitoring running biomechanics/technique (Clermont *et* *al.*, 2019; Janssen *et al.*, 2020), and social connectivity (Kuru, 2016; Stragier, Vanden Abeele and De Marez, 2018). In terms of barriers, one of the leading reasons for non-use is a perception that it is not necessary. Janssen *et al.* (2020) reported that non-users perceive no benefit (40%) or no need for technology (37%), or that it does not align with their running goals (24%). Similarly, Mertala and Palsa (2024) reported that if runners were not goal-oriented or if they had already met their goals, there was no need for using technology. Furthermore, Mertala and Palsa (2024) found that runners associated technology use with an increased risk of injury, as they can become hyper fixated on the data, rather than listening to their bodies. This finding may be in line with reports of obsessive data monitoring, where runners can become hyper-fixated on achieving certain results or maintaining a certain training load/intensity (Rönnby *et al.*, 2018).

For perceived ease of use or effort expectancy, just two studies seem to have investigated this in runners. Rönnby *et al.* (2018) found that runners require a positive balance between the burden of using technologies and the feedback received in order to engage with them (Rönnby *et al.*, 2018). Mertala and Palsa (2024) found that non-users perceived running technologies as burdensome, requiring frequent charging or updates, they associated them with a short lifespan, and they perceived them as uncomfortable. To enhance ease of use, findings suggest data input requirements should be short in duration, completed in a single input session, and integrated into daily life. Data should also be presented in graphical formats to allow runners to understand and interpret it (Rönnby *et al.*, 2018). The purposes and explanations of monitored items should also be clear and explicit, with runners expressing concerns regarding sharing data, especially in relation to personal health and mental well-being, reporting it as a potential barrier (Rönnby *et al.*, 2018). As research is somewhat limited in terms of running technologies, to better understand the ease of use or effort expectancy, research investigating wearable technologies for general health or fitness were reviewed. Often being two sides of the same coin, facilitators and barriers to the ease of use or effort expectancy are presented in Table 3.

Table 3. Facilitators and barriers to the perceived ease of use of general fitness/health wearable technologies

| Aspect of technology | Facilitator | Barrier |
|---|---|---|
| **Cost** | Low cost (Canhoto and Arp, 2017) | High cost (Kinney, 2019) |
| **Aesthetics** | Comfort, pleasing aesthetics (Canhoto and Arp, 2017; Hermsen *et al.*, 2017; Kononova *et al.*, 2019; Luczak *et al.*, 2020; Bardus *et al.*, 2021) | Uncomfortable, poor aesthetics (Kinney, 2019; Luczak *et al.*, 2020; Bardus *et al.*, 2021) |
| **Technical features** | Good battery life (Canhoto and Arp, 2017) | Poor battery life (Hermsen *et al.*, 2017) |
| | Compatibility with other devices (Lazar *et al.*, 2015; Vos *et al.*, 2016; Canhoto and Arp, 2017; Hermsen *et al.*, 2017; Bardus *et al.*, 2021) | Inconsistent functioning (Luczak *et al.*, 2020) |
| | | Adverts/Pop-ups (Bardus *et al.*, 2021) |
| | | Broken device (Bardus *et al.*, 2021) |
| **Feedback** | Enjoyment and encouragement messages (Canhoto and Arp, 2017) | Not engaging (Bardus *et al.*, 2021) |
| **Ease of use** | Low need for behaviour change (Canhoto and Arp, 2017) | Difficult to use (Bardus *et al.*, 2021) |
| **Community** | Social connectivity (Canhoto and Arp, 2017) | |

In addition to performance and effort expectancy, the UTAUT demonstrates how moderators, such as gender and age, influence behavioural intention to use and actual usage behaviour (Venkatesh *et al.*, 2003) (Figure 12). It is important to understand the differences in runners' needs, expectations and uses of technologies to allow for more meaningful outputs from devices (Kuru, 2016; Janssen *et al.*, 2017; Aroganam, Manivannan and Harrison, 2019; Clermont *et al.*, 2019). Differences in type of device used, data captured, and use of data across different types of runners are presented in Table 4. These findings demonstrate that runners who are more competitive and run more frequently seem to seek and appreciate more advanced features of wearable technologies than runners of a more recreational nature.

Table 4. How different ‘types’ of runners use of running technologies

| Study | Types of runners | Type of device used | Data captured | Use of data |
|---|---|---|---|---|
| (Janssen *et al.*, 2017) | Classified by demographics (age, gender, educational level), and running-related characteristics (training frequency, group/individual runner, event participation, other sport participation). | Sports watch users: older (≥36 years), ran with a club, participated in ≥2 running events annually, trained ≥2 times per week, and perceived more advantages of running.<br>Smartphone app users: younger (≤35 years), ran individually, participated in fewer running events annually, did not consider running their main sport, and who scored higher on individual motives for quitting running were more likely to use smartphone apps | NR | NR |
| (Clermont *et al.*, 2019) | Recreational: running <4 times/week (n=327)<br>Competitive: running ≥4 times/week (n=336) | GPS watch users: competitive runners<br>Smartphones app users: recreational runners | Both groups deemed distance, speed and time as important metrics for injury prevention<br>Significantly more competitive runners deemed cadence to also be important | Both groups: primarily interested in tracking personalised data<br>Competitive runners: significantly more interested in monitoring running technique.<br>Recreational runners: significantly more interested in enhancing motivation to run. |
| (Janssen *et al.*, 2020) | (i) Casual individual runners (n=886): primarily women, >35 years, higher education levels, ran 5km-10km, more inexperienced, running was not the main sport, trained less frequently, participated in fewer events, and ran more individually.<br>(ii) Social competitive runners (n=100: highly competitive, less experienced, trained less | Sport watches used by 68% of type (i), 58% of type (ii), 45% of type (iii), and 67% of type (iv)<br><br>Smartphone apps used by 41% of type (i), 28% of type (ii), 25% of type (iii), 21% of type (iv). | Distance (96%), time (90%) and speed (86%) were the most common metrics among all users (regardless) of type<br><br>Heart rate: captured by 10% of types (i) and (ii), | Type (iii) runners utilize data the most, with 82% reviewing data post-session, 66% monitoring data over time, and 15% using the data to adapt their training. |

| | | | | |
|---|---|---|---|---|
| | frequently, 5km-10km runners, and ran with friends/colleagues/small groups.<br>(iii) Individual competitive runners (n=1012): mostly male, competitive, high identification with running lower/middle education level, running was the main sport, long training distances, and lower susceptibility to dropout for individual reasons.<br>(iv) Devoted runners (n=821) were >45 years, had low/middle education, running was the main sport, long training distances, high identification with running, low susceptibility to dropout, not as competitive. | Non-users: 14% type (i), 16% of type (ii), 7% of type (iii), 12% of type (iv). | 7% of type (iii), and 9% of type (iv).<br><br>Other data (incl. cadence and calories burned): 3% of type (i), 6% of types (ii) and (iii), and 9% of type (iv). | |

NR: Not reported

Although it appears that performance enhancement is the primary motivator for runners' use of technology, they may also be useful for monitoring injury risk and enhancing injury prevention (Aroganam, Manivannan and Harrison, 2019; Feng and Agosto, 2019). In theory, technologies can track training loads in real-time (or near real-time) and identify training errors prior to the occurrence of injury (Moore and Willy, 2019), they can provide real-time feedback on aspects of running technique or kinematics that may be associated with injury (e.g., impact peak and 'running softer') (Chan *et al.*, 2018), and they can be used to predict a user's state of recovery, potentially identifying risk of overtraining (Gabbett, 2016). Despite these capabilities, research appears to have focused on performance enhancement as the primary motivators for runners' use of wearable technologies. Just one study has seemingly focused on capturing runners' perceptions of running technologies for preventing injuries (Clermont *et al.*, 2019). This study examined runners' perceptions of the metrics perceived to be related to RRIs, and the usefulness of wearable technologies for preventing injury. Detailed in Table 4 above, differences in motivators for technology use and perceptions of metrics related to injury risk between competitive and recreational runners were found. Clermont *et al.* (2019) concluded that runners perceive basic running metrics (i.e., distance, speed and duration of sessions), which are largely related to training load, as the most important metrics for preventing injury, despite not being supported by evidence (section 2.2.1.3). With this being the sole study, further research is needed to better understand runners' use of running technologies for monitoring and preventing RRIs.

To enhance use of new technologies, minimizing the effort required by the user (i.e., improve the perceived ease of use/effort expectancy) and maximising their interest (i.e., enhance the perceived usefulness/performance expectancy) (Davis, 1989; Venkatesh *et al.*, 2003) appears to be key. With their ability to monitor multiple risk factors for injury (Aroganam, Manivannan and Harrison, 2019; Feng and Agosto, 2019) and capture data from large sample sizes over prolonged periods of time, strengthening statistical power (Moore and Willy, 2019), wearable technologies have the potential to be used to advance RRI prevention research. This research is not without challenges however, chiefly in the terms of participant recruitment and retention.

### 2.4. Recruitment and retention of research participants

The design of methodologically sound surveillance studies will yield no meaningful insights if a sufficient and representative sample cannot be recruited, nor if their interest and adherence cannot be maintained for its duration (Cooke and Jones, 2017). The recruitment and retention of participants is considered one of the most challenging and critical aspects of research (Khatamian Far, 2018), with failure in doing so threatening the feasibility, validity, and quality of research (Patel, Doku and Tennakoon, 2003; Khatamian Far, 2018; Pulsford *et al.*, 2023). The recruitment and retention of participants for the type of injury surveillance being advocated for in this thesis is associated with several challenges. Firstly, the long-term commitment can deter individuals from initially signing up and result in high rates of dropout (Davis, Broome and Cox, 2002; Teague *et al.*, 2018). Secondly, the high frequency of data capture required can place a high burden on participants (Davis, Broome and Cox, 2002; Teague *et al.*, 2018). Thirdly, participants may be reluctant to share information regarding their health, or may have privacy and security concerns regarding their personal information being collected (Borg *et al.*, 2024). Finally, the use of smart technologies can cause additional challenges with poor digital literacy (Daniore, Nittas and Von Wyl, 2022), and sampling bias (Pulsford *et al.*, 2023).

While these are general challenges to research participation, in order to optimize recruitment and retention, it is important to understand the specific and individual barriers and facilitators of runners (Teague *et al.*, 2018; Daniore, Nittas and Von Wyl, 2022). However, no studies have investigated recreational runners' perceived barriers and facilitators to participation in longitudinal injury research involving wearable technologies. This highlights a clear gap, warranting further investigation.

### 2.4.1. Recruitment of research participants

Participant recruitment involves researchers' attempts to identify, contact and enrol potential participants (Patel, Doku and Tennakoon, 2003). It should ensure that the target sample population (e.g., recreational runners) is appropriately represented by the recruited participants, and with inter- and intra-individual differences in risk factors for RRIs, a sufficiently large sample size is needed for statistical power requirements and ecological validity (Patel, Doku and Tennakoon, 2003; Oliveira and Pirscoveanu, 2021). Barriers, facilitators and recruitment strategies are important aspects of research recruitment to consider.

#### 2.4.1.1. Barriers and facilitators to recruitment, and recruitment strategies

There are several reviews detailing the barriers and facilitators of patients' recruitment into clinical trials (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Watson *et al.*, 2022), randomized controlled trials (Houghton *et al.*, 2020), and for those with disabilities (Leahy and Ferri, 2022; Shariq *et al.*, 2023) for example. However, there appear to be no reviews, nor any studies, which examine the barriers and facilitators of runners' recruitment into research. For this review of literature, several reviews were examined to investigate the barriers and facilitators of recruiting participants into research in general (Sheridan *et al.*, 2020), physical activity research (Cooke and Jones, 2017), clinical trials (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021), longitudinal studies (Borg *et al.*, 2024), and research involving wearable technologies (Daniore, Nittas and Von Wyl, 2022). An overview of the findings of these reviews is presented in Table 5, with themes relating to study design, potential participant characteristics, use of technologies, or other. While a number of facilitators have been identified, there appears to be a greater number of barriers, challenging the recruitment of potential research participants (Table 5). While some factors act in isolation (i.e., as either a barrier or a facilitator), many appear to exist as two sides of the same coin (e.g., the requirement of too many complex tasks acting as a barrier, while fewer, more simple tasks acting as a facilitator (Daniore, Nittas and Von Wyl, 2022). To facilitate recruitment, Daniore, Nittas and Von Wyl (2022) developed a framework based on three elements: the participant motivation profile (intrinsic and extrinsic motivators), the task complexity (physical and mental tasks required), and the scientific requirements (study design) (Figure 13). To enhance participant recruitment, researchers should consider participants' motivations for engaging in research and make participation as convenient and attractive as possible.

Table 5. Barriers and facilitators to recruitment of resaerch participants

| Barriers | Supporting reviews | Facilitators | Supporting reviews |
|---|---|---|---|
| *Study design* | | | |
| Practical difficulties (e.g., transport/ cost) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Borg *et al.*, 2024) | Low burden/Convenient participation (e.g., autonomous data collection, low frequency and complexity of tasks, tasks daily with daily life, reminders to attend) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Daniore, Nittas and Von Wyl, 2022; Borg *et al.*, 2024) |
| Unsuitable information and knowledge of the research (e.g., too complex/difficult to understand) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | Suitable information and knowledge of the research (e.g., having the option of exiting a study) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |
| Concerns regarding privacy and confidentiality of data | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Borg *et al.*, 2024) | Incentives (e.g., financial benefit, free medical testing) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Daniore, Nittas and Von Wyl, 2022; Borg *et al.*, 2024) |
| Lack/Poor style of communication | Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Borg *et al.*, 2024) | Variety of physical activities required | (Cooke and Jones, 2017) |
| Burdensome involvement (e.g., too time-consuming, tasks too frequent and complex) | (Daniore, Nittas and Von Wyl, 2022; Borg *et al.*, 2024) | Greater group cohesion among participants | (Cooke and Jones, 2017) |
| | | Perceived fun/enjoyment with participating | (Cooke and Jones, 2017) |
| *Participant profile* | | | |

| | | | |
|---|---|---|---|
| Fear and perceived risk (e.g., to health, adverse effects, personal consequence) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | Personal benefit (e.g., therapeutic benefit, closer monitoring, access to treatments, gaining knowledge) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |
| Distrust of research/researchers/ healthcare | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | Confidence/Trust in research/ researchers/healthcare | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Daniore, Nittas and Von Wyl, 2022) |
| Treatment preferences (e.g., against placebo) | (Sheridan *et al.*, 2020) | Personal characteristics (socioeconomic, ethnic, demographic, personality, and psychological) (e.g., younger patients more easily recruited) | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |
| Stigma associated with health condition | (Sheridan *et al.*, 2020) | Personal benefits (e.g., cultural, religious) | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |
| Personal health (e.g., too ill to participate) | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | Willingness to participate, personal likes associated with study | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |
| Desire for autonomy (e.g., feeling forces to participate due to illness) | (Sheridan *et al.*, 2020) | Positive previous experience | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |
| Personal characteristics (including socioeconomic, ethnic, demographic, personality, psychological) (e.g., males more difficult to recruit) | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Borg *et al.*, 2024) | | |
| Personal beliefs (e.g., cultural, religious) | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | | |

| | | | |
|---|---|---|---|
| Unwillingness to participate, personal dislikes associated with study | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Borg *et al.*, 2024) | | |
| Poor previous experience | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | | |
| *Technology-related* | | | |
| Difficult-to-use technologies | (Daniore, Nittas and Von Wyl, 2022) | User-friendly technologies | (Daniore, Nittas and Von Wyl, 2022) |
| Lack of technical support | (Daniore, Nittas and Von Wyl, 2022) | Technical support | (Daniore, Nittas and Von Wyl, 2022) |
| Poor technical literacy | (Daniore, Nittas and Von Wyl, 2022) | Good technical literacy | (Daniore, Nittas and Von Wyl, 2022) |
| | | Passive data collection | (Daniore, Nittas and Von Wyl, 2022) |
| *Other* | | | |
| Influences of others (e.g., discouragement from family/friends) | (Cooke and Jones, 2017; Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | Influence of others (e.g., encouragement from family/friends) | (Cooke and Jones, 2017; Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021; Borg *et al.*, 2024) |
| Misconceptions about research | (Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) | Altruism (e.g., benefitting science/ other people | (Sheridan *et al.*, 2020; Rodríguez-Torres, González-Pérez and Díaz-Pérez, 2021) |

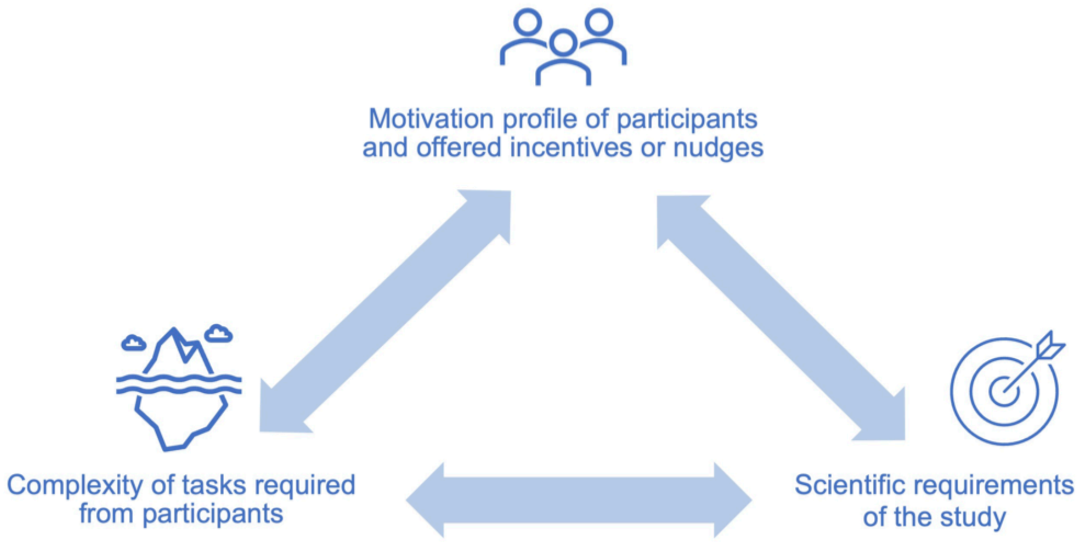



Figure 13. Guiding framework for remote digital health studies (Daniore, Nittas and Von Wyl, 2022)

There is a lack of evidence on strategies on how best to recruit research participants in general (Cooke and Jones, 2017), with seemingly just one single study examining recruitment strategies used with runners (Manzanero *et al.*, 2018). This particular study found that among a variety of strategies (including social media campaigns, web-based media, attendance at running events, referrals, emails, and incentives), each was associated with participants of varying demographics (differing across sex, age, country of citizenship, and weekly running distance) (Manzanero *et al.*, 2018). While Internet strategies were found to be the most effective (Facebook in particular), this study concluded that strategies should be designed based on the sample target population (e.g., email may not be useful for older participants) (Manzanero *et al.*, 2018). These findings also highlight the usefulness of using multiple recruitment and strategies to ensure participants of different demographics and running backgrounds are recruited, reducing sampling bias. This is supported by a previous review on longitudinal studies in which it was found that specific recruitment strategies for varying demographics may be necessary to enhance recruitment (Borg *et al.*, 2024).

In a review of physical activity intervention studies, Cooke and Jones (2017) describe several recruitment strategies (including media publicity, flyers and signposting, attendance at community health centres, universities, clubs or sports events, social media campaigns, and word of mouth) as either passive or active. Passive strategies prompt potential participants to identify themselves to researchers, whilst active strategies are where researchers initiate contact with potential participants (Cooke and Jones, 2017). They found that active strategies (e.g., attendance at events) appear to result in a more representative participant sample than passive strategies (e.g., media campaigns); however, it is unclear as to which methods are more effective at engaging particular populations (Cooke and Jones, 2017). Their review also found that, unless clearly designed to target specific population demographics, recruitment strategies fail to capture some underrepresented populations (e.g., males) (Cooke and Jones, 2017).

These findings demonstrate that multiple strategies can enhance the representativeness of participants, while group-specific strategies can maximise the recruitment of underrepresented groups. Specificity of effective recruitment strategies for runners is limited however, warranting further research.

### 2.4.2. Retention of research participants

Retention is considered to be as important an aspect as initial recruitment (Khatamian Far, 2018). It involves developing and maintaining relationships with participants to encourage and persuade them to be committed and continue with participation (Patel, Doku and Tennakoon, 2003; Khatamian Far, 2018). Similar to recruitment, it is important to understand runners' perceived barriers and facilitators to retention in research in order to employ appropriate strategies (Teague *et al.*, 2018; Daniore, Nittas and Von Wyl, 2022). However, no research has been conducted to examine this.

#### 2.4.2.1. Barriers and facilitators to retention, and retention strategies

With overlap identified across the barriers, facilitators and strategies to participant retention, these aspects will be discussed together in this section. There appear to be no reviews investigating the retention of runners' in research; therefore, reviews of randomized trials (Gillies *et al.*, 2021), longitudinal research (Teague *et al.*, 2018; Borg *et al.*, 2024), physical activity intervention studies (Cooke and Jones, 2017), and research involving smart technologies (Amagai *et al.*, 2022; Daniore, Nittas and Von Wyl, 2022; Pulsford *et al.*, 2023) were considered. In terms of barriers and facilitators to retention, Table 6 describes several findings across the themes of general study design and wearable technology design.

Table 6. Barriers and facilitators to retention of research participants

| **Barriers** | **Supporting reviews** | **Facilitators** | **Supporting reviews** |
|---|---|---|---|
| *General study design* | | | |
| Lack of incentives/compensation | (Amagai *et al.*, 2022) | Providing incentives/compensation | (Amagai *et al.*, 2022; Daniore, Nittas and Von Wyl, 2022) |
| Low barriers to exit (i.e., for individuals in which a study is 'easy to join', it may also be 'easy to leave') | (Amagai *et al.*, 2022) | Low barriers to entry (e.g., using app-based consent rather than in-person) | (Amagai *et al.*, 2022) |
| Unappealing requirements (e.g., individual-based activities rather than group-based) | (Cooke and Jones, 2017) | Less time-consuming tasks | (Daniore, Nittas and Von Wyl, 2022) |
| | | In-person distribution of devices | (Pulsford *et al.*, 2023) |
| *Wearable technology design* | | | |
| Poor app features (e.g., lack of social/technical support, lack of notifications, lack of 'gamification' [i.e., winning badges]) | (Amagai *et al.*, 2022) | Positive app features (e.g., social/technical support, reminders to use, 'gamification') | (Amagai *et al.*, 2022) |
| Technical difficulties (e.g., 'glitches', unfamiliarity with app) | (Amagai *et al.*, 2022) | Wearable device location (wrist-based devices) | (Pulsford *et al.*, 2023) |
| Successful results/usefulness of an app (i.e., if successful at achieving the goal (e.g., quitting smoking), a user may taper their use and reduce engagement) | (Amagai *et al.*, 2022) | | |
| Wearable device location (e.g., waist-based devices) | (Pulsford *et al.*, 2023) | | |

In terms of retention strategies, Teague *et al.* (2018) identified four key domains: (i) barrier-reduction strategies (e.g., transport assistance), (ii) community-building strategies (e.g., study merchandise, sharing study results), (iii) strategies to improve follow-up rates (e.g., incentives), and (iv) tracing strategies (e.g., collecting next-of-kin contact information). They found that studies using any type of barrier-reduction strategy were associated with higher retention rates compared with those that did not use this domain, while issuing incentives and reminders were associated with lower retention rates. This latter findings is contrary to a recent review on longitudinal research, in which maintaining regular contact and issuing reminders for follow-up were found to be beneficial for facilitating retention (Borg *et al.*, 2024). Teague *et al.* (2018) also found that using more strategies was not associated with greater retention (Teague *et al.*, 2018). Gillies *et al.* (2021) also identified numerous strategies to retention, however they found no high-certainty evidence to suggest that they are effective (Gillies *et al.*, 2021).

From the reviewed evidence discussed in this section, it appears that specific investigation is needed to optimize recruitment and retention strategies for individual populations, and types of research (Davis, Broome and Cox, 2002; Teague *et al.*, 2018; Daniore, Nittas and Von Wyl, 2022; Borg *et al.*, 2024). Just one study (specific to genetic-based research) has reported on the recruitment and/or retention of recreational runners in research (Manzanero *et al.*, 2018), highlighting a clear dearth of evidence. Without insight into runners' perceived barriers and facilitators to long-term, injury based research, involving wearable technologies, studies may suffer from small and misrepresentative samples and high rates of attrition, resulting in evidence which lacks statistical power and ecological validity (Patel, Doku and Tennakoon, 2003; Oliveira and Pirscoveanu, 2021).

### 2.5. Review of literature summary

In summary, there is a lack of foundational epidemiological evidence which has limited the advancement of RRI prevention. While there is a theoretical understanding that RRIs are caused by a multifactorial process resulting in an imbalance between tissue loading and tissue integrity, there is a lack of consistent evidence to support any risk factors for injury, beyond previous injury. Inconsistencies in injury definitions is likely a contributing factor. However, definitions; appropriateness and ability to accurately reflect the development process of injury may also be attributable. This has not been reviewed prior, nor have the methods of determining RRI severity; an equally important aspect of epidemiological research. To progress the development of effective injury prevention interventions, it appears that returning to the foundational concept of what constitutes an injury may be necessary. In order to do this, understanding the experiences of runners, a seemingly underutilized source of evidence, seems crucial.

After 'injury' is more appropriately understood, a comprehensive investigation into RRI development is needed. This may be achieved via a long-term, prospective research study, potentially using wearable technologies, such as a smartphone app to capture extensive, consistent and reliable data. However, challenges such as wearable technology adoption and participant recruitment and retention exist. Unfortunately, there is limited evidence describing specific barriers and facilitators to runners' use of injury-focused technologies, and their participation in research, warranting investigation.

# 3. Chapter 3: Study 1: Definitions and surveillance methods of running-related injuries: A scoping review

This paper is published in the European Journal of Sport Science. It is presented in full with only minor formatting changes.

Lacey, A., Whyte, E., Dillon, S., O'Connor, S., Burke, A. and Moran, K. (2024) 'Definitions and surveillance methods of running-related injuries: A scoping review', *European Journal of Sport Science*, 24(7), pp, 950-963. DOI: 10.1002/ejsc.12123.

## 3.1. Abstract

Inconsistent and restricted definitions of injury have contributed to limitations in determining injury rates and identifying risk factors for running-related injuries (RRIs). The aim of this scoping review was to investigate the definitions and surveillance methods of RRIs. A systematic electronic search was performed using PubMed, Scopus, SPORTDiscuss, MEDLINE and Web of Science databases. Included studies were published in English between January 1980 and June 2023 which investigated RRIs in adult running populations, providing a definition for a general RRI. Results were extracted and collated. 204 articles were included. Three primary criteria were used to define RRIs: physical description, effect on training, and medical intervention, while three secondary criteria are also associated with definitions: cause/onset of injury, location, and social consequences. Further descriptors and sub-descriptors form these criteria. The use of Boolean operators resulted in nine variations in definitions. Inconsistency is evident among definitions of RRIs. Injury definitions seem to be important for two main reasons: firstly, determining accurate injury rates, and secondly, in research examining risk factors. For the latter, definitions seem to be very limited, only capturing severe injuries and

failing to recognise the full development process of RRIs, precluding the identification of conclusive risk factors. A potential two-approach solution is the initial use of a broad definition acting as a gatekeeper for identifying any potential injury, and follow-up with an extensive surveillance tool to capture the specific consequences of the varying severity of RRIs.

**Key words:** running-related injuries, definition, surveillance methods

### 3.2. Introduction

Running-related injuries (RRIs) are problematic for runners, being highly prevalent (52%) (Dillon *et al.*, 2023), and associated with negative physical (Hespanhol Junior, van Mechelen and Verhagen, 2017), psychological (Maschke *et al.*, 2022), social (Sleeswijk Visser *et al.*, 2021), and financial (Hespanhol Junior, van Mechelen and Verhagen, 2017) consequences. While previous injury (Buist *et al.*, 2010; Hulme *et al.*, 2017) and training errors (Damsted *et al.*, 2018) have been suggested to contribute to the onset of RRIs, there is a lack of agreement on which other factors increase the risk of injury (e.g. running technique, lower limb alignment) (Ceyssens *et al.*, 2019; Mousavi *et al.*, 2021; Peterson *et al.*, 2022; Fredette *et al.*, 2022). Multiple methodological factors contribute to this lack of agreement, including: overuse of retrospective studies (Willwacher *et al.*, 2022), one-off laboratory-based assessments (Kiernan *et al.*, 2018), and small samples (Bas Kluitenberg *et al.*, 2015). However, inconsistency in the definition of injury is perhaps the most problematic, as evidenced by their impact on incidence rates (Kluitenberg *et al.*, 2015; Yamato *et al.*, 2015; Kluitenberg *et al.*, 2016). Yamato and colleagues (Yamato *et al.*, 2015) conducted a systematic review of injury definitions to help establish a consensus definition:

*running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration or training) for at least seven days or three consecutive scheduled training sessions, or that required the runner to consult a physician or other healthcare professional* (Yamato, Saragiotto, & Lopes, 2015 , pp.377).

However, eight years later, despite improvements in research methodologies (e.g. Running Injury Surveillance Centre (RISC) (Burke et al., 2023; Dillon et al., 2021; 2023), and recommendations for standardized injury registration methods (Kluitenberg, van Middelkoop, *et al.*, 2016), there is still disagreement on injury rates and risk factors for injury (Ceyssens *et al.*, 2019; Peterson *et al.*, 2022; Fredette *et al.*, 2022).

This prompts three questions. Are there still inconsistencies in how RRIs are defined? Are RRIs being defined appropriately? Has Yamato's (Yamato, Saragiotto and Lopes, 2015) consensus definition been adopted? In relation to the first question, inconsistency in definitions may largely relate to the varied criteria commonly used, such as physical complaints, effects on training, and the need for medical attention (Yamato *et al.*, 2015), and the inclusion of Boolean operators (i.e., AND/OR) allowing for either their isolated or combined use. With much RRI research published since the original systematic review (Yamato *et al.*, 2015), an updated investigation is warranted. In relation to the second question, with the strict criteria commonly used to define RRIs (Yamato *et al.*, 2015), definitions may not appropriately represent the true overuse, progressive nature of RRIs (Bertelsen *et al.*, 2017); potentially failing to recognise the lower-level injuries that runners often train through (Lacey et al., 2023; Soligard et al., 2016; Verhagen et al., 2021). Furthermore, the psychological and social consequences of RRIs (Lacey *et al.*, 2023), are not represented in these definitions. In relation to the third question, since the publication of the initial RRI consensus definition (Yamato, Saragiotto and Lopes, 2015), no review has examined if it has been adopted.

Lastly, it is important to investigate if RRI data is recorded in a way that captures its progressive nature. With the development of injury surveillance tools (such as the Oslo Sports Trauma Research Centre (OSTRC) questionnaires (Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2014; 2020)), the capture of overuse injuries has improved. However, while adopted for other sports (Clarsen *et al.*, 2020), it is unknown if and how such tools are being implemented in RRI research.

Therefore, the broad aim of this scoping review is to investigate the registration of RRIs in the literature. This was addressed through the primary aim: to investigate how RRIs are defined by examining: (i) the criteria used to define RRIs, and (ii) how the consensus definition has been adopted since publication, and the secondary aim: to investigate the methods of RRI surveillance.

## 3.3. Methods

### 3.3.1. Protocol and registration

A scoping review was deemed appropriate for the current review as our objective was to broadly examine the registration of RRIs in the literature (i.e., definitions and surveillance methods of RRIs) and map the existing literature on this topic (Grimshaw, 2008; Tricco, 2017; Pollock *et al.*, 2023). The Joanna Briggs Institute Evidence Synthesis and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses scoping review (PRISMA-ScR) guidelines (Tricco *et al.*, 2018) were followed as they reflect best practice (Pollock *et al.*, 2023) (see Appendix B1for the PRISMA-ScR checklist). The study protocol for this scoping review has not been previously published; however, it has been registered with Open Science Framework (https://doi.org/10.17605/OSF.IO/UG4JW).

### 3.3.2. Information sources

As the overall aim of this review was to investigate how RRIs are registered in the literature, only research articles published in academic journals were of interest. The search was therefore restricted to sources from academic journals involving human subjects and published in English between January 1980 and June 2023. Reviews, opinion articles, conference proceedings or posters, case studies, commentaries and study protocols were excluded. The search terms used were combined using Boolean phrases (Appendix B2). Bibliographies were also searched for articles considered for inclusion.

### 3.3.3. Search strategy

Four authors (AL, EW, SD and KM) determined the patient, concept and context of interest to this review, after which a comprehensive search strategy was developed detailing search terms, limits applied, possible sources of information, and the inclusion and exclusion criteria of articles (Appendices B2 and B3). A systematic search was undertaken by two authors (AL and SD) on 19$^{th}$ June, 2023. PubMed, Scopus, SPORTDiscuss, MEDLINE and Web of Science databases were searched for studies defining RRIs.

### 3.3.4. Study selection

Articles considered for inclusion were analysed in two phases. Firstly, titles and abstracts were reviewed using predetermined selection criteria (AL). Secondly, the full texts were independently reviewed by two authors (AL and SD). If the full text could not be obtained, respective authors were contacted with a request to provide the full text. If the RRI definition applied was not clearly identified on review of the full text, the respective authors were contacted and asked to provide clarity on the definition. Any disagreements were resolved via discussion or third-party mediation (KM).

#### 3.3.5. Data extraction

The data extracted process was planned *a priori*. A data extraction form was developed to extract and summarise the relevant information, guided by the aims of the review. This form was tested in a pilot phase in which two authors (AL and SD) independently reviewed and extracted data from a percentage (10%) of the included studies. Authors compared their data extraction to ensure consistency and assess the appropriateness of the data extraction form. Through an iterative process, this form was updated in order to ensure the diversity of RRI definitions and surveillance methods were captured appropriately. The full data extraction process was performed independently by two authors (AL and SD). Extracted data included: authors' name, publication year, study design, study length, study aim, sample size, sex, age, type of runner investigated, injury rate reported (incidence and/or prevalence), injury definition (i.e., criteria used), source of definition (i.e., cited research or custom definitions), measure of injury severity (if applicable), method of surveilling RRIs, and types of data captured. In terms of injury rates, incidence is only reported on in the current review as this was the predominant measure of injury rate that was utilised in included articles. Primary criteria for defining RRIs were identified *a priori* based on previous findings (Yamato *et al.*, 2015). A content analysis approach was conducted to analyse definitions further (Peters *et al.*, 2020), with descriptors and sub-descriptors being identified. Microsoft Excel (version 16.75, Microsoft Corporation) was used to perform the analyses.

### 3.4. Results

#### 3.4.1. Overview of findings

The electronic search identified 16,893 studies. After duplicates were removed (n=9,975), 6,918 titles and abstracts were screened, and 596 full texts were assessed for eligibility (of which 405 were excluded). Reasons for exclusion were: no RRI definition was provided, wrong study design, and wrong patient population. Reviewing the bibliographies revealed an additional 13 articles, resulting in 204 articles being included in this review (Figure 14; Appendix B4).

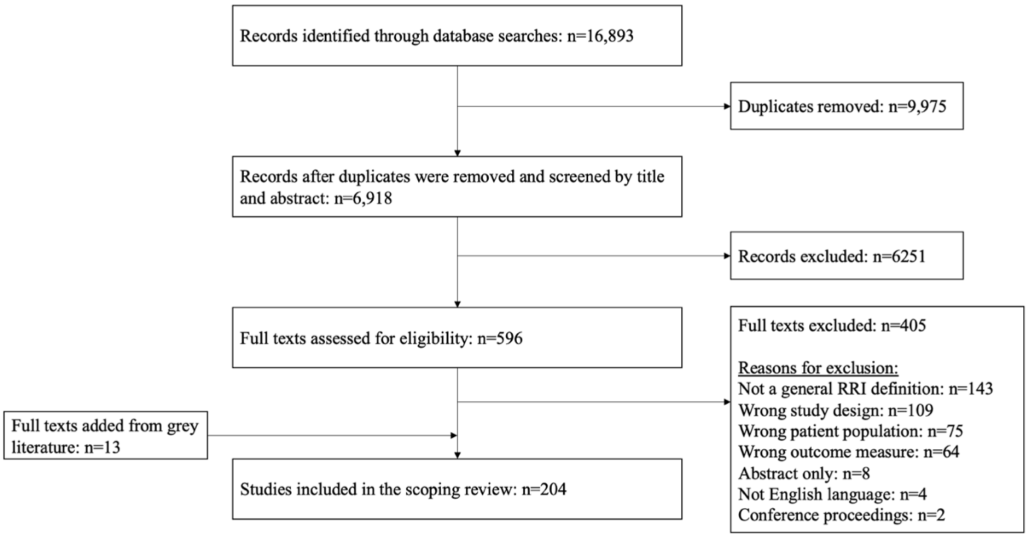



Figure 14. Preferred Reporting Items for Systematic Reviews and Meta-Analysis scoping review (PRISMA-ScR) flow diagram. RRI: running-related injury.

#### 3.4.2. Article information

Article publication years ranged from 1981-2023, with most studies (80%, n=164) published after 2011 (Figure 15). Among the 204 articles, the majority were prospective (51%, n=105), cross-sectional (22%, n=44) or retrospective (12%, n=24). Study lengths ranged from six days (Bishop & Fallon, 1999) to 12 years (Roberts, 2000). For those that ran longitudinally (n=135), the majority were six – 12 months (28%, n=38), three – six months (29%, n=39), or one week – three months (26%, n=35).

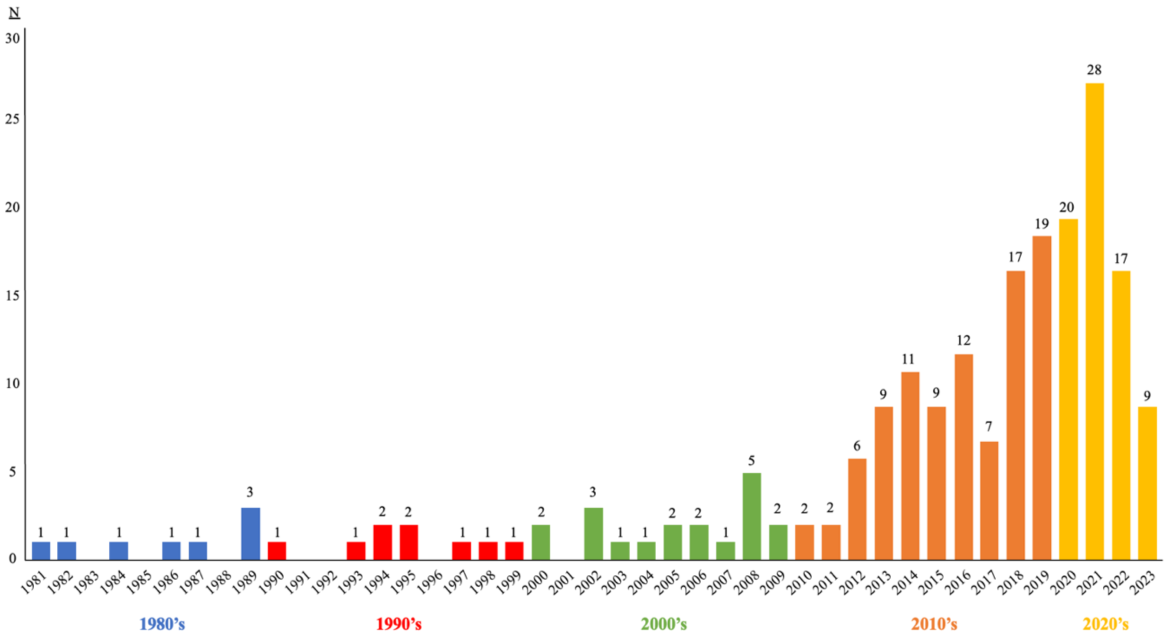



Figure 15 Years of study publication (until June 2023)

### 3.4.3. Population information

A total of 223,755 participants were included across 204 studies. Seventeen studies did not report sex/gender, and so to those applicable (n=187), 56% (n=80,490) identified as male and 44% (n=60,374) as female. Their average age was 38.2 ±[4] 9.7 years. One fifth of studies (21%, n=42) did not specify the type of runner; of those that did (n=162), recreational runners were the most common (38%, n=62), followed by novice runners (20%, n=32) and marathon/half-marathon runners (14%, n=23) (Figure 16).

[4] ± refers to standard deviation

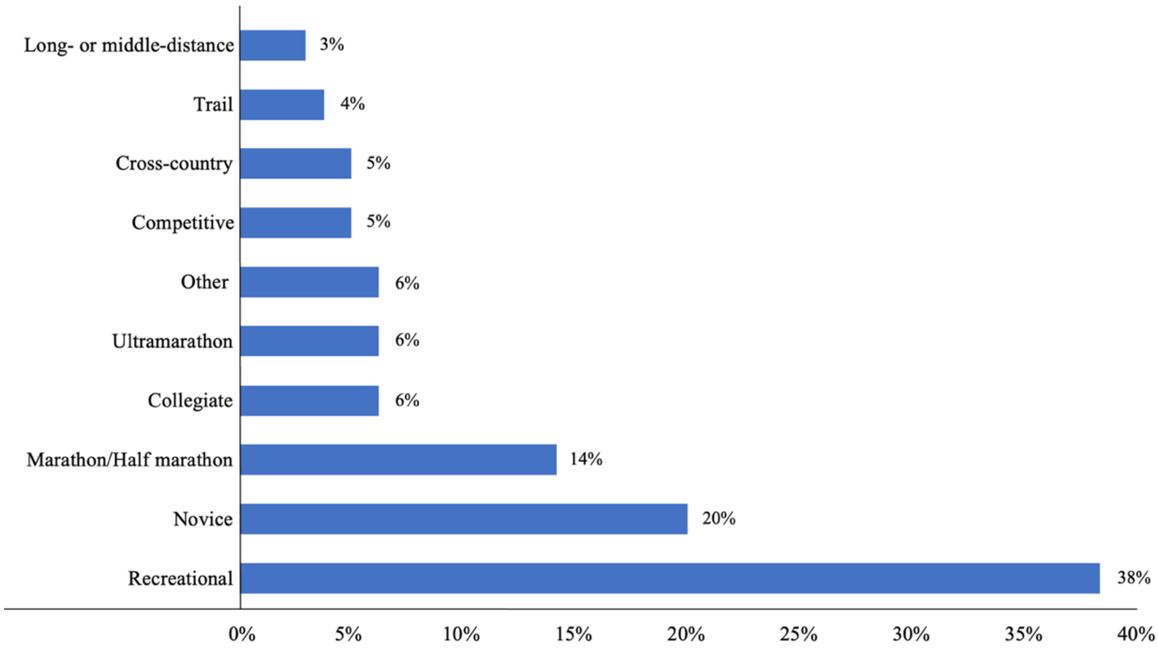



Figure 16. Types of runners (excluding those not specified)

### 3.4.4. Criteria used to define running-related injuries

Three primary criteria were used: physical description, effect on training, and requiring medical intervention; and three secondary criteria were used: cause/onset of injury, location of injury, and social consequences. Further descriptors and sub-descriptors of these criteria are detailed (Table 7). Overall, 'physical description' was the most used criterion (94% of definitions, n=192), followed by 'effect on training' (85%, n=174), and requiring 'medical intervention' (36%, n=74). Studies engaged with these three criteria either in isolation or in combination (AND/OR), with nine different variations of use (Figure 17); the most frequently used being: (i) physical description AND effect on training (50%, n=103), (ii) physical description AND effect on training OR medical intervention (26%, n=53), and (iii) physical description in isolation (9%, n=19).

Table 7 Criteria, descriptors, and sub-descriptors used to define running-related injuries

| | **Primary criteria (% of total studies)** | **Descriptors (% of associated criterion)** | **Sub-descriptors (% of associated descriptor)** |
|---|---|---|---|
| **1** | Physical description (94%, n=192) | Pain (45%, n=87) | - |
| | | Injury (28%, n=52) | - |
| | | Physical complaint (20%, n=39) | - |
| | | Other (15%, n=29) | - |
| | | Symptom (7%, n=14) | - |
| | | Problem (4%, n=7) | - |
| **2** | Effect on training (85%, n=174) | Training restriction (74%, n=128) | Reduced volume (55%, n=70) |
| | | | Reduced intensity (52%, n=67) |
| | | | Reduced duration (41%, n=53) |
| | | | Reduced frequency (30%, n=38) |
| | | | General restriction (27%, n=35) |
| | | | Other (14%< n=18) |
| | | | Reduced performance (5%, n=6) |
| | | Time-loss (51%, n=89) | Missed training (100%, n=89) |
| | | | Missed competition (4%, n=4) |
| **3** | Medical intervention (36%, n=74) | Medical attention (95%, n=70) | - |
| | | Medication (19%, n=14) | - |
| | | Diagnosis 97%, n=5) | - |
| | **Secondary criteria** | **Descriptors** | **Sub-descriptors** |
| **1** | Cause/Onset of injury (75%, n=153) | Running-related (96%, n=147) | - |
| | | Overuse (11%, n=17) | - |
| | | Other (1%, n=2) | - |
| **2** | Location (72%, n=146) | Musculoskeletal (84%, n=123) | - |
| | | Lower limb (65%, n=95) | - |
| | | Lower back (35%, n=51) | - |
| | | Other (9%, n=13) | - |
| **3** | Social consequences (3%, n=6) | Daily life effects (100%, n=6) | - |

Note: frequencies and percentages represent the overall number of studies in which each primary criterion, descriptor or sub-descriptor was included (not the frequency or percentage they were used in combination with one another).

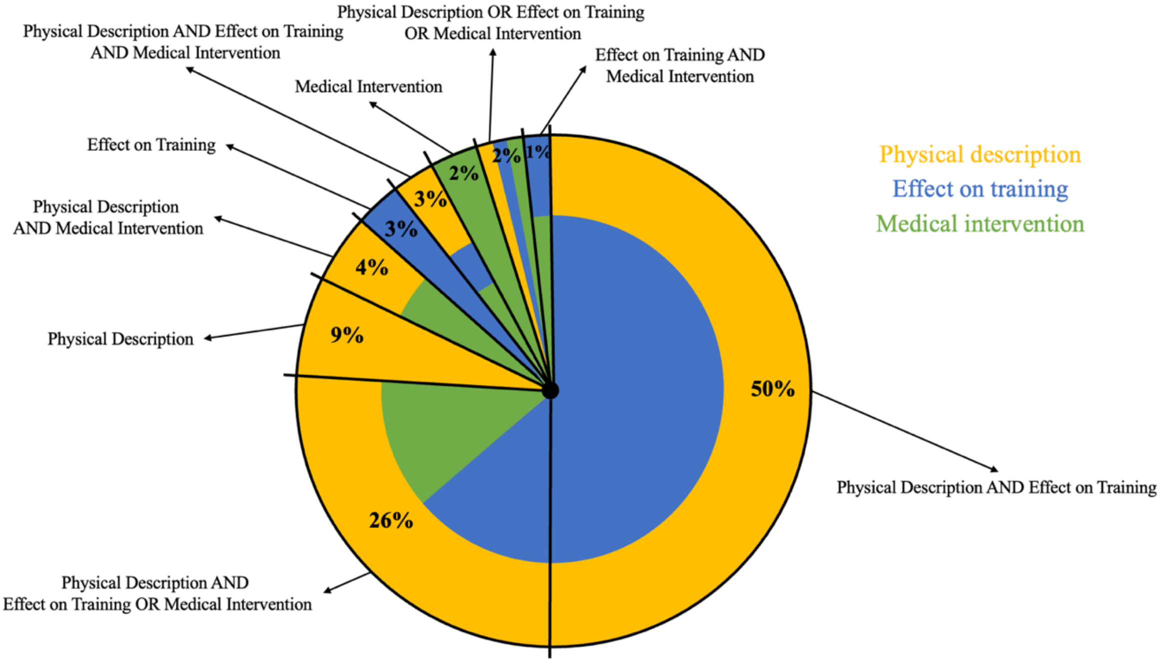



Figure 17. Nine variations of criteria combinations used to define running-related injuries

#### 3.4.4.1. Physical description

Where 'physical description' was used (94%, n=193), six descriptors were identified: pain, injury, physical complaint, symptom, problem and other. With regard to how these descriptors were used, they were more commonly used in isolation rather than in combination with one another, with pain (in isolation) being the most frequently used (33%, n=63), followed by 'injury' (in isolation) (21%, n=40), and physical complaint (in isolation) (16%, n=30) (Figure 18). Just 6% (n=11) of these studies included a minimum time-frame, ranging from one session to 10 days, with the most common being 'at least one week' (36%, n=4).

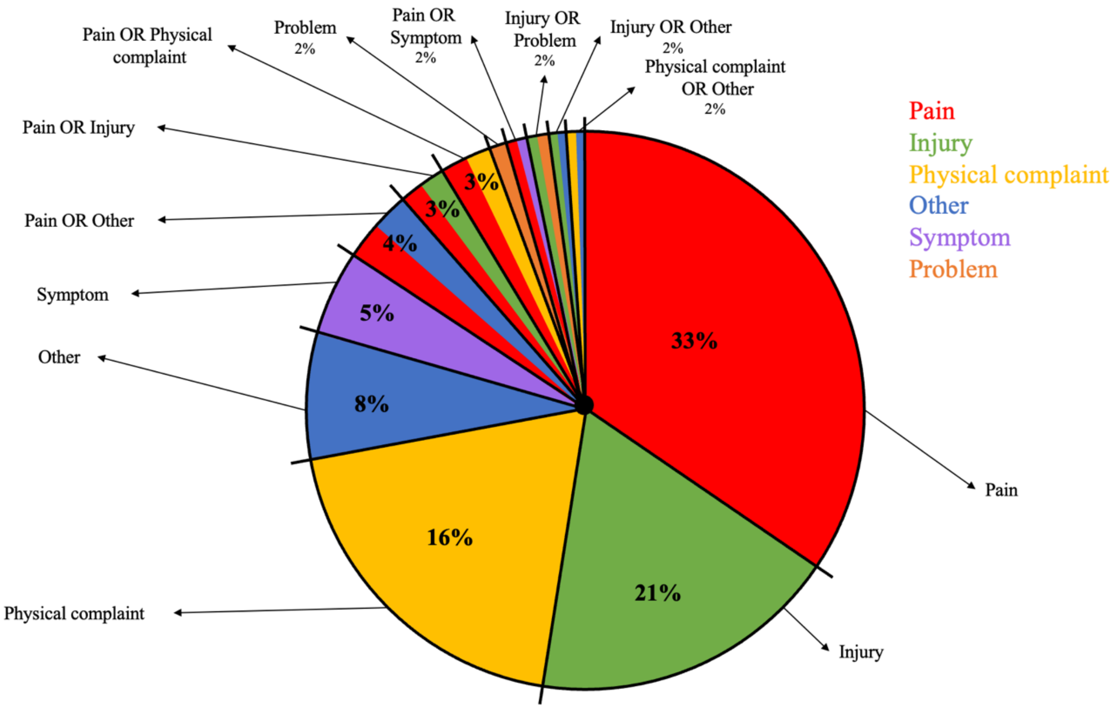



Figure 18. Six descriptors associated with the 'physical description' criterion

#### 3.4.4.2. Effect on training

Where 'effect on training' was used (85% of total, n=174), two descriptors were identified: 'time-loss' (referring to a complete stop to running), and 'training restriction' (referring to a restriction of running) (Figure 19). 'Training restriction' in isolation was used in 49% (n=85), 'time-loss' in isolation in 26% (n=45), and 'time-loss' OR 'training restriction' in 25% (n=44). For 'time-loss', two descriptors were identified: a missed training session, or missed competition. Of all studies that mentioned time-loss (n=89), the vast majority (96%, n=85) referred to a missed training session in isolation. Additionally, 80% of these (n=71) also mentioned a minimum time-frame, ranging from 'at least a partial session' to 'at least four weeks'. Of these, the majority specified time-loss of at least one week (or three sessions) (55%, n=39), at-least one day/one session (38%, n=27), and more than one day but less than one week (7%, n=5). In terms of 'training restriction', seven sub-descriptors were commonly used: a general (non-specific) restriction in training, reduced intensity, reduced duration, reduced frequency, reduced volume, reduced performance, and other. Of these (n=128), 27% (n=34) referred to a general (non-specific) restriction in training, 19% (n=24) referred to a reduction in intensity, duration, frequency OR volume, and 17% (n=22) referred to a reduction in intensity, duration OR volume. Additionally, 63% (n=81) of these studies mentioned a minimum time-frame, ranging from 'at least one day' to 'at least two weeks', with the majority of these (94%, n=76) referring to training restriction of at least one week (Figure 20).

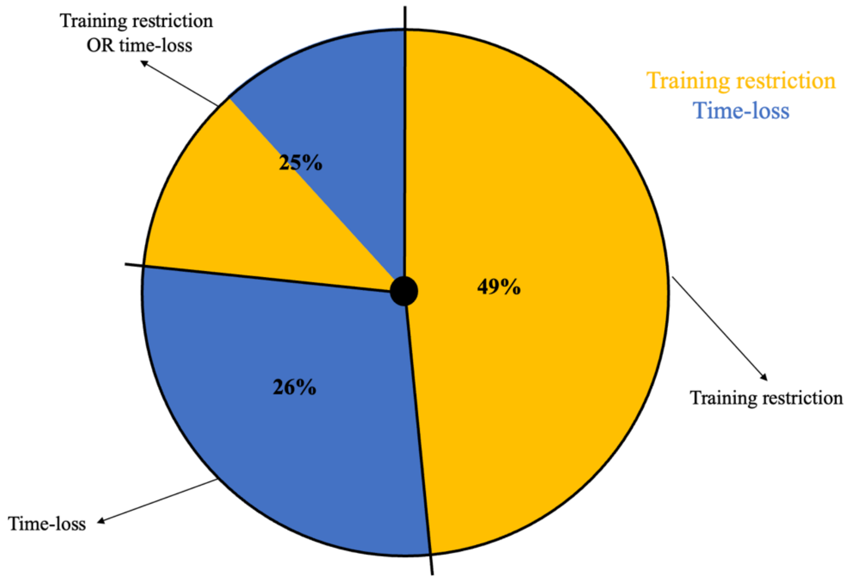



Figure 19. Two descriptors associated with the 'effect on training' criterion

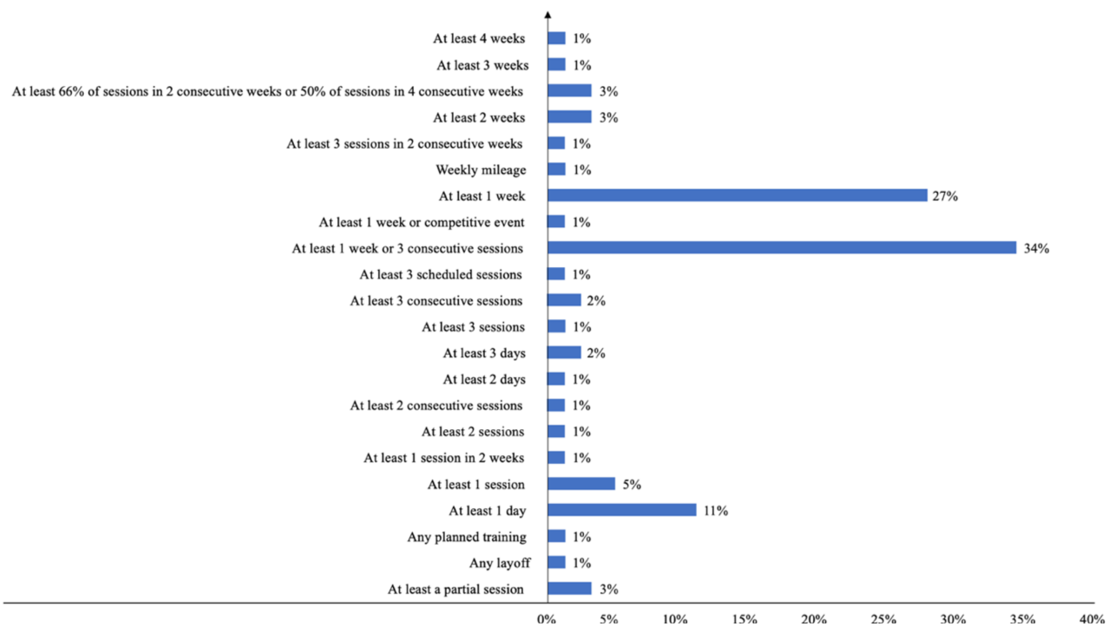



Figure 20. Minimum lengths required for the 'effect on training' criterion

#### 3.4.4.3. Medical intervention

Where 'medical intervention' was used (36% of total, n=74), three descriptors were identified: medical attention from a healthcare professional, a need to take medication, and specific diagnosis by a healthcare professional (Figure 21). Medical attention alone was the most used descriptor (74%, n=55), followed by medical attention OR taking medication (18%, n=13). Just one study (0.5%) specifically referred to a minimum time-frame for requiring 'medical intervention' (at least one session).

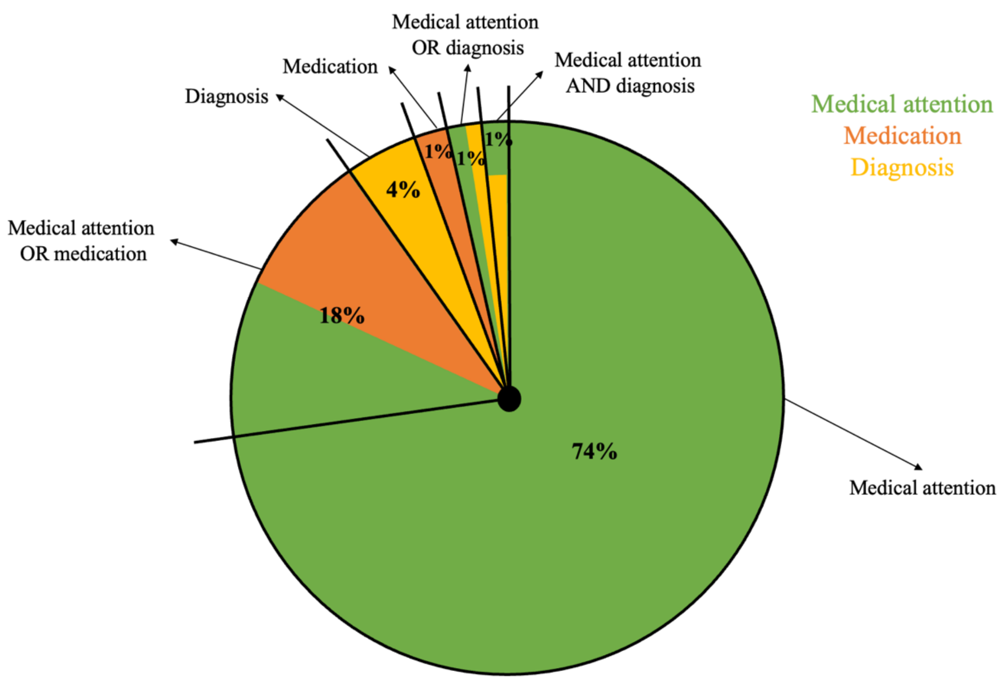



Figure 21. Three descriptors associated with the 'medical intervention' criterion

#### 3.4.4.4. Secondary criteria

Three additional secondary criteria were identified for defining RRIs, however, these were merely used as adjunct criteria: (i) injury cause/onset (75%, n=153), (ii) injury location (72%, n=146), and (iii) social consequences (3%, n=6). Of those that specified injury cause/onset, 'running-related' was the most common descriptor (96%, n=147). Of those that specified injury location, the musculoskeletal system was mentioned most often (84%, n=123), followed by the lower limb (65%, n=95), and the lower back (35%, n=51). Finally, where social consequences were included, negative effects on a runners' daily life (e.g., inability to go to work or school) were mentioned in all (100%, n=6).

#### 3.4.4.5. Incidence rates

The lowest average incidence rate (5% (Willwacher *et al.*, 2016)) was associated with a definition using 'physical description' in isolation, while the highest average (96% (Small and Relph, 2018)) was associated with a 'physical description' AND 'effect on training' definition (Figure 22). Averaging the incidence rates for each of the nine variations of definition, the lowest average incidence rate was a 'physical description' AND an 'effect on training' AND 'medical intervention' (29% ± 0.1%); however, only two studies employed this definition (Hendricks and Phillips, 2013; Chan *et al.*, 2018). The highest average incidence rate (83%) solely utilised a 'medical intervention'; however only one study employed this, and was an ultra-marathon event (Graham *et al.*, 2021).

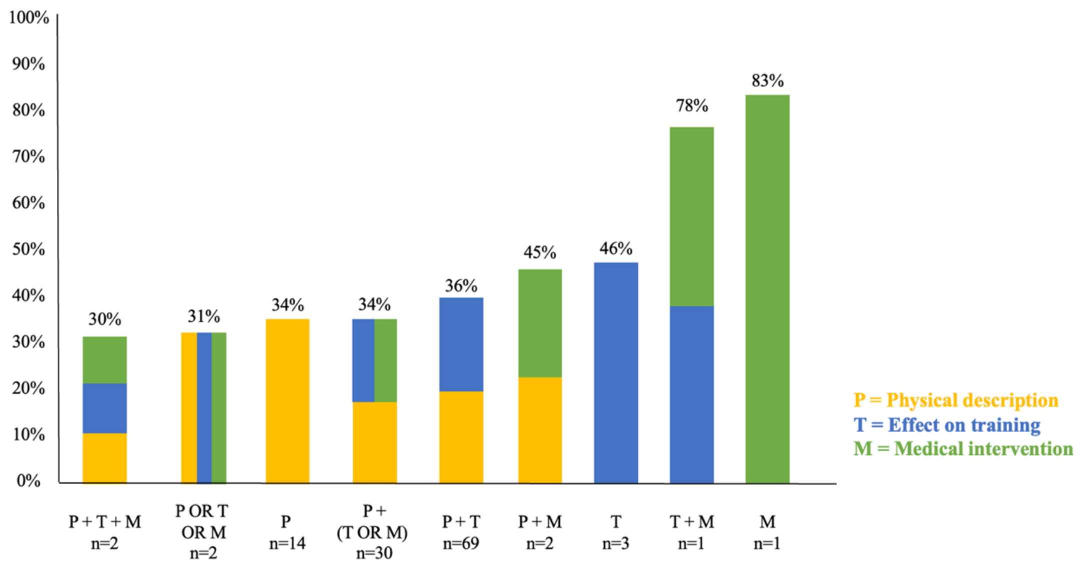



Figure 22. Average incidence rate based on the definition of injury

There was little difference between the average incidence rate of the most used definitions. A 'physical description' AND 'effect on training' definition had an average incidence rate of 36% ± 0.2% (n=69), while for 'physical description' AND 'effect on training' OR 'medical intervention' it was 34% ± 0.2% (n=30). The largest difference in average incidence rates appears due to the minimum duration employed. A 'time-loss' or 'training restriction' of at-least one day resulted in an average incidence rate of 30%, while for at-least one week it was 43%; a 13% difference.

#### 3.4.5. Adoption of the consensus definition

Most definitions used either a single citation or multiple citations (59%, n=121), with 75 different references employed. The remaining 41% (n=83) provide no citation. The most common citation was the consensus definition (Yamato, Saragiotto and Lopes, 2015), referenced in 19% (n=38) of all studies, followed by Buist *et al.* (2008) referenced in 6% (n=13). Since the publication of the consensus definition in 2015, its first citation was in 2018 by Besomi *et al.* (2018). Since then, 108 studies were published, of which 40% (n=44) used the consensus definition either by directly citing it (n=38), or by using the same criteria (n=6) (Appendix B5).

Table 8 details how studies used the nine variations of definitions overall, prior to the consensus definition, and after its publication. The use of 'physical description' AND 'effect on training' remained the most frequently used definition pre- to post- consensus publishing. Regarding 'physical description' synonyms, use of the term 'pain' increased following the consensus definition (36% to 49%). With 'effect on training', the use of 'training restriction' in isolation reduced (47% to 36%), while the use of 'time-loss' OR ‘training restriction’ increased (15% to 28%). Finally, medical attention was used more frequently (22% to 45%).

Table 8. Comparison of definitions of running-related injuries pre- and post-consensus definition

| Definition of injury used | Total studies (n=204) | Pre-consensus definition (n=95) | Post-consensus definition (n=109) |
|---|---|---|---|
| **Physical AND Training** | 50% (n=103) | 62% (n=59) | 40% (n=44) |
| **Physical AND Training OR Medical** | 26% (n=53) | 15% (n=14) | 36% (n=39) |
| **Physical** | 9% (n=19) | 8% (n=8) | 10% (n=11) |
| **Physical AND Medical** | 4% (n=8) | 4% (n=4) | 4% (n=4) |
| **Training** | 3% (n=7) | 4% (n=4) | 3% (n=3) |
| **Physical AND Training AND Medical** | 3% (n=6) | 2% (n=2) | 4% (n=4) |
| **Medical** | 2% (n=3) | 2% (n=2) | 1% (n=1) |
| **Physical OR Training OR Medical** | 2% (n=3) | 2% (n=2) | 1% (n=1) |
| **Training AND Medical** | 1% (n=2) | - | 2% (n=2) |

### 3.4.6. Methods of running-related injury surveillance

Four methods of injury surveillance were primarily utilised: (i) surveys/questionnaires (84%, n=174), (ii) training diaries (25%,n=52), (iii) interviews/phone calls (5%, n=11), and (iv) medical assessments (5%, n=10). For the surveys/questionnaires (n=174), most sources were not referenced (83%, n=145). Of those that did provide a reference, 20 various references were used, with the most common being the OSTRC health version (OSTRC-H) and OSTRC overuse injury version (OSTRC-O) (5% and 4%, respectively). The OSTRC-O and OSTRC-H were first published in 2013 and 2014, respectively. Since their first use by Hespanhol et al. (2016), 13% of the 124 studies used one of the OSTRC tools.

One-hundred-and-sixteen studies captured injury data on repeated occasions, with the majority having captured data weekly (32%, n=37), every session (14%, n=16), or every 2 weeks (13%, n=15) (Table 9).

Table 9. Frequency of injury data capture compared with lengths of studies.

| Length of study | Every session (n=16) | Every week (n=37) | Every 2 weeks (n=15) |
|---|---|---|---|
| 3-4 weeks | 6% (n=1) | 19% (n=7) | 13% (n=2) |
| 6 weeks | 19% (n=3) | 24% (n=9) | 4% (n=7) |
| 8-10 weeks | 25% (n=4) | 14% (n=5) | 13% (n=2) |
| 12-15 weeks | - | 5% (n=2) | 13% (n=2) |
| 12 months | 44% (n=7) | 30% (n=11) | 13% (n=2) |
| 18 months | 6% (n=1) | - | - |
| 5 years | - | 5% (n=2) | - |
| XC season | - | 3% (n=1) | - |

XC: cross-country

### 3.5. Discussion

Our aim was to investigate the registration of RRIs in the literature, primarily by examining injury definitions in the form of (i) the criteria used to define RRIs, and (ii) how the consensus definition has been adopted since publication, and secondly to investigate the methods of RRI surveillance. The definition of injury is important for two primary reasons. Firstly, inconsistent definitions across studies affects incidence and prevalence rates (Kluitenberg *et al.*, 2015; Yamato *et al.*, 2015; Yamato, Saragiotto and Lopes, 2015). The use of Boolean phrases, which result in varying definitions, can influence average incidence rates by up to 54%. Additionally, when the minimum time-frame associated with a definition is considered, a difference of 13% was found between incidence rates. Only one study appears to have directly examined the effect of the definition of injury on the rate of injury (Kluitenberg *et al.*, 2016), similarly finding significant differences in reported injury incidence. Secondly, the definition of injury is important in examining potential risk factors for injury. Should definitions continue to only capture higher-level injuries and fail to identify complaints (Verhagen, Warsen and Silveira Bolling, 2021) or lower-level injuries (Lacey *et al.*, 2023), research may fail to identify conclusive risk factors. For example, it is possible that lower-level injuries may not result in week-long training restrictions, and would therefore be missed with a definition that requires this length (76% of studies that used a time-frame for ‘effect on training’). However, they may lead to alterations in running that may predispose other structures to excessive loading and injury (Wilke, Vogel and Vogt, 2019), which then do meet the week-long criterion. If the lower-level injury is not recorded, its potential role as a risk factor and the associated changes in running technique will be overlooked.

### 3.5.1. Criteria used to define running-related injuries

Our findings are similar to a previous review (Yamato *et al.*, 2015) in identifying three primary criteria are predominately used to define RRIs: physical description, effect on training, and requiring medical intervention. Novel to our review however is how these criteria are used in isolation and/or in combination, resulting in nine variations of definition (Figure 17), creating inconsistencies. Inconsistency escalates when the sub-descriptors are additionally considered.

#### 3.5.1.1. Primary criteria: Physical description

Various synonyms of ‘physical descriptions’ are used to define RRIs, with ‘pain’ the most common (Yamato *et al.*, 2015). This finding aligns with the OSTRC-O in which respondents are specifically questioned about the extent of ‘pain’ they experience (Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2020). However, our findings do not align with the terms used in consensus definitions of injury in other sports, such as athletics (Timpka *et al.*, 2014), soccer (Fuller *et al.*, 2006) or rugby (Fuller *et al.*, 2007). In these definitions, the term ‘physical complaint’ is more generally used, allowing for a broader scope of injury to be captured, not limited to those injuries only associated with ‘pain’. ‘Pain’s’ frequent use, along with its specific inclusion in the consensus definition (Yamato, Saragiotto and Lopes, 2015), may signify that only ‘adequately severe’ RRIs are being captured. However, RRIs are often associated with a range of alternative physical descriptions such as tightness, awareness, discomfort, or stiffness (Lacey *et al.*, 2023), and if 'pain' is continually used in definitions, injuries not strictly associated with 'pain' may be omitted. Furthermore, with the perception of 'pain' being subjective and individualised (de Jonge, Balk and Taris, 2020; De Oliveira *et al.*, 2021), definitions that insist on 'pain' may fail to capture injuries where some runners do not perceive pain, contributing to the inconsistent capture of RRIs.

There is also no clear specification of *when* or for *how long* a 'physical description' should be present in order to define a RRI. This review identified that definitions do not specify whether a 'physical description' related to injury should be present during running or outside of running. This may cause issues in injury reporting as pain patterns may not always be consistent with running practice. For example, during the development of tendinopathies, a runner may experience tendon pain at the start of a session, but with continued activity the pain subsides, and so they disregard the complaint (Kountouris and Cook, 2007; Rio *et al.*, 2014). Towards the opposite end of the injury spectrum, runners have highlighted the importance of the timing of physical complaints (Lacey *et al.*, 2023), describing that pain outside of running sessions (e.g., during activities of daily living) is indicative of more severe injuries (e.g., a muscle strain). Furthermore, when 'physical description' is used to define RRIs, it rarely includes a minimum timeframe, offering no guidance to research participants on how long they *should* be experiencing it until it qualifies as an injury.

There are various nuances to consider regarding different types of 'physical complaint' and the associated time effect. Inclusion of an umbrella term such as 'physical complaint' may be more appropriate than a limiting term (such as 'pain'). Additionally, the timing of 'physical descriptions' should not be limited to training/competition, as often, experiences of 'physical complaints' occur outside of these.

#### 3.5.1.2. Primary criteria: Effect on training

The definitions of RRIs have solely used two descriptors to define how RRIs' effect running: 'time-loss' and 'training restriction', with injuries causing time-loss typically considered more severe (Kluitenberg *et al.*, 2016). While some definitions do not explicitly state 'time-loss' or 'training restriction', terms such as 'prevent' or 'stop' refer to a 'time-loss injury', while 'restrict', 'reduce' or 'change' refer to a 'training restriction injury' (Yamato *et al.*, 2015). The sub-descriptors often associated with this criterion provide clarity on the components of running that are limited by injury. Typically with time-loss definitions, this limitation is mainly an effect on training (rather than competition), while for 'training restriction' definitions, a general, non-specific effect on training is predominately utilised. Six aspects of training are typically referred to: reduced volume, intensity, duration, frequency, performance, and other. This finding builds on a previous review which reported that definitions largely only referred to limited training, running, or distance (Yamato *et al.*, 2015). Our findings, in comparison to Yamato's review (Yamato *et al.*, 2015), signify a change in how RRIs are being defined, as more specificity is being provided on the components of running that RRIs limit. As a novel finding, our review found very few definitions included a minimum extent of what these restrictions should be (e.g., a percentage in redacted volume), leaving room for interpretation from research participants, and an assumption from readers that any limitation to training is indicative of injury.

Arguably, beyond the type and extent of limitations to training, the minimum length of these limitations appears more important in defining RRIs (Yamato *et al.*, 2015; Kluitenberg *et al.*, 2016). As reflected by our finding of a 13% difference in incidence rates, a requirement for longer interruptions to training in order to define injury appears to underestimate the impact of injury, while the opposite is suggested with shorter interruptions (Yamato *et al.*, 2015; Kluitenberg *et al.*, 2016). Additionally, interruption length affects reported RRI incidence rates, as shorter interruptions (i.e., one-day vs. one-week) result in significantly higher incidence rates (Kluitenberg *et al.*, 2016). Our review found that 'time-loss' or 'training restriction' of one-week (or three consecutive sessions) was most commonly used (Yamato *et al.*, 2015). However, the appropriateness of this timeframe should be considered. Firstly, as RRIs develop gradually, runners will often not interrupt training (Lopes *et al.*, 2011; Clarsen, Myklebust and Bahr, 2013; Linton and Valentin, 2018; Verhagen, Warsen and Silveira Bolling, 2021; Lacey *et al.*, 2023). Secondly, when injuries do cause interruptions, they are often interspersed with attempts to continue training (sometimes with modifications), therefore not causing multiple interrupted days in succession (Bahr, 2009; Clarsen, Myklebust and Bahr, 2013; Lacey *et al.*, 2023). Therefore, with the requirement of longer timeframes, definitions are potentially missing injuries.

#### 3.5.1.3. Primary criteria: Medical intervention

Medical attention is the most frequently used 'medical intervention' descriptor when defining RRIs (Yamato *et al.*, 2015). Similar to the possible limitations for 'physical description' and 'effect on training', the use of 'medical attention' may result in definitions only allowing for the capture of more severe injuries. We identified that 'using medication' was more frequently referred to than a previous review (Yamato *et al.*, 2015), possibly reflecting a change in how runners manage RRIs. Recent findings show that runners primarily self-manage injuries for as long as possible, only seeking medical attention (from healthcare professionals) when their self-management has failed, or their injury becomes too severe (Russell and Wiese-Bjornstal, 2015; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022; Lacey *et al.*, 2023). By including self-management strategies (such as 'use of medication') in definitions of injury, they may be more likely to capture the complaints (Verhagen, Warsen and Silveira Bolling, 2021) or lower-level injuries (Lacey *et al.*, 2023) with which runners may not seek medical attention. The appropriateness of specifying 'medical attention' in definitions should also be considered in light of associated barriers, such as cost (Hespanhol Junior, van Mechelen and Verhagen, 2017), the use of self-management strategies (Russell and Wiese-Bjornstal, 2015; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022; Lacey *et al.*, 2023), and a perception that their injuries are not severe enough to warrant medical attention (Grønhaug and Saeterbakken, 2019). By requiring injuries to result in medical attention from healthcare professionals, definitions may also fail to capture those injuries with which runners seek other forms of 'medical advice', such as from the Internet or social media (Lupton, 2013; Verhagen, Warsen and Silveira Bolling, 2021; Lacey *et al.*, 2023). Furthermore, a runner may not seek medical attention without first experiencing a 'physical description' or an 'effect on their training'. Therefore, it is unclear if it is necessary to include 'medical attention' in definitions.

#### 3.5.1.4. Secondary criteria

Although the secondary criteria identified in the current review do not directly determine what qualifies an 'injury', they provide guidance on the cause/onset (e.g., during running) and the anatomical locations (e.g., musculoskeletal system) of RRIs. The frequent inclusion of the cause/onset and location of injury in definitions is in line with previous research (Yamato *et al.*, 2015). However, as novel findings, our review identifies the scant inclusion of the social consequences of RRIs in definitions, and the absence of consideration of the psychological consequences of injury, despite their occurrence (Russell and Wiese-Bjornstal, 2015; Hespanhol Junior, van Mechelen and Verhagen, 2017; Lacey *et al.*, 2023). While not necessary for defining RRIs, methods of data collection should be comprehensive enough to ensure they are being recorded.

### 3.5.2. Adoption of the consensus definition

Following the execution of a similar systematic review, Yamato *et al.*, (2015) stated that there was no consistency in the definition of RRIs, inspiring the publication of the consensus definition (Yamato, Saragiotto and Lopes, 2015) (see section 3.2 for quote). Our findings reveal that the most used definition includes 'physical description' and 'effect on training' as criteria, while the second most commonly used definition also mentions 'medical intervention'. These criteria closely reflect the consensus definition (Yamato, Saragiotto and Lopes, 2015). Additionally, almost one-fifth of reviewed studies directly used the consensus definition since its publication, indicating that it is being somewhat adopted. The impact of the consensus definition can perhaps be seen in the following: firstly, the use of the term 'pain' is the most common 'physical description' synonym; secondly, RRIs are more frequently defined by 'training restriction' rather than 'time-loss', a positive reflection on their true consequences; thirdly, 'medical attention' remains the most common factor within 'medical intervention'; and finally, at-least one week (or three consecutive sessions) is the most common minimum timeframe for both time-loss and training restriction. However, inconsistency seems to remain among RRI research as over two fifths of definitions are not accompanied by a citation, implying that these are either custom definitions used by each individual study, or appropriate recognition is not being given to the source of definition used.

### 3.5.3. Methods of running-related injury surveillance

No other systematic review has addressed the question of RRI surveillance methods. The team at the OSTRC have reported that their questionnaires have been widely adopted in sports injury research, being utilized by a range of elite sport organisations (e.g., United States, Australian and Norwegian Olympic programmes) (Clarsen *et al.*, 2020). Our findings suggest these tools have not been widely adopted in RRI research. While not specifically related to RRIs, the OSTRC questionnaires, in particular the overuse injury version (Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2020), are appropriate tools for capturing RRIs as their focus on capturing the signs and symptoms of overuse injuries correlates with the nature of RRI development (Bertelsen *et al.*, 2017), capturing beyond the typically strict criteria and time-frames that often define injury. The importance of monitoring 'lower level injuries' or non-time-loss injuries has been evidenced by research on semi-professional soccer players (Whalan, Lovell and Sampson, 2020). With 68% of all time-loss injuries being preceded by a non-time-loss injury (Whalan, Lovell and Sampson, 2020), these findings highlight the contribution non-time-loss injuries have in the development of more serious injuries. Additionally, these findings demonstrate that self-reporting non-time-loss injuries was a 'good' predictor of subsequent time-loss injuries within seven days (Whalan, Lovell and Sampson, 2020). It has been suggested that RRI research needs a unified tool that is capable of capturing the entire injury development process (i.e., lower-level injuries and injuries with significant consequences (i.e., time-loss or medical attention)) (Kluitenberg *et al.*, 2016), with the Running Injury Continuum potentially being useful in developing such a tool (Lacey *et al.*, 2023).

## 3.6. Recommendations and implications

### 3.6.1. Recommendations

While we must be mindful to (i) avoid adding to the already evident inconsistencies in injury definitions (Yamato *et al.*, 2015), (ii) understand the positive impact the consensus definition (Yamato, Saragiotto and Lopes, 2015) has had on RRI research, and (iii) build on the recommendations for improvements in injury surveillance (Kluitenberg, van Middelkoop *et al.*, 2016), our findings allow for several recommendations. Above all, when implementing injury definitions and surveillance methods, researchers should be guided by their research question, design and setting, ensuring that their chosen surveillance strategy allows the aims of their research to be addressed (Nielsen *et al.*, 2020).

In relation to the definition of injury, a question regarding the absoluteness of definitions must be asked considering the findings of the current review. In line with recommendations from the International Olympic Committee for an inclusive definition of injury (Bahr *et al.*, 2020), and rather than a runner being considered as strictly injured or uninjured, we suggest that a RRI definition should be inclusive of the entire injury development process, acting as a gatekeeper in identifying the minimum possible level of injury. Due to recent research enhancing our understanding of the breadth of the RRI development process (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022; Lacey *et al.*, 2023) and the limitations that definitions can impose in capturing the entirety of this process (as described above), a definition of injury should allow for the recognition of *if or when* a runner is experiencing any level of injury, with further investigation following to explore *which* level of injury they are experiencing. A broader definition of injury will allow for flexibility in investigating all levels of RRIs, as previously, research has shown that non-time-loss injuries in soccer increase the risk of time-loss injuries three-seven fold (Whalan, Lovell and Sampson, 2020). Indeed, runners have also clearly described their experiences of lower-level injuries escalating into more serious time-loss injuries (Verhagen, Warsen and Silveira Bolling, 2021; Lacey *et al.*, 2023). Therefore, we suggest RRIs be defined by a 'physical complaint' definition, not enforcing further criteria such as time-loss, training restriction, or medical attention requirement:

*"A musculoskeletal physical complaint of the lower limb or back that results from running, regardless of the extent of consequences sustained".*

This definition differs from the consensus definition (Yamato, Saragiotto and Lopes, 2015) in that the single primary criterion used to define injury is a physical description. A physical description is possibly the baseline criterion of what constitutes an injury, as well as being the most used criterion found in the current review. Use of ‘physical complaint’ will allow for the capture of all physical descriptions which possibly signify physiological changes or tissue damage that may be indicative of injury (Wilke, Vogel and Vogt, 2019; Whalan, Lovell and Sampson, 2020), rather than just those severe enough to be associated with pain. Additionally, injury surveillance is suggested to be enhanced by the capture of all physical complaints (Clarsen and Bahr, 2014), therefore the generalisation of this definition allows for any runner who may be experiencing some level of injury to be identified.

This recommendation must be considered in light of possible limitations that have been suggested in relation to the overestimation of injury incidence associated with broad definitions (Yamato *et al.*, 2015), and previous questions posed regarding the accuracy and usefulness of monitoring non-time-loss injuries in team sports (Orchard and Hoskins, 2007). There is also difficulty in differentiating between ‘normal responses to training’ that are necessary to provoke positive adaptations to training (if managed appropriately) (Wilke, Vogel and Vogt, 2019), and those which may signify physiological changes which, if not properly managed, may initiate progression along the injury development process (Clarsen, Myklebust and Bahr, 2013; Wilke, Vogel and Vogt, 2019; Lacey *et al.*, 2023). This challenge may be ever existent; however, with a ‘physical complaint’ definition, it is less likely that those progressing along the injury development process will be overlooked, and it may be found to be an appropriate biomarker for personal injury prevention systems. Additionally, while we acknowledge the discussion points of the METHODS MATTER meeting during which is was suggested that there is no need for a universally accepted definition of injury (as this will depend on the context and research question) (Nielsen *et al.*, 2020), there has also been numerous consensus statements published over the past two decades which provide guidance to researchers in addressing the ongoing challenge of defining and surveilling injuries in sport (Bahr, Clarsen and Ekstrand, 2018; Bahr *et al.*, 2020). This need for consistency in injury surveillance research is evident from these recommendations (Bahr *et al.*, 2020), as well as from issues associated with inconsistent definitions (as previously described; (Kluitenberg *et al.*, 2015; Yamato *et al.*, 2015; Yamato, Saragiotto and Lopes, 2015)).

While the primary purpose of this review has been to examine how RRIs are defined, it may be of value to propose that methods of injury surveillance are more important than the definition of injury. Recent findings suggest that a runner experiencing any level of injury along the Running Injury Continuum may be at risk of injury and should be monitored (both in terms of causative and surveillance research) (Whalan, Lovell and Sampson, 2020; Lacey *et al.*, 2023). We suggest that a comprehensive tool capable of capturing and monitoring the full scope of RRIs, in line with the Running Injury Continuum (Lacey *et al.*, 2023) (i.e., all levels of injury, all possible consequences, and the nature of the injury), is developed and implemented in RRI research. Research should capture all possible responses to the injury development process (including, but not limited to the physical descriptions, effect on running, management strategies required (medical and non-medical), social consequences, and psychological responses), while the nature of injury should be detailed through the capture of the cause/onset of injury and the location of injury. Support for capturing beyond the ‘typical’ scope of RRI surveillance and monitoring the biopsychosocial responses to injury is evidenced by runners’ explicit description of their experiences of injury (Lacey *et al.*, 2023), and recognition of the importance of incorporating a holistic approach to the management of other musculoskeletal conditions (Laisné, Lecomte and Corbière, 2012). While we have suggested that a broad definition be implemented to identify all of those undergoing the

RRI development process, each aspect of injury surveillance should be as specific as possible, providing detailed information to assist future research and clinical practice. This process of a two-phase approach to injury data collection (i.e., the use of a gatekeeper definition initially, and then the use of a broad injury surveillance tool), must be investigated to determine its usefulness. To consider the points made by Nielsen and colleagues (Nielsen *et al.*, 2020), it is possible that, once the entirety of the injury development process and its broad scope of consequences is capture consistently (allowing comparison of findings across research), researchers may be able to apply a definition of injury that specifically addresses the aims of their research post-hoc. RRI surveillance needs to be expanded to determine if lower-level injuries lead to more severe injuries, as identified with 'niggles' in soccer (Whalan, Lovell and Sampson, 2020). While this extensive type of injury surveillance may be burdensome for injury recorders (Clarsen, Myklebust and Bahr, 2013), the capabilities of modern technologies to collect, manage and analyse large data (Zadeh *et al.*, 2021) bring researchers potentially closer to understanding and preventing RRIs.

### 3.6.2. Implications

This review has clear implications for researchers investigating both risk factors for RRIs and for injury surveillance. Regarding risk factors for injury, our findings highlight the importance of utilising a broad definition of injury and a comprehensive surveillance tool to ensure that non-time-loss injuries (e.g., complaints, lower-level injuries) are captured and considered as potential risk factors for the development of more serious time-loss injuries. Capturing and monitoring these lower-level injuries is possibly the missing link in identifying risk factors for RRIs (Lacey *et al.*, 2023). Regarding injury surveillance research, the use of a broad definition and a comprehensive surveillance tool may more appropriately reflect the full extent of RRI rates, rather than just the 'tip of the iceberg' as previously suggested (Clarsen, Myklebust and Bahr, 2013).

In line with previous findings (Kluitenberg *et al.*, 2016), this review highlights that the definition of injury is of high importance for the clinical interpretation of research findings, where clinicians should ensure that both the definition of injury and method of injury surveillance are considered when employing an evidence-based practice.

### 3.7. Limitations

This review should be interpreted considering some limitations. Firstly, we only included studies that provided a general RRI definition, rather than those which defined a specific RRI (e.g., Achilles tendinopathy). Secondly, while we have stated that a definition of injury should ensure the aims of a study can be addressed, due to the extent of included studies in the current review, we were unable to investigate the relationship between definition of injury and study aims. Future research should consider exploring this research question. Finally, as it was beyond the scope of this review, injury severity was not examined. As a crucial aspect of injury surveillance research however (Yamato *et al.*, 2015; Bahr, Clarsen and Ekstrand, 2018), we suggest future research investigates how injury severity has been determined in the literature.

### 3.8. Conclusion

Despite an abundance of RRI research (as evidenced by the current review), along with improvements in research methodologies and advancements in technologies used to capture injury, there are large variances in injury incidence rates reported and a lack of consistent evidence supporting conclusive risk factors for RRIs. Clearly, how RRIs have been defined and captured may be the missing link. There is a clear inconsistency among definitions of what constitutes a RRI. While the consensus definition by Yamato, Saragiotto and Lopes (2015) has helped in providing uniformity and is being somewhat adopted by researchers, inconsistencies remain evident with the frequent use of Boolean operators, the range of criteria and descriptors often included, and the varying terminology and thresholds within these criteria and descriptors. A second issue is the appropriateness of definitions and surveillance methods used, with research largely failing to recognise, capture and investigate the full development process of injury. With advancements in our understanding of (i) the extent of the injury development process (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022; Lacey *et al.*, 2023), and (ii) the vast impact RRIs have on runners (Russell and Wiese-Bjornstal, 2015; Lacey *et al.*, 2023), the appropriateness of injury definitions and surveillance methods must be considered, with a question of whether they are capable of capturing the entire injury continuum (e.g. from 'Discomfort' to 'Career-ending injury' (Lacey *et al.*, 2023)). As definitions seem to be limited to only capture 'significant' injuries, failing to recognise the lower-level injuries that runners experience is possibly underestimating the true rate of RRIs, ignoring potential risk factors for those significant injuries. Ultimately, to better understand RRIs and identify conclusive risk factors, we must use consistent, reliable and accurate methods of defining and capturing them.

### 3.9. Data availability

All data supporting the findings of this review are available within the paper, its supplementary material and in an online data repository, available at: https://doi.org/10.17605/OSF.IO/CGB2F.

*Link section: Chapter 3 to 4*

There are two key issues evident from the findings presented in Chapter 3. Firstly, RRIs are defined inconsistently. This clearly limits researchers' ability to compare findings between studies, impeding the advancement of injury prevention research. Secondly, the definitions and surveillance methods imposed may not be fully appropriate for capturing the true nature of RRI development. Taking a dichotomous approach to injury, where a runner is simply viewed as either injured or uninjured, does not reflect the complex development process that occurs. As high thresholds are commonly used for injury definition criteria, lower level injuries are often not recorded or reported, it is plausible to question whether 'injury' is being investigated accurately.

Not defining injuries consistently or appropriately are likely contributing to the wide variances in rates of injury reported and the lack of clarity in identifying risk factors, stunting the progression of the fundamental step in the sequence of injury prevention (van Mechelen, 1992). Definitions of injury only make up one piece of the injury prevention puzzle, with knowledge and understanding of injury severity as a second piece. This piece is apparently lacking (Yamato et al., 2015). To better understand RRIs and their associated risk factors, and make progress with preventing them, we must consider the whole picture of injury, including injury severity.

Therefore, the aim of Chapter 4 is to examine how the severity of RRIs is measured, considering both the criteria used to define injury severity, and how it is graded. With potential to influence the outcomes of a study (as with definitions (Kluitenberg et al., 2016), a secondary aim is to investigate if the way in which injury severity is measured influences the rates of injury reported and the risk factors identified.

# 4. Chapter 4: Study 2: An investigation into the measurement of injury severity in running-related injury research: A scoping review

This paper has been published in the Scandinavian Journal of Medicine and Science in Sports. It is presented in full with only minor formatting changes.

Lacey, A., Whyte, E., Burke, A., O'Connor, S., Dillon, S. and Moran, K. (2024) 'An investigation into the measurement of injury severity in running-related injury research: A scoping review', *Scandinavian Journal of Medicine and Science in Sport*, 34(8), p. e14704. DOI: 10.1111/sms.14704.

## 4.1. Abstract

Understanding injury severity is essential to inform injury prevention practice. The aims of this scoping review were to investigate how running-related injury (RRI) severity is measured, compare how it differs across studies, and examine whether it influences study outcomes (i.e., injury rates and risk factor identification). This scoping review was prospectively registered with Open Science Framework. A systematic electronic search was conducted using PubMed, Scopus, SPORTDiscuss, MEDLINE and Web of Science databases. Included studies were published in English between January 1980 and December 2023, investigated RRIs in adult running populations, and included a measure of injury severity. Results were extracted and collated. Sixty-six studies were included.

Two predominant primary criteria are used to define injury severity: the extent of the effect on running and/or the extent of the physical description. When secondary definition criteria are considered, 13 variations of injury severity measurement are used. Two approaches are used to grade injury severity: a categorisation approach or a continuous numerical scale. Overall, the measurement of RRI severity is relatively inconsistent across

studies. Less than half of studies report incidence rates per level of injury severity, while none report specific risk factors across levels, making it difficult to determine if the approach to measuring injury severity influences these study outcomes. This lack of information is possibly contributing to inconsistent rates of RRIs reported, and the lack of clarity on risk factors.

**Key words:** running-related injuries, injury severity, injury surveillance

### 4.2. Introduction

The consequences of running-related injuries (RRIs) are far reaching (Bahr *et al.*, 2020), and can cause negative physical (Hespanhol Junior, van Mechelen and Verhagen, 2017) , psychological (Maschke *et al.*, 2022) and social outcomes (Sleeswijk Visser *et al.*, 2021), disruptions and time-loss from training (van der Worp *et al.*, 2015), and significant financial cost (from time lost from work and the cost of medical treatments) (Hespanhol Junior, van Mechelen and Verhagen, 2017). With high rates of RRIs (Dillon *et al.*, 2023), the development of effective injury prevention strategies is essential.

There are two primary steps in the process of preventing injuries: firstly, to establish the magnitude of the injury problem (e.g., incidence and prevalence rates), and secondly, to identify their risk factors (Van Mechelen, Hlobil and Kemper, 1992; Finch, 2006). Most RRI studies to date appear to capture injury dichotomously (i.e., considering someone as either injured or uninjured) (Yamato *et al.*, 2015; Lacey *et al.*, 2024), despite there clearly being varying levels of injury severity (Verhagen, Warsen and Silveira Bolling, 2021; Lacey *et al.*, 2023). It is important to capture the severity of injury because it provides meaningful insight into the full extent and burden of injuries, helping to determine the appropriate allocation of resources for injury management (Van Mechelen, 1997; Dekker *et al.*, 2000; Üstün *et al.*, 2003; Clarsen *et al.*, 2015; Hespanhol Junior *et al.*, 2015; Bahr, Clarsen and Ekstrand, 2018). Furthermore, capturing injury severity over time is crucial for the assessment of the effectiveness of injury prevention or rehabilitation interventions (Van Mechelen, 1997; Clarsen, Myklebust and Bahr, 2013; Bolling *et al.*, 2018). When investigating risk factors, injury severity is also a key aspect for directing the focus of injury prevention research (Rössler *et al.*, 2014), as different severities of injury may have different underlying risk factors. In addition, a lower severity injury to one structure may itself be a risk factor for a more severe injury to another structure, due to a reduced capacity to control movement and/or due to compensatory protective changes in running technique (Whalan, Lovell and Sampson, 2020; Burke *et al.*, 2021). A failure to appropriately consider injury severity may in part explain the lack of foundational epidemiological evidence with inconsistencies in both the rates of injury reported across studies (Kluitenberg *et al.*, 2015; Kakouris, Yener and Fong, 2021) and their associated risk factors (Ceyssens *et al.*, 2019; Burke *et al.*, 2021, 2023; van Poppel *et al.*, 2021). While some RRI research seems to consider injury severity (Yamato *et al.*, 2015), various approaches to its measurement appear to be employed (Lun, 2004; Malliaropoulos, Mertyri and Tsaklis, 2015), which may affect study outcomes and impede between-study comparisons (and meta-analyses).

Despite its importance, only one systematic review examining the descriptors used to define RRIs has included RRI severity in their report, but only examined it as a tertiary aim (Yamato *et al.*, 2015). Therefore, the present study has two aims. Primarily, to investigate how the severity of general RRIs is measured, by (i) describing the injury severity scales used (in terms of the criteria for defining injury severity and its grading), and (ii) comparing to what extent these scales differ. A secondary aim is to examine if the way in which injury severity is measured influences study outcomes, in terms of (i) the rate of injury reported, and (ii) the risk factors identified.

## 4.3. Methods

### 4.3.1. Protocol and registration

It was deemed appropriate to conduct a scoping review to map the existing evidence on the topic of injury severity in the RRI literature (Arksey and O'Malley, 2005; Grimshaw, 2008; Tricco, 2017; Pollock *et al.*, 2023). The Joanna Briggs Institute Evidence Synthesis and the Preferred Reporting Items for Systematic Reviews and Meta-Analysis scoping review (PRISMA-ScR) guidelines were followed (Tricco, 2017) as these reflect best practice (Pollock *et al.*, 2023) (Appendix C1). This scoping review was registered with Open Science Framework (https://doi.org/10.17605/OSF.IO/NGJQV).

### 4.3.2. Information sources

The search for information sources was limited to fully published research articles from academic journals involving human subjects and published in English between January 1980 and December 2023. Review articles, study protocols, conference proceedings, opinion pieces, commentaries or case studies were excluded. The search terms were combined using Boolean phrases (Appendix C2). The bibliographies of included articles were also searched for possible sources.

### 4.3.3. Search strategy

Five authors (AL, KM, EW, AB, and SOC) determined the patient, concept, and context of interest, along with a comprehensive search strategy detailing the search terms, search limits, possible sources of information, and inclusion and exclusion criteria (Appendices C2 and C3). A systematic search was undertaken by one author (AL) on 1st December 2023. Databases PubMed, Scopus, SPORTDiscuss, MEDLINE and Web of

Science were searched, according to the search strategy, for studies which included a measure of injury severity for general RRIs.

### 4.3.4. Selection of studies

Articles were considered for inclusion in two phases. Firstly, article titles and abstracts were screened by two authors independently (AL and AB) using the predetermined selection criteria. The full texts of those which met the inclusion criteria were independently reviewed by two authors (AL and AB). If the full text could not be obtained, the respective authors were contacted with a request to provide the full text. If the details of the employed injury severity scale were not provided or were unclear, respective authors were contacted for clarification. Any disagreements regarding inclusion were mediated through discussion, or by a third reviewer if necessary (KM).

### 4.3.5. Data extraction and analysis

Data extraction was planned *a priori* with a data extraction form developed to aid the process and summarise relevant information. This form was tested in a pilot phase in which two authors (AL and AB) independently reviewed and extracted a percentage of the included studies. To assess consistency and the effectiveness of the data extraction form, authors compared their data extraction. The data extraction form was updated iteratively to ensure it could comprehensively capture the diversity of injury severity scales. The full data extraction process was then independently performed by two authors (AL and AB). Extracted data included: authors' names, publication year, study design, study length, study aim/purpose, sample size, sex, age, type of runner, measure of injury severity used (definition criteria used, grading approach employed, citation if provided), definition of injury (if provided), and study outcomes (e.g., incidence rate). Table 10 details the phraseology that will be used in order to report and discuss injury severity.

Table 10. Phraseology used to report and discuss general RRI severity

| **Phraseology** | **Explanation** |
|---|---|
| Injury severity scale | The measurement scale used in each individual study, being made up of the *definition criteria* and a *grading approach* |
| Definition criteria | How injury severity was defined (e.g. 'effect on running') |
| Grading approach | How each scale progresses from least to most severe level of injury |
| Level of injury | Each individual point on an injury severity scale (e.g., 'mild injury') |
| Comparison scale | An amalgamated scale of injury severity developed by the present authors to represent the scope of injury severity captured by each definition criterion (described below). |

A content analysis was conducted to determine the definition criteria used to measure injury severity (Peters *et al.*, 2020). Visual representations of each injury severity scale were developed, with each level of injury plotted on a horizontal scale (Appendices C4-C6). If a study defined the least severe level of injury as 'no injury' (or other equivalent phraseology), this level was included in the visual representation, but not considered a level of injury. An amalgamated comparison scale of injury severity was developed by the authors for each primary criterion (e.g., effect on running) by comparing all individual injury severity scales associated with that primary criterion (Appendices C4-C6). Where no length of time was specified for a level of injury (e.g., a level defined solely as an "inability to run"), the minimum possible length was assumed (i.e., at least one day).

A rate of injury was considered an 'incidence' rate if it was reported as the number of new injuries that were sustained during a specific period of time (Noordzij *et al.*, 2010), whereas they were considered a 'prevalence' rate if the rate reflected the proportion of people who were injured at a single point in time (Noordzij *et al.*, 2010).

## 4.4. Results

### 4.4.1. Overview of findings

The electronic search identified 7,618 studies. After duplicates were removed (n=1,288), 6,330 titles and abstracts were screened. 164 full texts were assessed for eligibility, of which 98 were excluded. Primary reasons for exclusion were injury severity was not measured, and wrong outcome measure (i.e., RRIs were not investigated) (Figure 23; Appendices C2 and C3). Reviewing bibliographies identified no further articles, resulting in a total of 66 studies being included for analysis (Figure 23).

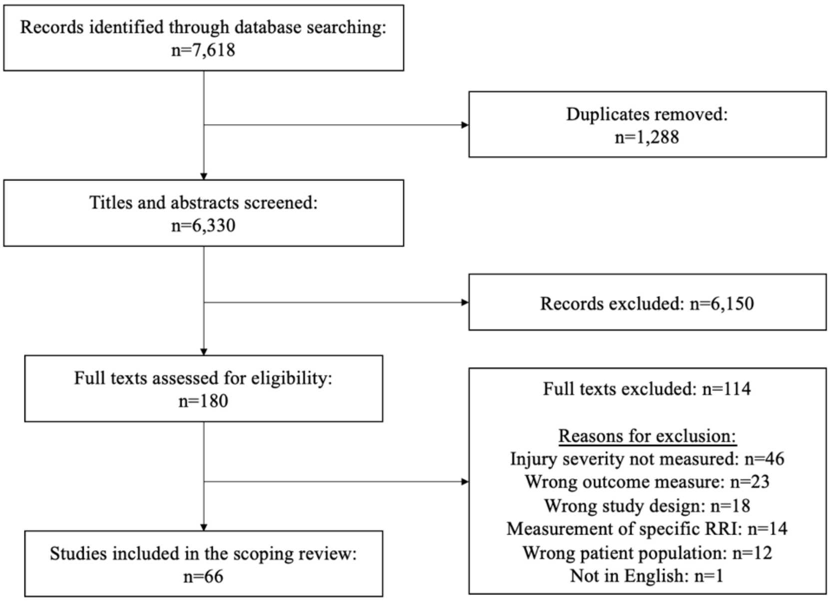



Figure 23. Preferred Reporting Items for Systematic Reviews and Meta-Analysis scoping review (PRISMA-ScR) flow diagram

### 4.4.2. Article information

Publication years ranged from 1986 to 2024, with 2021 being the year with most publications (21%, n=14) (Figure 24) (Note: One study has a publication date of January 2024, despite being identified in the December 2023 search). The majority of studies were prospective (64%, n=42), followed by cross-sectional (27%, n=18), and retrospective (9%, n=6). Of the prospective studies, the majority were less than 6 months in duration (69%, n=29). Primarily, studies were conducted to examine injury epidemiology (e.g., rates of injury) (82%, n=54) and risk factors (52%, n=34).

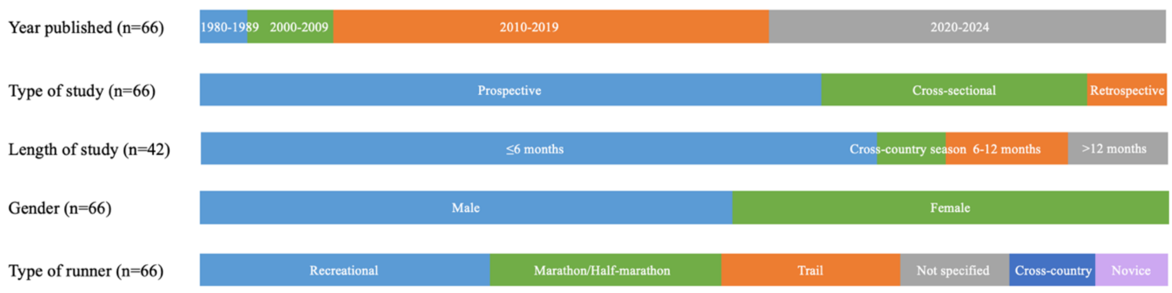



Figure 24. Article and population information[5]

### 4.4.3. Population information

A total of 37,395 participants were included across studies, with 55% identifying as male and 45% as female (Figure 24). The average age of participants was 37.6 ± 11.1 years. The majority of studies examined recreational runners (30%, n=20), marathon/half-marathon runners (24%, n=16) or trail runners (18%, n=12) (Figure 24).

[5] The year published 2020-2024 spans five years, while the other periods span ten years.

### 4.4.4. Measurement of general running-related injury severity

In line with the primary aim of this review, the methods used to measure injury severity have been grouped into the description of the injury severity scales (sections 4.4.4.1 Description of the criteria for defining injury severity and 4.4.4.2 Description of the grading of injury severity) and comparing the extent to which these scales differ (section 4.4.5) (Appendix C7).

#### 4.4.4.1. Description of the criteria for defining injury severity

Injury severity was defined using primary, secondary, and tertiary definition criteria (Figures 25 and 26; Appendix C8). There were two primary definition criteria identified: ‘effect on running’ and ‘physical description’ (Figure 25), used in three combinations: (i) ‘effect on running’ in isolation, (ii) ‘effect on running AND physical description’, and (iii) ‘physical description’ in isolation (Figure 26). Within the ‘effect on running’ criterion, there were six secondary definition criteria, with ‘restricted training’ being the most common (67%) (Figure 25, Appendix C8). Five tertiary definition criteria were identified within ‘restricted training’ alone, with ‘restricted distance/mileage’ being the most common (73%) (Figure 25, Appendix C8). Three secondary definition criteria within ‘physical description’ were identified, with ‘intensity of pain/symptoms’ being the most common (76%) (Figure 25, Appendix C8). Considering all secondary definition criteria combinations, 13 different injury severity scales were used across studies (Figure 26), with the most frequent being: (i) ‘restricted training AND effect on performance AND intensity of symptoms/pain’, (ii) ‘length of time-loss’ in isolation, (iii) ‘intensity of pain/symptoms’ in isolation, and (iv) ‘restricted training AND length of time loss’ (Figure 26).

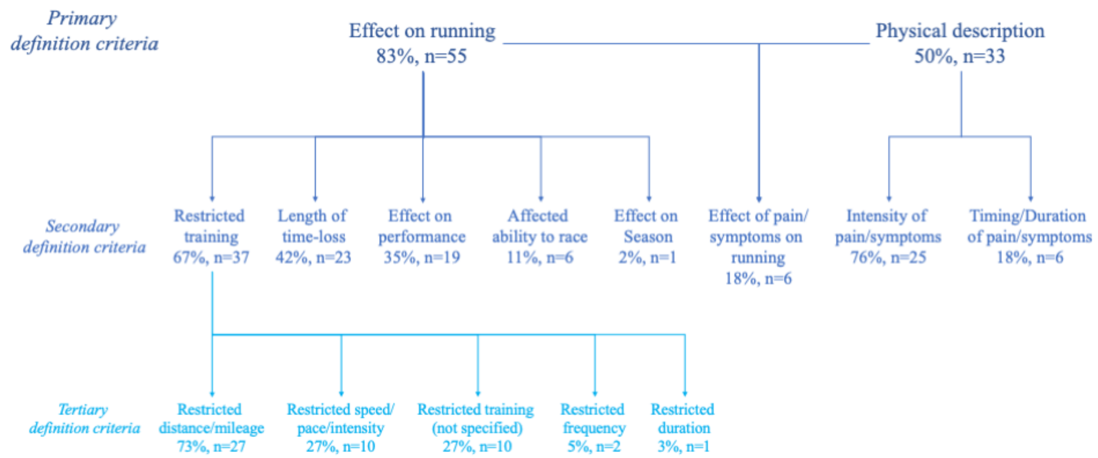



Figure 25. Flowchart of primary, secondary, and tertiary definition criteria

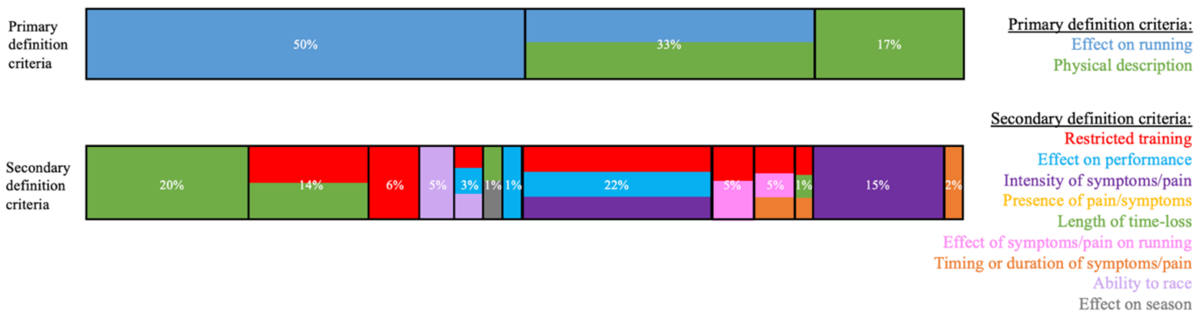



Figure 26. Combination of the primary and secondary definition criteria of injury severity[6]

#### 4.4.4.2. Grading of injury severity

Two approaches to the grading of injury severity were identified: a categorisation scale or a continuous numerical scale (Figure 27; Appendix C7). Between two and six levels of injury were used in the 'categorisation' approaches (Figure 28; Appendix C8). Descriptor terms (e.g., mild, moderate, severe), a numbering system (e.g., grade I, grade II, grade III), or no system (i.e., only including an explanation of each level) was used to categorise

[6] Combination of the primary and secondary definition criteria of injury severity (Note: Multi-coloured segments relate to primary or secondary definition criteria used in combination with one another (e.g., effect of running AND physical description, represented by the blue and green segments). All primary and secondary definition criteria were used in an AND combination. Secondary definition criteria are organised based on descending frequency of use, relative to the primary definition criterion).

these levels (Figure 27). Five studies measured injury severity on a continuous numerical scale but subsequently translated it into a categorical scale for their analysis and reporting, and therefore, these studies were included in the categorisation grading approach.

For those that used a continuous numerical scale, a minimum and maximum level was defined, however no further description of the intermediate levels was provided. The majority of these studies used either the Oslo Sports Trauma Research Centre (OSTRC) severity score from 0-100, a pain intensity scale, or the length of time-loss in days (Figure 27).

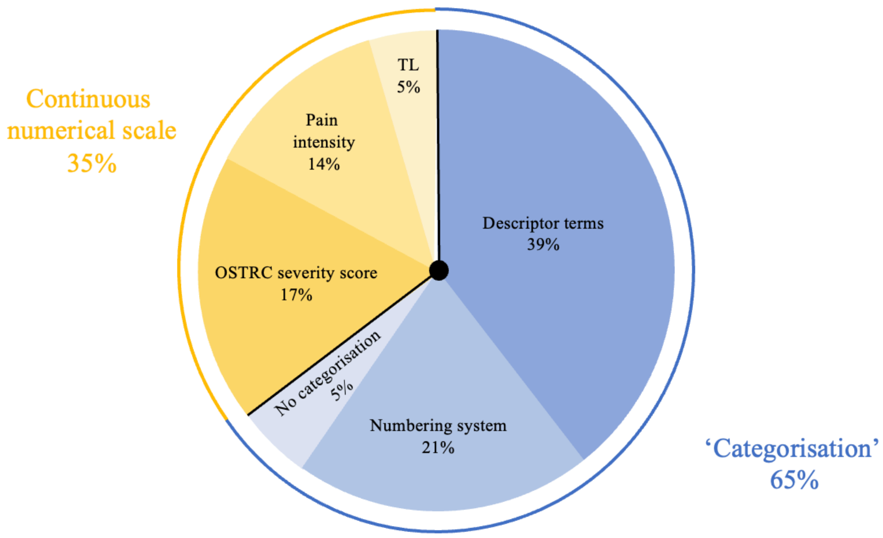



Figure 27. Grading approaches of injury severity used[7]

[7] Note: OSTRC = Oslo Sports Trauma Research Centre, TL = length of time-loss. Percentages are in relation to the total number of included studies (n=66).

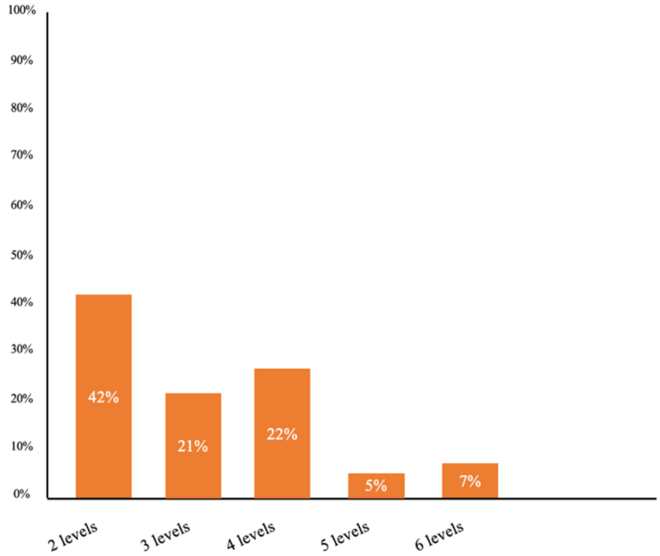



Figure 28. Number of levels used across scales of injury severity

The OSTRC severity score was the most commonly cited tool, used in 24% (n=16) of studies. Of these, the OSTRC health version questionnaire (OSTRC-H) was used in 69% (n=11) and the OSTRC overuse injury questionnaire (OSTRC-O) was used in 31% (n=5). The majority (94%, n=15) defined injury severity with the primary definition criterion ‘effect on running AND a physical description’ as per the original publications (Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2014), with just one study (Stenerson *et al.*, 2023) modifying the scale to use ‘effect on running’ in isolation. The majority were classified as continuous numerical scales (69%, n=11), using the OSTRC 0-100 severity score, while the remaining 31% (n=5) applied a categorisation in addition to using the continuous OSTRC severity score. In the majority of these latter studies (80%, n=4), injuries were predominately categorised as ‘no problem’ (severity score = 0), a ‘problem’ (severity score > 0) or a ‘substantial problem’ (if questions 2 and 3 scored ≥ 13/25) (Hespanhol Junior, van Mechelen and Verhagen, 2017; Bertelsen *et al.*, 2018; Franke, Backx and Huisstede, 2019; Hofstede *et al.*, 2020). Just one study (Stenerson *et al.*, 2023) applied a different categorization in which injuries were classified as mild, moderate, or severe.

### 4.4.5. Comparison of the extent to which injury severity scales differ

Following examination of the description of injury severity scales, a comparison across scales took place to examine the extent to which they differ. Individual scales were first grouped based on the primary definition criteria, and then compared with one another according to their secondary definition criteria and grading approach to report on the scope of injury severity captured and, assess the consistency of RRI severity measurement. Studies were grouped and analysed based on the primary definition criterion approach employed. An amalgamated comparison scale for the primary definition criteria of 'effect on running' (Figure 29) and 'effect on running AND physical description' (Figure 30) was developed. It was not possible to develop a comparison scale for 'physical description' in isolation as different secondary criteria were used.

#### 4.4.5.1. 'Effect on running'

The comparison scale identified two broad aspects of injury severity in studies using 'effect on running' in isolation (50%, n=33): restricted training, and time-loss, with time-loss representing the majority of this scale (Figure 29). Twelve levels, which are not equidistant from one another, were identified, with the most frequently used level being a stoppage of running for one day (48%, n=16). Ten studies (30%) used a scale that captured the entirety of this comparison scale.

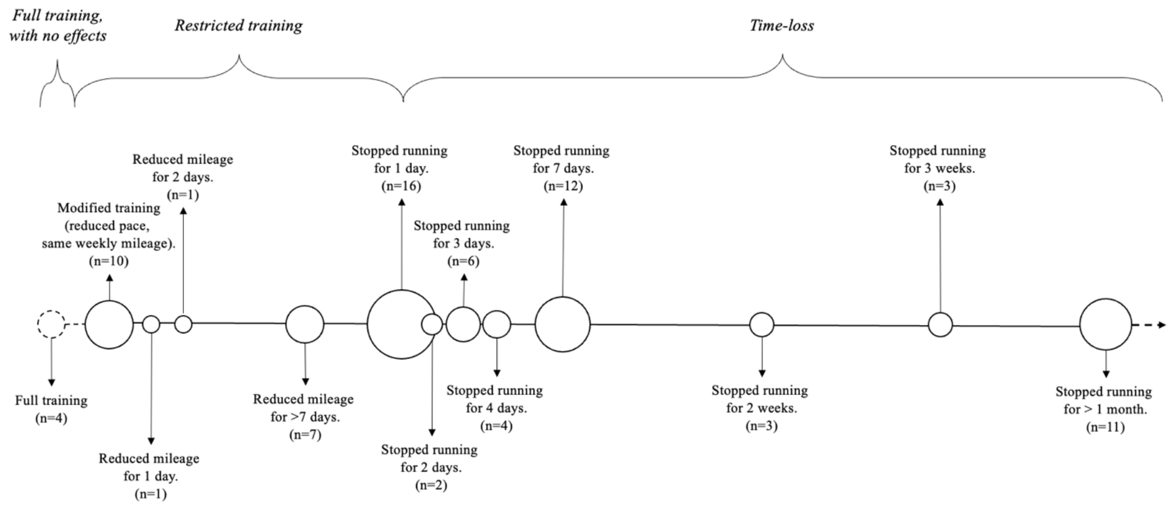



Figure 29. Comparison scale of injury severity for the 'effect on running' primary definition criterion (n=27)[8]

Scales could be grouped further with consideration of the secondary definition criteria (Appendix C8) with 'length of time-loss' in isolation (n=13) and 'restricted training AND length of time-loss' (n=9) the most frequently used combinations (Figure 26; Appendix C5).

In relation to 'length of time-loss' in isolation (n=13), the injury severity scales seem to be similar to one another, typically using one day of time-loss as the least severe level of injury, and either at least 21 days (three weeks) or 28 days (four weeks) as the most severe (Appendix C5). Additionally, most studies (62%, n=8) recognised a length of time-loss for seven days as a level of injury. Three studies did not provide any categorisation alongside the length of time-loss (Hendricks and Phillips, 2013; Quirino *et al.*, 2021; Viljoen *et al.*, 2024) (i.e., they did not define mild/moderate/severe injuries), three studies recognised two levels (Kerr *et al.*, 2016; Vitez *et al.*, 2017; Malisoux *et al.*, 2020), while seven studies recognised between four and five levels of injury (Theisen *et*

[8] Each circle represents a level of injury. The size of the circles indicates the number of studies that used the relevant category of injury.

*al.*, 2014; Malisoux *et al.*, 2015; Malisoux *et al.*, 2016; Begizew, Grace and van Heerden, 2019; Matos *et al.*, 2020; Moreno *et al.*, 2020; Gutiérrez-Hellín *et al.*, 2021). Typically, 'slight' injuries resulted in one-to-three days of time-loss, 'minor' injuries resulted in four-to-seven days of time-loss, 'moderate' injuries resulted in eight-to-28 days of time-loss, and 'severe' injuries resulted in more than 28 days of time-loss.

With regard to 'restricted training AND length of time-loss' (n=9), restricted training was defined as reduced pace, reduced mileage, or both (Appendix C5). Three studies appear to use the same scale entirely, being consistent across: the least and most severe levels of injury, the number of levels defined, and the definition of these levels (Chorley *et al.*, 2002; Parker *et al.*, 2011; Warne *et al.*, 2021). The remaining six studies do not align however, with no commonality across the least or most severe levels, the number of levels, or the definition of these levels (Marti, 1988; Marti *et al.*, 1988; Lun, 2004; Messier *et al.*, 2018; Mihalko *et al.*, 2021; Tao, Thompson and Weber, 2021).

#### 4.4.5.2. 'Effect on running AND physical description'

The comparison scale identified three broad aspects of injury severity in studies using an 'effect on running AND physical description' (33%, n=22): full training with pain, restricted training with pain, and time-loss (Figure 30). Ten levels, which are not equidistant from one another, were identified, with the most frequently used levels being a stoppage of running for at least one day (100%, n=22) and pain during running with restrictions (86%, n=19). Some scales specified restrictions in training as distance, speed, or duration. However, this was not consistent across studies, and so a general training restriction was defined in the comparison scale. Four studies (18%) appear to have used a scale that captured the entirety of this comparison scale (Taunton *et al.*, 2003; Buist *et al.*, 2008; Kluitenberg *et al.*, 2016; Viljoen *et al.*, 2021).

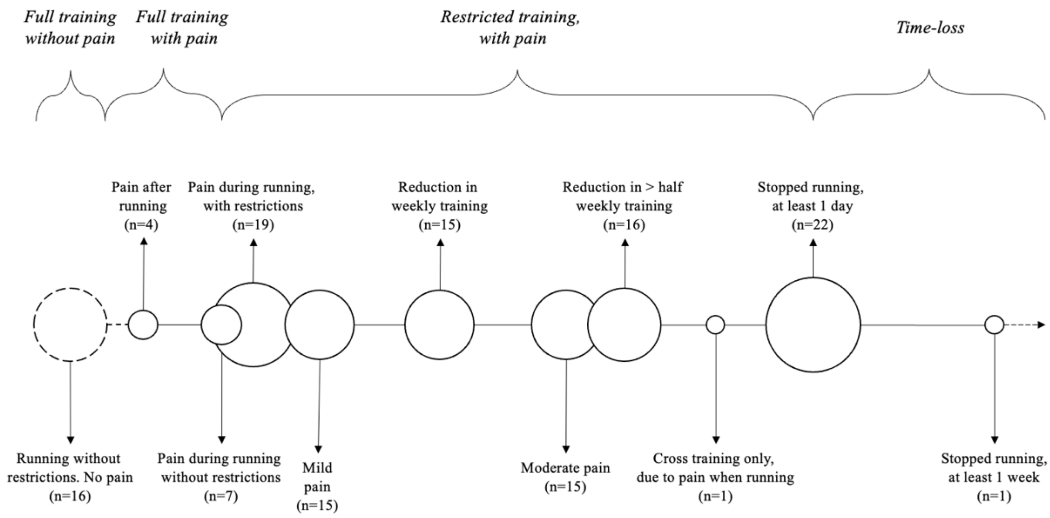



Figure 30. Comparison scale of injury severity for the 'effect on running AND physical description' primary definition criterion (n=20)[9]

Considering the secondary definition criteria (Appendix C8), these scales could be grouped further, with one dominant approach identified: 'intensity of pain AND restricted training AND effect on performance' (n=15) (Appendix C6). All studies that used this approach used the OSTRC-H or -O tools. These studies used this standardised tool in the same manner: the least severe level of injury was determined consistently by using the OSTRC severity score of 0-100, the number of levels was consistent (either four or five levels, represented by the scoring system of 0, 8, 17, 25 or 0, 6, 13, 19, 25, depending on the relevant question), and the description of these levels was consistent (e.g., reduced training volume to: a minor, moderate or severe extent), although there were slight differences between the health (OSTRC-H) and overuse injury (OSTRC-O) versions.

[9] Each circle represents a level of injury. The size of the circles indicated the number of studies that used the relevant category of injury.

#### 4.4.5.3. ‘Physical description’

It was not possible to develop a comparison scale for studies using ‘physical description’ in isolation (n=11) because the secondary criteria differed across studies, and the levels of injury were often not accompanied with a comparable description (Appendix C4). However, eight studies (73%) using ‘intensity of pain/symptoms’ in isolation as a secondary criterion used a numerical rating scale from 0-10 to rate the intensity of pain (with lower scores correlating with less severe pain). This approach appears to facilitate consistency in measuring intensity of pain.

### 4.4.6. Influence of injury severity measurement on study outcomes

In line with the secondary aim, six study outcomes were identified, with rates of injury (i.e., investigation into the incidence and/or prevalence of RRIs) (82%, n=54) and risk factor investigation (53%, n=35) being the most common. Other outcomes included investigating consequences of injury (11%, n=7), RRI prevention (9%, n=6) and research methodologies (5%, n=3).

#### 4.4.6.1. Rates of injury

Incidence rates were reported in 89% (n=48), of the 54 relevant studies, with an overall average rate of 43.0 ± 20.5% (range 0.6 - 86.0%). Prevalence was reported in 28% (n=15), with an overall average rate of 37.4 ± 26.2% (range 0.0 - 90.0%). Despite these studies capturing multiple levels of injury severity, less than half (48%, n=26) reported an incidence rate for each specific level (Table 11a; note: only incidence rates were examined due to low numbers of studies reporting prevalence). With different definitions of severity employed across studies, it was not possible to obtain an accurate average incidence rate per level of severity. However, a trend can be observed with levels of lower severity typically being associated with a higher incidence rate (Table 11a). While not providing an incidence rate for each level of severity, some studies reported the frequency of injuries at each level, out of the total number of injuries. However, there seems to be no obvious trend, as some studies reported that injuries of a lower severity were more frequent, while others reported the opposite (Table 11b).

Table 11. Incidence rate and frequency of injury suffered across different levels of injury severity

| Table 11a Incidence rate reported across different levels of injury severity (n=9) | | | | | | |
|---|---|---|---|---|---|---|
| **Study** | **Least to more severe levels of injury** | | | | | |
| | **Least severe level** | | | | | **Most severe level** |
| (Marti *et al.*, 1988) | 62% | 63% | 44% | | | |
| (Marti, 1988) | 29% | 26% | 14% | | | |
| (Kerr *et al.*, 2016) | 60% | 11% | | | | |
| (Kluitenberg *et al.*, 2016) | 58% | 29% | 23% | 26% | 10% | 8% |
| (Matos *et al.*, 2020) | 66% | 26% | 8% | | | |
| (Toresdahl *et al.*, 2020) | 49% | 9% | | | | |
| (Toresdahl *et al.*, 2022) | 49% | 10% | | | | |
| (Toresdahl *et al.*, 2022) | 12% | 2% | | | | |
| (Stenerson *et al.*, 2023) | 37% | 33% | | | | |
| Table 11b Frequency of injuries suffered across different levels of injury severity (n=18) | | | | | | |
| **Study** | **Least to most severe level of injury** | | | | | |
| | **Least severe level** | | | | | **Most severe level** |
| (Lun, 2004)28/08/2024 07:23:00 | NR | NR | NR | NR | NR | 24% |

| | | | | | | |
|---|---|---|---|---|---|---|
| (Parker *et al.*, 2011) | 44% | 56% | | | | |
| (Theisen *et al.*, 2014) | 28% | 20% | 22% | 30% | | |
| (Malisoux *et al.*, 2015) | 44% | 20% | 21% | 16% | | |
| (Malisoux *et al.*, 2016) | SS: 27%<br>MCS: 21% | SS: 7%<br>MCS: 24% | SS: 41%<br>MCS: 36% | SS: 25%<br>MCS: 18% | | |
| (Messier *et al.*, 2018) | 48% | 52% | | | | |
| (Begizew, Grace and van Heerden, 2019)28/08/2024 07:23:00 | 23% | 15% | 33% | 29% | | |
| (Hayes, Boulos and Cruz, 2019) | 75% | 25% | | | | |
| (Franke, Backx and Huisstede, 2019) 28/08/2024 07:23:00 | 50% | 50% | | | | |
| (Malisoux *et al.*, 2020) | SfS: 54%<br>HS: 69% | SfS: 46%<br>HS: 31% | | | | |
| (Moreno *et al.*, 2020) | 21% | 26% | 53% | | | |
| (Gajardo-Burgos *et al.*, 2021)28/08/2024 07:23:00 | 19% | 27% | 34% | 14% | 7% | |
| (Gonzalez-Lazaro, Arribas-Cubero and Rodriguez-Marroyo, 2021) | 75% | 25% | | | | |
| (Gutiérrez-Hellín *et al.*, 2021) | 14% | 51% | 35% | | | |
| (Thorpe, Blockman and Burgess, 2021) | 33% | 67% | | | | |
| (Viljoen *et al.*, 2021) | 23% | 26% | 33% | 18% | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| (Warne *et al.*, 2021) | 6% | 19% | 20% | 30% | 25% | |
| (Zapata-Rodrigo *et al.*, 2023) | 69% | 20% | 8% | 3% | | |

Note: NR = not reported, SS: standard shoe, MCS: motion-control shoe, SfS: soft shoe, HS: hard shoe

The anatomical locations (65%, n=35) and types (33%, n=18) of injuries sustained were reported in some studies. However, few report information on the severity of injuries per location (Marti *et al.*, 1988; Ryan *et al.*, 2014; Malliaropoulos, Mertyri and Tsaklis, 2015; Fuller *et al.*, 2017; Franke, Backx and Huisstede, 2019; Viljoen *et al.*, 2021) or type (Marti *et al.*, 1988) of injuries (Appendix C9).

#### 4.4.6.2. Risk factor investigation

Of the 35 studies examining risk factors, 80 potential risk factors were investigated and grouped into six categories: training-related, socio-demographic, health-related, sport history, biomechanical, and psychosocial (Appendix C10). No studies reported risk factors for specific levels of injury, and in consequence, no studies compared different risk factors for specific levels of injury severity. This makes it challenging to examine whether the measurement of injury severity directly influences the risk factors identified. Therefore, the primary definition criteria were compared across the studies that identified the most frequently identified statistically significant risk factors: previous injury (37%, n=13), running inexperience (20%, n=7) and high weekly mileage (17%, n=6) (Table 12).

Studies which defined injury severity by an 'effect on running' in isolation identified previous injury and running inexperience as significant risk factors most frequently, when compared to studies that used other primary definition criteria (Table 12). No clear pattern was evident for high weekly mileage.

Table 12. The influence of the primary definition criteria on the identification of significant risk factors for RRIs

| **Risk factor** | **Investigated** | **Identified as significant** | **Identified percentage** |
|---|---|---|---|
| **Previous injury** | | | |
| Effect on running | n=11 | n=10 | 91% |

| | | | |
|---|---|---|---|
| Effect on running AND physical description | n=9 | n=2 | 22% |
| Physical description | n=4 | n=1 | 25% |
| **Running inexperience** | | | |
| Effect on running | n=9 | n=6 | 67% |
| Effect on running AND physical description | n=5 | n=1 | 20% |
| Physical description | n=4 | n=0 | 0% |
| **High weekly mileage** | | | |
| Effect on running | n=13 | n=2 | 15% |
| Effect on running AND physical description | n=10 | n=3 | 30% |
| Physical description | n=2 | n=1 | 50% |

Note: n: number of studies; %: the proportion of studies that identified a risk factor as significant among those that investigated the risk factor

### 4.5. Discission

The aims of this scoping review were twofold. Primarily, to investigate how the severity of general RRIs is measured, by (i) describing the injury severity scales used (in terms of the criteria used to define injury severity and its grading) and (ii) comparing to what extent these scales differ. A secondary aim was to examine if the way in which injury severity is measured influences study outcomes in terms of (i) the rate of injury reported, and (ii) the risk factors identified.

Overall, there is inconsistency in how injury severity is measured due to the inter-related factors of different criteria being used to define injury severity (with 13 variations identified), and different approaches taken to grading injury severity (with two approaches identified, and between two and six categorical levels used) (discussed below). The reason for this inconsistency may be related to the challenge imposed by the insidious nature of RRI development, which typically lacks a definite 'point' of injury onset (Hreljac, 2004).

Approaches more suitable for determining the severity of acute injuries (e.g., length of time loss), where the 'point' of injury onset is more explicit, appear to be utilised by some in RRI research. A more consistent and appropriate method of measuring RRI severity is needed.

### 4.5.1. Measurement of general running-related injury severity

Four factors delineate general RRI severity measurement: the definition criteria, the lowest level of injury severity defined, the number of levels (if applicable), and the distribution of these levels (if applicable). The former two factors relate to how injury severity is defined, while the latter two refer to how it is graded.

Regarding the definition of injury severity, the criteria capture a broad scope of injury (Figures 29 and 30), based on the least severe level of injury defined. However, many studies fail to capture lower severity injuries. This appears to be due to the slow, progressive nature associated with RRIs, and associated difficulty in determining when 'injury' occurs (Hreljac, 2004). It seems that many studies use traditional approaches (i.e., length of time-loss) which are more suitable in acute injury research when identifying the point of 'injury' onset is more explicit (Bahr, 2009). The complexity of RRI severity is enhanced further with some athletes not considering themselves 'injured', even when experiencing pain and restricted training (Verhagen, Warsen and Silveira Bolling, 2021; Lacey *et al.*, 2023), and many considering pain as 'good' (see Tarr and Thomas (2021) for an in-depth description of this in dancers). Failing to capture the entire scope of injury severity may be influencing the wide range of injury rates reported (Kluitenberg *et al.*, 2016) (Table 11) and the lack of consideration for potential risk factors (Whalan, Lovell and Sampson, 2020) (Table 12), contributing to the unclear and limited foundational epidemiological evidence stunting the progression of injury prevention research.

With regard to the grading of injury severity, the inconsistent use of numerous levels of injury severity makes comparisons across studies challenging. This challenge is not exclusive to chronic injuries; it is also evident in the analysis of acute injury severity as seen by the Munich Consensus Statement using four grades to classify muscle injuries (Mueller-Wohlfahrt *et al.*, 2013), while the British Athletics Muscle Injury Classification uses 10 grades (Pollock *et al.*, 2014). Consideration should also be given to the finding that many levels of injury severity are not distributed equally within their respective scales. For example, injuries based on the length of time loss were often categorised as slight (1-3 days), minor (4-7 days), moderate (8-28 days) and major (more than 29 days). This difficulty is mirrored in the discussion of the updated OSTRC statement (Clarsen *et al.*, 2020). The OSTRC severity score was previously suggested as a continuous measure (0-100) (Clarsen *et al.*, 2013; 2014); however, more recently, it was discussed that this tool does not represent equidistance between possible outcomes, and therefore, it should be considered an ordinal measure. This latter finding may be problematic for some statistical analyses which require uniformity in outcome scores (e.g. chi-square tests) (Hopkins *et al.*, 2009; Almaraz Luengo *et al.*, 2022). It is worth noting that no study within the current review appears to explicitly justify the use of a non-equidistant approach to injury severity grading. This may reflect a presumed non-linear relationship between grading and injury severity (Figure 31). It could be argued that a continuous approach to grading injury severity is advantageous for exploring the relationship between RRI severity and injury rates or risk factors (e.g., for some statistical analyses). The validity and implications of this approach requires further investigation.

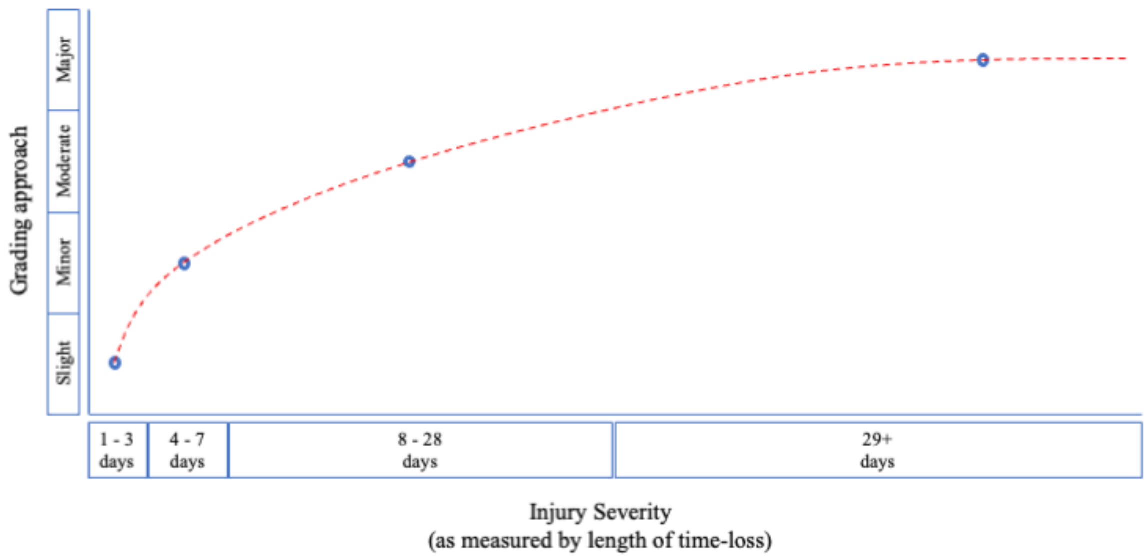



Figure 31. Non-linear relationship between the grading approach and the injury severity (as measured by length of time-loss)

The predominant approach of defining general RRI severity by an 'effect on running' and/or 'physical description' is comparable to both the consensus definition of a RRI (Yamato, Saragiotto and Lopes, 2015), and to runners' own descriptions of injury (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022; Lacey *et al.*, 2023). It is also similar to methods used in sport in general, with the OSTRC tools determining injury severity by the extent of: (i) difficulties participating in training/competition, (ii) training modifications required, (iii) reductions in performance, and (iv) symptoms/pain (Clarsen *et al.,* 2013; 2014). In contrast to this predominant approach in RRIs, many consensus statements for other sports (such as athletics (Timpka *et al.*, 2014), aquatic sports (Mountjoy *et al.*, 2016), and tennis (Pluim *et al.*, 2009)) define injury severity solely by the length of time-lost from activity. Using additional criteria, the approach taken in RRI research seems to be advantageous (for overuse injuries) over these consensus statement recommendations, as two consequences of injury are captured, and the lower levels of injury severity are recognised.

It is interesting to note that none of the reviewed studies included the need for medical attention to measure injury severity. This is in contrast to this criterion often being used for defining a RRI dichotomously (i.e., considering someone as either injured or uninjured) (Yamato *et al.*, 2015), and it being a commonly used criterion for measuring the severity of general sport injuries (Van Mechelen, Hlobil and Kemper, 1992). However, this criterion may not be the most appropriate for defining RRI severity as runners often do not seek medical advice when injured (especially for lower severity injuries) (Verhagen, Warsen and Silveira Bolling, 2021; Lacey *et al.*, 2023), and there is wide variety in individuals' access to and use of medical services (Niessen *et al.*, 2018). Therefore, using medical attention for defining injury severity may not be appropriate, although capturing detail on the utilisation of medical attention (e.g., duration, type, expertise required) can provide insight into the full burden of injury (Bahr, Clarsen and Ekstrand, 2018). Similarly, while possibly not necessary for *defining* injury severity, capturing and reporting the psychosocial effects of injury may enhance our understanding of the true burden of injuries with varying severities (Üstün *et al.*, 2003; Bahr, Clarsen and Ekstrand, 2018). These additional insights may also be useful in monitoring injury prevention and rehabilitation strategies (Van Mechelen, Hlobil and Kemper, 1992; Finch, 2006).

#### 4.5.2. Influence of injury severity measurement on study outcomes

While it is well understood that the definition of injury can affect the outcomes of research (Bahr, 2009; Kluitenberg *et al.*, 2016), little is known specifically about how the approach to measuring RRI severity affects study outcomes; this is the first review to examine the topic. Two primary study outcomes were identified: rates of injury (with incidence being the predominant figure reported) and potential risk factors.

#### 4.5.2.1. Influence of injury severity measurement on rates of injury

No studies directly compared whether different approaches to injury severity measurement, either in terms of its definition or its grading, influenced the rate of injury reported. Therefore, to examine this, we have taken the somewhat methodologically weaker approach of comparing across studies. Surprisingly, the definition criteria do not appear to affect the average incidence rate reported. There does, however, appear to be a trend with regard to the grading approach, with lower severity injuries associated with a higher incidence rate, and conversely, higher severity injuries having a lower incidence rate (Table 11). This is not surprising given the progressive nature of RRIs, in which they develop insidiously (i.e., starting as low severity injuries), with opportunities for appropriate management intervention strategies that can decrease the likelihood of progression to higher severity injuries (as opposed to acute injuries which immediately result in a higher severity injury) (Lacey *et al.*, 2023). This finding also reflects runners' lived experience of low severity injuries being highly frequent (Lacey *et al.*, 2023). However, less than half of the studies in this review reported a specific incidence rate for each level of injury severity measured. Even fewer studies reported data on the locations and types of injury sustained per level of severity. Without information on rates (and locations and types) of injuries per severity level, it is more challenging to accurately determine the magnitude of the injury problem (Van Mechelen, Hlobil and Kemper, 1992; Finch, 2006), inhibiting the development of targeted, effective injury prevention programmes.

#### 4.5.2.2. Influence of injury severity measurement on risk factors for injury

Despite 35 studies capturing severities of injury when exploring risk factors, none report risk factors for specific levels of injury. This makes it challenging to determine whether the approach to measuring injury severity influences the ability to identify risk factors. The primary definition criterion of ‘effect on running’ appears most effective at identifying risk factors, based on whether a statistically significant effect was identified (Table 12). This observation is limited due to the possibility of confounding factors affecting the identification of significant risk factors (e.g., study design, population sample, definition of injury) (Norton and Strube, 2001). The importance of considering the effect of injury severity on risk factor identification can be explained by the following example. A runner sustains a lower severity injury to their knee; however, they continue to run (despite experiencing symptoms and training modifications). Simultaneously, this lower severity injury causes a (subconscious) change in the runner’s technique in an attempt to offload the injury at the knee. The runner subsequently goes on to develop a higher severity injury at their hip, forcing them to stop running. If researchers or clinicians are unaware of the lower severity injury at the knee, they may fail to recognise its potential impact as a risk factor for the development of the (higher severity) injury at the hip. Future research clearly needs to capture, report, and directly compare differences in risk factors across levels of injury severity in a single cohort, and how lower severity injuries relate to higher severity injuries.

### 4.6. Recommendations and practical implications

There is a complex interaction of multiple factors to consider when choosing a measure of injury severity, including, but not limited to: (i) ensuring the aims of the study can be addressed, (ii) attempting to be consistent with other researchers' practices to facilitate comparison of findings, and (iii) ensuring the full scope of injury severity is captured (especially the least severe levels). With this being the first review to investigate how injury severity is measured, and examine possible influences on study outcomes, RRI research seems to have overlooked the crucial role severity of injury plays in understanding the true burden of injury (Bahr, Clarsen and Ekstrand, 2018). It appears that, in line with recommendations (Bahr *et al.*, 2020), studies have chosen measures of injury severity to allow their aims to be addressed. However, this has subsequently resulted in inconsistency and an inability to compare findings across studies.

While it may not be practical nor applicable for each study to analyse data pertaining to varying levels of injury severity (e.g., if a sample size estimation was performed to address a specific question), there needs to be a concerted approach from researchers to better understand RRIs. We make two recommendations. Firstly, where consistent with study aims (and an appropriate sample size permits), researchers should capture injury severity using a consistent, continuous measure, acquiring information on the intensities and types of pain, the extent of training restriction (e.g., volume, duration, frequency, intensity), and the length of time-loss; supported by the OSTRC. Specific injury severity measures (e.g., length of time-loss categories) can then be applied *post-hoc* to address individual study aims. Initially, it is unlikely that there will be enough participants in a single study to provide conclusive findings. Therefore, our second recommendation is for the formation of an expert group to guide the establishment of a single repository for RRI data, promoting the collection of continuous data. This continuous data repository could facilitate various statistical analyses that require larger data (e.g., machine learning/artificial intelligence, non-linear approaches) and comparison of findings across studies, ultimately advancing RRI prevention. Examples of disease-based repositories include the European Cystic Fibrosis Society's Patient registry (www.ecfs.eu/ecfspr), National Institute of Diabetes and Digestive and Kidney Diseases Central Repository (www.repository.niddk.nih.gov), and Parkinson's Progression Markers Initiative (www.ppmi-info.org).

In terms of practical implications, clinicians, coaches and runners clearly need to consider lower severity injuries and their potential role in contributing to higher severity injuries. Clinicians and coaches should also consider that runners may be perceiving low severity injuries in a positive manner, when possibly, they are 'true' injuries with consequences that need to be addressed.

### 4.7. Limitations

This review should be considered in light of some limitations. Firstly, only measures of 'general' RRI severity were included, with no inclusion of studies which measured the injury severity of specific RRIs (e.g., Achilles tendinopathy). The findings in relation to the effect of injury severity on injury rate reported and/or risk factor identification should be considered in light of this, as findings may differ when considering specific RRIs. Future studies should explore this. Secondly, with the segregation of studies into various groups of definition criteria, grading approaches, and outcomes, low numbers of studies were available for some analyses. Finally, for those that used either of the OSTRC tools, the majority were classified as 'continuous' because only the 0-100 severity score was used, as referenced in the original papers (Clarsen *et al.*, 2013; 2014). Considering recent discussion on the OSTRC tools' more appropriate consideration as an ordinal measure (Clarsen *et al.*, 2020), it is possible that these studies could be considered 'categorical'.

## 4.8. Conclusion

Injury severity is a key aspect of effective injury surveillance research (Van Mechelen, 1997). However, many studies have not captured or reported on the severity of general RRIs (Yamato *et al*., 2015), thereby reducing our understanding the true burden of RRIs. The current review describes, compares, and examines the influence of the different approaches to measuring injury severity, identifying a broad array used. Primary and secondary criteria are used to define all scales of injury severity, with a categorisation approach to grading prevailing. With a failure to recognise lower severity injuries, the majority of studies do not capture the entire scope of injury severity. While there is some consistency among studies which use specific approaches (e.g. length of time-loss), the wide variety of approaches result in overall inconsistency in RRI severity measurement. The approach to measuring RRI severity may affect study outcomes, with a noticeable trend in low severity injuries being associated with a higher incidence rate, and an 'effect on training' approach to defining injury severity seemingly the most effective at identifying significant risk factors. The current review highlights that less than half of included studies report rates of injury for specific levels of severity, and none report data on risk factors for specific levels. This deficiency is possibly contributing to the inconsistent findings for rates of injury (Kluitenberg *et al.*, 2015; Kakouris, Yener and Fong, 2021), and a lack of clarity on risk factors for injury (Ceyssens *et al.*, 2019; Burke *et al.*, 2021; van Poppel *et al.*, 2021), thus hampering attempts to prevent injuries. By capturing consistent, continuous data on injury severity, and founding an expert group to guide the establishment of a repository for RRI data, significant advancements in understanding and preventing RRIs are possible.

### 4.9. Data availability

All data supporting the findings of this review are available within the paper, its supplementary material and in an online data repository, available at: https://doi.org/10.17605/OSF.IO/YJ87C.

*Link section: Chapter 4 to 5*

In addition to the majority of studies not capturing or reporting on RRI severity (Yamato et al., 2015), three challenges are evident from Chapter 4. Firstly, while it was concluded that some approaches to injury severity measurement are consistent, there are a wide variety of approaches taken, resulting in overall inconsistency. Secondly, with high thresholds imposed in definition criteria, many injuries of lower severities are not recognised, and therefore the entire development process of injury is likely not being captured. Thirdly, less than half of studies report rates of injury for specific levels of severity, and none report data on risk factors for specific levels. These challenges are possibly contributing to the inconsistent findings for rates of injury and the lack of clarity on risk factors, thus limiting our understanding of the true burden of RRIs, and hampering attempts to prevent them.

From Chapters 3 and 4, we understand how RRIs and their severity are defined and captured. Considering these findings from a pragmatic position, these methods have largely been developed by researchers, with little input from other stakeholders (e.g., runners). Capturing runners' lived experience of injuries may enhance researchers' understanding of them, especially in relation to the entire injury development process. By adopting an interpretative perspective, this insight may contribute to the development of a more holistic, runner-focused approach to injury surveillance, addressing the challenges of the fundamental way in which 'injury' is viewed. Therefore, the aim of Chapter 5 is to explore recreational runners' description of injury, and their management of the process of injury development.

# 5. Chapter 5: Study 3: The Running Injury Continuum: A qualitative examination of recreational runners' description and management of injury

This paper is published in Plos One. It is presented in full with only minor formatting changes.

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## 5.1. Abstract

A critical step in understanding and preventing running-related injuries (RRIs) is appropriately defining RRIs. Current definitions of RRIs may not represent the full process of injury development, failing to capture lower levels of injury that many athletes continue to train through. Understanding runners' description and management of the injury development process may allow for a more appropriate examination of all levels of injury. This study aimed to examine recreational runners' description and management of the injury development process. A qualitative focus group study was undertaken. Seven semi-structured focus groups with male (n = 13) and female (n = 18) recreational runners took place. Focus groups were audio and video recorded, and transcribed verbatim. Transcripts were reflexively thematically analysed, a critical friend approach was taken and multiple methods of trustworthiness were executed. Runners describe injury on an eight-level continuum, ranging from injury-free to career-ending injury. There are lower and higher levels of injury. Each level of injury is described across four categories of descriptors; physical description, outcome (effect on running and daily life), psychological description, and management. The Running Injury Continuum is a tool that can be used

for injury surveillance (for healthcare professionals and researchers) and for research investigating RRI risk factors. Healthcare professionals, researchers and coaches must ensure they monitor the development of all levels of RRIs, across all categories of descriptors. Runners need to be educated regarding appropriate self-management strategies for lower level injuries, with access to evidence-based information being a critical management tool.

**Key words:** running-related injury development, injury description, injury consequences, injury management

### 5.2. Introduction

Despite recreational running being an extremely popular physical activity and sport (Hulteen *et al.*, 2017) it is associated with high rates of injury (Hollander *et al.*, 2021), with incidence rates of 40% (Kakouris, Yener and Fong, 2021) or 7.7 injuries/1000 hours (Videbæk *et al.*, 2015) reported. The vast majority of running-related injuries (RRIs) are overuse injuries (Bertelsen *et al.*, 2017) which occur when excessive, repetitive loads are applied to tissues beyond their adaptive capability (Bertelsen *et al.*, 2017; Edwards, 2018; Kalkhoven, Watsford and Impellizzeri, 2020). While RRIs develop from the interaction between multiple risk factors (Meeuwisse *et al.*, 2007; Malisoux *et al.*, 2015; Bertelsen *et al.*, 2017), there is little consensus on what these risk factors are (Hulme, Nielsen, *et al.*, 2017; Ceyssens *et al.*, 2019). This is potentially due to a commonly employed approach that uses definitions of injury that are limited, focusing on injuries causing time-loss, rather than capturing the process of injury development (Kluitenberg *et al.*, 2015; Kluitenberg *et al.*, 2015; Yamato *et al.*, 2015).

Clearly, a critical step in understanding and ultimately preventing RRIs is appropriately defining a RRI. Traditionally, time-loss from activity has been the main criterion for defining overuse injuries, with the duration of time-loss determining severity (Clarsen, Myklebust and Bahr, 2013). The current consensus definition of a RRI expands on this definition to also include training restriction or the need for medical attention as criteria (Yamato, Saragiotto and Lopes, 2015). Although this approach broadens the scope of a RRI, it may not represent the full process of injury development, failing to capture the *lower levels of injury* that many athletes continue to train through (Clarsen, Myklebust and Bahr, 2013). It has been acknowledged that *lower levels of injury* exist prior to those that cause time-loss, as evident from: (i) a general physiological perspective as represented in the Well-Being Continuum (Soligard *et al.*, 2016), (ii) a general sports perspective through the development of the Oslo Sports Trauma Research Centre (OSTRC) questionnaires (Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2014; 2020), and (iii) directly from capturing runners' perceptions of RRIs through the Injury Pathway model (Verhagen, Warsen and Silveira Bolling, 2021).

Understanding runners' perceptions of RRIs may allow for a more appropriate examination of these *lower levels of injury*. Only three studies appear to have reported on runners' perception of the process of injury development (Jelvegård *et al.*, 2016; Johansen *et al.*, 2017; Wickström *et al.*, 2019; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022), with just two studies alluding to runners' perception of *lower levels of injury (*Wickström *et al.*, 2019; Verhagen, Warsen and Silveira Bolling, 2021). These studies reported that RRIs are perceived as progressive, with injury 'categories' suggested in one study, although not described further *(*Wickström *et al.*, 2019), and the identification of a 'complaint' level in the process of injury development (prior to time-loss, training restriction or seeking medical attention) described in another (Verhagen, Warsen and Silveira Bolling, 2021). However, it is unclear if this 'complaint' level of injury is a single level, or if it comprises multiple unique levels of injury. Therefore, a greater understanding of this process of injury development (i.e., runners' description and management of each level of this process*)* is clearly needed if researchers and clinicians are to better understand the multifactorial and progressive nature of RRIs, their risk factors, and ultimate prevention.

It is also important for future research aiming to identify RRI risk factors to understand how *lower levels of injury* may interact with other risk factors to develop into a significant injury (i.e., as per the consensus definition (Yamato, Saragiotto and Lopes, 2015)), or indeed, how these *lower levels of injury* may themselves be risk factors for injury (Soligard *et al.*, 2016). In addition, with the dynamic relationship between multiple risk factors and the onset of injury, it is important to understand how runners react to this process of injury development (i.e. a *lower level injury*), and how they manage all levels of injury. This may not only help to differentiate between various levels of injury, but also provide insight into how these levels act as potential risk factors themselves for further injury. Not considering these *lower levels of injury* could potentially mask important information that is relevant in identifying risk factors for injury. Therefore, the aim of the present study was to explore recreational runners' description of injury, and their management of the process of injury development.

## 5.3. Methods

### 5.3.1. Design

Interpretative phenomenology (IP) was deemed to be an appropriate methodological approach because, as a branch of phenomenology, it focuses on the lived experiences of humans, eliciting insightful accounts of individuals' subjective experiences regarding a certain topic (Polit and Beck, 2014; Korstjens and Moser, 2017). Focus groups were deemed an appropriate method of data collection as they can yield rich, in-depth data through the interaction of participants (Kitzinger, 2006; Queiros, Faria and Almeida, 2017; Moser and Korstjens, 2018), and can enhance personal accounts by benefitting from the rapport built in a homogeneous sample (Flowers, Knussen and Duncan, 2001). Although suggested to be incompatible by some (Webb and Kevern, 2001), executing focus groups with an IP approach was congruent with the aim of the study and allowed for enrichment of the data regarding the phenomenon of interest through the interaction between participants (Bradbury-Jones, Sambrook and Irvine, 2009). Despite the complex interactional environment that is created by conducting focus groups, the opportunity to engage with a homogenous sample (i.e., runners) as a group can elicit insightful and experiential data (Palmer *et al.*, 2010). While it has been suggested that there is difficulty in developing phenomenological accounts of data due to the complexity of group dynamics (from interactional, social and contextual perspectives) (Love, Vetere and Davis, 2020), the complexity of individual and shared contexts (Love, Vetere and Davis, 2020), and the influence and position of the researcher(s) (Sloan and Bowe, 2014; Bush, Singh and Kooienga, 2019; Love, Vetere and Davis, 2020), the free-flowing and engaging nature of focus group discussion can allow for social interaction of shared, similar or conflicting lived experiences of the phenomenon of interest (Bradbury-Jones, Sambrook and Irvine, 2009; Gaskell and Williams, 2019).

### 5.3.2. Participants

A purposive sample of 31 adult recreational runners were recruited. Between April and June 2022 local running clubs/groups were contacted via email or telephone and asked to distribute research information and contact details of researchers to potential participants. Those interested then contacted the researchers. Eligible participants were recreational runners (someone running at least once per week for the previous six months (Mulvad *et al.*, 2018), aged 18 years or older, and had no previous education or training in musculoskeletal injuries (e.g., Athletic Therapist or Physiotherapist). Participant demographics are presented below.

### 5.3.3. Pilot study

A semi-structured focus group schedule was developed during several brainstorming meetings between researchers (AL, EW, SOK, and KM (Appendix D1)). Question content, sequencing, phrasing and timing were discussed during meetings. The schedule was tested on colleagues to determine its appropriateness, and then used in the pilot study (details below). A pilot study was conducted to test the focus group schedule. Five male and five female physically active participants were recruited as a convenience sample, aged 23.8 ± 5.9 years. Two focus groups were moderated by two researchers (AL and SOK), each taking place in-person, on University grounds, and lasted 59.7 ± 5.6 minutes. Focus groups were audio and video recorded, and transcribed verbatim. Data obtained from the pilot study are not included as part of the results.

### 5.3.4. Main study procedures

Data was collected between April and June 2022. Ethical approval was granted by the local university's Ethics Committee (DCUREC/2022/071), and the Standards for Reporting Qualitative Research were followed (O'Brien *et al.*, 2014) (Appendix D2). Participants were organised into groups based on their availability to attend, running background and age (brief demographic information was collected prior to each focus group). Seven focus groups were moderated by two researchers (AL and SOK) and lasted 83.9 ± 18.1 minutes. On arrival to each focus group, participants were introduced to one another by the moderators, and a casual conversation (not recorded) took place prior to starting. Authors (AL and SOK) had access to participants' identifying information during data collection. Participants provided informed consent before commencing. Each focus group began with a brief introduction and the aims of the study were outlined (Appendix

D1). Participants were encouraged to speak freely, ask each other questions, and were given the opportunity to ask the moderators questions at any point. Firstly, participants were asked how they would define a RRI, and then how they would describe a RRI (approx. 10 minutes of discussion). Participants were prompted to elaborate on their descriptions and asked to draw (as a group) their description of RRIs on a whiteboard (approx. 45 minutes of discussion). They were then asked how they manage RRIs, and asked to insert these descriptions on the drawing (approx. 30 mins). Conversation pursued naturally, not being led by the moderators, but with the moderators prompting participants to give as much detail as possible. Participants were asked to complete a short individual questionnaire (hard-copy) gathering further demographic information, training practices, and injury history (including their experience of running-related pain/discomfort). Questions included were in the form of Likert scales and open-ended responses. Additionally on this questionnaire, participants were asked to draw their individual description of a RRI (approx. 5 mins). On closing the focus groups, participants were given another opportunity to ask questions or provide additional information. The progressive nature of RRIs was not described to participants, nor was the concept of *levels of injuries*.

A reflective and iterative approach was taken to focus groups moderation. Following each focus group, moderators discussed their perception of each focus group, expressed their opinions on the appropriateness of the focus group schedule, and discussed how they could potentially improve for the next group. Both moderators included additional probes to encourage further explanation of some points raised and to encourage all participants to share their perceptions.

### 5.3.5. Data analysis

Frequencies and descriptive statistics were generated from the questionnaire responses using SPSS (IBM Corporation; version 27) and all participants were given an identification number and coded by self-identified gender (e.g., male 4 = M4, female 2 = F2) in order to maintain anonymity. All focus groups were audio and video recorded. Audio recordings were sent to an external transcription service to be transcribed verbatim. On their return, the primary author reviewed the transcripts alongside the video recordings, corrected any discrepancies, inserted nuance (to account for sarcasm and gestures), and assigned dialogue to the according speaker. This facilitated significant familiarisation with the data.

The transcribed focus groups were coded by the primary author using NVivo (QSR International; release 1.6.2). A reflexive thematic analysis (RTA) approach was taken to data analysis according to Braun and Clarke's principles (Braun and Clarke, 2019; 2021). This process followed six recursive phases: (i) the primary author familiarised herself with the data by reading the transcripts, correcting discrepancies, adding nuance, and re-reading the transcripts, (ii) brief labels (codes) were generated to identify important aspects of the data, (iii) themes were generated through examining and organizing the codes, (iv) themes were then reviewed against the whole dataset, and developed further, (v) developed themes were then refined, defined and named, and (vi) the data were organised into a written report.

An 'order of themes' document was used to organise the codes, sub-themes, themes and core categories and was reflexively updated throughout data collection and analysis phases. Based on the developing coding, further levels of sub-themes were developed while some sub-themes were merged. Additionally, as a level of data triangulation, the primary author reviewed each group's whiteboard drawing alongside the corresponding transcript and video recording. Further detail from the transcript was added to each drawing, which clarified these visual representations and ensured consistency between transcripts and drawings. Data-driven, exploratory, and reflexive, inductive coding was initiated after transcription of the first focus group and continued throughout data collection (Braun and Clarke, 2013). Each drawing from focus groups (n=7) were combined to develop the final eight-point continuum. The final Running Injury Continuum was arrived at based on how participants described each level and where they placed each level. A visualisation of the methods of data analysis is detailed in Figure 32. A similar sample size has been used in previous research and allowed for the collection of a rich description from participants regarding RRIs (Miller, Chan and Farmer, 2018; Middlebrook *et al.*, 2021), as well as aligning with the aims of the study.

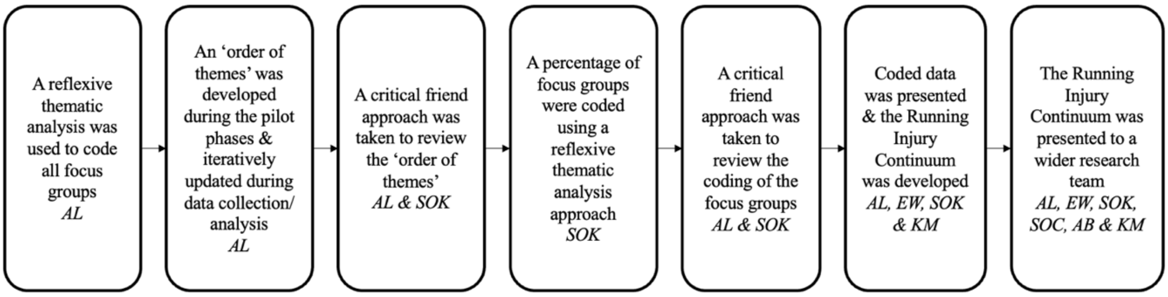



Figure 32. Data analysis and the Running Injury Continuum development process[10]

### 5.3.6. Trustworthiness

Throughout the data collection and analysis phases, discussions on the developing codes, sub-themes, themes and core categories ensued (between AL, EW, SOK and KM), which challenged and facilitated multiple interpretations of the data, encouraging reflexivity. To further enhance the analytical process (McGannon *et al.*, 2019) and to

[10] AL: Aisling Lacey; SOK: Sinéad O'Keeffe; EW: Enda Whyte; KM: Kieran Moran; SOC: Siobhán O'Connor; AB: Aoife Burke

ensure reliability and rigour of results presented (Smith and McGannon, 2018), a method of 'sense-checking' via a critical friend approach was taken between researchers. The goal of this approach was not to reach a consensus, but rather, to encourage reflexivity in the co-construction of knowledge (Cowan and Taylor, 2016; Smith and McGannon, 2018), and facilitate the exploration of multiple interpretations of the data (Sparkes and Smith, 2013; McGannon *et al.*, 2019). After all focus groups had been coded by the primary author, a percentage (approximately 30%) of the transcripts were independently coded by another experienced qualitative researcher (SOK). Taking a critical friends approach, researchers (AL and SOK) met occasions to discuss their interpretations of the transcripts, challenging each other's interpretations of the data. Codes, sub-themes, themes and core categories were reflexively reviewed and discussed. The process facilitated the development of additional codes, while some existing sub-themes were merged/expanded. On finishing data collection and analysis, a wider group of researchers (AL, EW, SOK, SOC, AB and KM) met to discuss their interpretations of the findings. Again, the goal was not to reach consensus, but to encouraging reflexivity by incorporating diverse perspectives.

Aligning with the aims of the study and ensuring their lived experiences were reflected, transcripts and whiteboard drawings were returned to participants, giving them the opportunity to alter their individual dialogue, and to ensure that they were satisfied with our interpretation of the discussion. No requests were received to alter group drawings or individual dialogue. This also built rapport with participants and the research team, for possible continued research. Furthermore, multiple examples of direct quotations from participants are presented, enhancing the accuracy and trustworthiness of findings. A broad and diverse contribution from participants is also included, reducing the likelihood of individual bias (Tracy, 2010).

## 5.4. Results

### 5.4.1. Demographics

Seven focus groups were conducted with 18 (58%) female and 13 (42%) male recreational runners. Participants were aged 39.7 ± 12.7 years (range 20–65 years). The majority of runners had been running for more than 5 years (n = 17, 55%), fewer running 1–3 years (n = 10, 32%), and the least amount running 4–5 years (n = 4, 13%). Participants trained either 2–3 times per week (n = 16, 52%) or 4–6 times per week (n = 15, 48%), with the majority of runners participating in organised running events (n = 27, 87%). Most (n = 17, 55%) runners predominately trained on their own, with the remainder training in small (n = 7, 23%) or large (n = 7, 23%) groups. Injury prevention was 'very' or 'extremely' important to the majority of runners (n = 21, 68%), with fewer stating that it was 'slightly' or 'moderately' important (n = 9, 29%), and just one participant reporting it was 'not at all' important (n = 1, 3%). Further details on training practices are presented in Table 13. According to the consensus definition of injury (Yamato, Saragiotto and Lopes, 2015), most runners reported having a previous RRI (n = 27, 87%), while few reported never having a RRI (n = 4, 13%). Nineteen participants had at least one RRI in the previous 12 months (n = 19, 70%). All participants reported previously experiencing a *lower level injury*. Further details on RRI history are detailed in Table 13.

Table 13. Running practices and injury history

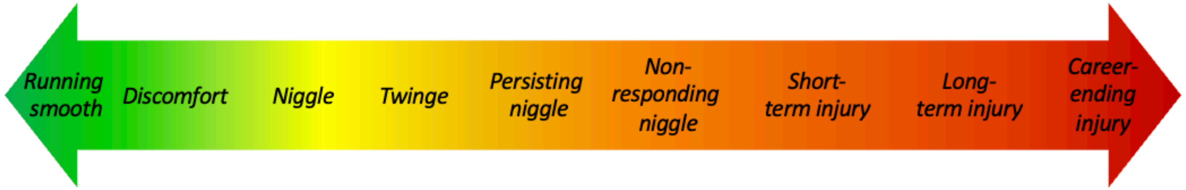
| **Preferred running events (n=31)*** | |
|---|---|
| <5km | n=5 |
| 5km | n=21 |
| 10km | n=18 |
| 16km/10 mile | n=18 |
| Half marathon (21.1km) | n=6 |
| Marathon (42.2km) | n=3 |
| Ultramarathon (>42.2km) | n=1 |
| Triathlon | n=1 |

| | |
|---|---|
| Other | n=1 |
| **Weekly mileage (n=31)** | |
| <10km | n=1 |
| 10-20km | n=12 |
| 21-30km | n=10 |
| 31-40km | n=1 |
| 41-50km | n=5 |
| >50km | n=2 |
| **Amount of missed training with worse ever RRI (n=27)** | |
| <1 week | n=2 |
| 7-10 days | n=4 |
| 2-3 weeks | n=5 |
| 4-6 weeks | n=2 |
| >6 weeks | n=13 |

*: multiple choice available; n: number of participants; RRI: running-related injury

### 5.4.2. Runners' description of injury

Runners described RRIs and the process of injury development on an eight-level continuum, with each level increasing in severity of injury (Figure 33). Although there were technically nine individual levels identified, the first level of 'running smooth' was not considered as an 'injury', but will be presented as the initial level on the Running Injury Continuum. The eight levels of RRIs identified were: 'discomfort', 'niggle', 'twinge', 'persisting niggle', 'non-responding niggle', 'short-term injury', 'long-term injury', and 'career-ending injury' (Table 14). Runners described each level of the Running Injury Continuum in terms of four key categories of descriptors: physical description, outcome (effect on running and effect on daily life), psychological description and management (Figure 33, Table 14).




| ***Name of stage*** | ***Running smooth*** | ***Discomfort*** | ***Niggle*** | ***Twinge*** | ***Persisting niggle*** | ***Non-responding niggle*** | ***Short-term injury*** | ***Long-term injury*** | ***Career-ending injury*** |
|---|---|---|---|---|---|---|---|---|---|
| **Physical description** | Pain-free | Tightness<br>Tiredness<br>DOMS<br>Temporary | Awareness<br>Low pain<br>Repeated | Darting pain<br>Intense<br>Temporary | Low/Mild pain<br>Persistent | Medium pain<br>Constant | Severe discomfort<br>High/Sharp pain | Extreme discomfort<br>Very high pain | Severe pain |
| **Outcome** | | | | | | | | | |
| Effect on running | No effect | No effect | No effect.<br>Reduced load.<br>Altered warm up | Stop mid-session.<br>Reduced load mid-session | No effect.<br>Reduced load.<br>Rest days | Reduced load.<br>Rest days.<br>Stop running: short-term | Stop running: short-term | Stop running: long-term | Never running again |
| Effect on daily life | No effect | No effect | No effect | No effect | No effect | Pain during day.<br>Conscious effort to offload | Pain during day.<br>Conscious effort to offload | Pain during day.<br>Conscious effort to offload | Pain during day.<br>Conscious effort to offload |
| **Psychological description** | Happy place | Mental fatigue | Caution | Caution | Concern.<br>Anxiety | Anxiety | Anxiety | Anxiety.<br>Frustration | Frustration.<br>Depression |
| **Management** | | | | | | | | | |
| Self-management | None.<br>Injury prevention | None.<br>Continue running.<br>Stretching | None.<br>Stretching.<br>Rest day | Stretching.<br>Reduce load.<br>Stop mid-session | Reduce load.<br>Rest days | Reduce load.<br>Rest days.<br>Short-term rest | Short-term rest | No longer self-managing | No longer self-managing |
| External management | None. | None.<br>Friends.<br>Online resources | None.<br>Friends.<br>Online resources | Friends.<br>Online resources | Friends.<br>Online resources.<br>Physiotherapist/ Athletic Therapist | Friends.<br>Physiotherapist/ Athletic Therapist | Physiotherapist/ Athletic Therapist | Physiotherapist/ Athletic Therapist.<br>Medical specialist.<br>Surgery | Surgery |

*Lower level injuries* (Discomfort – Non-responding niggle) *Higher level injuries* (Short-term injury – Career-ending injury)

Figure 33. The Running Injury Continuum

Table 14. 'Order of themes' document: Description and management of each level of the Running Injury Continuum

| | Core categories | Theme | Sub-theme | Secondary sub-theme | Tertiary sub-theme |
|---|---|---|---|---|---|
| **1** | **Running smooth** | | | | |
| | Physical description | Sensation | Pain free | | |
| | Management | Injury prevention | | | |
| | | No management required | | | |
| | Psychological description | Happy place | | | |
| **2** | **Discomfort** | | | | |
| | Physical description | Sensation | Tightness | | |
| | | | Delayed onset muscle soreness (DOMS) | | |
| | | | Tiredness | | |
| | | | Low pain | | |
| | | | Stiffness | | |
| | | | Uncomfortable | | |
| | | Frequency/Onset | Temporary | | |
| | | | Infrequent | | |
| | | Precursor to injury | | | |
| | Outcome | Effect on running | Full training | Stick to training plan | |
| | | Effect on daily life | | | |
| | Psychological description | Mental fatigue | | | |
| | Management | Self-management | Additional stretching | | |
| | | | Continue training | | |
| | | | Therapies | Massage gun | |
| | | External management | Friends | | |
| | | | Internet sources | Google | |
| | | No management | | | |
| **3** | **Niggle** | | | | |
| | Physical description | Sensation | Pain | Severity of pain | Low pain |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | Not painful |
| | | | | | Dull pain |
| | | | | Type of pain | Aches |
| | | | Awareness | Different from opposite side | |
| | | | Discomfort | | |
| | | | Tightness | | |
| | | | Irritation | | |
| | | | Tiredness | | |
| | | Frequency/Onset | Repeated | | |
| | | | Temporary | | |
| | | | Constant | | |
| | | | Post-session complaint | | |
| | | | Felt while running | | |
| | | Precursor to injury | From an unknown cause | | |
| | Outcome | Effect on running | Full training | Run through it | |
| | | | | Pressure to continue | Desire to continue |
| | | | | | Stick to training plan |
| | | | | Doesn't affect training | |
| | | | | Can ignore | |
| | | | Altered training | Altered warm up | |
| | | | | Forced change to training | Reduce load |
| | | | | Altered technique | |
| | | Effect on daily life | No effect | | |
| | Psychological description | Caution | | | |
| | | Affects motivation to train | | | |
| | | Annoying | | | |
| | Management | Self-management | Altered training | Additional stretching | |
| | | | | Rest | Additional rest day |

| | | | | | |
|---|---|---|---|---|---|
| | | | | Reduce load | |
| | | | | Session preparation | |
| | | | | Change technique | |
| | | | Therapies | Foam rolling | |
| | | | Strength & conditioning | | |
| | | | Accessory supports | Footwear | |
| | | External management | Friends | | |
| | | | Internet sources | YouTube exercises | |
| | | | Massage | | |
| | | No management | Resolves on its own | | |
| | | | Ignore niggle | | |
| | | | Ignore advice | | |
| **4** | **Twinge** | | | | |
| | Physical description | Sensation | Pain | Type of pain | Darting pain |
| | | Frequency/Onset | Temporary (short-lived) | | |
| | Outcome | Effect on running | Altered training | Stop mid-session | |
| | | | | Reduced load | |
| | | | Full training | Run through it | |
| | Psychological description | Caution | | | |
| | | Annoying | | | |
| | Management | Self-management | Altered training | Reduce load | |
| | | | | Rest | Stop mid-session |
| | | | | Additional stretching | |
| | | External management | Friends | | |
| | | | Google | | |
| **5** | **Persisting niggle** | | | | |
| | Physical description | Frequency/Onset | Persistent | | |
| | | Sensation | Pain | Severity of pain | |

| | | | | | |
|---|---|---|---|---|---|
| | Outcome | Effect on performance | Altered training | Reduce load | |
| | | | | Rest days | |
| | Psychological description | Anxiety | | | |
| | | Annoyed | | | |
| | Management | Self-management | Altered training | Reduce load | |
| | | | | Stop running | Short-term rest |
| | | | Therapies | | |
| | | External management | Friends | | |
| | | | Athletic Therapist/Physiotherapist | | |
| | | | Internet sources | Google | |
| **6** | **Non-responding niggle** | | | | |
| | Physical description | Sensation | Pain | Pain stops running | |
| | | Frequency/Onset | Constant | | |
| | | | Pain while running | | |
| | Outcome | Effect on running | Altered training | Reduce load | |
| | | | | Altered technique | |
| | | | Continue to train | | |
| | | | Stop running | | |
| | | Effect on daily life | Effects daily life | Pain during day | |
| | | | | Conscious off-loading | |
| | Psychological description | Anxiety | | | |
| | Management | Self-management | Altered training | Stop running | Rest |
| | | | | Additional stretching | |
| | | | | Reduce load | |
| | | | Medication | | |

| | | | | | |
|---|---|---|---|---|---|
| | | External management | Athletic Therapist/Physiotherapist | | |
| | | | Friends | | |
| | | | Failed self-management | | |
| **7** | **Short-term injury** | | | | |
| | Physical description | Frequency/Onset | Progressively worsening | | |
| | | | Acute onset | 'Snap' | |
| | | | | 'Pulled muscle' | |
| | | Sensation | Pain | Type of pain | Severe discomfort |
| | Outcome | Effect on running | Stop running | | |
| | | | Continue to run (with pain) | | |
| | | Effect on daily life | Effects daily life | Pain during day | |
| | | | | Conscious off-loading | |
| | Psychological description | Anxiety | | | |
| | Management | External management | Athletic Therapist/Physiotherapist | Stop running | |
| | | Self-management | Rest | | |
| **8** | **Long-term injury** | | | | |
| | Physical description | Sensation | Pain | Extreme discomfort | |
| | | | | Severe pain | |
| | Outcome | Effect on running | Stop running | Unable to run – long term (months) | |
| | | Effect on daily life | Effects daily life | Pain during day | |
| | | | | Conscious off-loading | |
| | Psychological description | Anxiety | | | |
| | | Frustration | | | |
| | Management | External management | Medical speciality | | |
| | | | Athletic Therapist/Physiotherapist | | |
| | | Self-management | Stop running | | |

| 9 | **Career-ending injury** | | | | |
|---|---|---|---|---|---|
| | Physical description | Frequency/Onset | Constant | | |
| | | | Pain outside running | | |
| | | Sensation | Pain | Severity of pain | Very high |
| | Outcome | Effect on running | Unable to run – permanently | | |
| | | | Career-ending injury | | |
| | | Effect on daily life | Effects daily life | Pain during day | |
| | | | | Conscious off-loading | |
| | Psychological description | Frustration | | | |
| | | Depression | | | |
| | Management | External management | Requires surgery | | |

Note: DOMS: delayed onset muscle soreness

#### 5.4.2.1. Running smooth

'Running smooth' was described as *"zero pain"* (M4), *"smooth"* (M3) and *"completely perfect"* (M9). Runners did not describe a negative physical complaint, a negative outcome, or a negative psychological reaction with this level.

In relation to managing this level, some participants suggested they would complete injury prevention exercises because they *"don't want injury to happen"* (F11), so they *"try to prevent it by doing* [their] *stretching"* (F11). However, some runners also suggested that no management strategies would be taken at this level, suggesting that they would be *"complacent"* (F10) when injury free, and they would *"wait for something to happen and then treat it"*(F10), being *"reactive rather than proactive"* (F10) to injury management.

#### 5.4.2.2. Discomfort

'Discomfort' was described with terms and phrases such as *"tightness"* (F17), *"tiredness"* (M3), *"a little bit of pain"* (F6), and *"stiffness"* (F3). Many participants also suggested that this level could be associated with previous training (i.e., delayed onset muscle soreness [DOMS]) and *"being tired from running the previous day"* (M3). They described it as something *"temporary"* (M8) and that they *"know that* [it] *will go away"* (F16);

*"I think discomfort is fairly mild, no injury. Discomfort is something that is there. It isn't going to stop you… You could have discomfort on one run and go out two days later and it is gone"* (F11)

Some participants described this level of injury as a *"satisfying pain"* (F6) and perceived that if they experience discomfort, it means they have worked hard and completed a 'good session', but they are also confident that it will not persist into a more serious injury; *"There is a good tightness. Like your quads after a speed session"* (F18). However, some runners described this level as a *"precursor to injury"* (M1) and suggested that further injury can develop from this level because "*you have planted the little injury seed… the injury is on its way"* (M4). With regard to the outcome, this level was not suggested to cause a negative effect on running, with participants suggesting that *"you'd definitely run"* (F6) and complete full training at this level; *"you don't back off your mileage because you are tight"* (F15). Additionally, this level did not have a negative effect on a runner's daily life, however, some runners associated it with 'mental fatigue' and described how they *"don't feel mentally strong"* at this level (M3).

The majority of runners take no management strategies because "*you know you will recover in half a day, in two days, three days"*(M8) and continuing training is the best management strategy; *"for the stiffness one, the treatment of that one probably would be to go for a run… to loosen it out"* (F3). Some participants however described using self-management strategies such as stretching; *"it will remind me to do the stretching that I know I should be doing anyway"* (M1). Additionally, some runners may look to external sources such as YouTube for appropriate stretches/exercises; *"I find myself YouTubing quite a lot. If I have a pain in my calf, I just do a five minute exercise that I find on YouTube and it will be gone that day"* (M7), or casually chat to their running friends about the complaint: *"but only by the by, if it came up in conversation I might mention it"* (F10).

#### 5.4.2.3. Niggle

'Niggle' was a term used by all participants in all focus groups with different descriptions presented. In its mildest form, some runners physically described a 'niggle' as being more *"aware"* (M13) or "*conscious"* (F8) of a certain body part, describing it as *"not* [being] *the same as the other side* [of the body]*"* (M1), or suggested it is *"background noise"* (F10). Other runners described a 'niggle' as something slightly more severe, with phrases such as *"background pain"* (F15), and *"a pain that shouldn't be there"* (M4). The majority of participants described a 'niggle' as something *"repeated"* (F8), *"persistent"* (F3) and *"something that lingers"* (F11): "*discomfort can come and go*, *whereas a niggle is sort of always there*" (F10). In relation to the outcome, the majority of participants continue full training with a 'niggle', with the perception that runners are *"quite high functioning with a niggle"* (F17). Many runners described a 'niggle' as *"not bad enough"* (F7) to stop training, and suggested that they can *"cope with a niggle"* (F11), *"ignore it a lot of the time"* (F13), or they can *"run through it"* (F18). Some also described how they feel pressure to continue training with a 'niggle', whether it is due to running with a group: *"if I am with a group I am like 'oh I need to keep going'*, *but I'd probably be making it worse"* (F11), or whether it's a personal desire to continue:

*"you are chasing the high*, *chasing the endorphins*. *When you just get that niggle… you really just keep pushing yourself… And then because it is not an external thing*, *you can't see it*, *you can just kind of ignore it"* (F13)

However, this level of injury can begin to affect running for some runners, causing them to *"start reducing* [their] *mileage because the niggle has hit"* (F17), or to complete a more vigorous warm up because they feel *"I should warm up properly if I have a niggle"* (F17). There was no effect to a runner's daily life, but as a psychological description, some suggested they are *"cautious"* (F5) of a 'niggle' and that it can affect their motivation to train; *"it makes the run harder to complete mentally*, *rather than it stops you running"* (F6).

Some runners don't practice any management strategies because they suggested that 'niggles' can resolve on their own, they *"get away with a lot of niggles"* (M4) or they can *"ignore it"* (M11). However, some runners use self-management strategies and alter their training, describing how *"niggles encourage me to stretch"* (F15). Some may also *"take a day or two off"* (F15) or reduce their training load, *"not run as far"* (F2), or *"slow down"* (F5). Some may also use additional therapeutic modalities such as foam rolling; *"You know that roller that is over in the corner of the front room that you occasionally use, that is when you use it"* (M3). Some participants described that they would also turn towards external management strategies, such as online resources or asking their running friends for advice or support; *"it might come from an external source… somebody says, 'maybe you should have that looked at'… if you complained about it enough to somebody else, rather than deciding yourself"* (F9).

As well as describing a 'niggle' in terms of its physical and psychological descriptions, its outcome, and management, many participants reported that 'niggles' are *"inevitably a fact of running"* (F6), that *"runners constantly have niggles"* (F16) and they live in *"Niggle City"* (F17). Many participants did not perceive a 'niggle' to be an 'injury', but described that it can contribute to the development of an 'injury'; F16—*"it could turn into an injury, but I wouldn't consider it an injury"*. Many participants reported that they perceive 'niggles' to be an *"early warning sign"* (M11), a *"potential injury"* (M13), or the *"root to an injury"* (F17).

#### 5.4.2.4. Twinge

A 'twinge' was described as a *"darting pain"* (M7) or an *"intense, quick, sharp pain"* (F6), that is intense enough to cause a runner to *"stop and walk"* (F3) mid-session, or to stop their session completely; *"I might stop if I had a darting pain"* (F4). However, a twinge was described as something temporary, short-lived, and typically a once-off; *"by the time it happens, it is gone"* (F3). Runners described that it would not be felt during the next session, and they would *"forget about it"* (M7). There was no description of an effect on a runner's daily life, but participants associated a 'twinge' with *"caution"* (F7).

In relation to management, all runners use some sort of self-management strategy by this level; *"if I had a darting pain I would do something. I wouldn't just keep on running with that one"* (F4). Some runners described that *"stretching would come in here"* (M11), they would *"stop and walk"* (F3), or do *"slower runs"* (F7) at the onset of a 'twinge'. Some participants also suggested they would continue to consult friends, asking *"what do you think? What would you do?"* (M9), and online resources *"you would definitely Google it"* (M9).

#### 5.4.2.5. Persisting niggle

A 'persisting niggle' was described as a progression of a 'niggle', however, it differs because it was described as more severe and more persistent. Progressing from milder terms (such as tightness or tiredness) used to describe a 'niggle', a 'persisting niggle' was associated with a description of pain, with *"low-medium"* (F2) pain and *"mild pain"* (F12) being suggested. It was also described as *"persistent"* (M5) and as occurring on *"consistent occasions, consistent runs"* (F4).

*"Having the same niggle a few runs in a row, where you know it is not a niggle anymore. If it happens again the next week, and the next week, it doesn't become a niggle anymore, it becomes a problem where you know it is not going to go away"* (M7)

In relation to the outcome, some runners will continue to train fully at this level because *"it is tolerable to keep running"* (F6) and they want to "*take a chance"*(M7) and hope that it will not progress to a further level. However, the majority of runners will change their training at this level by "*decreasing* [their] *load"* and *"hopefully* [going] *back to no injury"* (F9). Some runners may also take additional rest days; *"I might stop and take a little bit of a rest, but be back at it. The pain wouldn't need to go. It would just need to be a bit better and then I would go again"* (F4). There was still no description of this level affecting a runner's daily life, however, in relation to the psychological description, this level inspired the first mention of associated concern and *"anxiety"* (F7).

With regard to management, self-management strategies progress from previous levels with further alterations to training being made. Some runners will *"decrease* [their] *load"* (F9) because they *"can't go full tilt"* (F2), while others will *"take a break for a few days"* (F3). As external strategies, there is a continuation of consulting friends and getting *"peer advice"* (F6), as well as using the internet: *"using Google because it's the go-to"* (M9). This level is associated with the first mention of obtaining medical professional attention from a Physiotherapist/ Athletic Therapist. Some participants described that they would be *"looking for physio support"* (F2) because they *"probably should go and get it looked at"* (F2).

#### 5.4.2.6. Non-responding niggle

A 'non-responding niggle' was described as the point at which all attempts to manage complaints thus far have failed, and runners are at a *"crossroads"* (M4) because their 'injury' is *"not responding"* (M4). Participants described how it is more evident that they need to make a decision at this level of whether they continue running (with altered training), stop running (for an unknown period of time), or seek external medical attention.

Physically, this level was described as causing *"more intense"* (F15) pain that is *"getting worse"* (F16) and is increasingly persistent to the point of being *"constant"* (F16). It was described as pain that *"doesn't stop"* (F4) despite management attempts being made. In relation to the outcome, some runners will continue training, although with a reduced training load, because they are "*not prepared to leave"* (M3). Furthermore, some runners normalised running with this level of injury and suggested that *"everybody runs with an injury… I have never met anybody who didn't run with an injury"* (M9). However, others suggested that they *"shouldn't be running"* (F3) at this level, and that they will stop training in the short-term: *“middle of the road to me is where we are going to rest for a week”* (M9). This level was the first mention of a negative effect on a runner’s daily life, with description of *“pain filter*[ing] *through the rest of your day”* (F9) and pain being present *“as you’re walking around”* (F18). Participants suggested that they will begin to make conscious decisions and efforts to protect this level of injury; “*I might choose to bring the dog to a field and throw a stick and let him run*, *rather than me having to walk the 4km with him”* (F15). With regard to a psychological description, runners would become increasingly anxious at this level, thinking *“do I need to worry here*?*”* (F16).

In relation to management, some runners continue with self-management strategies by choosing to take a short-term break from training; *“I would rest myself. Ease up for a week and see how it felt”* (M9), while others will seek external advice because these are *“the injuries where we run out of ideas of how to treat it* [ourselves]*”* (M3) and they are at *“the point where you go to a physio”* (F15). Some participants also described how they would still consult their running friends or *“someone who has a lot of running knowledge”* (M7) for advice or support.

#### 5.4.2.7. Short-term injury

A ‘short-term injury’, was described as causing *“severe discomfort”* (M6), *“dull pain”* (F12), and *“really sharp pain”* (M10). It was described as causing runners *“constant pain”* (F12) if they continue to run, and getting progressively worse; *“I’ll keep going and make it worse until I have to stop”* (M13). Additionally, some runners perceived that this level would cause a physical sign or a *“visible effect”* (F6) of an injury, such as limping or swelling. In relation to the outcome, this level will cause a *“short-term stoppage”* (F6) to running (i.e., days/weeks) for the majority of runners, and was referred to as a *“stopping injury”* (M13) where they cannot continue to train. It will also continue to affect a runners' daily life, with *"pain outside of running, pain in work"* (F12) and having an effect on decisions such as *"taking the car instead of walking somewhere"* (F7). Runners are also becoming increasingly anxious at this level and describe that an injury which *"stops you running… really messes with your head"* (M7).

As well as being described as a progression along the Running Injury Continuum, some participants described this level of injury as one which has an acute onset (e.g., muscle strain or joint sprain), causing a short-term stoppage to running (i.e., for a number of weeks); *"a sudden injury where you just have to come to a standstill"* (F5). At this level, external management strategies take over as the primary method of management, with participants describing that they *"need some sort of intervention"* (M6). Participants suggested that Physiotherapists/Athletic Therapists are their primary sources of medical intervention, and they feel they "*have to go to physio now because it is not going away"* (M11). Few runners will continue to self-manage by taking a short-term rest (i.e., weeks) from training, and described this level as the *"point you need to realise you have to rest, cut back"* (F12).

#### 5.4.2.8. Long-term injury

With 'long-term injury', there was less emphasis placed on the physical description, although some runners still described *"extreme discomfort"* (M6) and *"very high pain"* (M6), with a greater focus on the outcome. At this level, all runners have stopped running in the long-term (i.e., months or longer) because they are unable to run and describe being *"out of action for a few months"* (M3). Similar to the previous level, runners' daily lives are affected and conscious decisions are made to offload the injured area. As a psychological description, runners are increasingly anxious and becoming frustrated; *"the injury is about the frustration of not being able to do what you want to do"* (M9).

By this level, all participants are using external management strategies, with runners turning towards interventions from medical specialists or *"the correct doctor"* (M6). Some will continue to consult an Physiotherapist/ Athletic Therapist to dictate the most appropriate course of action, however, runners described that this level requires specialist intervention;

"*When I have gone to the physio four times, five times, and the physio says 'look, what I have done should have helped it, it is not helping it, so there is obviously something else wrong here, so my advice is you need to get referred to a consultant*'" (M11).

#### 5.4.2.9. Career-ending injury

While no participant reported experiencing a 'career-ending injury', this was perceived as the most severe injury a runner could sustain, and a suitable end-point for the Running Injury Continuum. With this level, there is less attention on the physical description, although severe pain and *"the worst possible pain you could imagine"* (F6) was suggested, and more significance to the outcome. This is a level which "*stops you running*, *forever"* (F3), is a "*permanent"* (M10) injury and a *"show stopper"* (M3). Some suggested that this level would significantly affect their daily life where *"you can't do ordinary stuff*, *even in your household duties"* (M5), with associated feelings of frustration and depression regarding their injury.

Some runners described using external management strategies as final attempts to manage this level of injury, with *"need*[ing] *surgery"* (F4) being suggested as a potential strategy. However, as the worst possible injury suggested by runners, it was described that they would never run again.

### 5.4.3. Individual perception

It is important to note that many participants suggested that runners' description of injury and their management of the process of injury development is *"not the same for everyone"* (M8) and *"there are a whole host of external factors that inform your perception of it"* (F10). Such factors include their running habits and history, individual factors, and injury-related factors (Table 15).

Table 15. 'Order of themes' document: Factors that influence runners' description and management of the injury development process

| **Core categories** | **Themes** | **Sub-themes** |
|---|---|---|
| Running habits & history | Running experience | |
| | Motivations | Competitiveness |
| | | Chasing high |
| | | Goals |
| | | Stick to a plan |
| | Other sport participation | |
| | Run setting | Group setting |
| | | Race |
| | | Individual |
| | | Training session |
| | Event coming up | |
| | Knowledge | |
| Individual | Individual perception | |
| | Daily life | Children |
| | | Mood |
| | | Menstrual cycle |
| | | Fatigue |
| | Age | |
| | Sex | |
| Injury | Previous injury | |
| | Type of injury | |

With regard to running habits and history, some participants suggested that description and management of injury is *"based on your experience"* (M9) and *"the length of time people are running, or the experience* [they] *have with injury"* (F17). Participants suggested that more experienced runners will have a better understanding of the levels of injury, and manage these levels more appropriately: *"newbie runners… they don't know what a niggle is"* (M2). Additionally, participants described how a runner's *"motivational factors"* (F9) influence their management of the process of injury development: *"it boils down to what your objectives are"* (M10). Runners suggested that those who are more competitive or those training for a specific goal will continue training with a *lower level injury*, rather than reducing their load because *"sometimes the benefits just outweigh the risks"* (F12).

In relation to individual factors, participants suggested that description and management of injury *"depends on the person"* (F15), and can vary from runner to runner: *"some of your definitions of niggles would not be mine"* (M1). Some participants also discussed how a runner's daily life can influence their description and management of injury, with factors such as *"state of mind"* (F3) on a particular day or their menstrual cycle making someone feel *"sluggish"* (F6) influencing their description and management of injury. Additionally, some female participants suggested that having children to care for will influence their management of injury because they "*can't afford to be laid up in a bed"* (F2):

> *"the person who doesn't have children, or can have all that time to rest before and after the run, they might be more likely to do the run* [while having a lower level injury]... *If you had to come home and you go, 'right, if I go for a run this morning I will not be able to do the nursery football with the children after school because I will be in pain'"* (F9)

Finally, participants also suggested that injury-related factors, such as previous injuries and *"how impacted you have been by injury in the past"* (F11) will influence how a runner describes and manages all levels of injury. Participants described that they would *"intervene earlier if it is something* [they] *have had before… and go quicker through the* [management] *steps"* (F8), compared to an injury they have never had.

## 5.5. Discussion

This study provides a qualitative insight into how recreational runners describe injury and manage the process of injury development. By capturing the lived experiences of runners, the authors present a comprehensive representation of RRIs, highlighting their progressive, overuse nature. The current study used an IPA to explore this topic, and the authors cannot overstate the richness and depth of data that was captured, primarily facilitated by the social interaction between participants during focus groups.

### 5.5.1. The Running Injury Continuum

The Running Injury Continuum (Figure 33) reflects runners' descriptions of RRIs from injury-free to career-ending injury, and is made up of eight levels of injury, each increasing in injury severity. The eight levels are categorised into *lower* and *higher level injuries*. *Lower level injuries* span between 'discomfort' to 'non-responding niggle', while *higher level injuries*, which are most associated with the RRI consensus definition (Yamato, Saragiotto and Lopes, 2015), span between 'short-term injury' to 'career-ending injury'. The consensus definition defines a RRI as: "running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration, or training) for at least seven days or three consecutive scheduled sessions, or that requires the runner to consult a physician or other healthcare professional" (Yamato, Saragiotto and Lopes, 2015, p. 377). *Higher level injuries* overlap with this definition by virtue of the commonalities between our participants' description and the criteria used in the consensus definition. Firstly, a description of pain is associated with *higher level injuries* and is required to define injury within the consensus definition (Yamato, Saragiotto and Lopes, 2015). Although pain is mentioned in earlier levels of the Running Injury Continuum, it is described in milder forms and becomes significantly more prominent at these *higher level injuries*. Secondly, within *higher level injuries*, runners will stop running, at least in the short-term (e.g., a week), a criterion and time-frame strongly associated with the consensus definition (Yamato, Saragiotto and Lopes, 2015). While earlier *lower levels of injury* were described as causing restrictions to running (such as reducing load), they were not associated with this length of a time-frame, distinguishing them from the consensus definition. Finally, *higher level injuries* result in runners requiring medical attention, an evident criterion in the consensus definition (Yamato, Saragiotto and Lopes, 2015). It can be argued that descriptions of the 'non-responding niggle' (medium pain causing alterations to training, short-term rest, or healthcare professional (HCP) intervention) are consistent with elements of the consensus definition; however, this level is not included as a *higher level injury* for two reasons. Firstly, the opinions of participants varied across the categories of descriptors (e.g., some described continued running, whereas others described a stoppage to running), with more agreement being evident within *higher level injuries*. Secondly, there was a strong description of this level being a 'crossroads', more so as a transition level from *lower* to *higher level injuries*. Runners described each level of injury using four categories of descriptors: physical description, outcome (the effect on running and on daily life), psychological description, and management (self-management, and external management strategies). This is a bi-directional continuum, on which runners can progress or regress, either increasing or decreasing in injury severity depending on their management of each level. During injury development (or recovery), runners do not have to progress through the immediate succeeding (or preceding) level of injury (e.g., runners can progress from a 'niggle' straight to a 'non-responding niggle').

Both end-levels of the continuum (i.e., 'running smooth' and 'career-ending injury') were clearly described by participants, with a high level of agreement achieved amongst all participants. However, there was variance in opinion regarding the seven levels in-between, with some overlapping descriptions across adjacent levels. This is captured in the term 'continuum' which is "a continuous sequence in which adjacent elements are not always perceptibly different from each other, but the extremes are quite distinct" (Oxford University Press, 2023). It also reflects runners' perception of the progressive and regressive nature of RRIs. While the categories of descriptors used to differentiate levels of injury were sometimes not unique (e.g., caution was used to psychologically describe both 'niggle' and 'twinge'), it was possible to differentiate between levels of injury by comparing across *all* categories of the descriptors used (e.g., 'niggle' was described as a repeated low pain, whereas 'twinge' was described as a temporary darting pain). The term 'niggle' was the most commonly used term to suggest a *lower level injury*, used by every participant in every focus group. From our findings, a 'niggle' can be defined as: *'a repeated physical sensation (discomfort or low pain) with which a runner can continue to run'*. However, the level 'discomfort' is the first level of a complaint along the Running Injury Continuum and initiates the progression of *lower level injuries*. From this complaint of temporary discomfort or tightness, the Running Injury Continuum advances into three distinct levels of progressive and worsening 'niggles': the 'niggle', the 'persisting niggle', and the 'non-responding niggle'. These three entities describe levels of injury which become increasingly more severe in terms of their physical description, their outcome (effect on running and daily life), their psychological description, and the management strategies required. However, amongst these three levels of niggle, there is a further *lower* *level injury* that does not follow this progressive nature; the 'twinge'. A 'twinge' can be defined as: *'an acute onset of pain resulting in an immediate outcome (either a reduction in training load within a session*, *or the stoppage of a training session)*, *but which does not persist to the next session'*.

The Running Injury Continuum supports previously published representations of overuse injuries. A comparison can be made between our participants' description of escalating levels of injury severity and the Well-Being Continuum (Soligard *et al.*, 2016), which describes the escalating levels of biological and physiological tissue damage associated with overuse injury development. Our findings also support the Injury Pathway which represents runners' own views on the process of RRI development (Verhagen, Warsen and Silveira Bolling, 2021). While other papers have implicitly referred to an 'early phase of injury' during the injury development process, using phraseology such as "early phase" (Clarsen, Myklebust and Bahr, 2013) and "injury category" (Wickström *et al.*, 2019), to the best of our knowledge, only one study has explicitly identified and named a *lower level injury* during this process: the 'complaint' stage of the Injury Pathway (Verhagen, Warsen and Silveira Bolling, 2021). However, our study explores this to a greater extent and appears to be the first to explicitly provide sub-categories within this phase. Additionally, rather than concluding the process of injury development at a single point termed "injury" (as with the Injury Pathway (Verhagen, Warsen and Silveira Bolling, 2021)), we have identified further sub-categories within this later phase (i.e., *higher level injuries*) which map with the consensus definition (Yamato, Saragiotto and Lopes, 2015). Furthermore, we provide a rich and in-depth account of runners' description and management of the process of injury development, in both the early and late phases.

The OSTRC Overuse Injury Questionnaire (OSTRC-O) is a widely cited tool for surveilling overuse injuries in sport research (Clarsen *et al.*, 2020). It acknowledges *lower level injuries* in that it recognises the importance of non-time loss injuries, and does so through monitoring both the characteristics of pain (physical descriptor) and effect on running (outcome) (Clarsen, Myklebust and Bahr, 2013). However, our findings build upon the OSTRC-O, indicating the importance of capturing additional categories of descriptors, including the psychological response to injury and the management strategies used, both of which can impact injury development (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022; Tranaeus, Martin and Ivarsson, 2022). Additionally, a limitation to the OSTRC-O is that it does not capture injuries from a 'traditional' definition point (such as that defined by the consensus definition (Yamato, Saragiotto and Lopes, 2015), injuries which are clearly described and experienced by runners. It has been suggested that the development of a single tool capable of monitoring the continuous development process of overuse injuries (as done by the OSTRC-O) as well as registering injuries from a more 'traditional' point (i.e., time-loss) is warranted and could greatly assist injury surveillance research (Kluitenberg *et al.*, 2016). We suggest that the Running Injury Continuum may provide a basis for such a tool. Additionally, in studies investigating risk factors for injury, it may be beneficial for researchers to determine the specific level of injury (e.g. niggle) experienced by athletes, as these *lower level injuries* have the potential to not only interact with other possible risk factors for injury (increasing injury risk), but also to potentially act as risk factors for injury themselves. By using regular surveillance and capturing this level of detail, researchers could be provided with significant insight into: the risk factors for RRIs, the development process of RRIs, and understanding how the consequences of injury change during this process.

Our findings highlight the importance of the psychological response to injury experienced by runners. It is well accepted that athletes may experience psychological distress in response to injury (Smith, 1996; Wiese-Bjornstal *et al.*, 1998); however, due to the insidious nature and longevity associated with RRIs, runners often experience significant and prolonged psychological distress during the injury development process

(Flint, 1998; Russell and Wiese-Bjornstal, 2015). Specifically, our findings suggest that runners experience a progressive psychological response to injury that increases in severity as the Running Injury Continuum progresses. Our findings support previous research which highlights runners' experiences of psychosocial distress in response to overuse injuries (van Wilgen and Verhagen, 2012; Russell and Wiese-Bjornstal, 2015; Peterson *et al.*, 2022), with reports of frustration, fear, general psychosocial distress, and social influences experienced by runners during the injury process (Russell and Wiese-Bjornstal, 2015). However, in contrast to previous research which identified that these responses occur from injury onset (defined as the point where runners perceive themselves to be injured, or pain is affecting their running) (van Wilgen and Verhagen, 2012), our findings indicate a psychological response that occurs from an earlier phase during the injury development process. We identified the first description of a negative psychological response to injury at the level of a 'discomfort', where runners describe 'mental fatigue'. This level identifies the start of a pathway of worry, concern and anxiety experienced by runners during the injury development process. The capture of runners' description of anxiety during these *lower level injuries* is a novel finding as, to the best of the authors' knowledge, previous research has not reported such an extreme psychological response at such an early phase of injury development. It is crucial that clinicians, coaches, runners and other personnel involved with runners' well-being are aware of this finding and understand the level of psychological distress experienced by runners, especially during the early phases of injury development.

### 5.5.2. Management

Our results support previous research which identified runners' desire for autonomy in the dealing with *lower level injuries* by predominantly using self-management strategies, and concur with the finding that once runners lose this autonomy and require external professional assistance, they perceive themselves as 'injured' (Verhagen, Warsen and Silveira Bolling, 2021). Typical self-management strategies involve reductions in training load and using therapies such as ice, stretching or general rehabilitation exercises to prevent or slow the progression of their *lower level injury*, while maintaining some level of training. Our findings also agree with previous research which reports runners' reliance on non-evidence based sources of information (such as web-based or peer advice and previous personal experience) to inform self-management of their *lower level injuries* (Russell and Wiese-Bjornstal, 2015; Besomi *et al.*, 2018; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022), as well as their reluctance to attend HCPs, despite experiencing physical and psychosocial distress (Russell and Wiese-Bjornstal, 2015). Participants suggested several reasons for not attending a HCP. Firstly, *lower level injuries* are not severe enough to warrant HCP input. Secondly, some runners described wishful thinking regarding their *lower level injury*, hoping that it will resolve on its own without the need for HCP intervention. Wishful thinking is a bias pervading the management of persistent musculoskeletal pain, where decisions and beliefs regarding an injury are based on what is pleasing to imagine, rather than based on evidence, rationality or reality (Gojanovic, Fourchet and Gremeaux, 2022). Finally, runners suggested that their previous experience with injury removes the need to attend a HCP. This finding is similar to previous research in which runners have reported that those with more running experience are better able to self-manage RRIs (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022). It has also been suggested that novice runners are more at risk for RRIs (Linton and Valentin, 2018), while coaching or education (i.e., increasing runners' understanding of the injury development process) is theorised to enhance injury prevention (Hespanhol, van Mechelen and Verhagen, 2018).

The decision to seek HCP advice most often came at the level of 'short-term injury', and from this point on, as the injury becomes more severe or impactful, HCP advice becomes more specialised. Runners described several reasons for seeking HCP advice. Firstly, when their attempts to self-manage injury had failed, or their injury had become too severe where they can no longer self-manage, similar to previous running-based research (Peterson *et al.*, 2022). Secondly, they would attend a HCP because they are seeking validation of their injury, typically in one of two ways. Runners are either seeking confirmation that they are actually injured and the injury is not in their head (as often, there are no physical signs of injury and they may be able to continue training); or they are looking for reassurance that their injury is not as serious as they may be concerned about, and they are seeking guidance on continuing their training.

### 5.5.3. Implications

Our findings have several implications for HCPs, coaches and researchers.

#### 5.5.3.1. Education

Support for the relationship between education and injury prevention has been described in terms of the translation of knowledge to enhance the adoption of injury prevention interventions (Goddard *et al.*, 2021), and enhancing the recovery process to prevent injuries (Palmi *et al.*, 2021). Research specifically examining this relationship involving runners seems to be limited; however, an online injury prevention intervention consisting of educational videos informing participants about the aetiology and mechanisms of injury, combined with evidence-based injury prevention advice was shown to have a positive effect on knowledge, attitude, intention, and behaviour (Adriaensens *et al.*, 2014). Additionally, runners' perception of injury risk and their attitudes towards the importance of executing injury prevention measures were positively affected by the intervention, which included these educational messages (Adriaensens *et al.*, 2014).

Furthermore, another study examining the effectiveness of an online injury prevention intervention found no significant effect of their intervention on actual preventative behaviour (Hespanhol, van Mechelen and Verhagen, 2018). One suggestion for this was a difference in the content of the injury prevention interventions, such as the educational videos which were included in Adriaensens and colleagues' (Adriaensens *et al.*, 2014) study (Hespanhol, van Mechelen and Verhagen, 2018). These findings highlight, that with enhanced knowledge and education regarding injury risk and management, runners are more likely to adopt injury prevention practices.

From our findings, it is clear that the education of runners regarding evidence-based information on managing and preventing RRIs is required. Firstly, HCPs should be aware that runners typically do not attend an HCP with a *lower level injury* because they believe they can be primarily self-managed. While this is a positive finding in the sense that runners feel empowered to self-manage their own *lower level injuries*, it is also clear that HCPs need to educate their patients on appropriate self-management strategies, by directing them towards trustworthy sources of information, ensuring runners are using evidence-based recommendations to prevent and rehabilitate injury. Similarly, coaches, running clubs, and governing bodies need to educate runners, encouraging them to use evidence-based practices in the management of their injuries (e.g., Athletic Therapists/ Physiotherapists, evidence-based sources of information). Secondly, there is a need for enhanced dissemination of evidence-based information to runners. Researchers need to ensure their findings are freely accessible to runners, disseminating findings in user-friendly formats (e.g., infographics, podcasts, blog posts) using plain language, ensuring runners understand key information.

#### 5.5.3.2. Appropriate monitoring of running-related injuries

Our findings highlight the importance of a wider scope of monitoring RRIs, not just across all levels of injury, but across all categories of descriptors. Firstly, HCPs should consider the potential importance of *lower level injuries* acting as risk factors for *higher level injuries* (as discussed above), and appreciate that a runner presenting with a *higher level injury* may have had a preceding *lower level injury*, in order to better manage the whole continuum of injury. Secondly, when designing injury management strategies, HCPs should understand that runners will likely have made attempts to self-manage their injury prior to presenting to them, and these attempts should be taken into consideration. Finally, with the emphasis placed by participants in the current study on the psychological description of each level of injury, it is crucial that HCP's include biopsychosocial assessments when dealing with recreational runners, ensuring this psychological response is captured, monitored and incorporated into management strategies. HCPs should also educate their patients regarding the psychological aspect of the process of injury development, and ensure patients understand that it is normal to experience these responses (i.e. to experience anxiety or concern, especially with a *lower level injury*) (Russell and Wiese-Bjornstal, 2015). Similarly, in helping athletes manage injuries, coaches need to be aware of the importance of not only monitoring all levels of injury and supporting athletes with appropriate management strategies, but also on monitoring athletes across all categories of descriptors.

Future research should also broaden its scope of investigating RRIs (and overuse injuries) to ensure that all categories of descriptors are captured in order to better understand the wider impact of an injury. In particular, this will allow examination of whether *lower level injuries* are risk factors for injury, and/or how they interact with other potential risk factors.

## 5.6. Strengths and limitations

A representative sample was included in the current study, gathering the perceptions of runners of various ages and running backgrounds. We included a larger sample size of runners compared to previous research (Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022), to ensure the broad scope of the study was explored in detail, and to enhance the reliability of our findings. Richness and depth of data was facilitated through focus groups guided by IP (Bradbury-Jones, Sambrook and Irvine, 2009). Furthermore, as IP considers participants' lived experiences as well as how they reflect on these experiences, it enhanced our interpretation of their lived experiences of the injury development process, in the forum of the Running Injury Continuum (Braun and Clarke, 2013). Additionally, we encouraged reflexivity throughout the data collection and analysis phases, challenging multiple interpretations of the data. Furthermore, several methods of trustworthiness were executed to ensure appropriate interpretation of findings and enhance the credibility of results.

The study's findings should also be considered in light of some limitations. Our sample consisted of only Irish runners, therefore these findings may not be representative of the global population of runners. In particular, specific terminology used (e.g. niggle) or methods of management employed (e.g., access to clinicians) may not be consistent across other nationalities or socio-demographics. Furthermore, as we only recruited recreational runners, findings may differ with elite or novice runners. As the aim of this study was to explore the lived experience of runners, it was necessary for participants to have previous experience with *lower level injuries*; however, it is possible that different findings would be reported from runners with less/no experience of *lower level injuries*. Given the adopted terminology of 'niggle', 'persisting niggle' and 'non-responding niggle', a 'twinge' can be viewed as a distinct level from these because of its associated sharp pain, its immediate effect on running, and its presence for only one session. The location of ‘twinge’ between ‘niggle’ and ‘persisting niggle’ or ‘persisting niggle’ and ‘non-responding niggle’ was not consistent across all focus groups; however, its placement on the Running Injury Continuum was arrived at because all participants described it as something more severe than a ‘niggle’, while the majority described it as less severe than a ‘persisting niggle’.

### 5.7. Conclusion

Through capturing the lived experiences of recreational runners, we present the Running Injury Continuum as a representation of the development process of RRIs. Expanding on previous research (Jelvegård *et al.*, 2016; Johansen *et al.*, 2017; Wickström *et al.*, 2019; Verhagen, Warsen and Silveira Bolling, 2021; Peterson *et al.*, 2022), eight distinct levels of injury were identified in the current study, with each level being described across four categories of descriptors: physical description, outcome, psychological description, and management. For research purposes, the Running Injury Continuum is a tool that can be used in both injury surveillance research and research investigating risk factors for RRIs.

Our findings clearly highlight the importance of education and accessibility of evidence-based information. HCPs need to educate their patients on appropriate self-management strategies for RRIs, while researchers should ensure recreational runners have access to evidence-based information, and can utilize this information in their running practices. HCPs, coaches and researchers should broaden their scope of monitoring RRIs to ensure that all levels of injury and categories of descriptors are captured, in order to better understand the wider impact of RRIs, to more appropriately manage RRIs, and potentially enhance injury prevention.

*Link section: Chapter 5 to 6*

From Chapter 5, it was found that runners describe the progression of injury on a bidirectional continuum, consisting of eight levels of injury. They describe each of these levels across four key categories of descriptors: the physical description, the outcome, the psychological description, and the management strategies employed. These findings highlight that 'injury' is an extensive construct, consisting of multiple levels of injury severity and associated with multiple consequences. This far exceeds how they have been investigated and reported in research to date, from the findings of Chapters 3 and 4. Findings from Chapter 5 suggest that the entirety of the Running Injury Continuum should be recognised, captured, and investigated in research, along with the breadth of consequences of injury experienced. This may provide clarity on the rates of RRIs, and improve the investigation of potential risk factors, bridging the gap between current research and the development of injury prevention programmes for runners.

Wearable technologies and smartphone apps make the collection of frequent, continuous, and longitudinal data more convenient for runners, potentially addressing some of the methodological weaknesses outlined in Chapter 1. However, from a pragmatic standpoint, in order for these devices to be effective at collecting this data, we need to ensure runners will engage with them. Developing evidence and practical recommendations grounded from runners' perspectives could facilitate this engagement. Therefore, the aim of Chapter 6 is to examine the factors that affect recreational runners' adoption of injury-focused running technologies.

# 6. Chapter 6: Study 4: A qualitative examination of the factors affecting the adoption of injury focused wearable technologies in recreational runners

This paper is published in Plos One. It is presented in full with only minor formatting changes.

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## 6.1. Abstract

Understanding the perceived efficacy and ease of use of technologies will influence initial adoption and sustained utilization. The objectives of this study were to determine the metrics deemed important by runners for monitoring running-related injury (RRI) risk, and identify the facilitators and barriers to their use of injury focused wearable technologies. A qualitative focus group study was undertaken. Nine semi-structured focus groups with male (n = 13) and female (n = 14) recreational runners took place. Focus groups were audio and video recorded, and transcribed verbatim. Transcripts were reflexively thematically analysed, a critical friend approach was taken, and multiple methods of trustworthiness were executed. Excessive loading and inadequate recovery were deemed the most important risk factors to monitor for RRI risk. Other important factors included training activities, injury status and history, and running technique. The location and method of attachment of a wearable device, the design of a smartphone application, and receiving useful injury-related information will affect recreational runners' adoption of injury focused technologies. Overtraining, training-related and individual-related risk factors are essential metrics that need to be monitored for RRI risk.

RRI apps should include the metrics deemed important by runners, once there is supporting evidence-based research. The difficulty and/or ease of use of a device, and receiving useful feedback will influence the adoption of injury focused running technologies. There is a clear willingness from recreational runners to adopt injury focused wearable technologies whilst running.

**Key words**: wearable technologies, injury prevention

### 6.2. Introduction

Wearable technologies, including mobile phones and smart watches, are devices that can be worn or carried by an individual that can include measurement capabilities used to assess and monitor physical activity, movement, health and well-being (Patel *et al.*, 2012; Bunn *et al.*, 2018). Advancements in wearable technologies have made it possible for the early detection of illnesses and injuries by allowing for continued monitoring of individuals (Malasinghe, Ramzan and Dahal, 2019). The use of wearable technologies has become increasingly popular within the running community, with approximately 90% of runners using some form of technology to monitor their training (DeJong, FIsh and Hertel, 2021). Primarily, wearable devices in this market function to collect global positioning system (GPS) data and information on running technique to provide summary reports for assisting running performance (Jensen and Mueller, 2014; Moore and Willy, 2019; Giraldo-Pedroza *et al.*, 2020). This is achieved by the tracking of personal running data (Wiesner *et al.*, 2018; Clermont *et al.*, 2019), planning of running goals, and/or by increasing a runner's motivation to train (Wiesner *et al.*, 2018; Menheere *et al.*, 2020). However, despite the high incidence of running related injuries (RRIs), recently reported at 40% (Kakouris, Yener and Fong, 2021) and 46% (Desai *et al.*, 2021), and the popular use of wearable devices to manage other illnesses and injuries (Papi *et al.*, 2015; Jalloul, 2018; Celik *et al.*, 2021), there is a dearth of research investigating the perceived usefulness of injury focused wearable technologies in runners. Additionally, no effective injury prevention programmes for reducing RRIs have been identified in the literature thus far (Fokkema *et al.*, 2019). It has also been hypothesized that this is due to previous injury prevention programmes focusing on reducing the impact of a single risk factor, when the cause of RRIs is multifactorial (Fokkema *et al.*, 2019).

Understanding the underlying factors that drive adoption of wearable technologies is a crucial step in ensuring their successful uptake (Kalantari, 2017). One such factor is the perceived usefulness of a device to the user (Davis, 1989; Venkatesh, Thong and Xu, 2012). Adapting the six-stage Translating Research into Injury Prevention Practice (TRIPP) framework (Finch, 2006) to the current context, it is clear that understanding and including the factors contributing to RRI's, while understanding the perceptions and behaviours of potential users in their own sporting context is pivotal in developing a useful device. Therefore, it is crucial to identify the metrics recreational runners perceive as important for monitoring injury risk and adopting injury focused technology.

Identifying runners' perceived facilitators and barriers to the use of wearable technologies is also deemed essential for technology adoption (Janssen *et al.*, 2020); however, the majority of this research has to date focused on *performance* insights as motivators to the use of wearable technologies (Vos *et al.*, 2016; Pobiruchin *et al.*, 2017; Stragier, Vanden Abeele and De Marez, 2018; Feng and Agosto, 2019; Janssen *et al.*, 2020) rather than on injury. Only one study (Clermont *et al.*, 2019) appears to have examined the barriers and facilitators to the use of running technologies for reducing RRIs.

Previous research investigating runners' usage of wearable technologies in relation to performance and injury has predominantly used questionnaires and surveys as the methodological approach (Pobiruchin *et al.*, 2017; Stragier, Vanden Abeele and De Marez, 2018; Clermont *et al.*, 2019; Feng and Agosto, 2019; Janssen *et al.*, 2020). To further explore runners' perceptions of such topics, a qualitative study would provide more insightful and detailed understanding (Glaser and Strauss, 1967; Verhagen and Bolling, 2018). Therefore, the aim of this study was to examine the factors that affect injury focused technology adoption in recreational runners, to identify the metrics perceived as important to monitor for RRI risk, and to identify the perceived facilitators and barriers to the utilization of injury focused technologies.

## 6.3. Methods

### 6.3.1. Design

Constructivist grounded theory was deemed an appropriate methodological choice for the current study, as a theory addressing the factors affecting the adoption of injury focused running technologies in recreational runners is yet to be identified. Grounded theory (GT) consists of strategies for developing theories through the analysis of qualitative data (Glaser and Strauss, 1967; Charmaz, 2006). It allows for the investigation of how and why people, communities or organisations experience and respond to events, challenges and problematic situations (Holt, 2016), and elicits rich, narrative accounts of this experience in order to generate an inductive theory (Gill, 2020). Constructivist grounded theory (CGT) assumes that rather than theories being discovered as in GT, we construct theories through past and present experiences and interactions with people, perspectives and practices (Gill, 2020). CGT is an iterative process that follows repeated cycles of data collection and analysis to allow for continuous improvement, expansion and clarity of the developing theory (Kennedy and Lingard, 2006). There was a need to identify both the perceived facilitators and barriers to adoption as certain factors may act in a bi-directional manner, serving as both facilitators and barriers (Busetto *et al.*, 2018;

Goswami *et al.*, 2019). Ethical approval was granted by the local university's Ethics Committee. The Standards for Reporting Qualitative Research (O'Brien *et al.*, 2014) (Appendix E1) were adhered to. A semi-structured focus group schedule was developed by the researchers, and followed an iterative process throughout the pilot study phase (Appendix E2).

### 6.3.2. Participants

A purposive sample of 27 adult recreational runners were recruited. Running clubs/groups were contacted via email and asked to distribute research information and contact details to potential participants. Those interested then contacted the researchers. Eligible participants had to be aged between 20 and 60 years and meet Mulvad *et al.'s* (2018) definition of a recreational runner: someone running at least once per week for at least six months. A minimum/maximum running volume or the use of wearable technologies was not included in the inclusion criteria.

### 6.3.3. Pilot study

A pilot study was conducted to educate and train the primary author in efficient focus group moderation techniques, and for analysing qualitative data. The results of the pilot study were not included in the main study results. The focus group schedule was updated throughout this pilot phase to include more open-ended questions and additional probes to include all participants in the discussion (e.g., "What do you think M#, have you any thoughts on that?"). Four male and five female recreational runners were recruited as a convenience sample, aged 25.1 years ± 2.2 years. Three separate pilot study focus groups were facilitated by the primary author, each taking place via remote video conferencing software (Zoom, version 5.7.0) and lasted 39.1 minutes ± 5.4 minutes.

### 6.3.4. Main study procedures

Prior to taking part in a focus group, participants were required to provide informed written consent and complete a short pre-focus group questionnaire. The questionnaire was used to gather demographic information, as well as details on participants' running habits, their usage of running technologies and their experience with RRI's (Appendix E3). A RRI was defined as any musculoskeletal pain in the lower back/lower limbs that causes a restriction to or stoppage of running for at least seven days or three consecutive scheduled sessions, or that causes a runner to consult a healthcare professional (Yamato, Saragiotto and Lopes, 2015). On completion of the questionnaire, participants were contacted via email to arrange a suitable focus group time. To encourage as much interaction as possible, the focus groups were stratified to include participants of similar age, with similar running backgrounds.

Nine separate online focus groups took place with 27 recreational runners (range= 2-4, median = 3 participants per group). Focus groups were moderated by the primary author and lasted 45.1 minutes ± 11.4 minutes. Each focus group began with a brief introduction to the study and the aims of the focus group were outlined (Appendix E2). Participants were encouraged to speak freely and given the opportunity to ask questions throughout. Group discussion began by each participant describing the types of running technologies they use. Following this, a discussion regarding the facilitators and barriers to technology use progressed, with a specific emphasis placed on injury focused running technologies. To aid discussion of injury focused technologies, it was suggested that a hypothetical smartphone application (app) could collect both sensed data (from a sensor) and data that users would be required to input manually (potentially before and/or after a run). Participants were probed to discuss this in relation to their experience with other running- and/or health-related apps, as well as their perceived use of a new injury focused technology (i.e., the hypothetical technology described). Conversation then moved to discuss participants' perceived risk factors for RRIs, and the metrics they deemed important to monitor for RRI risk. On the closing of the focus groups, participants were given another opportunity to ask questions and to provide further comments or statements that they felt may be important. A reflective and iterative approach was taken with regard to focus group moderation and the content of the focus group schedule. Additional probes were included in the focus group schedule and adjustments to moderation techniques, (e.g., ensuring equal speaking opportunities for all participants) were made during this data collection phase.

### 6.3.5. Data analysis

Frequencies and descriptive statistics were generated from the questionnaire responses using SPSS (version 27.0; IBM Corporation). Focus groups were audio and video recorded using built in software available in Zoom (version 5.7.0), and transcribed verbatim by the primary author. Participants were allocated an identification number during transcription to maintain anonymity and protect their confidentiality, with responses coded by participant gender (e.g., male = M; female = F). The transcribed focus groups were coded by the primary author using NVivo (QSR International). Braun and Clarke's (2019; 2021) methodology for reflexive thematic analysis was utilised during data analysis, following the six recursive phases: familiarisation with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report (Braun and Clarke, 2019; 2021). From the developed codes, core categories were identified, with subsequent themes and sub-themes. An 'order of themes' document was developed and reflexively updated by the primary author throughout the data collection and analyses phases (Appendix E4). Inductive coding, being reflexive and driven by the data, was initiated after transcription of the first focus group and continued throughout data collection (Braun and Clarke, 2013). Theoretical sampling continued until data saturation was reached (Aldiabat and Le Navenec, 2018).

### 6.3.6. Trustworthiness

Multiple methods of trustworthiness were undertaken to ensure the rigorous and accurate presentation of findings. A critical friend approach to 'sense-check' that data was used to enhance the analytical process (McGannon *et al.*, 2021), and to establish reliability and ensure rigour of results (Smith and McGannon, 2018). The goal of critical friends is not to reach consensus or agree on all aspects of the findings, but rather to encourage reflexivity by challenging each other's construction of knowledge (Cowan and Taylor, 2016; Smith and McGannon, 2018). The approach also gives the opportunity for researchers to explore multiple interpretations of the data (Sparkes and Smith, 2013; McGannon *et al.*, 2021). After all transcripts had been coded by the primary author, a percentage of transcripts were independently coded by an external researcher with experience in qualitative research (SOK). Researchers (AL and SOK) met on multiple occasions to conduct a coding consistency check, with varying interpretations presented. This stage of analysis led to the development of some additional codes, as well as the merging of existing codes.

Following this, trustworthiness was further enhanced by the primary author meeting with two other members of the research team (KM and EW), with similar approaches taken to review and discuss the coded data. Additionally, in the presentation of the representative and accurate findings, multiple examples and direct quotations from transcripts are provided (Appendix E5), indicating a broad and diverse contribution from participants during focus groups, reducing the chance of individual bias (Tracy, 2010). Included quotations were agreed upon by researchers.

### 6.4. Results

Nine focus groups were conducted with 13 (48.1%) male and 14 (51.9%) female recreational runners. Participants were aged 35.0 years ± 10.7 years (range: 23-53 years). Running and injury histories are detailed in Table 16. All participants were currently using, or had done so in the past, at least one form of wearable technology to monitor their running, with GPS watches and mobile phones being the most popular devices [used by 55.6% (n=15) and 48.1% (n=13) of participants respectively].

Table 16. Participant running and injury history (n=27)

| | | | |
|---|---|---|---|
| **Running history** | | | |
| Is running your main sport? | *Yes* | *No* | *Unsure* |
| | 63% (n=17) | 33% (n=9) | 4% (n=1) |
| How long have you been running? | *Less than 3 years* | *4-5 years* | *More than 5 years* |
| | 15% (n=4) | 4% (n=1) | 82% (n=22) |
| How often do you run? | *Once a week* | *2-3 times a week* | *4 times a week or more* |
| | 7% (n=2) | 44% (n=12) | 48% (n=13) |
| **Injury history** | | | |
| Have you ever had a RRI? | Yes | No | |
| | 82% (n=22) | 19% (n=5) | |
| Thinking of your worst injury, how much training did you miss?* | *Less than 10 days* | *2-3 weeks* | *4 weeks or more* |
| | 24% (n=5) | 24% (n=5) | 52% (n=11) |
| How many RRI's have you had in the last 12 months? * | *None* | *1 RRI* | *2 RRI's* |
| | 24% (n=5) | 33% (n=7) | 43% (n=9) |
| How important is injury prevention to you? (n=22) | *Moderately important* | *Very important* | *Extremely important* |
| | 18% (n=4) | 27% (n=6) | 55% (n=12) |
| **Running technology use** | | | |
| *What types of running technologies do you use?* | | | |
| Mobile phone & applications | 48% (n=13) | | |
| GPS watch | 56% (n=15) | | |
| Heart rate monitor | 33% (n=9) | | |

| | |
|---|---|
| Smartwatch | 7% (n=2) |
| Wristband activity tracker | 7% (n=2) |
| Body worn sensor | 4% (n=1) |
| Other | 4% (n=1) |

n = number of participants, RRI = running-related injury, * = missing data

### 6.4.1. Metrics perceived as important for monitoring running-related injury risk

Three core categories of risk factors were identified as important for monitoring with injury focused running technologies: overtraining, training-related risk factors, and individual-related risk factors. Within each core category, various themes and sub-themes were developed (Table 17).

Table 17. Running-related injury risk factors perceived as important to monitor using wearable technology devices by recreational runners

| **Core categories** | **Themes** ***(number of participants & focus groups to discuss theme)*** | **Sub-themes** ***(number of participants & focus groups to discuss sub-theme)*** |
|---|---|---|
| Overtraining | Excessive loading *(17* participants in 9# focus groups)* | High accumulative load *(12 participants in 7 focus groups)* |
| | | High intensity training *(11 participants in 8 focus groups)* |
| | | In-session fatigue *(5 participants in 5 focus groups)* |
| | Inadequate recovery *(13 participants in 7 focus groups)* | Fatigue & poor sleep *(6 participants in 5 focus groups)* |
| | | Poor nutrition *(6 participants in 4 focus groups)* |
| | | Insufficient rest days *(5 participants in 4 focus groups)* |
| Training-related risk factors | Training activities *(13 participants in 6 focus groups)* | Concurrent training activities *(12 participants in 6 focus groups)* |
| | Running technique *(10 participants in 5 focus groups)* | Foot strike technique *(5 participants in 4 focus groups)* |
| | | Bilateral asymmetry *(4 participants in 3 focus groups)* |
| | | Cadence *(3 participants in 3 focus groups)* |
| | Running environment *(9 participants in 7 focus groups)* | Terrain *(8 participants in 7 focus groups)* |
| | Footwear *(8 participants in 5 focus groups)* | Type of footwear *(6 participants in 4 focus groups)* |
| | | Infrequent changing of footwear *(4 participants in 4 focus groups)* |
| Individual-related risk factors | Injury status & history *(11 participants in 5 focus groups)* | Ongoing niggle *(7 participants in 6 focus groups)* |
| | | Previous injury *(6 participants in 3 focus groups)* |
| | Population characteristics *(5 participants in 3 focus groups)* | Age *(4 participants in 3 focus groups)* |
| | | BMI *(3 participants in 2 focus groups)* |
| | Type of runner *(3 participants in 2 focus groups)* | Preferred distance/event *(3 participants in 2 focus groups)* |

Note: Themes and sub-themes are presented in order of those most frequently discussed. * indicates out of 27 participants. # indicates out of 9 focus groups.

#### 6.4.1.1. Overtraining

Excessive loading and inadequate recovery were perceived to contribute to overtraining, and increase an individual's risk for sustaining a RRI. Participants suggested that these factors be monitored by injury focused technologies. Overall, the most common theme developed from the discussion of risk factors for RRI's was excessive loading. Runners perceived high accumulative loads, high intensity training and in-session fatigue to contribute to excessive loading, increasing the risk for sustaining a RRI (Table 17). Participants perceived that the *"volume of training"* (F6) and *"total mileage"* (M8) are "*big risk factor*[s]*"* (M8) for RRI onset. Additionally, the type and intensity of training, and *"whether you were pushing hard"* (M3) was also perceived to impact the risk of injury; F6 - *"The type of running you're doing. If you're doing interval training, long distance, sprints, or the volume of training maybe… the impact of that on your injuries"*. Another participant (M2) felt that these factors should be monitored in order to make sure "*the body is able to accumulate those miles"* and how injury focused technologies could function *"to make sure that you're not going into a red zone"* in terms of loading. Some participants also discussed how in-session fatigue can lead to inappropriate running technique, and *"as you go into the longer distances"* (M1), your risk of sustaining an injury increases - M7- *"the more tired I get and if I try and stick to a particular pace, the whole form goes out, and I would think that would lead to more injuries in that regard"*. Inadequate recovery was commonly discussed as a perceived risk factor for developing RRI's (Table 17). With the first sub-theme of fatigue and poor sleep, it was perceived that if *"you're not sleeping properly"* (F1), you are more susceptibility to injury. One participant (F8) described sleep as having a *"huge impact"* on injury risk and if you *"don't get enough sleep… your muscles just don't repair as quick, they don't recover as quick*. Insufficient rest days taken was also perceived to increase injury risk. One participant (F3) described how many runners may be *"over running"* and "*probably are* *injured because they're not actually taking rest days",* while also describing the importance of monitoring this to ensure *"they're not over-doing it"*. It was also perceived by some that inadequate nutrition may increase the risk of a RRI, with one participant (F11) suggesting that *"so many people don't fuel themselves properly"* and *"so many runners don't eat enough"*, which was perceived as a *"huge factor"* for injury risk.

#### 6.4.1.2. Training-related risk factors

Training-related risk factors for RRI onset included: training activities, running technique, running environment, and footwear (Table 17). Other training activities that runners may be participating in were commonly discussed. It was perceived that certain activities may either reduce or increase the likelihood of sustaining a RRI, and that it is "*very important to take into account what other sports they're doing"* (M2). It was suggested that participation in various sports (e.g., Gaelic football, rugby, golf, track events) *"predisposed"* (M2) runners to injury, and that it was *"important to take into account… other sporting activity to see if it's an injury related to running, versus related to something else, or a compound of both"* (M2). Participation in activities such as yoga, strength training and swimming were perceived to reduce the likelihood of injury, and that it would be important to monitor *"what people do outside of running, to make themselves stronger"* (M10). One participant (M3) for example perceived that by "*improving my stretching, by doing yoga",* it *"makes me less injury prone".* With running technique, participants suggested that foot strike technique, bilateral asymmetries (i.e., a difference between left and right lower limbs), and cadence may be factors that influence the onset of RRI's. Although unclear as to how these factors may influence RRI risk, participants perceived that they were important metrics to monitor. Some participants felt that monitoring *"foot strike"* (M5), *"asymmetry in the heel strike or ground contact time"* (M13), *"whether you're landing heavier left or right foot"* (M7), or *"stride length"* (M12) and *"cadence"* (M12) would give insight into risk of injury. The terrain on which people ran was commonly perceived as a potential risk factor for injury. There was generally a lack of consensus between participants as to which surfaces posed the greatest risk, despite one participant (M2) describing this metric as *"really important to take into consideration"*. However, this theme was frequently identified as an important metric to monitor. Some participants suggested that *"running up a hill"* (F2), running on *"solid concrete"* (M2), and *"constant running on the roads"* (F7) increased the risk of injury. Runners also perceived their type of footwear, and how the infrequent changing of footwear may be important factors in relation to RRI risk. One participant (M7) described their interest in understanding "*how more injury prone you are, dependent on both the age of the runners* [shoes] *you use, and the different brands of runner* [shoe] *you use".* Some participants described how they would regularly change their footwear to reduce the risk of injury, and how prolonged use of a single pair of shoes can increase the risk of injury; F11 - *"I feel like so many people don't change their runners often enough and I really think that's a huge factor in injuries".*

#### 6.4.1.3. Individual-related risk factors

The final core category of risk factors surrounded individual-related risk factors (Table 17). Participants discussed the importance of tracking the ongoing injuries and/or *"niggles"* (F2) that they may have, and how monitoring these may give further insight into the development or prevention of a more serious RRI. One participant (M7) queried whether *"niggles"* were *"precursors to an injury"* or if they were "*just the little aches and pains that we all get?".* Some participants also described the impact that previous injuries may have on the risk for further injuries, suggesting they should be monitored by injury focused technologies. One participant (M6) described the relationship between previous injuries and their current running, stating; *"the injuries I have, they're all… rugby related* *and contact related, so I find the issues I have running are probably tied back to the issues that I've had playing rugby".* In relation to population characteristics, participants generally perceived that older age increased the risk of injury and how "*when you're getting older, you're probably going to get more injury prone"* (M8). A greater BMI was also perceived by some to be a risk factor for injury, as *"the more you weigh… the higher your impact forces, and I guess that that will be a straight impact… on the risk factors"* (M8). A runner's perception of a run was also perceived to be important for monitoring injury risk, as one participant (F14) described; *"how hard did the run feel… were you tired before starting, tired during, tired after".* Mood and *"feelings"* (M10) were also discussed by some participants, with the perception that they *"play a part in your training"* (M10) and should be monitored. As the final sub-theme, it was perceived that the *"type of runner"* (M8) and differences in preferred running distance may influence susceptibility to injury. It was suggested (M4) that *"different types"* of runners *"would have different injuries"*, and that because of their 'differences', runners *"don't have a lot in common in relation to the type of injuries that [they're] likely to pick up"* (M9).

### 6.4.2. Facilitators to the use of injury focused running technologies

Ease of use and receiving useful feedback were identified as core categories of facilitators to the use of injury focused running technologies (Table 18).

Table 18. Facilitators and barriers to the use of injury-focused wearable technologies

| Core categories | Themes | Sub-themes | Facilitators | | Barriers | |
|---|---|---|---|---|---|---|
| | | | **Secondary sub-theme** | **Tertiary sub-theme** | **Secondary sub-theme** | **Tertiary sub-theme** |
| Use of a wearable device | Application design | User demand | User-friendly system *(22 participants in 9 focus group)* | Quick input session *(17 participants in 9 focus groups)* | High user input requirement *(16 participants in 7 focus groups)* | Time consuming (>5 mins) *(13 participants in 5 focus groups)* |
| | | | | Synced with other applications *(7 participants in 5 focus groups)* | | High quantity of questions (>4 questions) *(6 participants in 4 focus groups)* |
| | | | | Notification reminders *(6 participants in 4 focus groups)* | | Repetitive/Irrelevant data required *(6 participants in 3 focus groups)* |
| | | | | Automatic downloading of data *(5 participants in 3 focus groups)* | | |
| | | | Current usage habits *(13 participants in 8 focus groups)* | Fits with current usage habits *(13 participants in 8 focus groups)* | | |
| | Sensor design | Location | Lower back *(8 participants in 6 focus groups)* | Convenient *(7 participants in 5 focus groups)* | Lower back *(8 participants in 3 focus groups)* | Uncomfortable *(4 participants in 3 focus groups)* |
| | | | Foot/Shoe *(8 participants in 5 focus groups)* | Convenient *(8 participants in 5 focus groups)* | | Not secure *(4 participants in 2 focus groups)* |
| | | | Wrist/Arm *(5 participants in 5 focus groups)* | Convenient *(5 participants in 5 focus groups)* | Wrist/Arm *(3 participants in 2 focus groups)* | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Chest/Torso *(5 participants in 4 focus groups)* | Convenient *(5 participants in 4 focus groups)* | Obvious/Noticeable to others *(3 participants in 2 focus groups)* | |
| | | Application method | Discrete (non-specific attachment method) *(7 participants in 5 focus groups)* | | Uncomfortable/Irritating (non-specific attachment method) *(8 participants in 5 focus groups)* | |
| | | | Comfortable (non-specific attachment method) *(6 participants in 5 focus groups)* | | Time consuming set-up *(3 participants in 3 focus groups)* | |
| | | | Convenient *(6 participants in 5 focus groups)* | | | |
| | | | Belt mechanism *(5 participants in 4 focus groups)* | Convenient *(3 participants in 3 focus groups)* | Belt mechanism *(5 participants in 3 focus groups)* | Uncomfortable *(4 participants in 2 focus groups)* |
| | | | Clip mechanism *(3 participants in 2 focus groups)* | Convenient *(3 participants in 2 focus groups)* | | |
| | | Specifications of sensor | Small (5 *participants in 4 focus groups)* | | Bulky (8 *participants in 7 focus groups)* | |
| | | | Lightweight (5 *participants in 4 focus groups)* | | Large (3 *participants in 2 focus groups)* | |
| | | Technical features | Infrequent charging (3 *participants in 2 focus groups)* | | Frequent charging (3 *participants in 2 focus groups)* | |
| Feedback | | Feedback received | Injury-related feedback (20 *participants in 2 focus groups)* | Reduce injury risk *(11 participants in 7 focus groups)* | | |
| | | | | Monitor rehab from injury *(10 participants in 5 focus groups)* | | |
| | | | | Understand injury mechanisms *(7 participants in 6 focus groups)* | | |
| | | | | Advice/Recommendations *(6 participants in 3 focus groups)* | | |

| | | | | | |
|---|---|---|---|---|---|
| | | | Extend running career<br>*(3 participants in 1 focus group)* | | |
| | | Enhanced data<br>*(8 participants in 4 focus groups)* | Cadence/Stride information<br>*(3 participants in 3 focus groups)* | | |

#### 6.4.2.1. Ease of use

Perceived ease of use was the first core category identified, with application design and sensor design developed as themes (Table 18). In relation to the application design, participants suggested a *"user-friendly system"* (M2) that fitted with their current usage habits would facilitate use. In particular, technologies with quick or *"succinct"* (F3) and *"easy to do"* (M11) input sessions, combined with user-friendly questions (such as *"hit a smiley face or give a rating of one to ten"* (M3) or *"tick the box, rate the scale-type things"* (M9)) would encourage use. Participants suggested that a time requirement of 30 seconds to two minutes would be optimal and facilitate their use. The ability to sync a runner's current applications and technologies with a new device was also suggested by many as a facilitator. This was perceived to reduce the burden placed on users, while optimizing the reception of new and useful data; M3 - *"especially if the information is already there, maybe you can get it from Strava and tie it in"*. Participants suggested that being prompted by their smartphone would enhance engagement and facilitate their use of an application; F9 -*"a reminder… a notification coming up is really handy, because it's easy to forget"*. It was suggested (M5) that data collected by a wearable device that *"updates automatically"* would be *"great"* as reducing user demand would increase compliance; M5 - *"the less that data we have to put in, the better"*. It was also commonly suggested that a system and device that fitted into participants' current technology usage habits would be easily adoptable. One participant suggested that engaging with a new application wouldn't be an issue for them as *"I'd be recording it anyway, so to add in something small, it'd be no problem for me"* (M2), while another suggested that it may become part of their current habits; "*at the end of the training session or running session, I would automatically go to my smartphone, look at the Garmin app"* (F8).

With regard to sensor design, the location, attachment method, and specifications of the sensor were sub-themes of facilitators identified (Table 18). Although some locations were deemed more preferable than others, there was a lack of agreement between participants on the most preferable location. Participants suggested that once the location was comfortable, convenient and allowed for the device to be stable, this would facilitate their use. One participant (F11) described their perception of the lower back as a potential location and felt that "*your shorts would hold it in place"* and *"it wouldn't be moving around too much".* Another (M9) participant described the convenience of the foot/shoe as a potential location because "*if it's on my runners… I'm much more likely to just leave it there… rather than forget about it"*, while another participant (F1) felt that the wrist/arm would be suitable as *"you don't want to have something that has to be carried or have to adapt to clothes to take along with you"*. Finally, it was also perceived by some that the chest/torso would be suitable as from previous experience, *"I don't notice it's there really"* (M11).

Participants also felt that the attachment method of a sensor may act as a facilitator to device use. Personal preference varied amongst participants, however the overwhelming consensus suggests that a stable, comfortable, discrete and convenient attachment method would facilitate device use. Participants suggested that *"if it fits… properly"* (M6), and "*can be easily worn and it's not… impacting you in any way"* (F8), and "*as long as it's not a cumbersome thing that's interfering with the running"* (M1), they would have "*no problem wearing it"* (M1). Some participants described their preference for a belt-type attachment method as it was perceived as *"straightforward"* (F8) and *"easy to wear"* (F14), while others suggested that a *"paperclip kind of action"* (F2) application method would be *"easy"* (M2) to attach. Participants discussed the favourability of a *"lightweight"* (M8) and "*unobtrusive*" (M8) device, where *"the smaller* [it was] *the better"* (M10), and how this would facilitate use. Finally, it was suggested that a device with a *"good battery life"* (F1) would enhance user compliance and facilitate device use.

#### 6.4.2.2. Receiving useful feedback

Participants discussed their willingness to engage with a device (i.e., an application and sensor) should it reduce their risk of sustaining an injury and how potentially beneficial "*a device that you can put in your back pocket that will measure when you're putting your body under a level of stress that is likely to cause an injury"* (M1) could be. Others discussed the commonality of injury and how *"everyone picks up a few niggles a year"* (F11), or how there is "*always that chance that you're going to get injured"* (F1)*,* and their interest in using such a device to reduce this risk; "*I think we've all had our fair share of niggles and injuries that you'd rather not have"* (F1). Others discussed the benefits of a device that could monitor their rehabilitation from injury and potentially provide them with data to explain the mechanics of injury; "*I'm sure often there's obvious reasons that we don't even notice, but sure by having an app you'd be like 'Oh well, I did this, and I did this and I shouldn't have done this'"* (F11). Finally, some described their interest in using technologies if they could prolong their running career *"what would… make me… able to run for more years without the body failing me"* (M2).

Others described their interest in a device that could provide recommendations for *"preventing the injury developing further"* (F5), or receiving advice on *"whatever you should do"* (F5) to best manage injuries. One final facilitator to encourage use of injury focused technologies was enhanced data that runners could receive. Some participants described the desire for additional data that may give them *"an edge"* (F2) and that could potentially "*improve* [them] *as a runner*" (M2). Participants suggested that receiving data related to performance progressions would facilitate their use, while some expressed their interest in receiving *"the extra thing"* (F1) that they may not be getting with their current devices. Examples included information regarding cadence, stride length, or the *"biomechanics"* (M13) of running technique, while others were interested in *"reaffirming some data that I'm collecting already"* (M13).

### 6.4.3. Barriers to the use of injury focused running technologies

Difficulty of use and ineffective feedback were identified as core categories of barriers to the use of injury focused running technologies (Table 18).

#### 6.4.3.1. Application design

Participants discussed how the application design could act as a barrier to injury focused technology use, with a high demand on the user serving as a barrier. This was discussed in relation to participants' previous experience with other health- and running-related applications, as well as their perceived behaviour for engaging with a hypothetical injury focused application. Participants considered that this hypothetical app would collect both sensed data (from a sensor) and data that they would be required to input manually (potentially before and/or after a run). A large time requirement for inputting data was identified as a potential barrier to technology use, with M5 suggesting: "*realistically if it'll be any more than a couple minutes and people get bored putting in the data*". Participants discussed their tolerance and willingness to engage with such an application, and it was identified that five minutes was deemed the maximum amount of time runners were willing to spend using an application - M6 - "*five minutes probably would be my max*". From previous experience, a requirement to respond to a high quantity of questions (more than four questions) was described as *"onerous"* (F8) therefore identifying a further potential barrier. Questions deemed as irrelevant and repetitive were also described as a barrier with one participant indicating; "*It just gets a bit tedious…basically it'd* [wearable wrist-based device monitoring sleep and recovery] *ask you loads of questions, and it's like the same questions over and over"* (M11).

#### 6.4.3.2. Sensor design

The second theme of barriers to the use of injury focused wearable technologies was sensor design. Sub-themes of barriers included: attachment method, location, specifications of the sensor and technical issues (Table 18). Personal preference varied in relation to unfavourable device attachment methods. The general consensus suggested that attachment methods which would *"take too long to get in place"* (F11), required the runner to wear *"some contraption"* (M8), may *"cause any discomfort or blistering"* (M10), or one that was loose-fitting, *"bouncing around"* (F6) or *"going to fall off"* (F6), were potential barriers to use. Differences in the non-preferred locations of a wearable sensor were evident, with some describing the lower back as an undesirable location as it was perceived as uncomfortable or that it may *"rub against your skin and get a bit sore"* (M8). Others suggested that wrist or arm-based sensors would be unsuitable as they *"get annoying after a while"* (M2). Variance in the opinion made it difficult to determine any specific location as a barrier to use; however, the majority agreed that locations perceived as uncomfortable, one's which resulted in excessive movement of the sensor, or were *"very obvious"* (F11) to others would result in reduced compliance, and therefore act as barriers to usage. It was frequently suggested that a *"bulky"* (F9), *"clunky"* (M13) or *"heavy"* (F6) sensor would act as a barrier to technology use, as runners perceived it may *"impact their running"* (F9) and may *"annoy [them] during the run"* (M10). Finally, participants reported that a sensor with a short battery life which would require frequent charging may discourage use as it can *"put me off if the battery is low on it"* (F3).

#### 6.4.3.3. Ineffective feedback

It was also mentioned by some participants that irrelevant or inaccurate data, or what they perceived to be *"too much"* feedback would potentially discourage their use of injury focused technologies. Some participants discussed their perception that ineffective data wasn't *"going to help [them]"* (F1) in their training or recovery from injury.

### 6.5. Discussion

The main objectives of the current study were to provide a qualitative examination of recreational runners' opinions on: (i) the important metrics to monitor for RRI risk, and (ii) the perceived facilitators and barriers to the use of injury focused running technologies. Overtraining, training-related, and individual-related risk factors are essential metrics that need to be monitored for RRI risk. Difficulty of use of a device will act as a barrier to the use of injury focused running technologies, while ease of use and receiving useful feedback will act as facilitators. Common themes of facilitators and barriers were identified, implying that many factors can act as facilitators as well as barriers (Busetto *et al.*, 2018). The findings of the current study are similar to the Technology Acceptance Model (TAM) (Davis, 1989) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Venkatesh *et al.*, 2003; Venkatesh, Thong and Xu, 2012), which suggest that individuals' use of technology will be influenced by a number of factors. Such factors include: the perceived ease of use and perceived usefulness of a device/app (as suggested by the TAM (Davis, 1989)), and the effort expectancy (which is preceded by ease of use, perceived ease of use, and complexity), performance expectancy (i.e., the degree to which an individual believes a technology will help to improve their injury risk [in the case of the current study]), and behavioural intention to use a device/app (as suggested by the UTAUT (Venkatesh *et al.*, 2003; Venkatesh, Thong and Xu, 2012)). Our findings map to these models and as discussed below, we found that perceived usefulness and/or performance expectancy (i.e., the metrics perceived as important for monitoring RRI risk and feedback received), and perceived ease of use and/or effort expectancy (i.e., difficulty/ease of use) will influence recreational runners' behavioural intentions to use injury focused wearable technologies. App developers (those developing smartphone applications) and technology developers (i.e., those designing wearable devices/sensors) can draw upon these theories and the findings of the current study to design and create injury focused wearable technologies suitable for use by recreational runners.

#### 6.5.1. Metrics important for monitoring running-related injury risk

The broad range metrics perceived as important to monitor for RRI risk highlights participants' awareness of the multifactorial aetiology associated with RRI's, as shown by multiple systematic reviews (Gijon-Nogeuron and Fernandez-Villarejo, 2015; Hulme *et al.*, 2017; van Poppel *et al.*, 2021). Overtraining, consisting of excessive loading and inadequate recovery, was perceived as a leading risk factor for the development of RRI's in the current study, in line with current knowledge about RRIs (Hreljac, 2005) and similar to the perceptions of recreational runners in a previous study (Verhagen, Warsen and Silveira Bolling, 2021). Also similar to the findings of Clermont and colleagues (2019), the current participants identified longer distances and higher intensity sessions to be important metrics to monitor for excessive load, and subsequent injury risk. Additionally, inadequate recovery (which included the sub-themes of fatigue and poor sleep, insufficient rest days, and poor nutrition) was also perceived to contribute to overtraining. As in similar research, the importance of sleep and food intake for injury prevention have previously been reported by recreational runners (Clermont *et al.*, 2019). Overtraining, as reported by participants of the current study, also maps to the biomechanical model of injury, whereby loading of tissues beyond their adaptive capability, combined with insufficient recovery, results in injury (Tessutti *et al.*, 2012; Saragiotto, Yamato and Lopes, 2014).

Participants identified the importance of monitoring certain training-related metrics for risk of RRI's. Terrain received significant attention as an important risk factor to monitor. While some perceived harder terrains to increase the risk of injury, there was a lack of consensus as to which type of terrain poses greater risks. Harder terrains with less deformation have been hypothesized to result in higher impact forces, increasing the risk of injury (Dixon, Collop and Batt, 2000; van der Worp, Vrielink and Bredeweg, 2016). However, while some individual studies have found harder surfaces to produce higher loading (Taunton *et al.*, 2003; Wang *et al.*, 2012; van der Worp, Vrielink and Bredeweg, 2016), other studies have not (Dixon, Collop and Batt, 2000; van Gent *et al.*, 2007). Previous systematic reviews (Satterhwaite *et al.*, 1999; van Poppel *et al.*, 2021) have not found terrain to be a significant risk factor for injury. Our participants perceived that participation in other sports (such as rugby, Gaelic football, golf and track events), increased a runner's risk of RRIs. While it has been suggested that additional participation in other sports adds to the cumulative stress placed on the body, increasing the risk of injury (Malisoux *et al.*, 2015), a prospective study found that increased weekly volume of other sport participation (i.e., concurrent training) reduced the risk of RRI's (Vannatta, Heinert and Kernozek, 2020). With running technique, it was suggested that foot strike technique, cadence, and bilateral asymmetry were important to monitor, although participants did not describe how these factors influenced RRI risk. In a similar study, certain aspects of running technique (such as joint motion, ground contact time, and centre of mass motion) were the lowest ranked metrics by participants amongst a list of factors presented to them by the authors as potentially preventing RRI's (Clermont *et al.*, 2019). Systematic reviews and meta-analyses have been unable to identify strong justifications for the role of specific biomechanical risk factors in the onset of RRI's (Daoud *et al.*, 2012; Ceyssens *et al.*, 2019). While foot strike technique has been suggested to be causative of RRI's based on the increased load that some techniques produce (especially rear-foot strike (Goss and Gross, 2012; Burke *et al.*, 2021)), a systematic review concluded that there is very low evidence to suggest a relationship with RRI's in general (Schubert, Kempf and Heiderscheit, 2014). In relation to increased cadence, while a systematic review found that increasing cadence reduces the magnitude of key biomechanical factors (such as joint kinematics and kinetics, and whole body loading) associated with RRI's (Brindle *et al.*, 2020), a recent systematic review and meta-analysis concluded that average cadence does not differ between injured and uninjured runners (Zifchock *et al.*, 2008). Bilateral asymmetry, which relates to differences between the left and right lower limbs, has been suggested as a risk factor for RRI's based on the premise that because one leg is subjected to more loading, it is predisposed to injury (Furlong and Egginton, 2018; Robadey *et al.*, 2018). Again the literature is contrasting, with some studies finding significant limb asymmetries in injured runners both retrospectively (Bredeweg *et al.*, 2013) and prospectively (Zifchock, Davis and Hamill, 2006) compared to uninjured runners, while some studies report no differences in asymmetry (Davis, Bowser and Mullineaux, 2016; Furlong and Egginton, 2018). No systematic review drawing an overall conclusion has been published to date. Footwear was the final sub-theme of training-related metrics identified, with perceptions that older shoe age increased injury risk. This perception may be associated with the theory that shoe cushioning decreases loading on the body (Baltich, Maurer and Nigg, 2015; van der Worp, Vrielink and Bredeweg, 2016), and a decrease in cushioning capacity with extended use increases the risk of RRI's (Nigg *et al.*, 2012; Malisoux *et al.*, 2020). However, a recent systematic review concluded that no evidence-based recommendations could be made for shoe age and preventing RRI's (van der Worp *et al.*, 2015).

The final core category identified as important for monitoring RRI risk was individual-related factors. Ongoing 'niggles' were suggested as an important risk factor for RRI onset in the current study. Different from an injury, in which a runner is forced to reduce or stop training for a period of time (Yamato, Saragiotto and Lopes, 2015), our participants' perception of 'niggles' is similar to previous research where runners described 'complaints' as 'small pains' with which they can continue to run (Verhagen, Warsen and Silveira Bolling, 2021). Interestingly, previous injury was only discussed in one third of focus groups, despite being found to be the strongest risk factor for further RRI's in a recent systematic review (van Poppel *et al.*, 2021). Runners have also failed to acknowledge the importance of a previous injury as a risk factor for injury in an earlier qualitative study (Bertelsen *et al.*, 2017). While this may reflect a sense of being 'unable to change' the occurrence of having a previous injury, it clearly should be taken into account (via an application) when monitoring for the purpose of preventing re-injury. Population characteristics, including age and BMI, were mentioned by some participants in the current study. It was perceived that older age and greater BMI increased the risk of RRI; however a recent systematic review found conflicting and inconsistent findings for both age and BMI as a risk factor for RRI in short and long-distance runners (van Poppel *et al.*, 2021).

It is also important to note that some risk factors for RRI's were not mentioned in the current study, despite being shown as potential risk factors in the literature. For example, sex was not mentioned but has received some attention in the literature. Although findings are mixed, systematic reviews have reported males (Dempster, Dutheil and Ugbolue, 2021; van Poppel *et al.*, 2021) and females (Zadpoor and Nikooyan, 2011; Messier *et al.*, 2018) to be at a greater risk for specific RRI's. Additionally, monitoring ground reaction forces (peak and rate) as an indication of how hard someone strikes the ground was not mentioned by participants in the current study, but previous systematic reviews (Kiernan *et al.*, 2018) and meta-analyses (Baltich, Maurer and Nigg, 2015; Ceyssens *et al.*, 2019) have investigated the relationship to RRI risk. While there are 'conflicting' (Ceyssens *et al.*, 2019) and 'inconsistent' (Daoud *et al.*, 2012) results for a relationship with RRI's in general, high peak and rates of loading have been found to contribute to the development of *specific* RRI's, such as bony and soft tissue injuries (van der Worp, Vrielink and Bredeweg, 2016) and stress fractures (Baltich, Maurer and Nigg, 2015).

These findings also raise the question about how runners form their opinions that a metric is a risk factor for RRIs, when the research evidence would suggest it is not a risk factor. These perceptions may be due to widely available information on popular running websites. There are many examples of low cadence (Runkeeper, 2021), heel-striking (Runner's World, 2018), and harder terrains such as concrete (Runner's World, 2015) being described as risk factors for RRI's on websites, despite a lack of supporting scientific evidence. Clearly there is a need for the scientific community to better educate runners.

These findings expand on the current evidence and report new findings in relation to the metrics deemed important by runners for monitoring RRI risk when using wearable technologies. Firstly, injury focused technologies should monitor risk factors that are deemed important by runners, where evidence-based research supports their relevance (e.g. excessive loading and inadequate recovery). The challenge for app developers is whether to include metrics that monitor risk factors that are: (i) not deemed important by runners, but research does support their relevance (e.g. previous injury), or/and (ii) that are deemed important by runners, but current research does not support their relevance (e.g. terrain and foot strike technique). In the case of the first point, the authors would strongly advocate for including factors supported by evidence-based research (e.g., previous injury), with efforts made by app developers to educate runners in potentially valuable metrics. This is important in order to improve the perceived usefulness of devices (Davis, 1989; Venkatesh *et al.*, 2003; Finch, 2006; Venkatesh, Thong and Xu, 2012). In the case of the second point, the inclusion of these metrics (e.g., terrain and foot strike technique) may be useful if they encourage technology adoption and uptake. This must be balanced against the additional time needed by the user to input this data, which itself may be a barrier to app adoption and continued utilization (discussed below). Also, a lack of research evidence (or mixed evidence) to support a relationship between a metric and an increased risk of a RRI does not necessarily indicate that there is no relationship, but may more reflect the inability of current research to effectively examine the relationship. For example, examining the relationship between running impact loading and injury has been predominantly limited to a one-off assessment, frequently in a laboratory environment (Kononova *et al.*, 2019). Further research is required to further support the perceived usefulness of metrics that are not currently evidence based but were deemed important by runners of the current study. In addition, future research should include clinicians and running coaches, as their thoughts and opinions may yield further insight into the metrics deemed important for monitoring RRI risk. Development of an app which incorporates a wearable sensor (e.g. an accelerometer) to monitor impact loading and collect user input data on injury status would allow long-term and ongoing monitoring of runners in their natural environment. This would provide more precise and ecologically valid data to better explore whether a relationship does exist. The above findings are also important to coaches and clinicians in developing intervention strategies for injury prevention, where uptake and adherence by runners is improved when runner perception aligns with intervention design (Finch, 2006).

#### 6.5.2. Difficulty/Ease of use

The first identified core category of both facilitators and barriers was in relation to the perceived difficulty and ease of use of injury focused technologies. Recommendations for the design of an injury focused smartphone app and wearable sensor are provided in Table 19.

Table 19. Recommendations for the design of an injury focused smartphone application and wearable sensor.

| **Recommendations for the design of an injury focused smartphone application** | | |
|---|---|---|
| *Sub-theme* | | *Author recommendations* |
| Application design | Quick input session | A single use of an app should take less than 5 minutes. |
| | Question format | Limit the amount of text entry-type questions. Include multiple choice/tick-the-box-type questions where possible. |
| | Synced with other applications | Design an app to be compatible with other apps commonly used by runners. |
| | Notification reminders | Send the user notifications to remind them to input data/sync their wearable sensor with their app. |
| | Automatic downloading of data | Where possible, all data collected by a wearable sensor should be automatically transferred to a smartphone app. |
| **Recommendations for the design of an injury focused wearable sensor** | | |
| Sub-theme | | *Author recommendations* |
| Location | | Design a wearable sensor with the flexibility to allow a range of locations. |
| Application method | | Design a wearable sensor with the flexibility to allow a range of application methods. |
| Sensor specifications | | Design a small and lightweight sensor which is discrete and comfortable to wear. |

#### 6.5.2.1. Device design

Participants indicated that excessive device weight and size are potential barriers to technology use, with unobtrusive and comfortable devices facilitating use. They also suggested that the attachment method of a device could act as a potential barrier and/or facilitator to use. Varied preferences existed, however the overwhelming consensus suggested that if a device caused irritation or was excessively mobile on the body and interfered with running, this would act as a barrier to use; while a device that was stable and discrete would facilitate use. These perceptions align with previous findings for comfort (Lazar *et al.*, 2015; Kuru, 2016; Hermsen *et al.*, 2017; Luczak *et al.*, 2020; Shih *et* *al.*, 2015), obtrusiveness (Luczak *et al.*, 2020; Shih *et al.*, 2015) and device aesthetics (Luczak *et al.*, 2020) in wearable technologies in general.

One sub-theme which generated a large amount of discussion was where the device was to be worn (wear-location); however no one location dominated as either a barrier or facilitator. For example, some participants perceived the foot or shoe to be a highly suitable location (a facilitator), while others perceived this location to be very unsuitable (a barrier). To the best of the authors' knowledge, sensor location has not been previously investigated in runners. However, it has been suggested that athletes of varying sports (e.g., volleyball) may find wear-location to be a potential barrier to use (Bergmann and McGregor, 2011). Additionally, some participants suggested that they would not like a device to be noticeable or obvious to others, as they did not want others to know they would be self-monitoring. This finding has not previously been identified in recreational runners, but has been found in relation to health based monitoring with wearables (Kinney, 2019). Therefore, we suggest a device that could be worn on a variety of locations without negatively impacting on the accuracy of the captured information. Finally, a device with a short battery life was identified as a further barrier to technology use, in line with previous studies on wearable devices (Hermsen *et al.*, 2017; Alnasser *et al.*, 2019; Shih *et al.*, 2015).

#### 6.5.2.2. Application design

Participants reported that their use of a device would be positively influenced by a user-friendly system, with minimal user input requirement, in line with previous findings for sport tracking technologies (Bergmann and McGregor, 2011). Our participants suggested that as the time requirement and manual input demand to engage with an application increased, their interest and tolerance to engage would decrease. Additionally, it was found that the format of questions within an application could influence compliance. Questions requiring a high amount of text input would discourage engagement, whereas questions formatted visually, with a quick response-time (e.g., tick-the-box) would encourage engagement. These findings have been reported in previous research for users of a weight-loss application (Saw, Main and Gastin, 2015), and an athlete self-reported measure (monitoring metrics including training, well-being, injury and nutrition) (Rogers, 2010).

It was identified that if the use of an injury focused device could conform with participants' current usage habits, it would also facilitate use. Similarly, easily integrating new technologies with existing routines, and the absence of a need for behavioural change has been reported as means of enhancing technology adoption (Canhoto and Arp, 2017; Bardus *et al.*, 2021). Compatibility between participants' current wearable devices and/or monitoring applications and a new injury focused device was also identified as a facilitator. Our participants perceived that this would reduce the manual input demand on the user, and result in more accurate and useful information; factors which have been found to enhance wearable technology use (Rogers, 2010; Lazar *et al.*, 2015; Vos *et al.*, 2016; Hermsen *et al.*, 2017; Bardus *et al.*, 2021). This is important as minimising burden and maximising interest in users leads to improved initial and sustained device compliance (Rogers, 2010).

### 6.5.3. Receiving useful feedback

One final core category of facilitators identified was receiving useful feedback. Receiving relevant, useful and accurate data regarding RRI risk was identified as a facilitator, with participants describing their desire for feedback that could reduce their injury risk, monitor their rehabilitation from injury, and help them understand the mechanisms of injury. It is well understood that maintaining user interest (Alnasser *et al.*, 2019) and receiving useful and accurate data (Lazar *et al.*, 2015; Bardus *et al.*, 2021) can facilitate the use of wearable technologies; while the collection and reporting of inaccurate data and irrelevant information have been suggested as barriers to use of physical activity tracking technologies (Bergmann and McGregor, 2011; Lazar *et al.*, 2015; Kuru, 2016; Vos *et al.*, 2016; Hermsen *et al.*, 2017; Shih *et al.*, 2015).

In line with the Translating Research into Injury Prevention Practice (TRIPP) model (Stage 5: intervention context to inform implementation strategies), the successful implementation of injury prevention practices will be determined by, among other factors, the likelihood of its uptake (Finch, 2006). In order to improve uptake, researchers (and those issuing injury prevention programmes) must understand why injury prevention practices may or may not be adopted by the target population and provide confidence that adoption of the intervention will reduce the likelihood of injury (Finch, 2006). Additionally, the TAM (Davis, 1989) and UTUAT (Venkatesh, Thong and Xu, 2012) models suggest that technologies are more likely to be adopted if they are perceived as both useful and easy to use. Receiving relevant feedback is one way of improving the perceived usefulness of a device, as suggested by participants of the current study.

Some participants also suggested that receiving enhanced data, specifically related to running performance, beyond what they are currently collecting would facilitate their use of injury focused technologies. In the interest of developing a useful injury focused device, these findings are particularly beneficial as they may help to improve perceived usefulness, and ultimately adoption and usage behaviour.

### 6.6. Strengths and limitations

The current study provides insight into the factors affecting the adoption of injury focused technologies in recreational runners. A representative sample was included, gathering the perceptions of runners of various ages and running backgrounds. Reflexivity was encouraged throughout data collection and analysis, challenging multiple interpretations of the data, with several methods of trustworthiness being executed.

Although all participants in the current study had used at least one form of wearable technology to monitor their running, bringing valuable experiences in the formation of opinions; the authors believe that the thoughts and opinions of non-users, and those who stopped using wearable technologies are equally as valuable, and should be included in further research. Participants were recruited from Irish running clubs, and therefore findings may not accurately represent the opinions of the global population of recreational runners. The current study did not stratify participants into 'type of runner' (e.g., casual, social or competitive) as in previous studies of recreational runners (Clermont *et al.*, 2019; Janssen *et al.*, 2020). Variance in opinion may potentially exist between types of recreational runner, and to examine this could yield further insights into the means of enhancing compliance. Finally, there was potential scope for additional probing during the data collection phase, with some topics requiring further exploration and explanation. For example, runners' perceptions of including an 'overall RRI risk score' into wearable technologies was not examined in the current study. This additional probing and line of questioning may potentially yield further information; an observation that should be considered by future researchers.

### 6.7. Conclusion

Overtraining, training-related, and individual-related risk factors are essential metrics that need to be monitored using wearable technologies for RRI risk. Some of the metrics valued by participants are supported by scientific evidence (e.g., excessive loading and inadequate recovery); however, they also identified factors that are not clearly supported by scientific evidence (e.g., terrain and foot strike technique), and placed less importance on some factors that are more strongly supported by scientific evidence (e.g., previous injury). Technology developers should include metrics deemed important by runners, once there is supporting evidence-based research. They should consider the impact of the inclusion of any additional metrics (i.e., those perceived as useful but not supported by evidence, and those supported by evidence but not perceived as useful) and their effect on sensor wearability and excessive user input requirement. Additionally, it would be interesting to investigate the thoughts and perceptions of running coaches and clinicians on the important metrics to include for reducing RRI risk. Difficulty of use of a device will act as a barrier to the use of injury focused running technologies, while ease of use and receiving useful feedback will act as facilitators. To further enhance user compliance, the authors suggest technology developers design an unobtrusive, discrete and comfortable device, designed with a user-friendly system. Findings suggest that if individual users could dictate device location and attachment method, without affecting the accuracy of the technology to monitor risk of injury, this would address these barriers. Preference was given to devices that would also provide runners with information on reducing their individual injury risk, monitor rehabilitation from injury, and provide insight into the mechanisms of injury. Overall, there is a clear willingness from recreational runners to adopt an injury focused wearable device whilst running.

*Link section: Chapter 6 to 7*

Chapter 6 captured runners' motivation for using injury focused wearable technologies, the metrics they deem important to monitor for RRI risk, and their perceived facilitators and barriers to the utilisation of injury focused technologies. Utilising these findings, the design and development of a user-friendly device is possible, enhancing the likelihood of runners' use of such devices both in research and possibly commercially. Identifying a clear willingness from recreational runners to adopt injury focused wearable technologies while running, the final challenge this thesis aimed to address can be examined: facilitating participation in long-term prospective research.

In order to accurately account for the inter- and intra- variability in terms of risk factors for injury, and running kinematic and kinetics, a sufficiently large sample size is needed. In addition to the high quantity of participants required, recruitment efforts may be made more challenging due to the high participant burden associated with frequent and extensive data collection. Furthermore, retention of participants can be particularly problematic in prospective research, in addition to some barriers associated with technology use. Developing specific strategies, grounded in a real-world context, may assist in address these challenges. Therefore, the aims of Chapter 7 are to identify means of facilitating the recruitment and retention of recreational runners in prospective, longitudinal RRI research involving wearable technologies.

# 7. Chapter 7: Study 5: Recruitment and retention of recreational runners in prospective injury research: A qualitative study

This paper is published in the International Journal of Qualitative Methods. It is presented in full with only minor formatting changes.

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## 7.1. Abstract

Continuous and long-term prospective monitoring of athletes in natural training environments is essential to provide further clarity on the risk factors for running-related injuries. However, participant recruitment and retention can be problematic. This study aimed to identify factors for facilitating the recruitment and retention of recreational runners in prospective, longitudinal running-related injury research involving running technologies. Twenty-seven recreational runners (14 female, 13 male) participated across nine semi-structured focus groups. Focus groups were audio and video recorded and transcribed verbatim. A reflexive thematic analysis approach was used, and a critical friend approach taken to enhance trustworthiness. Incentives, recruiting suitable participants, ease of use of running technologies, an appropriate research design, and good communication practices will facilitate recruitment and retention. Receiving study outputs, evidence-based information and undergoing laboratory testing were identified as incentives, however, researchers need to consider whether these may influence participant behaviour and adversely bias the findings of their study. Researchers should offer participants an option with regard to the type, content, frequency and mode of delivery of

incentives and communication. Appealing to potential participants' personal interests will facilitate initial recruitment, while attempts to 'feed' this interest throughout the course of a study will enhance retention. Employing a user-friendly smartphone app and unobtrusive sensor(s), and a research study that can work with runners' training schedules and technology usage habits, will further facilitate their recruitment and retention.

**Key Words:** running technologies, wearable sensors, running-related injuries, biomechanics, running, longitudinal research

### 7.2. Introduction

Running is one of the most popular physical activities worldwide (Gijon-Nogeuron and Fernandez-Villarejo, 2015; Hulme *et al.*, 2017; van Poppel *et al.*, 2021) with two in five people considering themselves a runner (World Athletics and Nielsen Sports, 2021). Despite its popularity and associated health benefits (Pedisic *et al.*, 2020) running is associated with an injury prevalence of between 18%-79% (van Gent *et al.*, 2007; Kluitenberg *et al.*, 2015; van der Worp *et al.*, 2015). Running-related injuries (RRIs) occur when excessive load is applied to tissues beyond their adaptive capabilities (Bertelsen *et al.*, 2017), with multiple contributory risk factors (Saragiotto *et al.*, 2014; Bertelsen *et al.*, 2017; Ceyssens *et al.*, 2019; Benca *et al.*, 2020; van Poppel *et al.*, 2021). The vast majority of RRIs are 'overuse' injuries (Kemler *et al.*, 2018) that develop over a period of time from repeated microtrauma (Bertelsen *et al.*, 2017). Despite a clear theoretical relationship between risk factors for RRI's and their onset (Hreljac, 2005; Bertelsen *et al.*, 2017), evidence is inconsistent to date (Hulme *et al.*, 2017; Ceyssens *et al.*, 2019). This inconsistency is possibly due to methodological weaknesses such as retrospective data collection (Willwacher *et al.*, 2022), a lack of internal and external load monitoring

(Soligard *et al.*, 2016), and the use of once-off assessments in laboratory environments (Kiernan *et al.*, 2018). Additionally, it has been reported that many athletes will continue to train and compete through the presence of an overuse injury (Clarsen, Myklebust and Bahr, 2013). Therefore, continuous (i.e., run-by-run) and long-term prospective monitoring of athletes in natural (out-of-laboratory) training environments is essential to provide further clarity on these risk factors for injury (Soligard *et al.*, 2016; Kiernan *et al.*, 2018; Ceyssens *et al.*, 2019).

Recent technological developments in wearable sensors (Benson *et al.*, 2018) and smartphone applications (apps) (Saw, Main and Gastin, 2015) which will collectively be referred to as running technologies, have made it possible to collect this prospective data, with many types of research seeing a trend towards using these technologies as methods of data collection (Izmailova, Wagner and Perakslis, 2018). For example, wearable sensors can measure aspects of external load (such as magnitude of loading (van der Worp, Vrielink and Bredeweg, 2016) training frequency and distance (Macera, 1992; Dupont *et al.*, 2010), and acute:chronic workload ratio (Gabbett, 2016)), while smartphone apps can monitor aspects of internal load (such as sleep quality and duration (Halson, 2014), and perceived exertion (Robinson *et al.*, 1991)). These in combination with the collection of other risk factors (such as previous injury (Dallinga *et al.*, 2019) and sex (van der Worp *et al.*, 2015)) could provide insight into individual injury patterns that are dynamically influenced by a variety of risk factors (Bittencourt *et al.*, 2016). Such an approach may also identify early stages of microtrauma (e.g. if there is a subtle alteration in running technique) and allow for the development of personalised interventions aimed at reducing the risk of a time loss injury (Meeuwisse *et al.*, 2007).

Due to the intra- and inter-individual variability in injury risk factors (such as age, sex, and psychological, metabolic, hormonal and genetic factors (Borresen and Lambert, 2009)) as well as the variability in running technique kinematics and kinetics (Bartlett, Wheat and Robins, 2007; Preatoni *et al.*, 2013), a sufficiently large sample size is required to represent this variability and ensure ecologically validity (Oliveira and Pirscoveanu, 2021). However, moving away from single-session testing to long-term run-to-run monitoring creates a challenge in terms of participant recruitment and retention. Retention has been described as a "major challenge" of longitudinal research (Mychasiuk and Benzies, 2012) due to the associated prolonged duration and high participant burden (Davis, Broome and Cox, 2002; Teague *et al.*, 2018). Participant retention has also been found to be particularly problematic in research involving wearable technologies (Attig and Franke, 2020; Meekes, Ford and Stanmore, 2021).

Gathering the opinions of potential participants can enhance the execution of research studies, including optimizing strategies for recruitment and retention (Cockcroft, 2020), while also helping to ensure relevant, ethical, and participant-friendly research is carried out (Bagley *et al.*, 2016). To the best of the authors' knowledge, no research has been conducted on ways to facilitate participation in long-term prospective RRI research involving running technologies. Therefore, the main aim of this study was to identify means of facilitating the recruitment and retention of recreational runners in prospective, longitudinal RRI research involving running technologies.

## 7.3. Methods

### 7.3.1. Design

Focus groups were deemed an appropriate method of data collection as they can yield rich and in-depth data through the interaction of participants (Kitzinger, 2006; Queiros, Faria and Almeida, 2017), while constructivist grounded theory was deemed a suitable methodological choice. Grounded theory elicits narrative accounts of the lived experiences of appropriate individuals in order to generate an inductive theory (Gill, 2020). Constructivist grounded theory assumes that we construct theories through our past and present experiences of people, perspectives and practices (Gill, 2020), capable of expanding on the current knowledge as well as offering new theoretical insights (Morris and Cravens Pickens, 2017; Kendellen and Camiré, 2019). Constructivist grounded theory follows an iterative process of data collection and analysis, to allow for continued improvement of the developing theory (Kennedy and Lingard, 2006). Ethical approval was granted by the local university's Ethics Committee. The Standards for Reporting Qualitative Research (O'Brien *et al.*, 2014) (Appendix F1) was adhered to. A semi-structured focus group schedule was developed by the researchers, and followed an iterative process throughout the pilot study phase (Appendix F2).

### 7.3.2. Participants

A recruitment email was distributed to running clubs/groups containing details of the research project and the contact information of the researchers. Participants contacted the researchers to indicate their interest in participating and a purposive sample of 27 adult recreational runners were recruited. Eligible participants were aged between 20 and 60 years, and met Mulvad *et al.*'s (2018) definition of a recreational runner: someone running at least once per week for the previous six months. The need to have previously participated in a research study was not an inclusion criterion.

### 7.3.3. Pilot study

A pilot study was conducted in order to educate and train the primary researcher in efficient focus group moderation techniques and for analysing qualitative data. The results of the pilot study are not included in the main study results. Five female and four male recreational runners were recruited as a convenience sample (aged 25.1 years ± 2.2 years). Three separate pilot study focus groups were moderated by the primary author using remote video conferencing software (Zoom, version 5.7.0). Pilot focus groups lasted 39.1 minutes ± 5.4 minutes. Following the pilot focus groups, the focus group schedule was updated to include additional probes and questions of a more open-ended nature.

### 7.3.4. Main study procedures

Each participant was required to provide written informed consent and complete a brief questionnaire gathering demographic information, running experience and injury history (Appendix F3). Participants were then contacted via email to organise a focus group. Focus groups were scheduled to include participants of similar age in order to encourage interaction (Krueger, 2014). Nine online focus groups were held with 27 participants (range: 2-4, median: 3 participants per group), and lasted 45.1 minutes ± 11.4 minutes. All focus groups were moderated by the primary author, and were audio and video recorded via Zoom Video Communications (version 5.7.0). Focus groups were initiated with a brief introduction and the aims of the study were described (Appendix F2). Participants were encouraged to speak freely and were given the opportunity to ask questions throughout. Participants' use of running technologies was discussed to open the focus groups and to familiarise the participants with one another. To provide context and aid discussion, a hypothetical injury-focused research study was proposed to participants, which involved monitoring participants' running habits and injury occurrence prospectively, potentially using a wearable sensor and app. Brief hypothetical requirements were explained to participants (e.g. using a wearable sensor and inputting data on an app), and participants were probed to discuss their perceived facilitators of, and barriers to, involvement in such a study. Before closing each focus group, participants were given another opportunity to ask questions or provide additional comments. A reflective and iterative approach was taken during the data collection phase. After each focus group, the success of the focus group and each discussion topic was considered by the researchers. Additional probes were added to the focus group schedule to encourage participants to elaborate on certain topics (e.g. frequency of communication).

### 7.3.5. Data analysis

Frequencies and descriptive statistics were generated from questionnaire responses using SPSS (version 27.0; IBM Corporation). Focus groups were transcribed verbatim by the primary author. During transcription, participants were allocated an identification number and coded by participant gender (M= male, F = female), in order to maintain anonymity. Using NVivo software (QSR International, version 1.6.2), a reflexive thematic analysis approach was taken to data analysis according to and Clarke's principles (Braun and Clarke, 2019, 2021). This process followed six recursive phases. Firstly, the primary author familiarised herself with the data by transcribing, reading and re-reading the transcripts. The data was coded by generating brief labels to identify important aspects of the data. Initial themes were generated through the examination and organization of codes. These themes were then reviewed against the whole dataset, and developed further. Developed themes were then refined, defined and named. The data was finally organized into a written report (Braun and Clarke, 2019, 2021). An 'order of themes' document was developed based on the developing, merging and expanding themes and sub-themes in order to organise the codes, sub-themes, themes and core categories and present them in a visual format. Inductive, or open coding, was conducting, initiated after transcription of the first focus group, continuing throughout the data collection phase (Braun and Clarke, 2013). Theoretical sampling continued until data saturation was reached (Aldiabat and Le Navenec, 2018).

### 7.3.6. Trustworthiness

To enhance the analytical process (McGannon *et al.,* 2021), and to ensure trustworthiness and rigour of results presented (Smith and McGannon, 2018), a critical friend approach (as 'sense-checking') was taken between the lead author and another researcher with qualitative research experience (SOK). The critical friend approach encourages reflexivity in the co-construction of knowledge (McGannon *et al.,* 2021; Smith and McGannon, 2018), and facilitates the exploration of multiple interpretations of the data (McGannon *et al.,* 2021; Sparkes and Smith, 2014). Throughout the data analysis phase, regular discussions on the developing codes, sub-themes, themes and core categories ensued (between AL and SOK), which challenged and facilitated interpretations of the data from multiple viewpoints. The process facilitated the development of additional codes, while some existing sub-themes were merged/expanded, leading to the order of themes. Trustworthiness was further enhanced via investigator triangulation as the primary author met with two other members of the research team in which similar processes were undertaken to review and discuss the coded data.

Multiple examples of direct quotations from participants are presented, enhancing the accuracy and trustworthiness of the findings. A broad and diverse contribution from participants is also included, reducing the likelihood of individual bias (Tracy, 2010) (Appendix F4).

## 7.4. Results

Nine focus groups were conducted with 14 female (52%) and 13 male (48%) recreational runners. Participants were aged 35.0 years ± 10.7 years (range 23-53 years). Details of participants' running experience, injury history, running technology use, and research participation is detailed below (Table 20).

Table 20. Participant research and running experience, and injury history

| | | | | |
|---|---|---|---|---|
| **Research experience** | | | | |
| Have you previously participated in any form of research? (n=27) | *Yes* | *No* | *Unsure* | |
| | 67% (n=18) | 29% (n=8) | 4% (n=1) | |
| **Running experience** | | | | |
| Is running your main sport? (n=27) | *Yes* | *No* | *Unsure* | |
| | 63% (n=17) | 33% (n=9) | 4% (n=1) | |
| How long have you been running? (n=27) | *Less than 3 years* | *4-5 years* | *More than 5 years* | |
| | 15% (n=4) | 4% (n=1) | 82% (n=22) | |
| How often do you run? (n=27) | *Once a week* | *2-3 times a week* | *4 times a week* | |
| | 7% (n=2) | 44% (n=12) | 48% (n=13) | |
| **Injury history** | | | | |
| Have you ever had a RRI? (n=27) | *Yes* | *No* | | |
| | 82% (n=22) | 19% (n=5) | | |
| Thinking of your worst RRI, how much training did you miss? (n=22) | *Less than 10 days* | *2-3 weeks* | *4 weeks or more* | |
| | 23% (n=5) | 27% (n=6) | 50% (n=11) | |
| How many RRIs have you had in the past 12 months? (n=22) | *None* | *1 RRI* | *More than 1 RRI* | |
| | 23% (n=5) | 36% (n=8) | 41% (n=9) | |
| How important is injury prevention to you? (n=27) | *Moderately important* | *Very important* | *Extremely important* | |
| | 22% (n=6) | 33% (n=9) | 45% (n=12) | |
| **Running technology use** | | | | |
| What types of running technologies do you use? (n=27) | | | | |
| *Mobile phone and application* | 48% (n=13) | | | |
| *GPS watch* | 56% (n=15) | | | |
| *Heart rate monitor* | 33% (n=9) | | | |
| *Smartwatch* | 7% (n=2) | | | |
| *Wristband activity tracker* | 7% (n=2) | | | |
| *Body worn sensor* | 4% (n=1) | | | |
| *Other* | 4% (n=1) | | | |
| For research purposes, would you be willing to carry your mobile phone while running? (n=27) | *Yes* | *No* | *Maybe* | *Other* |
| | 77% (n=21) | 4% (n=1) | 15% (n=4) | 4% (n=1) |

| | | | | |
|---|---|---|---|---|
| Where would you be willing to carry your mobile phone? (n=27) | *Arm* | *Lower back/ Waist* | *Chest/Torso* | *Other* |
| | 38% (n=10) | 42% (n=11) | 11% (n=3) | 7% (n=2) |

n = number of participants, RRI = running-related injury, GPS = global positioning pain

#### 7.4.1. Perceived facilitators to research involvement

Incentives, suitable participants, ease of use of running technologies and good communication practices were identified as facilitators of research participation, with further themes and sub-themes discussed (Table 21).

Table 21. Perceived facilitators of recreational runners to their involvement in prospective running related research

| Core categories | Themes | Sub-themes | Secondary sub-themes | Tertiary sub-themes |
|---|---|---|---|---|
| Incentives | Study outputs *(25* participants in 9# focus groups)* | Type of output *(21 participants in 9 focus groups)* | Interpreted individual metrics *(16 participants in 9 focus groups)* | |
| | | | Analysed group/individual findings *(8 participants in 4 focus groups)* | |
| | | | Basic individual metrics *(3 participants in 2 focus groups)* | |
| | | Content of output *(20 participants in 7 focus groups)* | Injury management *(20 participants in 7 focus groups)* | Identify how to reduce injury risk *(11 participants in 7 focus groups)* |
| | | | | Monitor rehabilitation from injury *(10 participants in 5 focus groups)* |
| | | | | Receive advice/recommendations on managing injuries *(6 participants in 3 focus groups)* |
| | | | | Identify how to extend running career *(3 participants in 1 focus group)* |
| | | | Performance-related feedback *(8 participants in 4 focus groups)* | Receive cadence/stride information *(3 participants in 3 focus groups)* |
| | | Frequency received *(16 participants in 8 focus groups)* | Regular feedback (weekly/ monthly) *(8 participants in 5 focus groups* | |
| | | | Summary data on end of study *(5 participants in 4 focus groups)* | |
| | | | Quarterly/Biannually *(4 participants in 2 focus groups)* | |
| | | Mode of delivery *(6 participants in 4 focus groups)* | Notifications through study app *(4 participants in 2 focus groups)* | |
| | | | Email *(4 participants in 2 focus group)* | |

| | | | | |
|---|---|---|---|---|
| | Provision of evidence-based information *(8 participants in 4 focus groups)* | Type of information *(8 participants in 4 focus groups)* | Injury prevention advice *(4 participants in 3 focus groups)* | |
| | | | Stretches/Strength & conditioning advice *(3 participants in 3 focus groups)* | |
| | | | Injury rehabilitation advice *(3 participants in 2 focus groups)* | |
| | | | Recovery strategies *(3 participants in 2 focus groups)* | |
| | | Mode of delivery *(3 participants in 2 focus groups)* | | |
| | Laboratory testing *(7 participants in 3 focus groups)* | VO2 max test *(3 participants in 3 focus groups)* | | |
| | | Body composition testing *(3 participants in 3 focus groups)* | | |
| | | Gait analysis *(3 participants in 2 focus groups)* | | |
| | | Experience of laboratory testing *(3 participants in 2 focus groups)* | | |
| | Prizes *(4 participants in 3 focus groups)* | | | |
| Suitable participants | Personal interest *(23 participants in 9 focus groups)* | Running injuries *(23 participants in 9 focus groups)* | Reduce injury risk *(14 participants in 8 focus groups)* | Prevent personal injury *(14 participants in 8 focus groups)* |
| | | | | Prevent injury in others *(3 participants in 2 focus groups)* |
| | | | | Extend running career *(3 participants in 1 focus group)* |
| | | | Understand mechanisms of injury | Mechanisms of injury |

| | | | | |
|---|---|---|---|---|
| | | | *(9 participants in 6 focus groups)* | *(7 participants in 6 focus groups)* |
| | | | | Impact of injury on performance *(3 participants in 3 focus groups)* |
| | | | Monitor rehabilitation from injury *(10 participants in 5 focus groups)* | |
| | | Assisting with research *(9 participants in 5 focus groups)* | | |
| | | Performance insights *(7 participants in 5 focus groups)* | Enhance performance *(6 participants in 4 focus groups)* | |
| | | | Receiving additional data *(5 participants in 4 focus groups)* | |
| | Daily schedule *(18 participants in 9 focus groups)* | Fits with current running technology habits *(15 participants in 8 focus groups)* | | |
| | | Fits with running schedule *(6 participants in 4 focus groups)* | | |
| Ease of use of running technologies | User-friendly app *(22 participants in 9 focus groups)* | Quick input sessions *(17 participants in 9 focus groups)* | | |
| | | Question format *(7 participants in 5 focus groups)* | | |
| | | Synced to other apps *(7 participants in 5 focus groups)* | | |
| | | Notification reminders *(6 participants in 4 focus groups)* | | |
| | | Automatic downloading of data *(5 participants in 3 focus groups)* | | |
| | Sensor design *(20 participants in 8 focus groups* | Location *(17 participants in 8 focus groups)* | Lower back/Waist *(8 participants in 6 focus groups)* | Convenient *(7 participants in 5 focus groups)* |
| | | | Foot/Shoe | Convenient |

| | | | | |
|---|---|---|---|---|
| | | | *(8 participants in 5 focus groups)* | *(8 participants in 5 focus groups)* |
| | | | Wrist/Arm<br>*(5 participants in 5 focus groups)* | Convenient<br>*(5 participants in 5 focus groups)* |
| | | | Chest/Torso<br>*(5 participants in 4 focus groups)* | Convenient<br>*(5 participants in 4 focus groups)* |
| | | Attachment method<br>*(11 participants in 8 focus groups)* | Discrete attachment method (non-specific)<br>*(7 participants in 5 focus groups)* | |
| | | | Secure attachment method (non-specific)<br>*(7 participants in 5 focus groups)* | |
| | | | Convenient attachment method (non-specific )<br>*(6 participants in 5 focus groups)* | |
| | | | Comfortable attachment method (non-specific)<br>*(6 participants in 5 focus groups)* | |
| | | | Belt mechanism<br>*(5 participants in 4 focus groups)* | Convenient<br>*(3 participants in 3 focus groups)* |
| | | | Clip mechanism<br>*(3 participants in 2 focus groups)* | Convenient<br>*(3 participants in 2 focus groups)* |
| | | Discrete sensor specifications<br>*(8 participants in 5 focus groups)* | Small<br>*(5 participants in 4 focus groups)* | |
| | | | Lightweight<br>*(5 participants in 4 focus groups)* | |
| | | Good technical features<br>*(3 participants in 2 focus groups)* | Infrequent charging of sensor<br>*(3 participants in 2 focus groups)* | |
| | Check-ins | Reassure valuable involvement<br>*(5 participants in 5 focus groups)* | | |

| | | | | |
|---|---|---|---|---|
| Good communication practices | *(11 participants in 7 focus groups)* | Reminders to engage with app *(5 participants in 5 focus groups)* | | |
| | | Reminder of community of runners/participants *(3 participants in 2 focus groups)* | | |
| | | Trouble-shooting with running technology *(3 participants in 1 focus group)* | | |
| | Mode of communication *(10 participants in 6 focus groups)* | Notifications from app *(4 participants in 2 focus groups)* | | |
| | | Email (*4 participants in 2 focus groups)* | | |
| | Frequency of communication *(6 participants in 4 focus groups)* | Semi-regular (monthly) *(5 participants in 3 focus groups)* | | |

Note: Themes and sub-themes are presented in order of those most frequently discussed. * indicates out of 27 participants. # indicates out of 9 focus groups.

#### 7.4.1.1. Incentives

Several incentives were suggested by participants as a means of facilitating research involvement, including: study outputs, the provision of evidence-based information, laboratory testing, and receiving prizes. Receiving study outputs on the data collected was described as *"very important"* (M2) and *"key"* (M1) to engaging runners in research. Participants discussed three types of output that they would be interested in receiving: (i) *basic individual metrics* (e.g. running distance and pace for a session) as a *"quick instantaneous read out"* (M13), (ii) *interpreted individual metrics* (i.e., basic metrics with interpretation/context, e.g. your acute:chronic workload ration has increased 1.5 from last week, which has been suggested to increase the risk of injury (16)) as *"some kind of a performance report that can be linked to the likelihood of an injury"* (F8), and (iii) *analysed group/individual findings* (i.e., on conclusion of a study, e.g. males who ran more than 50km per week were 10% more likely to develop an Achilles tendinopathy compared to males who ran 40-50km per week) as a *"general overview of the results at the end"* (M10).

As for the content of these outputs, participants were interested in both injury management and performance-related feedback. Content of study outputs that could (i) reduce participants' risk of injury and "*prevent* [runners] *from getting back into that situation of going from one injury to another"* (M3), (ii) monitor their rehabilitation from injury and *"seeing their recovery"* (F9), and (iii) offer recommendations on how to manage injuries to "*prevent the injury developing further"* (F6) were most frequently discussed. Some participants were also interested in performance-related feedback beyond what they are receiving from their current technologies in order to *"improve"* (M2) their running performance and *"change* [their] *running to be better"* (M2). Cadence and *"stride"* (M12) data, both from an injury risk and performance perspective, were specifically mentioned. There were varied suggestions as to the optimal frequency of receiving these outputs; regular or *"consistent feedback"* (M2) (i.e., weekly or monthly), periodic feedback, such as a *"report each quarter"* (F8), and summarized feedback as a *"general overview of the results at the end"* (M10) were all suggested but no overall consensus was reached Additionally, many participants understood that it may not be possible to receive these outputs until a study had finished, but once researchers could *"promise to share the results with us or give, I'd definitely be very much inclined to take part".* There was also a variety of preferences with regard to mode of delivery, with no single mode being identified as a clear facilitator. Some participants suggested that delivering outputs through an app associated with a study would be *"handy"* (F5), while others suggested email as a suitable mode.

The provision of evidence-based, running related information was commonly suggested as a means of recruiting and retaining participants. Information of interest related to injury prevention advice, suitable stretching routines, strength and conditioning advice, injury rehabilitation advice, and recovery strategies. For example, one participant (F8) described her interest in receiving information on "*the optimum way to recover… the optimum way to stretch… the way that you'll most help yourself prevent injury".* Another participant described her interest in engaging with a research study to receive advice on how to best manage injuries;

> F6: *"for example, 'I went for a run today'... and then I come back and I feel like I pulled or popped my hamstring… What should I do in the case of this?… Immediate advice to prevent the injury developing further"*

Some participants also suggested repeated laboratory testing as a facilitator. While some mentioned specific tests of interest (e.g. $VO_2$ max, body composition measurements or gait analyses), others indicated that simply having the experience of being tested would be sufficient, irrespective of the specific test; F10 - *“being brought up to a high performance centre to get tested… to experience what it’s like in the lab”*.

A few participants also suggested that the periodic potential to win a prize could be a means of encouraging participation, as it would be *“a token just to keep you motivated”* (F11).

#### 7.4.1.2. Suitable participants

The second core category of facilitators related to the type of participant involved, with themes of personal interest and daily schedule identified. Focus group members suggested that they would be *“interested”* (M10) in and *“curious”* (M8) about gaining insights into RRIs. Many participants also suggested this could be the case for other recreational runners; *“I think everybody’s interested in the mechanics of how and why we get injured”* (M6). Participants expressed specific interests in preventing RRIs and *“not wanting to get it* [an injury] *again”* (F14), understanding the mechanisms of injury and *“how injuries happen”* (M4), and monitoring injury rehabilitation to *“see improvements”* [from injury] (F9). A further facilitator was participants’ interest in *“assisting with research”* and the potential to *“improve injury prevention for other runners”* (M2); *“I’d have an interest in it insofar as that if runners themselves don't get involved in these things, we’re not going to get the information back out of it”* (M1). Some participants described their personal interest in receiving further performance insights, *“optimizing performance”* (F2), and “*changing* [their] *running to be better”* (M2), while others suggested that they *“find the data very interesting”* (M2), and receiving any additional data from a study would facilitate their participation.

Participants also suggested that should their involvement in a research project fit with their running schedule and technology usage habits, it would be “ *really easy to be involved”* (F6). Participants described how they’ll *“be running anyway”* (F7), and how they already *"spend a bit of time at that"* [engaging with running technologies] (M10); therefore, involvement in a research project that is complementary to these habits, would be easily facilitated.

#### 7.4.1.3. Ease of use of running technologies

Participants' perceived the ease of use of running technologies would act as a facilitator to research engagement, with a user-friendly app and sensor design developing as themes. A *"user-friendly"* (F8) app was suggested as an app with a low user demand. This was suggested as one which (i) runners can use *"really quickly"* (M5, (ii) has user-friendly formatted questions (e.g. *"tick-the-box"* and *"rate-the-scale"* (M9)) (iii) is "*connected to some of the other apps"* (F9) runners are already using (e.g. Garmin, Strava, MyFitnessPal), (iv) sends the user *"reminders"* (F8) to engage with the running technology, and (v) *"updates automatically"* (M5).

> M3: *"I'm sort of hoping that it will be set up in a way that it's just second nature, I don't really have to do much. Like M5 was talking about, it's maybe linked to Garmin or to Strava and the data goes up there. We might have an app where you have to hit a smiley face or give a rating of one to ten… you want to make it as easy as possible… and not to be a burden"*.

Wearable sensor design also received some attention, with the wear-location, attachment method and discrete sensor specifications identified as facilitators. Although some wear-locations and attachment methods were perceived as more preferable than others (e.g. lower back/waist or foot/shoe and belt or clip mechanism), the main facilitating factors were the convenience, discreteness, secureness and comfort of the wear-location and attachment method. Participants suggested that a sensor situated in a location where it *"doesn't bother* [them]*"* (F1) or they *"don't notice* [it]*"* (M11), and one that is *"easily worn"* (F4) and *"you can put it on and forget about it"* (M2) would facilitate running technology use and therefore research participation. A small and lightweight sensor was also highlighted as a facilitator, with one participant suggesting that they *"wouldn't really notice a really small and really light"* sensor (F9), while another suggested an *"unobtrusive and lightweight"* sensor *"doesn't take much hassle"* (M8).

Finally, a sensor with a *"good battery life"* (F1) that is *"easy to charge"* and *"doesn't need to be charged too frequently"* (F2) would facilitate running technology use, and therefore improve retention.

#### 7.4.1.4. Good communication practices

Good communication practices also received some attention with check-ins, mode of communication, and frequency of communication discussed. Participants reported that *"check-ins probably keep you on track"* (F4), as well as *"reminding you that you're still there and you're not forgetting about them"* (F10). These 'check-ins' were perceived to: (i) reassure participants of their valuable contribution, (ii) remind them to continue with their involvement, (iii) establish any issues/concerns participants may have and (iv) highlight their inclusion within a community of runners involved in such a project. The most commonly suggested modes of communication were notifications from a smartphone app associated with the study, and email. A *"notification"* was perceived as *"handy"* and may act as a *"reminder"* (F9) of their involvement in the study.

Monthly communication from the research team was the most commonly suggested frequency to maintain participant engagement as it was perceived as *"a nice time between things"* (F10); however, no overall consensus was reached regarding the optimal frequency. Nonetheless, once participants were reassured that their contributions were valuable and being monitored, they perceived this would facilitate their involvement; M3 -

*"We wouldn't need much. It's just those little pushes to say that you're part of something and then if it's working".*

### 7.4.2. Perceived barriers to research involvement

Difficulty of use of running technologies, poor communication practices, and impact on personal training schedule were identified as barriers to research involvement, with various themes and sub-themes developed (Table 22). The most frequently discussed barriers to research involvement were in relation to the design of a wearable sensor and the associated smartphone app.

Table 22. Perceived barriers of recreational runners to their involvement in prospective running related research

| Core Categories | Themes | Sub-themes | Secondary sub-themes |
|---|---|---|---|
| Difficulty of use of running technologies | Smartphone app design *(20[*] participants in 8[#] focus groups)* | High user input requirement *(16 participants in 7 focus groups)* | Time consuming (>5 minutes) *(13 participants in 6 focus groups)* |
| | | | High quantity of questions (>4 questions) *(6 participants in 4 focus groups)* |
| | | | Repetitive data required *(6 participants in 3 focus groups)* |
| | Wearable sensor design *(18 participants in 9 focus groups)* | Attachment method *(12 participants in 6 focus groups)* | Irritating/Uncomfortable *(8 participants in 5 focus groups)* |
| | | | Belt mechanism *(5 participants in 3 focus groups)* |
| | | | Time consuming set-up *(63 participants in 3 focus groups)* |
| | | Obtrusive sensor *(9 participants in 7 focus groups)* | |
| | | Location *(7 participants in 5 focus groups)* | Lower back/Waist *(8 participants in 3 focus groups)* |
| | | | Arm/Wrist *(3 participants in 2 focus groups)* |
| | | | Obvious/Noticeable to others *(3 participants in 2 focus groups)* |
| | | Logistic issues with sensor *(4 participants in 4 focus groups)* | Broken/Lost sensor *(3 participants in 3 focus groups)* |
| | | | Frequent charging requirement *(3 participants in 2 focus groups)* |
| | Inappropriate feedback from running technology *(4 participants in 2 focus groups)* | | |

| | | | |
|---|---|---|---|
| Poor communication practices *(7 participants in 5 focus groups)* | Excessive communication *(3 participants in 3 focus groups)* | | |
| | Lack of communication *(3 participants in 3 focus groups)* | | |
| | Mode of communication *(3  participants in 3 focus groups)* | | |
| Impact on personal training schedule *(5 participants in 5 focus groups)* | Strict training schedule required *(4 participants in 4 focus groups)* | | |
| | Interference with training schedule *(3 participants in 2 focus groups)* | | |

Note: Themes and sub-themes are presented in order of those most frequently discussed. * indicates out of 27 participants. # indicates out of 9 focus groups.

#### 7.4.2.1. Difficulty of use of running technologies

The design of a smartphone app was the most frequently discussed barrier to research involvement. An app that required "*too much manual input"* (M4), was *"poorly configured"* and required *"a lot of energy… to operate the things"* would be *"quite off-putting"* (M13). The use of an app which was time consuming (more than five minutes) or required a response for a high quantity of questions (more than four questions) was perceived as *"a little bit onerous"* (F8). Repetitive and irrelevant questions were also described by one participant (M11): *"It just gets a bit tedious…asking loads of questions, and it's the same questions over and over", which were* perceived to discourage participants from engaging with an app, therefore acting as a barrier to their involvement with research; F14 – "*There would be a consistency issue, long term with the app I'd say. Every morning having to answer a load of questions"*

Additional barriers were identified with regard to the attachment method, obtrusiveness and location of a wearable sensor. Firstly, it was perceived by some that if the attachment method of a wearable sensor was uncomfortable or caused skin irritation, this would be a *"main concern"* (M8): *"if it starts rubbing against your skin and the skin gets rubbed, then that's an issue"* (M8). A belt mechanism was also perceived as *"uncomfortable"* (M1), with one participant (F4) describing her thoughts: *"if it's something that I had to carry or strap to me, I know I'd find it really irritating… I hate those belts".* Additionally, participants reported they would *"get fed up of it fairly quickly"* (F11) if a sensor *"[took] too long to set up and get in place"* (F11). Secondly, it was suggested that an obtrusive sensor which was *"bulky"* (F6) or *"cumbersome"* (M9) would deter runners from using it; M1 - "*If it's something larger than mobile phones that you're having to sit on your waist or your chest… that's different. I'd try it, certainly, but I'm not sure whether I'd persist with it for 12 months".*

The potential wear-locations of a wearable sensor was also important. From previous experience, some participants found that a wearable sensor situated on the lower back was *"annoying"* and *"you just can't wait to throw it away"* (M2). Although this was the most frequently discussed location as a potential barrier to sensor use, location on the arm/wrist was also mentioned: *"I've had the armband… just gets annoying after a while"* (M2). With variations in personal preference between participants, no consensus was reached on one location as an evident barrier. Participants also described being *"iffy"* (i.e., uncertain) about a *"really visible"* (F8) sensor. Additionally, various logistic issues were reported as barriers. Participants suggested that lost or broken sensors would result in a reduction in their participation; F11- *"I could imagine one falling off during a run, me breaking it… and having to go to X and get it fixed"*. Participants also suggested that frequent charging of the sensor would also discourage their use as it is *"very annoying when they run out of battery quickly"* (M11). Finally, some participants suggested that receiving inappropriate feedback where they felt *"consumed by the data"* (F2), or receiving irrelevant feedback that *"I didn't need to know"* (F1) would be off-putting.

#### 7.4.2.2. Poor communication practices

Some participants felt that *"pestering"* (M13) research participants with excessive communication would dissuade them from participating, with too much communication perceived as *"annoying"* (F10) and *"off-putting"* (M13); *"just checking in on them but without hounding them"* (F10). Others felt a lack of communication would discourage their participation, as they may become *"disinterested"* (M3) and unsure if their involvement was being monitored. Some discussed how the mode of communication may discourage them from participating, with email being considered as *"a negative"* (F14) and *"always work"* (M11).

#### 7.4.2.3. Impact on personal training schedule

Finally, some participants suggested that if the design of a research study did not fit with their personal training schedule, it would act as a barrier to participation. If participants were required to train for the duration of a study (i.e., if involvement in a study would not allow them to take a break/off-season after an event or for holiday, for example), they would be less likely to participate; M1 - *"The reality is, most people will drop off for a month or two… so I'd be prepared to work with that".* Others reported that if a research project was to interfere with their running schedule (i.e., if the inclusion criteria had strict training limits, forcing participants to run more/less than they typically would) they would not participate; M1 - *"if your study interferes with my running, I won't be involved in your study. That would be my way of looking at it… If it's interfering with what I'm doing, that will discourage me".*

### 7.5. Discussion

The aim of the study was to identify facilitating factors for the recruitment and retention of recreational runners in prospective, longitudinal RRI research involving running technologies. To the best of the authors' knowledge, this is the first study to examine this research question. Offering incentives and recruiting suitable participants with a personal interest in participating will maximize interest, while the ease of use of running technologies, a research design that is complementary to participants' schedules, and good communication practices will minimize the burden of participation. It was evident that some factors acted in a bi-directional manner existing as both facilitators and barriers. To avoid repetition, these will be discussed together in terms of maximising interest and minimizing burden.

### 7.5.1. Maximising interest

#### 7.5.1.1. Incentives

Study outputs, evidence-based information and laboratory testing were identified as incentives to facilitate research participation. Study outputs can be looked at in terms of type, content, and frequency and mode of dissemination. In terms of type, study outputs were discussed in three forms: (i) *basic individual metrics* provided during the course of a study, (ii) *interpreted individual metrics* provided during the course of a study, and (iii) *analysed findings* provided on conclusion of a study. Despite the clear indication that the provision of these outputs would facilitate participation, researchers need to consider whether such inclusion will adversely bias (negatively affect) the findings of their study as these outputs may change participants' behaviour (Figure 34). Knowledge can influence behaviour (Gielen and Sleet, 2003; Glanz, Rimer and Viswanath, 2008) specifically, applied studies have demonstrated that knowledge of injury risk and injury prevention practices (IPPs) influences behaviour to adopt IPPs (Orr *et al.*, 2013; McKay *et al.*, 2014; Martinez *et al.*, 2017). The level of 'acceptable' change in behaviour may be dependent upon the prospective study design. In an observational study, researchers are purely observing the relationship between a number of variables, including behaviour, and an outcome measure (e.g. injury onset), and so it may be less important if participants change their behaviour (Song and Chung, 2010). However, in an intervention study, because researchers want to examine a specific relationship between a given intervention and an outcome, they generally do not want to simultaneously change other factors which would occur if participants changed their behaviour in light of receiving additional information during a study (Bergmann and Boeing, 2002). Researchers may want to consider limiting the amount of information they give participants, in particular when providing information that has the greatest potential to cause behaviour change (e.g. analysed findings) (Figure 34).

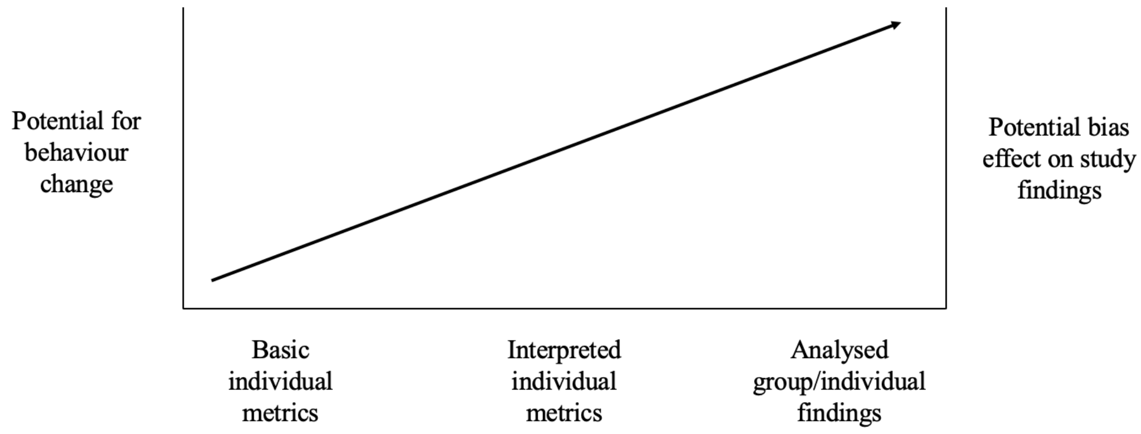


Figure 34. Effect of study outputs on potential behaviour change and potential bias on study findings

Of the three types of study outputs identified in the current study, *basic individual metrics* would have the lowest potential for causing behavioural changes because they would not be communicated with interpretation or comparison with other data collected (Figure 34). *Interpreted individual metrics* would have more potential for causing changes in participant behaviour as this type of feedback would be 'loaded' with interpretation and context. *Analysed group/individual findings* would have the greatest potential for causing behavioural changes due to the comprehensive nature of the information, the direct relevance of this information to participants, and possibly by virtue that participants helped 'create' this information/knowledge.

In relation to the content of study outputs, the vast majority of participants were interested in receiving personal feedback (related to risk factors for injury, monitoring injury rehabilitation, and understanding the mechanisms of injury), as well as how their findings compared with other participants. This is in line with previous health-based research (Mfutso-Bengo, Ndebele and Masiye, 2008; Cox *et al.*, 2011; Mein *et al.*, 2012; Long *et al.*, 2016; Purvis *et al.*, 2017). Regarding frequency of dissemination, there was no clear consensus as to exactly how often participants would like to receive these outputs, although the majority of participants reported a desire for periodic updates throughout the course of a study (e.g. weekly, monthly, quarterly, biannually). Similar to this, qualitative studies have reported that receiving feedback *throughout* the duration of longitudinal studies enhances participant retention (Mein *et al.*, 2012; Purvis *et al.*, 2017). Alternatively, some of our participants suggested that a summary of findings at the end of a study would suffice, still acting as a facilitator for retention, in line with health-based research (Long *et al.*, 2016). Regarding mode of dissemination, our findings show that recreational runners would most like research results to be distributed via a smartphone application (associated with the study) or via email; the latter corresponding to preferences in health-based research (Long *et al.*, 2016).

Where an app is developed to facilitate participation in prospective, longitudinal studies, it may be possible to easily tailor the study outputs delivered (the type, content, frequency and mode) to each individual's desire, as long as it does not adversely bias findings (as discussed above). Additionally, we recommend that researchers inform participants (during initial recruitment) of the study outputs that will/will not be disseminated during the study, in order to manage their expectations. We also suggest, with the importance of research transparency (Taylor, 2019), and suggestions from participants, that researchers ensure participants are provided with analysed findings in an appropriate format at the conclusion of a study.

To increase recruitment and retention, researchers should provide evidence-based information and facilitate laboratory testing (should facilities be available, and carefully considering the associated time and financial constraints), providing it doesn't adversely bias findings. Various forms of tangible incentives, such as tokens of appreciation and health education materials have been previously found to increase retention (Villarruel *et* *al.*, 2006; Bonk, 2010; Nicholson *et al.*, 2011), as well as being shown to be effective compared with no incentive (Edwards *et al.*, 2009).

#### 7.5.1.2. Suitable participants: Personal interest

Another facilitator for research participation was the recruitment of *suitable participants*. Many focus group members suggested that many recreational runners have a personal interest in both preventing injury and using running technologies, and this interest would greatly facilitate their participation in research. In particular, it was suggested that those interested in RRIs (preventing injury for themselves and other runners, understanding injury mechanisms, and monitoring injury rehabilitation), assisting with research, and enhancing their performance should be recruited. However, depending on the aims of the research, this strategy could introduce a clear bias. If the aim of a study is to purely observe recreational runners' behaviour with running technologies, then perhaps researchers would not mind how this behaviour materialises. However, if the aim of a study is to determine the extent to which recreational runners engaged with a particular/new technology (in order to enhance engagement with a sensor and/or app), then a clear bias would exist if only runners with certain characteristics (such as an interest in running technologies) were recruited. The authors suggest that researchers carefully consider the aims of their research and determine potential biases before introducing such a strategy. This suggestion from participants does however highlight key content material that researchers could consider including (where appropriate) when initially communicating with potential participants in order to maximise interest (e.g. mailing, media coverage, etc.). Highlighting the aims of a research project and how it may appeal to runners' personal interests may facilitate initial recruitment, while attempts to 'feed' this interest during the course of study (e.g. using incentives discussed above) facilitate retention.

These findings, related to personal interest, map with previous research in which altruism has been reported as a leading motivation for involvement in health-related research (Burgess *et al.*, 2009; Limkakeng *et al.*, 2014; Soule *et al.*, 2016) being discussed in terms of personal benefit (Wasan, Taubenberger and Robinson, 2009; McCann, Campbell and Entwistle, 2013; Martinsen *et al.*, 2016), benefitting science (Wasan, Taubenberger and Robinson, 2009; Limkakeng *et al.*, 2014), and helping others (Irani and Richmond, 2015; Quay *et al.*, 2017). Specifically examining motivations for participating in acute injury research, Irani and Richmond (2015) found altruism (in the form of helping other injured individuals and contributing to knowledge development) and individual curiosity were the second and fifth most common themes, respectively.

### 7.5.2. Minimizing burden of participation

#### 7.5.2.1. Ease of use of running technologies

Given that participant retention can be problematic in research involving wearable technologies (Attig and Franke, 2020; Meekes, Ford and Stanmore, 2021) and the association between high participant burden and greater attrition rates (Davis, Broome and Cox, 2002; Teague *et al.*, 2018), our findings emphasise the need for user-friendly apps with low user demand, and incorporating a sensor that is small, lightweight and unobtrusive. Researchers need to find a balance between gathering more data and the burden that this may place on participants. Our findings are similar to previous research in which high manual user demand decreased technology use (Saw, Main and Gastin, 2015; Alnasser *et al.*, 2019; Luczak *et al.*, 2020), while improved comfort (Lazar *et al.*, 2015; Kuru, 2016; Hermsen *et al.*, 2017; Kononova *et al.*, 2019; Shih *et al.*, 2015), reduced obtrusiveness (Lazar *et al.*, 2015; Shih *et al.*, 2015) and preferable sensor location (Bergmann and McGregor, 2011; Luczak *et al.*, 2020) influence general wearable technology use.

#### 7.5.2.2. Suitable participants: Daily schedule

It was suggested by our participants that in order to reduce the burden of participation, a study design should be flexible and researchers should work with participants’ current (and potentially changing) training schedules and technology usage habits. Provided the aims of a research study are being addressed, we suggest that researchers design a ‘participant-friendly’ research study that (i) is complementary to participants' training schedules (e.g. allowing participants to continue with their individual training plan), (ii) is complementary to participants’ daily schedules (e.g. arranging testing/data collection that suits participants’ work schedules) and (iii) allows for the easy adoption of running technologies (as discussed above). Previous research has similarly identified that time constraints and scheduling act as barriers to acute injury research participation (Irani and Richmond, 2015) and retention (Mein *et al.*, 2012; Irani and Richmond, 2015). Additionally, the adoption of new health and fitness wearable technologies has shown to be enhanced if their use can be integrated into a person’s current habits, without the need for accommodating behaviours (Doan *et al.*, 2003; Canhoto and Arp, 2017).

#### 7.5.2.3. Communication practices

Communication between researchers and research participants was commonly discussed as a means of minimizing the burden of participation, and therefore facilitating recruitment and retention. Communication was discussed in terms of content, frequency and mode. Focus group members suggested that researchers should use ‘check-ins’ to reassure participants of their valuable contributions and address any issues participants may be having, but avoid pestering them with unnecessary information or requests. A variety of opinions existed between participants as to the optimum time frame to contact participants, however monthly communication was most frequently suggested as most suitable. It is clear however that preferences may vary between research participants as to how often they would like to be contacted. While no specific mode of communication was suggested as a clear barrier or facilitator, notifications from a smartphone app (if applicable) and email were the most preferred modes in the current study. We suggest that communication from researchers should (i) ensure participants that their contributions are valuable and being documented, (ii) be communicated through a modality that is suitable for individual participants, one which they will most likely respond to, (iii) be frequent enough to remind participants about engaging with the study, but perhaps most importantly, (iv) be flexible, allowing for an increase or reduction in communication based on participants' desire for communication (i.e., encouraging 'non-responders' but avoiding 'pestering' participants).

Previous research has shown that similar check-ins (via email or text) can enhance participant retention in health research (Catherine *et al.*, 2020). While there is no particular timeframe to contact participants in order to maintain their participation in research (Cotter *et al.*, 2002), previous studies have shown that increasing the frequency of 'check-ins' helps to enhance participant retention (Catherine *et al.*, 2020), while reduced efforts to contact long-term research participants can result in significant attrition (Cotter *et al.*, 2002). Additionally, a lack of communication from researchers to potential participants has been identified as a barrier to initial recruitment in sports injury research (Braham, Finch and McCrory, 2004). Regarding mode of communication, a recent systematic review identified that email and instant messaging were the most studied digital tools for participant retention (Frampton *et al.*, 2020) and have been found to significantly increase response rates and yield quicker response times from participants of randomized controlled trials (Clark *et al.*, 2015). However, more research is required into communication through smartphone apps given their now widespread use.

### 7.6 Recommendations

The following is a summary of the authors' recommendations for facilitating the recruitment and retention of recreational runners in prospective research involving running technologies. These recommendations should be considered providing the aims of the study are being addressed, and the study's methodology allows. We suggest researchers:

1. disseminate study outputs to participants to maintain their interest, once researchers do not foresee unwanted behavioural changes, and allow participants to select their preferred type and content of output, and their frequency and mode of delivery
2. provide evidence-based information and facilitate laboratory testing throughout the course of a study, once researchers do not foresee unwanted behavioural changes.
3. highlight the aims of a study to potential participants during recruitment in order to pique their interest in participating (e.g. use of running technologies or improving injury prevention for runners)
4. ensure smartphone apps are user-friendly and sensors are unobtrusive.
5. design a participant-friendly research project that is flexible around participants' schedules and allows runners to continue with their preferred training plan.
6. allow participants to select their preferred frequency and mode of communication from researchers.

### 7.7 Strengths and limitations

A representative sample of recreational runners was included, with varying ages, running backgrounds and previous experience with research. Reflexivity was encouraged throughout data collection and analysis, and multiple interpretations of the data were challenged. Several methods of trustworthiness were also executed.

Although we did collect information on participants' previous experience with research, this was not used in the organisation of focus groups. Future research could arrange focus groups to stratify runners with/without previous research experience as this could potentially yield further insights. Additionally, as these focus groups addressed two research questions (as mentioned in the methods section) and there was an associated time constraint, there may have been scope for additional probing during data collection.

### 7.8 Conclusion

Providing incentives and recruiting suitable participants (with a personal interest in participating) will maximize participants' interest in participating in longitudinal RRI research involving running technologies, while ease of use of running technologies, an appropriate research design (complimentary to participants' schedules) and good communication practices will minimize the burden of participation. Receiving study outputs was identified as the most desirable incentive, however, researchers need to consider whether this may adversely bias the findings of their study because it may change participant behaviour too much. With the variance in opinion expressed in the current study regarding participants' preferences for incentives and communication practices, there is clearly no 'one-size fits all' Provided the aims of the research are addressed, researchers should, where possible, offer participants an option with regard to the type, content, frequency and mode of delivery of incentives and communication, once the study methodology allows. Additionally, where possible, designing a research study that is compatible with runners' training schedules and technology usage habits will further facilitate their recruitment and retention. Overall, there is a clear willingness and interest from recreational runners to participate in longitudinal, prospective RRI research involving running technologies.

# 8 Discussion

## 8.1 Overall discussion

This thesis imparts a substantial body of evidence towards changing the framework of investigating RRIs, laying the foundation for an innovative and pioneering approach to RRI surveillance. A unique aspect of this thesis is the identification of an alternative view of injury, not as a dichotomous, biological entity, but as a multi-level, biopsychosocial construct. This overall discussion will address two primary points: (i) the consideration of what running-related injuries are, and (ii) the process of capturing them.

### 8.1.1 What is a running-related injury?

The foundation of injury prevention research requires a clear understanding of the extent and causes of injury (Van Mechelen, Hlobil and Kemper, 1992). There is a lack of established foundational epidemiological (i.e., the wide range in injury rates) and aetiological (i.e., the uncertainty of risk factors) evidence in the RRI literature (Chapter 2). A missing link in advancing the prevention of RRIs may lie with the fundamental way 'injury' is considered, with an extensive, holistic approach to injury surveillance suggested as a possible solution. This thesis builds upon the single previous review conducted on RRI definitions (Yamato *et al.*, 2015) by providing an update on the ample research that has been conducted since its publication (Chapters 3 and 4). Furthermore, it contributes to the literature by reviewing and analysing the methods of RRI surveillance used and the measures of injury severity employed (not previously done), and by considering whether current definitions and severity measures are truly suitable for capturing the overuse nature of RRIs. This gives rise to four important conclusions: (i) 'injury' is mainly classified as a dichotomous entity, (ii) there is little consistency across definitions and severity measures, (iii) neither definitions nor severity measures capture the full injury development process by not recognising lower severity injuries, and (iv) the biopsychosocial consequences of injury are not reflected in current definitions or severity measures. These conclusions reflect a challenge imposed by the progressive, subtle, and oscillating nature of RRI development, in that, **the point of injury onset is not clear**.

It appears that injury definitions and severity measurements have largely been developed by researchers, and are being somewhat imposed on runners. This highlights a need for a greater understanding of runners' lived experiences of injury (Chapters 3 and 4). This thesis presents empirical evidence outlining a complex, multi-level, multi-dimensional continuum of injury development (Chapter 5). Identifying eight distinct levels of injury and describing their progression across four categories, the Running Injury Continuum (Figure 33) provides an in-depth understanding of RRI development. Its presentation of the multiple levels of injury, across a breadth of consequences suffered, can potentially change the fundamental way in which 'injury' is considered. It can also provide a foundation from which to develop a comprehensive RRI surveillance tool. This thesis presents three important take-home messages in relation to our understanding of what a RRI is:

1. Injury exists as a process. Not considering this and ignoring lower severities of injury, may contribute to the wide range of RRI rates (Peterson *et al.*, 2022; Fredette *et al.*, 2022) and the absence of clear risk factors (Correia *et al.*, 2024). It may also result in a failure to consider potential risk factors (Whalan, Lovell and Sampson, 2020), as well as difficulties in the early recognition of injury, preventing timely intervention (Bolling *et al.*, 2019).
2. Researchers' opinions have largely determined RRI surveillance methods to date, despite multiple other stakeholders involved (including runners, coaches, clinicians, governing bodies, and policy makers). The perceptions, opinions and experiences among all of these stakeholders may not align, and therefore, current RRI surveillance methods may not be totally appropriate.

3. Considering 'injury' solely by the physical descriptions and/or effects on training suffered is not fully reflective of the clear biopsychosocial experience of runners. Additionally, RRIs are likely caused by the interaction between multiple biopsychosocial risk factors (McClean *et al.*, 2024), and these should not solely be considered as consequences of injury.

### 8.1.2 Capturing running-related injuries

In terms of capturing RRIs, there are two key considerations to make: (i) consistency across studies, and (ii) the appropriateness of methods employed. It is important to note that this thesis *does* advocate for consistency, in line with previous research (Bahr *et al.*, 2020). However, achieving this consistency may be possible with an alternative approach (i.e., not a dichotomous view). Suggesting a novel approach could be thought of as 'adding' to the already evident inconsistency; however, it seems that efforts to understand the fundamentals of RRIs (i.e., rates and risk factors) have been largely unsuccessful. Therefore, perhaps the surveillance of RRIs needs to be re-evaluated. Building upon the work of the OSTRC (Clarsen, Myklebust and Bahr, 2013; Clarsen *et al.*, 2014; 2020), and the consideration of RRIs as a process (Verhagen, Warsen and Silveira Bolling, 2021), a potential solution which targets both the issues of inconsistency and appropriateness is as follows: consistent use of a broad surveillance system which captures all levels of injury as it develops, across all biopsychosocial consequences and risk factors. With a collaborative effort from researchers, if continuous data can be captured (i.e., without being restricted by varied definitions or severity measures) and shared within a **single RRI data repository**, significant advancements may be made in understanding and preventing RRIs. The application of study-specific definitions and severity measures *post-hoc* can then address individual research questions. The establishment of an expert group may assist with the inauguration of this single data repository, further encouraging collaboration across research groups.

Where previously it would not have been practical (or even possible) to collect data to this extent, advances in technology allow for relatively easy capture, storage, and analysis of large amounts of data, from potentially thousands of runners. In order to enhance the effectiveness of such a system, it is essential to ensure it aligns with runners' perceptions and desires in order to increase usability (van Wilgen and Verhagen, 2012). This is addressed by investigating the metrics runners deem important for monitoring injury risk, and identifying means of enhancing their use of a technology-based surveillance system (Chapter 6). A clear willingness from runners to engage with these types of technologies is evidenced, once meaningful data can be captured and runners are provided with feedback that will be useful for reducing their risk of injury. Runners' engagement will be further enhanced by designing an app which is user-friendly and linking with a wearable sensor which is not cumbersome. This thesis builds upon the only study to examine runners' perceptions of the usefulness of wearable technologies for injury prevention (Clermont *et al.*, 2019).

Ensuring validity and reliability of data requires adequate recruitment and retention of runners in research studies. With thousands of runners potentially required for a study of this calibre (Neal *et al.*, 2024), a clear challenge is evident. Runners' perceived barriers and facilitators to their involvement in RRI surveillance research are presented, with means of reducing participant onus addressed (Chapter 7). Appealing to runners' personal interests in preventing injury and improving their running will facilitate recruitment, while efforts to feed this interest throughout will encourage retention. Runners' willingness to participate in research is evident, once requirements align with their daily lives and they are provided autonomy over incentives received and communication with researchers.

This thesis is the first to present evidence on factors affecting runners' participation in injury-focused research involving wearable technologies.

### 8.2 Directions for future research

This thesis lays the foundation for future research across several domains. Firstly, the establishment of an expert RRI research group and subsequent RRI data repository, which could significantly advance RRI prevention efforts. This group may comprise an international, multi-centre and multidisciplinary panel of researchers, clinicians, runners, coaches, performance staff, data analytics specialists, and any other relevant stakeholders involved in running, injury epidemiology, injury prevention, or data analysis. They may develop and recommend the use of a consistent, continuous surveillance tool to capture the development of RRIs, aiming to establish clear evidence regarding RRI epidemiology and aetiology (i.e., in line with the initial steps of the sequence of prevention model [Van Mechelen, Hlobil and Kemper, 1992]). Once established, this group may then look towards developing injury prevention interventions, testing their effectiveness, efficacy, and practical implementation (i.e., in line with the latter steps of the TRIPP model [Finch, 2006; Verhagen and van Nassau, 2019]). The inclusion of Public and Patient Involvement (PPI) will likely be critical in such a group, in order to develop not only evidence-based interventions, but those which runners (coaches and clinicians) will engage with.

Secondly, the validity of the Running Injury Continuum needs to be investigated. With a small sample involved in its development (n=31), further quantitative studies can assess the views of a larger sample of runners on its appropriateness. Converting this theoretical model into a practical tool and assessing its ability to monitor the injury development process and potential risk factors for injury, is an essential step towards injury prevention.

Thirdly, capturing the opinions of other stakeholders involved with RRIs, such as coaches, clinicians, or other sub-groups of runners (e.g., novice, experienced) may further enhance surveillance methods. As end-users who may also use injury-related data, their opinions are invaluable to ensuring successful injury surveillance (van Wilgen and Verhagen, 2012). Qualitative approaches, similar to this thesis, may be of use to explore this question.

Fourthly, the execution of a large-scale, prospective study is needed in the pursuit of RRI prevention. This study should employ a comprehensive surveillance system (such as the Running Injury Continuum) to capture the entirety of the RRI development process and the multiple potential risk factors for injury (and how they interact). With this thesis largely underpinned by the biomechanical model of injury, suggesting injuries are caused by high loads relative to tissue integrity (Meeuwisse *et al.*, 2007; Malisoux *et al.*, 2015; Bertelsen *et al.*, 2017), this system should monitor the multiple factors contributing to both high loading and tissue integrity, measuring aspects of internal and external loading (Gabbett, 2016), on a frequent or run-by-run basis (Meeuwisse *et al.*, 2007).

The feasibility and practicality of such an extensive approach should be carefully considered, with challenges in terms of data collection and engagement. In terms of data collection, a recent study found it feasible to use wrist-based IMU/GPS data and other baseline patient reported outcome measures (PROMs) to prospectively monitor RRIs (Neal *et al.*, 2024). However, assessing the feasibility of prospectively captured PROMs and the use of the Running Injury Continuum as a method of injury surveillance, through a smartphone app, is required. In terms of engagement, runners have an 'internal' warning system for injury (i.e., sensations of and responses to lower level injuries) which they often ignore, and in some cases, injuries progress to a higher severity. There is a challenge therefore to ensure runners will respond to an 'external' system which indicates possible injury, when they do not listen to their own 'internal' system. This thesis provides recommendations for encouraging runners' buy-in (Chapters 6 and 7); however, further education of runners (and coaches, clinicians, etc.), and investigation into this, may be required. If feasible, this type of prospective research would ideally inspire the development of an injury prediction model (via machine learning), individual to each runner, to significantly enhance our capabilities of reducing and preventing RRIs. Figure 35 depicts the findings of this thesis in a 'pathway to understanding RRIs'. An overview of a smartphone app to potentially be used in such a study is provided in the appendix (Appendices G1 and G2). Within this large scale prospective study, some further specific research questions may be of interest:

- Examining whether lower level injuries (e.g., niggles or twinges) act as risk factors for more severe injuries (e.g., short- or long-term injuries).
- Examining whether lower level injuries interact with other possible risk factors (e.g., weekly running volume) to alter risk of more severe injuries.
- Examining whether rates of injuries and risk factors for injury differ across various levels of injury severity.
- Examining the management strategies used by runners when lower-level injuries *do not* progress to more severe injuries (i.e., what are runners doing right?).
- Examining the management strategies used by runners when lower-level injuries *do* progress to more severe injuries (i.e., what are runners doing wrong?).
- Examining the biopsychosocial factors (e.g., stress, mood, sleep, menstrual cycle, other training) that may affect risk or perception of injury.

### 8.3 Practical implications

This thesis also culminates in practical implications which may be important for clinicians, coaches, researchers, technology developers, and runners themselves. Firstly, clinicians should consider the potential influence RRI definitions, severity measurements, and surveillance tools have on the outcomes of research when employing an evidence-based practice. They should consider *lower-level injuries* as potential risk factors for more severe RRIs, understand that runners experience a complex biopsychosocial response throughout the entire injury development process, and recognise that runners often make attempts to self-manage injuries before to attending a HCP. These factors, also applicable to coaches and performance staff, are crucial in the management and rehabilitation of RRIs.

Secondly, along with the directions for future research detailed above, researchers should consider that specific recruitment and retention strategies may be required to enhance research engagement. While there are specific recommendations and potential strategies provided in Chapter 7, these may differ across sub-groups of runners.

Thirdly, technology developers may take the findings from this thesis to develop *easy to use* and *useful* devices (smartphone apps and/or wearable technologies) for runners to monitor and reduce their risk of injury. Following the translational research spectrum (Verhagen and van Nassau, 2019), these devices should be efficacious (i.e., monitor and target evidence-based risk factors), effective (i.e., retain their capacity to monitor and reduce injury risk in real-life settings), and implemented (i.e., sustained adoption by runners in real-life)

Fourthly, the education of runners regarding injury risk and management is essential, with the onus of this falling to all associated stakeholders (i.e., clinicians, researchers, coaches, governing bodies and runners). In line with evidence highlighting runners' desire for autonomy (Verhagen, Warsen and Bolling, 2021), and to continue empowering runners in effective self-management, education surrounding evidence-based information on managing and preventing RRIs is clearly required. This can be facilitated with enhanced dissemination from researchers to ensure their findings are freely accessible to runners, disseminating findings in user-friendly formats (e.g., infographics, podcasts, blog posts) using plain language, ensuring runners understand key information.

In line with this latter point, it is important to highlight some already executed and planned dissemination strategies for the findings of this thesis. In terms of executed dissemination to fellow researchers, all papers within this thesis have been published in peer-reviewed journals and several papers have been presented at national and international conferences (as outlined in the introductory sections of this thesis). In terms of lay-audience dissemination, findings have been published in RTÉ (Ireland's national media broadcaster), presented at runner-orientated symposiums, communicated through various podcasts, and made publicly available on social media platforms. For future dissemination, findings will be communicated to runners and other important stakeholders via blog posts and social media campaigns during recruitment for the upcoming prospective research study.

As a final thought and recommendation, I believe runners should be at the centre of RRI prevention research, informing injury surveillance that is representative of their lived experiences. Researchers should aim to work *with* runners, capturing the entirety of the injury development process, investigating multiple possible risk factors, and monitoring the host of biopsychosocial consequences suffered. I believe if researchers can employ strategies to feed runners' interest in preventing injuries and enhancing performance, while minimizing the burden placed on them to be involved in research, RRI research is in an affirmative position to enhance our understanding of RRI epidemiology, and move towards prevention.

### 8.4 Limitations

In addition to specific limitations highlighted in each chapter, it is important to consider some overarching limitations of this thesis. Firstly, while addressed in the delimitations (section 1.3), the inclusion of 'recreational runners' as a broad group of runners may not have elicited findings specific or relevant to various sub-groups of runners (e.g., novice, experienced). In a similar vein, participants of the current studies could be considered a sub-group of runners who are interested and willing to participate in research. It is important to consider 'harder-to-reach' populations and how findings may differ based on their perceptions or lived experiences.

Secondly, with further learning and experience gained throughout the course of this PhD, it is important to acknowledge my change in thinking regarding qualitative research. While a pragmatic approach was taken to ensure (i) the aims of my research were addressed (e.g., combining IP and RTA to capture lived experiences *across* the dataset) and (ii) that findings could be used in a practical manner (i.e., for the development of a novel smartphone app and specific recruitment and retention strategies), I understand that some methodological approaches may not be fully congruent. In progressing through my PhD studies, learning from each study undertaken, and in writing my overall thesis, I believe I have become a more *knowing* researcher (Braun and Clarke, 2023), acknowledging these potential limitations, but learning from them. This perspective helped me to realize that methodological congruence is not about rigidly adhering to predefined rules, but rather, about making informed, reflexive and iterative decisions that align with the research question. It is important that the findings of this thesis, and subsequent recommendations, are considered in light of these limitations.

### 8.5 Reflection

I set out to do this PhD in the pursuit of learning. On reflection, I have never learned more in a three year period about this research field, my practice as an Athletic Therapist, or myself as a person. From an intellectual standpoint, I have developed knowledge across a breadth of fields; from injury epidemiology, smartphone app design and development, quantitative research design, and qualitative methodologies, to name but a few. From my undergraduate degree, my focus was on learning information and gaining knowledge in order to apply it practically in a clinical setting. What this PhD has exposed me to is understanding *how* this information and knowledge is developed. With a positivist outlook, I prioritised qualities such as validity and reliability, considering these as 'gold standard'. However, with a pragmatic outlook, this has now shifted, allowing me to consider the nuance, complexity, and my role as a researcher in this whole process. This pragmatic approach has translated to my clinical practice, shaping me into a clinician who values evidence-based practice, but above all, holistically considers and treats the person in front of me as an individual. This experience has given me the opportunity to work with some of the most insightful and dedicated researchers, clinicians and runners, from whom I will take a huge amount of learning. It has presented me with challenges I never believed I could face, and emphasised traits of resilience and dedication in myself. It is something I will forever be grateful for and proud of.

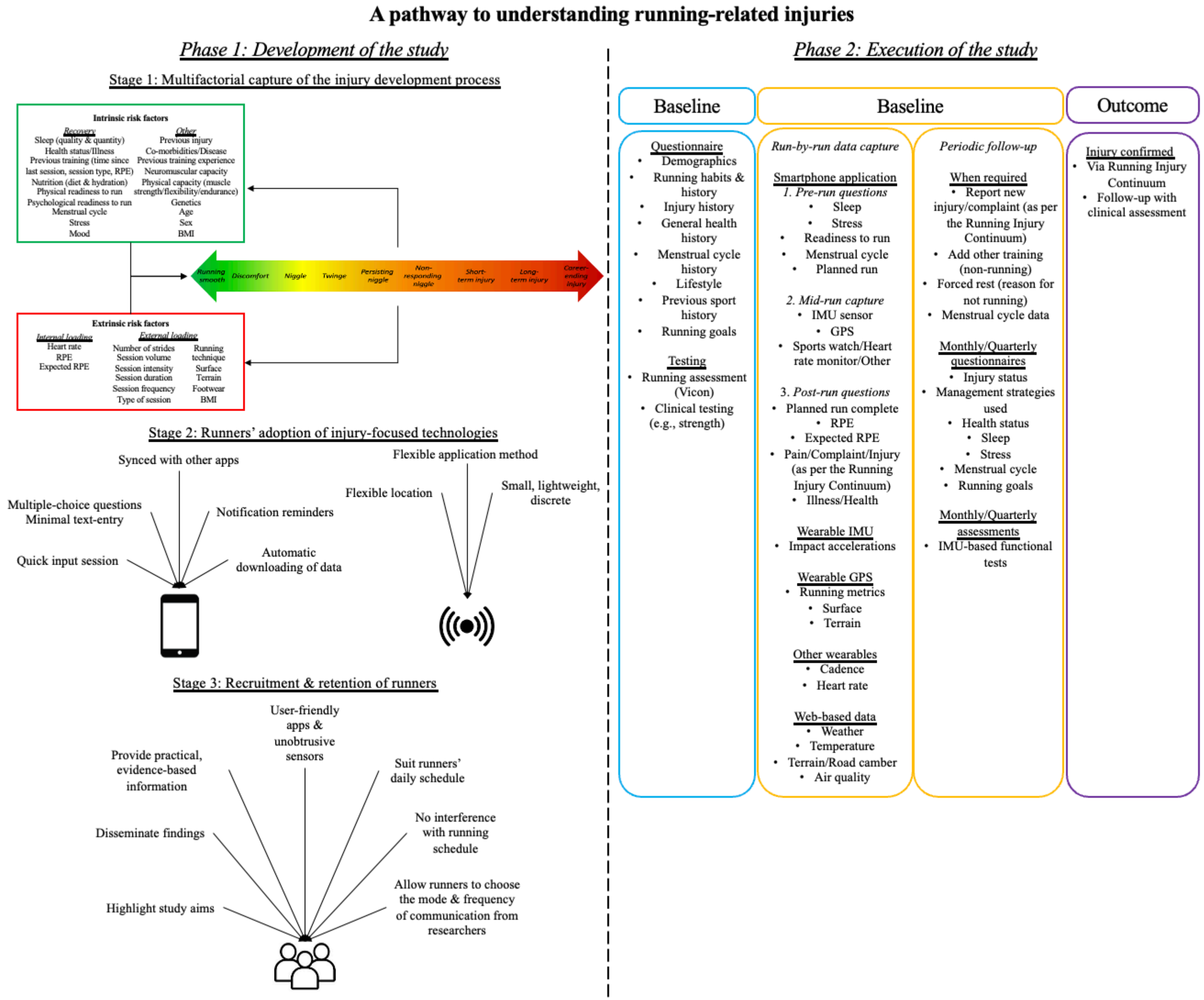


Figure 35. A pathway to understanding running-related injuries

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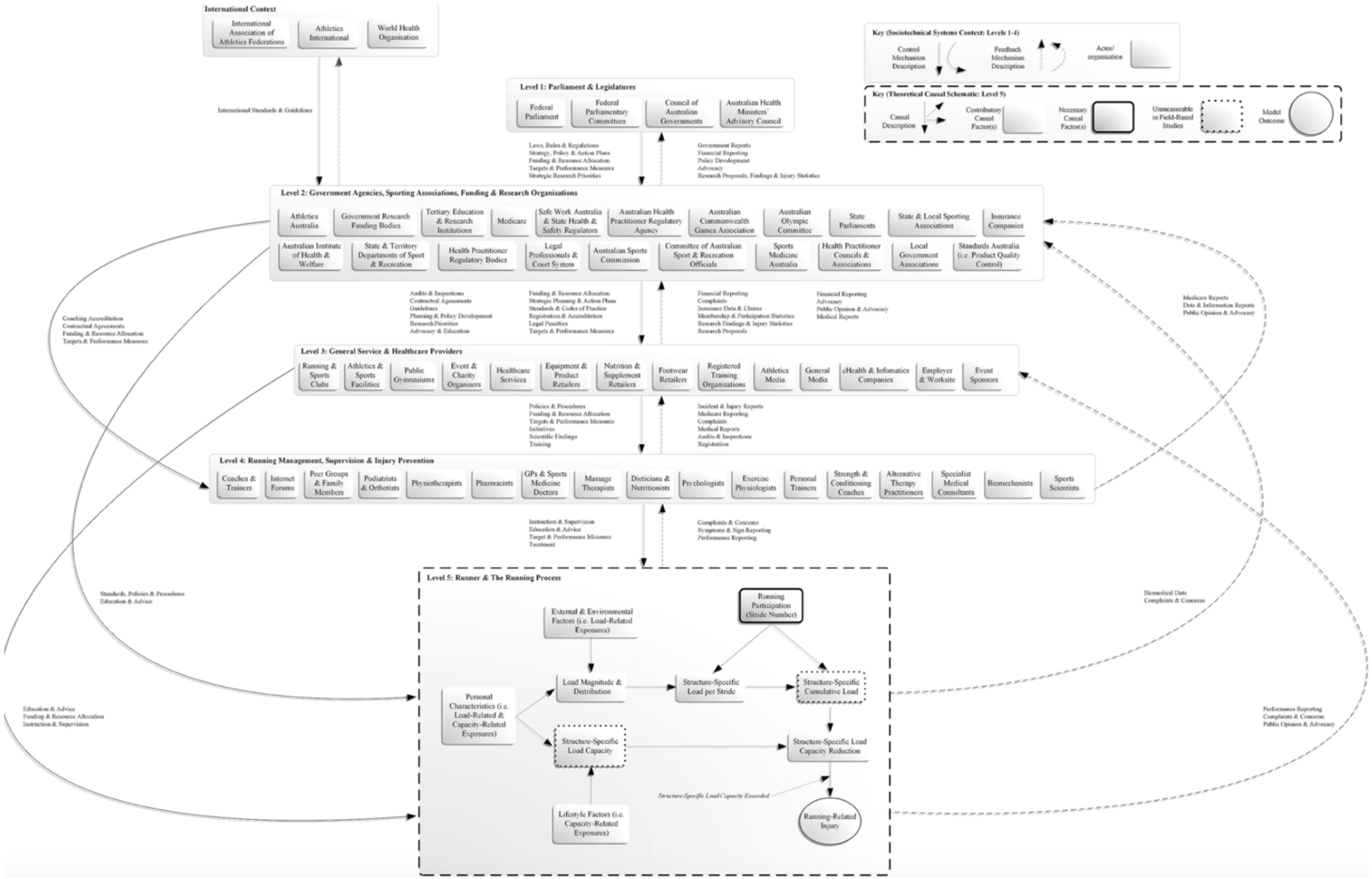
## 10. Appendices

## 10.1 Appendix A. Review of literature

*Appendix A1. The validated 'complex systems model' of the Australian distance running system (Hulme et al., 2017)*



## 10.2 Appendix B. Study 1: Definitions and surveillance methods of running-related injuries: A scoping review

*Appendix B1: Preferred Reporting Items for Systematic Reviews and Meta-Analysis scoping review (PRISMA-ScR) checklist (Tricco et al., 2018)*

| Section | Item | PRIMSA-ScR checklist item | Reported on page # |
|---|---|---|---|
| TITLE | | | |
| Title | 1 | Identify the report as a scoping review | 122 |
| ABTRACT | | | |
| Structured summary | 2 | Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives. | 122-123 |
| INTRODUCTION | | | |
| Rationale | 3 | Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach. | 123-125 |
| Objectives | 4 | Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives. | 125 |
| METHODS | | | |
| Protocol and registration | 5 | Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number. | 125 |
| Eligibility criteria | 6 | Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale. | 126 |
| Information sources | 7 | Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed. | 126 |
| Search | 8 | Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated. | 126 |
| Selection of sources of evidence | 9 | State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review. | 126-127 |

| | | | |
|---|---|---|---|
| Data charting process | 10 | Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators. | 127 |
| Data items | 11 | List and define all variables for which data were sought and any assumptions and simplifications made. | 127 |
| Critical appraisal of individual sources of evidence | 12 | If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate). | NA |
| Synthesis of results | 13 | Describe the methods of handling and summarizing the data that were charted. | 127 |
| RESULTS | | | |
| Selection of sources of evidence | 14 | Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram. | 128 |
| Characteristics of sources of evidence | 15 | For each source of evidence, present characteristics for which data were charted and provide the citations. | 128 |
| Critical appraisal within sources of evidence | 16 | If done, present data on critical appraisal of included sources of evidence (see item 12). | NA |
| Results of individual sources of evidence | 17 | For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives | 129-139 |
| Synthesis of results | 18 | Summarize and/or present the charting results as they relate to the review questions and objectives. | 129-139 |
| DISCUSSION | | | |

| | | | |
|---|---|---|---|
| Summary of evidence | 19 | Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups. | 139-150 |
| Limitations | 20 | Discuss the limitations of the scoping review process. | 151 |
| Conclusions | 21 | Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps. | 151-152 |
| FUNDING | | | |
| Funding | 22 | Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review. | vi |

*Appendix B2: Search strategy*

| | |
|---|---|
| **Search terms:** | Population: "runner" OR "running" |
| | Outcome: "injur*" |
| | Variables: "incidence" OR "prevalence" OR "risk" OR "rate" OR "burden" |
| **Limits** | Years: 1980-2023 |
| | Language: English |
| | Sample: Humans |
| **Excluded sources** | Review articles |
| | Case studies |
| | Commentaries |
| | Conference proceedings or posters |
| | Opinion articles |
| | Study protocols |

*Appendix B3: Inclusion and exclusion criteria*

| **Inclusion criteria** |
|---|
| 1. Studies which are prospective or retrospective cohort studies, clinical trials or cross-sectional studies examining running-related injuries. |
| 2. Studies which have investigated adult running populations (novice, recreational, elite, and collegiate athletes). |
| 3. Studies which have investigated lower limb musculoskeletal running-related injuries. |
| 4. Studies which are in English |
| 5. Studies which are fully published research articles. |
| **Exclusion criteria** |
| 1. Not a general running-related injury definition provided:<br>• Studies which provided a definition for a specific running-related injury (e.g., Achilles tendinopathy), rather than a general running-related injury definition. |
| 2. Wrong study design:<br>• Review articles, study protocols, or case studies.<br>• Studies which are published as conference proceedings, abstracts, or opinion pieces. |
| 3. Wrong patient population:<br>• Studies which have investigated cohorts that are not exclusively runners (e.g., track athletes, military personnel)<br>• Studies which have investigated cohorts that are not exclusively adult runners (e.g., child or adolescent runners) |
| 4. No definition of injury available |
| 5. Wrong outcomes:<br>• Studies which investigated upper limb musculoskeletal running-related injuries. |
| 6. Studies which are not in English |

*Appendix B4: List of included articles*

| | **Study** |
|---|---|

| | |
|---|---|
| **1** | (Valliant, 1981) |
| **2** | (Koplan, 1982) |
| **3** | (Hutson, 1984) |
| **4** | (Jacobs and Berson, 1986) |
| **5** | (Blair, Kohl and Goodyear, 1987) |
| **6** | (Bovens *et al.*, 1989) |
| **7** | (Macera, 1989) |
| **8** | (Walter, 1989) |
| **9** | (Fields, Delaney and Hinkle, 1990) |
| **10** | (van Mechelen *et al.*, 1993) |
| **11** | (Jakobsen *et al.*, 1994) |
| **12** | (Van Mechelek *et al.*, 1994) |
| **13** | (Koplan, Rothenberg and Jones, 1995) |
| **14** | (Messier *et al.*, 1995) |
| **15** | (Wen, Puffer and Schmalzried, 1997) |
| **16** | (Wen, Puffer and Schmalzried, 1998) |
| **17** | (Bishop and Fallon, 1999) |
| **18** | (Duffey *et al.*, 2000) |
| **19** | (Roberts, 2000) |
| **20** | (Chorley *et al.*, 2002) |
| **21** | (Hootman *et al.*, 2002) |
| **22** | (Taunton *et al.*, 2002) |
| **23** | (Taunton *et al.*, 2003) |
| **24** | (Lun, 2004) |
| **25** | (Gerlach *et al.*, 2005) |
| **26** | (Schache *et al.*, 2005) |
| **27** | (McKean, Manson and Stanish, 2006) |
| **28** | (Schwellnus and Stubbs, 2006) |
| **29** | (van Middelkoop *et al.*, 2007) |
| **30** | (Buist *et al.*, 2008) |
| **31** | (Gerlach *et al.*, 2008) |
| **32** | (Knobloch, Yoon and Vogt, 2008)K |
| **33** | (Van Middelkoop *et al.,* 2008) |
| **34** | (Van Middelkoop *et al.,* 2008) |
| **35** | (Hesar *et al.*, 2009) |
| **36** | (Van Ginckel *et al.*, 2009) |
| **37** | (Buist *et al.*, 2010) |
| **38** | (Buist *et al.*, 2010) |
| **39** | (Hoffman and Fogard, 2011) |
| **40** | (Voight *et al.*, 2011) |
| **41** | (Bredeweg *et al.*, 2012) |
| **42** | (Chang, Shih and Chen, 2012) |
| **43** | (Eskofier *et al.*, 2012) |
| **44** | (Ferreira *et al.*, 2012) |
| **45** | (Hespanhol Junior *et al.*, 2012) |
| **46** | (Vadeboncoeur *et al.*, 2012) |
| **47** | (Bredeweg *et al.*, 2013) |
| **48** | (Ellapen *et al.*, 2013) |

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|---|---|
| **49** | (Hamstra-Wright *et al.*, 2013) |
| **50** | (Hendricks and Phillips, 2013) |
| **51** | (Hespanhol, Costa and Lopes, 2013) |
| **52** | (Nielsen *et al.*, 2013) |
| **53** | (Nielsen *et al.*, 2013) |
| **54** | (Ramskov *et al.*, 2013) |
| **55** | (Rasmussen *et al.*, 2013) |
| **56** | (Adriaensens *et al.*, 2014) |
| **57** | (Agresta, Slobodinsky and Tucker, 2014) |
| **58** | (Hein *et al.*, 2014) |
| **59** | (Hoffman and Krishnan, 2014) |
| **60** | (Nielsen *et al.,* 2014) |
| **61** | (Nielsen *et al.*, 2014) |
| **62** | (Nielsen *et al.*, 2014) |
| **63** | (Nielsen *et al.*, 2014) |
| **64** | (Ryan *et al.*, 2014) |
| **65** | (Theisen *et al.*, 2014) |
| **66** | (van Poppel *et al.*, 2014) |
| **67** | (Dubois *et al.*, 2015) |
| **68** | (Hotta *et al.*, 2015) |
| **69** | (Kluitenberg *et al.*, 2015) |
| **70** | (Malisoux *et al.*, 2015) |
| **71** | (Malisoux *et al.*, 2015) |
| **72** | (Mann *et al.*, 2015) |
| **73** | (Peng *et al.*, 2015) |
| **74** | (Ramskov *et al.*, 2015) |
| **75** | (Switlick, Kernozek and Meardon, 2015) |
| **76** | (Davis, Bowser and Mullineaux, 2016) |
| **77** | (Hespanhol, Huisstede, *et al.*, 2016) |
| **78** | (Hespanhol Junior *et al.*, 2016) |
| **79** | (Hespanhol, de Carvalho, *et al.*, 2016) |
| **80** | (Kerr *et al.*, 2016) |
| **81** | (Kluitenberg *et al.*, 2016) |
| **82** | (Malisoux *et al.*, 2016) |
| **83** | (Smits *et al.*, 2016) |
| **84** | (Willwacher *et al.*, 2016) |
| **85** | (van der Worp *et al.*, 2016) |
| **86** | (van Poppel *et al.*, 2016) |
| **87** | (Vernillo *et al.*, 2016) |
| **88** | (Baltich *et al.*, 2017) |
| **89** | (Brund *et al.*, 2017) |
| **90** | (Dudley *et al.*, 2017) |
| **91** | (Fuller *et al.*, 2017) |
| **92** | (Hespanhol Junior, van Mechelen and Verhagen, 2017) |
| **93** | (Paquette, Milner and Melcher, 2017) |
| **94** | (Vitez *et al.*, 2017) |
| **95** | (Bertelsen *et al.*, 2018) |
| **96** | (Besomi *et al.*, 2018) |

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|---|---|
| **97** | (Chan *et al.*, 2018) |
| **98** | (Hespanhol, van Mechelen and Verhagen, 2018) |
| **99** | (Hjerrild *et al.*, 2018) |
| **100** | (Leppe and Besomi, 2018) |
| **101** | (Linton and Valentin, 2018) |
| **102** | (Kemler *et al.*, 2018) |
| **103** | (Kemler *et al.*, 2018) |
| **104** | (Mulvad *et al.*, 2018) |
| **105** | (Napier *et al.*, 2018) |
| **106** | (Ramskov *et al.*, 2018) |
| **107** | (Ramskov *et al.*, 2018) |
| **108** | (Small and Relph, 2018) |
| **109** | (Tillander *et al.*, 2018) |
| **110** | (van Poppel *et al.*, 2018) |
| **111** | (Vlahek and Matijević, 2018) |
| **112** | (Begizew, Grace and van Heerden, 2019) |
| **113** | (Besomi *et al.*, 2019) |
| **114** | (Brund *et al.*, 2019) |
| **115** | (Cahanin *et al.*, 2019) |
| **116** | (Dallinga *et al.*, 2019) |
| **117** | (Damsted *et al.*, 2019) |
| **118** | (Damsted *et al.,* 2019) |
| **119** | (Fokkema *et al.*, 2019) |
| **120** | (Fokkema *et al.*, 2019) |
| **121** | (Franke, Backx and Huisstede, 2019) |
| **122** | (Melgares, Fry and Sanchez, 2019) |
| **123** | (Onal *et al.*, 2019) |
| **124** | (Payne, D'Errico and Williams, 2019) |
| **125** | (Pérez-Morcillo *et al.*, 2019) |
| **126** | (Relph and Small, 2019) |
| **127** | (Smits *et al.*, 2019) |
| **128** | (Tenforde *et al.*, 2019) |
| **129** | (Van Oeveren *et al.*, 2019) |
| **130** | (Wiegand *et al.*, 2019) |
| **131** | (Benca *et al.*, 2020) |
| **132** | (Costa *et al.*, 2020) |
| **133** | (Craddock, Buchholtz and Burgess, 2020) |
| **134** | (de Jonge, Balk and Taris, 2020) |
| **135** | (Dijkhuis *et al.*, 2020) |
| **136** | (Fokkema *et al.*, 2020) |
| **137** | (Hofstede *et al.*, 2020) |
| **138** | (Jauhiainen *et al.*, 2020) |
| **139** | (Johnson *et al.*, 2020) |
| **140** | (Jungmalm *et al.*, 2020) |
| **141** | (Letafatkar, Rabiei and Afshari, 2020) |
| **142** | (Letafatkar *et al.*, 2020) |
| **143** | (Malisoux *et al.*, 2020) |
| **144** | (Matos *et al.*, 2020) |

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|---|---|
| **145** | (Moreno *et al.*, 2020) |
| **146** | (Taddei *et al.*, 2020) |
| **147** | (Tenforde *et al.*, 2020) |
| **148** | (Torres, Gomes and da Silva, 2020) |
| **149** | (Veras *et al.*, 2020) |
| **150** | (Winter *et al.*, 2020) |
| **151** | (Davis and Gruber, 2021) |
| **152** | (De Oliveira *et al.*, 2021)D |
| **153** | (Desai and Gruber, 2021) |
| **154** | (Desai *et al.*, 2021) |
| **155** | (Dillon *et al.*, 2021) |
| **156** | (Franke, de Vet and Huisstede, 2021) |
| **157** | (Gajardo-Burgos *et al.*, 2021) |
| **158** | (Graham *et al.*, 2021) |
| **159** | (Gruber *et al.*, 2021) |
| **160** | (Gutiérrez-Hellín *et al.*, 2021) |
| **161** | (Hespanhol *et al.*, 2021) |
| **162** | (Holmes *et al.*, 2021) |
| **163** | (Karsten Hollander *et al.*, 2021) |
| **164** | (Kliethermes *et al.*, 2021) |
| **165** | (Koech, Olivier and Tawa, 2021) |
| **166** | (Luedke and Rauh, 2021) |
| **167** | (Malisoux *et al.*, 2021) |
| **168** | (Mayne, Bleakley and Matthews, 2021) |
| **169** | (Mohseni *et al.*, 2021) |
| **170** | (Mousavi, Hijmans, *et al.*, 2021) |
| **171** | (Nakaoka *et al.*, 2021) |
| **172** | (Quirino *et al.*, 2021) |
| **173** | (Rhim *et al.*, 2021) |
| **174** | (Sanfilippo *et al.*, 2021) |
| **175** | (Sleeswijk Visser *et al.*, 2021) |
| **176** | (Warne *et al.*, 2021) |
| **177** | (Willems *et al.*, 2021) |
| **178** | (Viljoen, Sewry, *et al.*, 2021) |
| **179** | (Bunster *et al.*, 2022) |
| **180** | (Burke *et al.*, 2022) |
| **181** | (Cloosterman *et al.*, 2022) |
| **182** | (Desai and Gruber, 2022) |
| **183** | (Fortune *et al.*, 2022) |
| **184** | (Loudon and Parkerson-Mitchell, 2022) |
| **185** | (Madsen *et al.*, 2022) |
| **186** | (Malisoux *et al.*, 2022) |
| **187** | (Mokwena *et al.*, 2022) |
| **188** | (Ramskov *et al.*, 2022) |
| **189** | (Schmida *et al.*, 2022) |
| **190** | (Suda *et al.*, 2022) |
| **191** | (Swanevelder *et al.*, 2022) |
| **192** | (Toresdahl *et al.*, 2022) |

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|---|---|
| **193** | (van Iperen *et al.*, 2022) |
| **194** | (van Iperen *et al.,* 2022) |
| **195** | (Venable *et al.*, 2022) |
| **196** | (Baart *et al.*, 2023) |
| **197** | (Burke *et al.*, 2023) |
| **198** | (Chen *et al.*, 2023) |
| **199** | (Davinelli *et al.*, 2023) |
| **200** | (Desai *et al.*, 2023) |
| **201** | (Fokkema *et al.*, 2023) |
| **202** | (Frederico *et al.*, 2023) |
| **203** | (Slabber *et al.*, 2023) |
| **204** | (Van Der Does, Kemler and Gouttebarge, 2023) |

*Appendix B5: List of articles that directly or indirectly use the running-related injury consensus definition*

| | **Study** | **Use of consensus definition** |
|---|---|---|
| **1** | (Besomi *et al.*, 2018) | Direct |
| **2** | (Leppe and Besomi, 2018) | Direct |
| **3** | (Mulvad *et al.*, 2018) | Direct |
| **4** | (Napier *et al.*, 2018) | Direct |
| **5** | (Damsted *et al.,* 2019) | Direct |
| **6** | (Damsted *et al.,* 2019) | Direct |
| **7** | (Fokkema *et al.*, 2019) | Indirect |
| **8** | (Fokkema *et al.*, 2019) | Indirect |
| **9** | (Onal *et al.*, 2019) | Direct |
| **10** | (Payne, D'Errico and Williams, 2019) | Indirect |
| **11** | (Pérez-Morcillo *et al.*, 2019) | Direct |
| **12** | (Tenforde *et al.*, 2019) | Direct |
| **13** | (Craddock, Buchholtz and Burgess, 2020) | Direct |
| **14** | (de Jonge, Balk and Taris, 2020) | Direct |
| **15** | (Fokkema *et al.*, 2020) | Indirect |
| **16** | (Jauhiainen *et al.*, 2020) | Direct |
| **17** | (Johnson *et al.*, 2020) | Direct |
| **18** | (Jungmalm *et al.*, 2020) | Direct |
| **19** | (Letafatkar, Rabiei and Afshari, 2020) | Direct |
| **20** | (Malisoux *et al.*, 2020) | Direct |
| **21** | (Tenforde *et al.*, 2020) | Direct |
| **22** | (Davis and Gruber, 2021) | Direct |
| **23** | (De Oliveira *et al.*, 2021) | Direct |
| **24** | (Desai *et al.*, 2021) | Direct |
| **25** | (Dillon *et al.*, 2021) | Direct |
| **26** | (Hollander *et al.*, 2021) | Direct |
| **27** | (Malisoux *et al.*, 2021) | Direct |
| **28** | (Mousavi *et al.*, 2021) | Direct |
| **29** | (Nakaoka *et al.*, 2021) | Direct |
| **30** | (Quirino *et al.*, 2021) | Direct |

| | | |
|---|---|---|
| **31** | (Rhim *et al.*, 2021) | Direct |
| **32** | (Sleeswijk Visser *et al.*, 2021) | Indirect |
| **33** | (Bunster *et al.*, 2022) | Direct |
| **34** | (Burke *et al.*, 2022) | Direct |
| **35** | (Cloosterman *et al.*, 2022) | Direct |
| **36** | (Desai and Gruber, 2022) | Direct |
| **37** | (Fortune *et al.*, 2022) | Direct |
| **38** | (Malisoux *et al.*, 2022) | Direct |
| **39** | (Schmida *et al.*, 2022) | Direct |
| **40** | (van Iperen *et al.*, 2022) | Direct |
| **41** | (van Iperen *et al.,* 2022) | Direct |
| **42** | (Burke *et al.*, 2023) | Direct |
| **43** | (Chen *et al.*, 2023) | Indirect |
| **44** | (Desai *et al.*, 2023) | Direct |

## 10.3 Appendix C. Study 2: An investigation into the measurement of injury severity in running-related injury research: A scoping review

*Appendix C1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses scoping review (PRISMA-ScR) checklist (Tricco et al., 2018)*

| **Section** | **Item** | **PRISMA-ScR checklist item** | **Reported on page** |
|---|---|---|---|
| TITLE | | | |
| Title | 1 | Identify the report as a scoping review | 154 |
| ABSTRACT | | | |
| Structured summary | 2 | Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives. | 154-155 |
| INTRODUCTION | | | |
| Rationale | 3 | Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach. | 155-156 |
| Objectives | 4 | Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives. | 156 |
| METHODS | | | |
| Protocol and registration | 5 | Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number. | 157 |
| Eligibility criteria | 6 | Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale. | 157 |
| Information sources | 7 | Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed. | 157 |

| | | | |
|---|---|---|---|
| Search | 8 | Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated. | 157-158 |
| Selection of sources of evidence | 9 | State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review. | 158 |
| Data charting process | 10 | Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators. | 158-159 |
| Data items | 11 | List and define all variables for which data were sought and any assumptions and simplifications made. | 158-159 |
| Critical appraisal of individual sources of evidence | 12 | If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate). | NA |
| Synthesis of results | 13 | Describe the methods of handling and summarizing the data that were charted. | 159 |
| RESULTS | | | |
| Selection of sources of evidence | 14 | Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram. | 144 |
| Characteristics of sources of evidence | 15 | For each source of evidence, present characteristics for which data were charted and provide the citations. | 161 |

| | | | |
|---|---|---|---|
| Critical appraisal within sources of evidence | 16 | If done, present data on critical appraisal of included sources of evidence (see item 12). | NA |
| Results of individual sources of evidence | 17 | For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives | 161-176 |
| Synthesis of results | 18 | Summarize and/or present the charting results as they relate to the review questions and objectives. | 161-176 |
| DISCUSSION | | | |
| Summary of evidence | 19 | Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups. | 176-184 |
| Limitations | 20 | Discuss the limitations of the scoping review process. | 184 |
| Conclusions | 21 | Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps. | 185 |
| FUNDING | | | |
| Funding | 22 | Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review. | vi |

*Appendix C2: Search strategy*

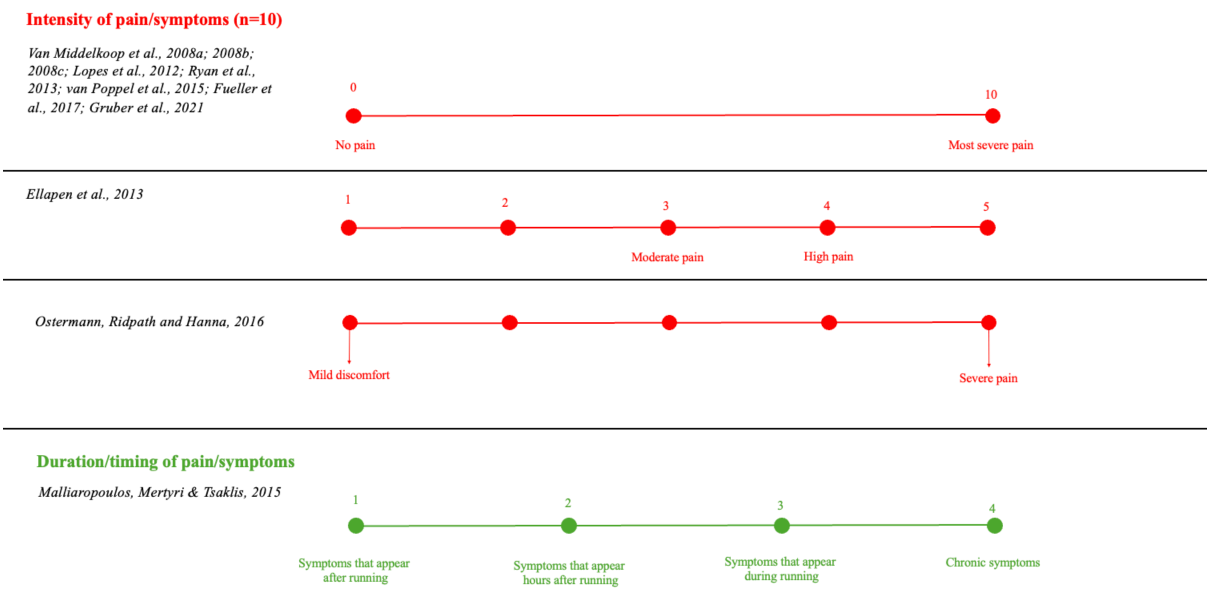
| | | |
|---|---|---|
| **Search terms** | Population: "runner" OR "running" |
| | Outcomes: "injur*" AND "sever*" |
| | Variables: "incidence" OR "prevalence" OR "rate" OR "risk" OR "burden" OR "impact" OR "health" OR "time loss" OR "restrict*" OR "financ*" OR "economic" OR "psych*" OR "fear avoidance" OR "social" OR "work" |
| **Limits** | Years: 1980-2023 |
| | Language: English |
| | Sample: Humans |
| | Publication type: journal articles |
| **Excluded sources** | Review articles<br>Case studies<br>Commentaries<br>Conference proceedings or posters<br>Opinion articles<br>Study protocols |

*Appendix C3: Inclusion and exclusion criteria*

| **Inclusion criteria** |
|---|
| 1. Studies which investigated running populations exclusively (e.g., novice, recreational, trail). |
| 2. Studies which investigated adult running populations. |
| 3. Studies which investigated running-related injuries. |
| 4. Studies which included a measure of injury severity. |
| 5. Studies which included injuries across an entire injury severity measure. |
| 6. Studies which included a severity measure for general running-related injuries. |
| 7. Studies which investigated lower limb musculoskeletal running-related injuries. |
| 8. Prospective/Retrospective cohort studies, cross-sectional studies, clinical trials |
| 9. Studies which are published in English. |
| **Exclusion criteria** |

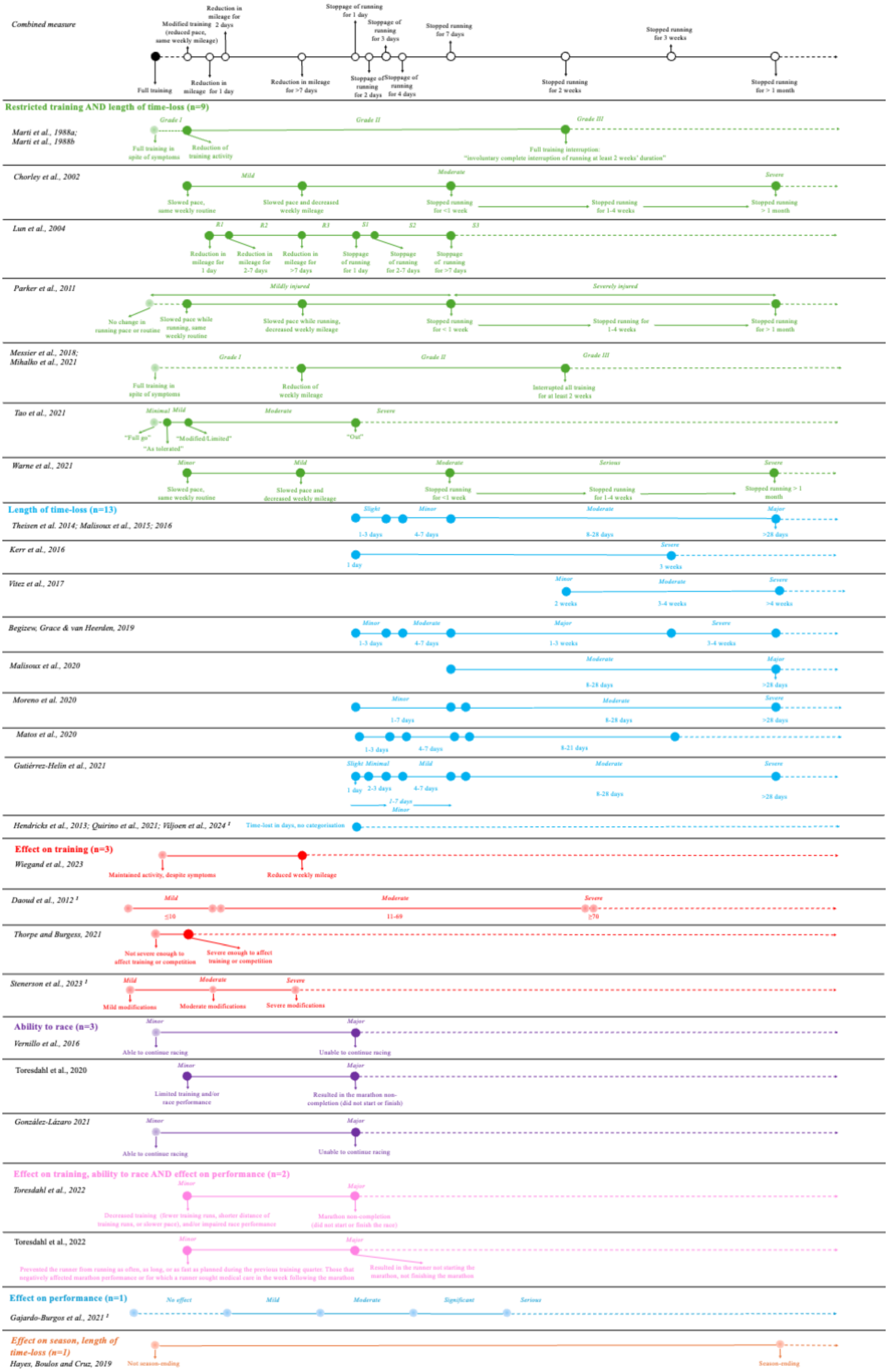
| |
|---|
| 1. Studies which did not investigate running populations exclusively (e.g., military personnel, track and field). |
| 2. Studies which did not investigate adult running populations (e.g., children, adolescents) |
| 3. Studies which did not investigate running-related injuries. |
| 4. Studies which did not include a measure of injury severity. |
| 5. Studies which only included injuries of a particular severity. |
| 6. Studies which included a severity measure for specific running-related injury (e.g., Achilles tendinopathy). |
| 7. Studies which did not investigate lower limb musculoskeletal running-related injuries. |
| 8. Review articles, study protocols, case studies, conference proceedings, abstracts, opinion pieces. |
| 9. Studies which are not published in English. |

*Appendix C4: Individual measures of injury severity defined by the primary criterion 'physical description'*



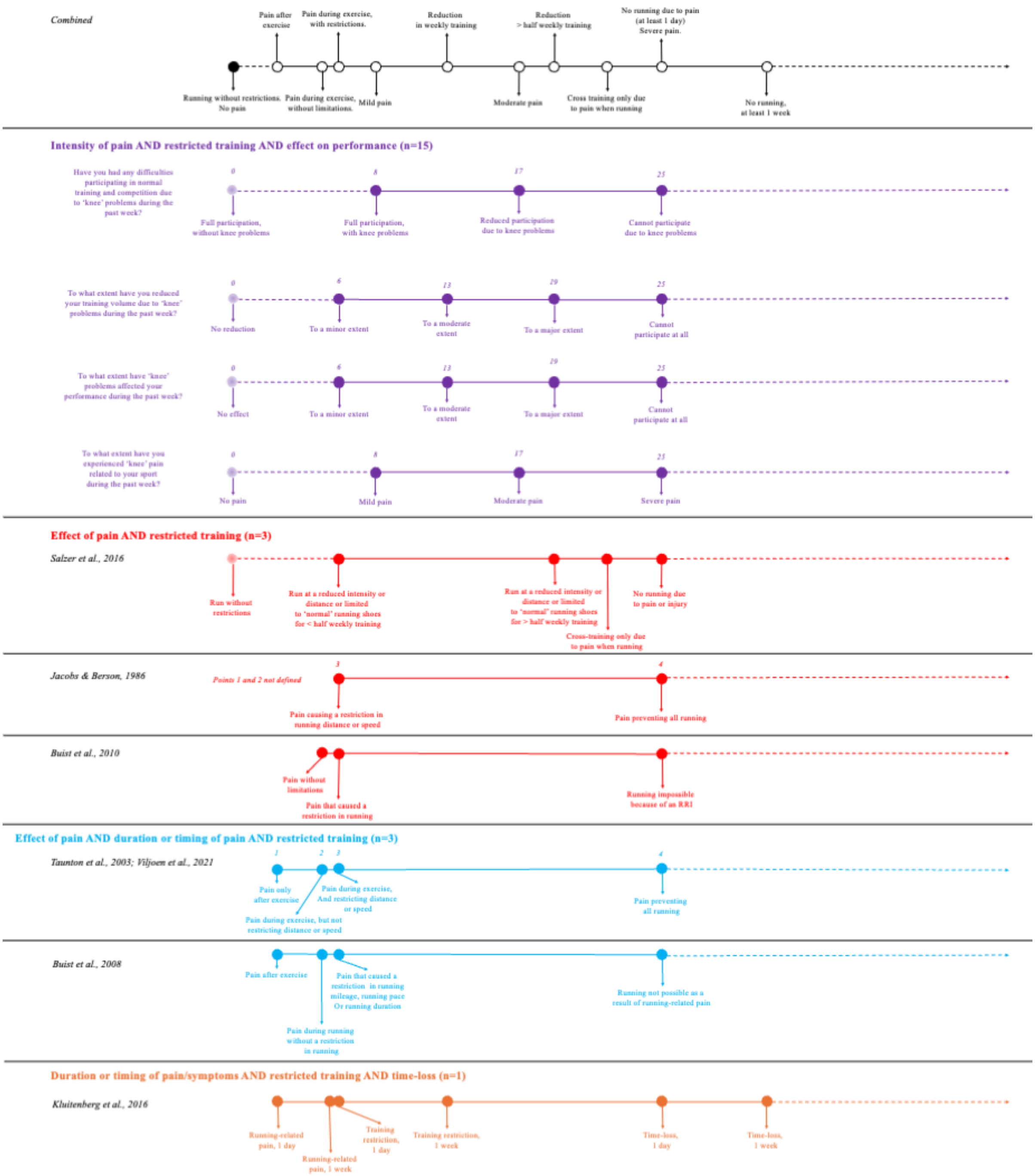

It was not possible to create a combined measure of injury severity for this primary criterion, therefore, individual measures are not aligned

*Appendix C5: Combined measure and individual measures of injury severity defined by the primary criterion 'effect on running'*[11]




[11] Some severity scales could not be aligned with others as there was no commonality in terms of how the levels of injury severity were described.

*Appendix C6: Combined measure and individual measures of injury severity defined by the primary criteria 'effect on running AND physical description'*[12]




[12] Some severity scales could not be aligned with others as there was no commonality in terms of how the levels of injury severity were described.

*Appendix C7: Details on the measurement of injury severity used per study*

| | Study | Aim/Purpose | Primary criteria of injury severity | Gradation system | Classification of grading system | Minimum point | Number of categories |
|---|---|---|---|---|---|---|---|
| **1** | (Jacobs and Berson, 1986) | Risk factor examination | Effect on running AND physical description | Categorical | Numeric (1-4) | Point 1 not defined. | 4 categories |
| **2** | (Marti *et al.*, 1988)28/08/2024 07:23:00 | Injury epidemiology, risk factor, and injury consequence examination | Effect on running | Categorical | Numeric (Grades I-III) | Full activity despite symptoms | 3 categories |
| **3** | (Marti, 1988) | Risk factor, injury consequence and running benefit examination | Effect on running | Categorical | Numeric (grades I-III) | Full activity despite symptoms | 3 categories |
| **4** | (Chorley *et al.*, 2002)28/08/2024 07:23:00 | Risk factor examination | Effect on running | Categorical | Descriptor (mild, moderate, severe) | Slowed pace, same weekly routine | 3 categories |
| **5** | (Taunton *et al.*, 2003) | Injury epidemiology, risk factor examination | Effect on running AND physical description | Categorical | Numeric (1-4) | Pain only after exercise | 4 categories |
| **6** | (Lun, 2004) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Numeric (R1-R3, S1-S3) | Reduction in running mileage for 1 day | 6 categories |
| **7** | (Van Middelkoop *et al.*, 2007) | Injury epidemiology, risk factor examination | Physical description | Continuous | Pain scale | 0/10 pain intensity | Continuous |
| **8** | (van Middelkoop *et al.*, 2007) | Injury epidemiology, injury consequence examination | Physical description | Continuous | Pain scale | 0/10 pain intensity | Continuous |
| **9** | (Van Middelkoop *et al.,* 2008) | Injury epidemiology, risk factor examination | Physical description | Continuous | Pain scale | 0/10 pain intensity | Continuous |
| **10** | (IBuist *et al.*, 2010) | Risk factor examination | Effect on running AND physical description | Categorical | None | Pain after running | 4 categories |
| **11** | (Buist *et al.*, 2010) | Risk factor examination | Effect on running AND physical description | Categorical | None | Pain without running limitations | 3 categories |
| **12** | (Lopes *et al.*, 2011) | Injury epidemiology | Physical description | Continuous | Pain scale | 0/10 pain intensity | Continuous |
| **13** | (Parker *et al.*, 2011) | Risk factor examination | Effect on running | Categorical | Descriptor (mild (1+2), moderate (3+4), severe (5+6) | No change in running pace or routine | 6 categories |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **14** | (Daoud *et al.*, 2012) | Injury epidemiology | Effect on running | Categorical | Descriptor (mild, moderate, severe) | Score <10 on the Running Injury Severity Score | Continuous<br>,<br>3 categories |
| **15** | (Ellapen *et al.*, 2013) | Injury epidemiology, risk factor examination | Physical description | Categorical | Numeric (1-5) | 1/5 pain scale | Continuous |
| **16** | (Hendricks and Phillips, 2013) | Injury epidemiology | Effect on running | Continuous | Number of days | Not specified | Continuous |
| **17** | (Theisen *et al.*, 2014) | Risk factor examination | Effect on running | Categorical | Descriptor (slight, minor, moderate, major) | 0-3 days' time-loss | 4 categories |
| **18** | (Ryan *et al.*, 2014) | Injury epidemiology, risk factor examination | Physical description | Continuous | Pain scale | 0/10 pain scale | Continuous |
| **19** | (van Poppel *et al.*, 2014) | Injury epidemiology | Physical description | Continuous | Pain scale | 0/10 pain scale | Continuous |
| **20** | (Malisoux *et al.*, 2015) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (slight, minor, moderate, major) | 0-3 days' time-loss | 4 categories |
| **21** | (Malliaropoulos, Mertyri and Tsaklis, 2015) | Injury epidemiology, risk factor examination | Physical description | Categorical | Numeric (Grade I-IV) | Symptoms that appear after running | 4 categories |
| **22** | (Hespanhol Junior *et al.*, 2016) | Injury consequence examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **23** | (Kerr *et al.*, 2016) | Injury epidemiology | Effect on running | Categorical | Length of time-loss | <1 day time-loss | 2 categories |
| **24** | (Kluitenberg *et al.*, 2016)28/08/2024 07:23:00 | Injury epidemiology, research methodology examination | Effect on running | Categorical | Numeric (R1-R3, S1-S3) | Reduction in running mileage for 1 day | 6 categories |
| **25** | (Malisoux *et al.*, 2016) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (slight, minor, moderate, major) | 0-3 days' time-loss | 4 categories |
| **26** | (Ostermann, Ridpath and Hanna, 2016)28/08/2024 07:23:00 | Injury epidemiology | Physical description | Continuous | Pain scale | Mild discomfort | Continuous |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **27** | (Salzler *et al.*, 2016) | Injury epidemiology, risk factor examination | Effect on running AND physical description | Categorical | None | Running at a reduced intensity/distance or limited to "normal" running shoes (due to pain in 5-toed shoes) for less than half of your weekly training | 4 categories |
| **28** | (Vernillo *et al.*, 2016) | Injury epidemiology | Effect on running | Categorical | Descriptor (minor, major) | Ability to continue in the race | 2 categories |
| **29** | (Baltich *et al.*, 2017) | Injury epidemiology | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **30** | (Fuller *et al.*, 2017) | Injury epidemiology, risk factor examination | Physical description | Continuous | Pain scale | 0/10 pain scale | Continuous |
| **31** | (Hespanhol Junior, van Mechelen and Verhagen, 2017)28/08/2024 07:23:00 | Injury consequence examination | Effect on running AND physical description | Categorical | Descriptor (not substantial, substantial) | >0/100 on OSTRC severity score | Continuous, 2 categories |
| **32** | (Vitez *et al.*, 2017) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (minor, moderate, severe) | 2 weeks' time-loss | 3 categories |
| **33** | (Bertelsen *et al.*, 2018) | Injury epidemiology | Effect on running AND physical description | Categorical | Descriptor (not substantial, substantial) | >0/100 on OSTRC severity score | Continuous, 2 categories |
| **34** | (Hespanhol, van Mechelen and Verhagen, 2018) | Injury prevention examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **35** | (Hollander *et al.*, 2018)28/08/2024 07:23:00 | Injury epidemiology | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **36** | (Messier *et al.*, 2018) | Risk factor examination | Effect on running | Categorical | Numeric (Grade I-III) | Full activity despite symptoms | 3 categories |
| **37** | (Begizew, Grace and van Heerden, | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (minor, moderate, major, severe) | Absent from training/ competition for 1-3 days | 4 categories |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2019)28/08/2024 07:23:00 | | | | | | |
| **38** | (Franke, Backx and Huisstede, 2019) | Injury epidemiology | Effect on running AND physical description | Categorical | Descriptor (not substantial, substantial) | >0/100 on OSTRC severity score | Continuous, 2 categories |
| **39** | (Hayes, Boulos and Cruz, 2019) | Risk factor examination | Effect on running | Categorical | Descriptor (not season ending, season ending) | Not season ending | 2 categories |
| **40** | (Hofstede *et al.*, 2020) | Injury epidemiology, risk factor, and injury prevention examination | Effect on running AND physical description | Categorical | Descriptor (not substantial, substantial) | >0/100 on OSTRC severity score | Continuous, 2 categories |
| **41** | (Malisoux *et al.*, 2020) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (moderate, major) | 8-28 days' time-loss | 2 categories |
| **42** | (Matos *et al.*, 2020)28/08/2024 07:23:00 | Risk factor examination | Effect on running | Categorical | Numeric (Grade I-III) | 1-3 days' time-loss | 3 categories |
| **43** | (Moreno *et al.*, 2020) | Injury epidemiology | Effect on running | Categorical | Descriptor (minor, moderate, severe) | 1-7 days until full recovery | 3 categories |
| **44** | (Toresdahl *et al.*, 2020)28/08/2024 07:23:00 | Injury epidemiology, injury prevention examination | Effect on running | Categorical | Descriptor (minor, major) | Limited training and/or race performance | 2 categories |
| **45** | (Franke, de Vet and Huisstede, 2021) | Research methodology examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **46** | (Gajardo-Burgos *et al.*, 2021)28/08/2024 07:23:00 | Injury epidemiology | Effect on running | Categorical | Descriptor (mild, moderate, significant, serious) | Mild | 4 categories |
| **47** | (Gamez-Paya *et al.*, 2021) | Injury epidemiology, injury consequence examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **48** | (González-Lázaro, Arribas-Cubero and Rodríguez-Marroyo, 2021)28/08/2024 07:23:00 | Injury epidemiology | Effect on running | Categorical | Descriptor (minor, major) | Ability to continue running | 2 categories |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **49** | (Gruber *et al.*, 2021) | Risk factor examination | Physical description | Continuous | Pain scale | 0/10 pain intensity | Continuous |
| **50** | (Gutiérrez-Hellín *et al.*, 2021) | Injury epidemiology | Effect on running | Categorical | Descriptor (minor, moderate, serious) | 1-7 days of time-loss | 3 categories |
| **51** | (Mihalko *et al.*, 2021)28/08/2024 07:23:00 | Injury consequence examination | Effect on running | Categorical | Numeric (grade I-III) | Full activity despite symptoms | 3 categories |
| **52** | (Quirino *et al.*, 2021) | Running kinematics examination | Effect on running | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **53** | (Tao, Thompson and Weber, 2021)28/08/2024 07:23:00 | Risk factor examination | Effect on running | Categorical | Descriptor (mild, moderate, severe) | "As tolerated" | 3 categories |
| **54** | (Thorpe, Blockman and Burgess, 2021)28/08/2024 07:23:00 | Injury management examination | Effect on running | Categorical | Descriptor (not severe enough, severe enough) | Not severe enough to affect training/competition | 2 categories |
| **55** | (Viljoen, Janse van Rensburg, Jansen van Rensburg, *et al.*, 2021)28/08/2024 07:23:00 | Injury epidemiology | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **56** | (Viljoen *et al.*, 2021) | Injury epidemiology, risk factor examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **57** | (Viljoen *et al.*, 2021) | Injury epidemiology, risk factor examination | Effect on running AND physical description | Categorical | Numeric (grade I-IV) | Symptoms after exercise | 4 categories |
| **58** | (Warne *et al.*, 2021) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (minor, mild, moderate, serious, severe) | Slowed pace, same weekly routine | 5 categories |
| **59** | (Cloosterman *et al.*, 2022) | Injury epidemiology, injury prevention examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **60** | (Toresdahl *et al.*, 2022) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (minor, major) | Decreased training (fewer runs, shorter distance or | 2 categories |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | slower pace) and/or impaired race performance | |
| **61** | (Toresdahl *et al.*, 2022) | Injury epidemiology, risk factor examination | Effect on running | Categorical | Descriptor (minor, major) | Decreased training (fewer runs, shorter distance or slower pace) | 2 categories |
| **62** | (Stenerson *et al.*, 2023)28/08/2024 07:23:00 | Injury epidemiology, injury prevention examination | Effect on running | Categorical | Numeric (1-3) | Mild extent of training modifications | 3 categories |
| **63** | (Van Der Does, Kemler and Gouttebarge, 2023) | Injury epidemiology, injury prevention examination | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **64** | (Wiegand, Tandy and Silvernail, 2023) | Injury epidemiology, research methodology examination | Effect on running | Categorical | Numeric (Grade I-II) | Full activity despite symptoms | 2 categories |
| **65** | (Zapata-Rodrigo *et al.*, 2023)28/08/2024 07:23:00 | Injury epidemiology | Effect on running AND physical description | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |
| **66** | (Viljoen *et al.*, 2024) | Injury epidemiology | Effect on running | Continuous | OSTRC severity score | 0/100 on OSTRC severity score | Continuous |

Note: OSTRC = Oslo Sports Trauma Research Centre

*Appendix C8: Primary, secondary and tertiary definition criteria used to define injury severity*

| **Primary definition criteria** | **Secondary definition criteria** | **Tertiary definition criteria** |
|---|---|---|
| Effect on running (83%, n=55) | Restricted training (67%, n=37) | Restricted distance/mileage (74%, n=27) |
| | | Restricted speed/pace/intensity (27%, n=10) |
| | | Restricted training (not specified) (27%, n=10) |
| | | Restricted frequency (5%, n=2) |
| | | Restricted duration (3%, n=1) |
| | Length of time-loss (42%, n=23) | |
| | Effect on performance (35%, n=19) | |
| | Affected ability to race (11%, n=6) | |
| | Effect on season (2%, n=1) | |
| Physical description (50%, n=33) | Intensity of pain/symptoms (76%, n=25) | |
| | Timing/Duration of pain/symptoms (18%, n=6) | |
| | Effect of pain/symptoms on running (18%, n=6) | |

*Appendix C9: Incidence rates per anatomical location and type of running-related injury (n=54)*

| | **Study** | **Incidence rate per anatomical location** | | | | | | **Incidence of types of RRIs** |
|---|---|---|---|---|---|---|---|---|
| | | **Back/Trunk** | **Hip/Groin/Pelvis** | **Thigh** | **Knee** | **Calf/Leg/Achilles** | **Ankle/Foot/Toes** | |
| **1** | Marti *et al.* (1988) | 2% | 6% | 5% | 28% | 30% | 29% | Joint injury (21.7%), tendon injury (17%), sprain/ligament injury (13.7%) |
| **2** | Marti (1988) | - | - | - | 13% | 12% | - | Periostitis (17%), muscle injury (10%), ligament injury (7%) |
| **3** | Taunton *et al*. (2003) | NR | NR | NR | NR | NR | NR | MTSS most commonly diagnosed (no incidence rate provided) |
| **4** | Lun (2004) | - | - | 9% | - | 9% | 15% | PFPS most commonly diagnosed (n=6) |
| **5** | Van Middelkoop *et al*. (2007) | - | 10% | 14% | 29% | 41% | 25% | NR |
| **6** | Van Middelkoop *et al*. (2007) | - | - | 19% | 27% | 34% | - | NR |
| **7** | Van Middelkoop *et al*. (2008) | - | - | 16% | 29% | 27% | - | NR |
| **8** | Lopes *et al*. (2011) | 6% | 5% | 4% | 12% | 5% | 9% | NR |
| **9** | Parker *et al*. (2011) | NR | NR | NR | NR | NR | NR | NR |
| **10** | Daoud *et al*. (2012) | NR | NR | NR | NR | NR | NR | Muscle strain (21.5%), MTSS (13.8%), knee pain (7.7%), ITBS (7.2%), Achilles tendinopathy (6.6%) |
| **11** | Ellapen *et al*. (2013 | - | 16% | 14% | 26% | 22% | 19% | NR |
| **12** | Hendricks and Phillips (2013) | 18% | 10% | 20% | 18% | 22% | 8% | NR |
| **13** | Ryan *et al*. (2014) | NR | NR | NR | NR | NR | NR | NR |
| **14** | Theisen *et al*. (2014) | 10% | 7% | 17% | 25% | 22% | 16% | Muscle/Tendon (70%), capsule/ligament (16%), fracture/bone (4%), other (4%), |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | contusion (3%), nervous system (3%) |
| **15** | Van Poppel *et al*. (2014) | - | 17% | - | 34% | 17% | - | NR |
| **16** | Malisoux *et al*. (2015) | 10% | 7% | 18% | 20% | 20% | 25% | NR |
| **17** | Malliaropoulos, Mertyri and Tsaklis (2015) | 43% | 35% | 35% | 40% | - | - | Bone stress (22%), ITBS (16%). Achilles tendon and lower back injuries were the most severe. |
| **18** | Kluitenberg *et al*. (2016) | NR | NR | NR | NR | NR | NR | NR |
| **19** | Kerr *et al*. (2016) | - | - | Male: 13% Female: 15% | Male: 11% Female: 12% | Male: 35% Female: 24% | Male: 16% Female: 15% | NR |
| **20** | Malisoux *et al*. (2016) | SS: 3% MCS: 0% | SS: 8% MCS: 3% | SS: 8% MCS: 12% | SS: 17% MCS: 12% | SS: 27% MCS: 21% | SS: 37% MCS: 42% | NR |
| **21** | Ostermann, Ridpath and Hanna (2016) | NR | NR | NR | NR | NR | NR | NR |
| **22** | Salzler *et al*. (2016) | - | - | - | 17% | 58% | 17% | NR |
| **23** | Vernillo *et al*. (2016) | NR | NR | NR | NR | NR | NR | Plantar fascitis (n=16), ankle sprain (n=16) |
| **24** | Baltich *et al*. (2017) | - | - | - | 46% | - | 31% | NR |
| **25** | Fuller *et al*. (2017) | NR | NR | NR | NR | NR | NR | NR |
| **26** | Vitez *et al*. (2017) | - | - | - | 30% | 36% | 15% | NR |
| **27** | Bertelsen *et al*. (2018) | NR | NR | NR | NR | NR | NR | NR |
| **28** | Hollander *et al*. (2018) | - | 9% | 9% | 24% | 12% | 23% | NR |
| **29** | Messier *et al*. (2018) | 3% | 16% | 8% | 28% | 12% | 33% | NR |
| **30** | Begizew, Grace and van Heerden (2019) | - | 4% | 6% | 34% | 29% | 29% | Muscle strain (36.4%), joint sprain (29.4%), tendonitis (20.3%), contusion (6.3%), fracture (5.6%) dislocation (2.1%). |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **31** | Franke, Backx and Huisstede (2019) | - | - | - | 15% | 26% | 13% | Muscle and tendon injuries (46.7%), overuse RRIs (31.5%) Ankle and groin injuries were the most severe. |
| **32** | Hayes, Boulos and Cruz. (2019) | - | 22% | - | 16% | 27% | 45% | |
| **33** | Hofstede *et al*. (2020) | - | - | - | 4% | 4% | 6% | NR |
| **34** | Malisoux *et al*. (2020) | SfS: 0%<br>HS: 3% | SfS: 11%<br>HS: 5% | SfS: 9%<br>HS: 7% | SfS: 22%<br>HC: 22% | SfS: 17%<br>HS: 20% | SfS: 41%<br>HS: 43% | NR |
| **35** | Matos *et al*. (2020) | NR | NR | NR | NR | NR | NR | NR |
| **36** | Moreno *et al*. (2020)* | - | 12% | 10% | 15% | 26% | 38% | Tendon (36.1%), strain/muscle injury (22.6%), sprain/ligament injury (21.3%), bone injury (9.8%), nerve injury (6.6%) |
| **37** | Toresdahl *et al*. (2020) | NR | NR | NR | NR | NR | NR | NR |
| **38** | Garjardo-Burgos *et al*. (2021) | NR | NR | NR | NR | NR | NR | NR |
| **39** | Gamez-Paya *et al*. (2021) | NR | NR | NR | NR | NR | NR | Achilles tendinopathy (35%), plantar fasciitis (30%), patellar tendinopathy (25%), ITBS (10%) |
| **40** | González-Lázaro *et al*. (2021) | - | - | - | 14% | - | 43% | NR |
| **41** | Gutiérrez-Hellín *et al*. (2021) | - | 15% | 16% | 10% | 27% | 26% | Muscle strain (19.6%), bone injury (13.7%), tendon injury (33.3%), sprain/ligament injury (7.8%) |
| **42** | Thorpe *et al*. (2021) | NR | NR | NR | NR | NR | NR | NR |
| **43** | Viljoen *et al*. (2021) | - | - | - | 27% | - | 38% | Muscle/tendon unit injury (44.1%), ligament/joint capsule injury (19.6%), tendinopathy (27.5%), joint sprain (19.6%), muscle injury (15.7%) |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **44** | Viljoen *et al*. (2021) | 5% | 6% | 8% | 30% | 18% | 27% | Muscle/tendon unit injury (52.7%), muscle injury (20.5%), joint sprain (8.8%) |
| **45** | Viljoen *et al*. (2021) | NR | NR | NR | NR | NR | NR | NR |
| **46** | Warne *et al*. (2021) | - | 15% | - | 17% | 16% | 34% | NR |
| **47** | Cloosterman *et al*. (2021) | - | - | - | 11% | - | - | NR |
| **48** | Toresdahl *et al*. (2022) | NR | NR | NR | NR | NR | NR | Major injury: bone stress (31.3%). Minor injuries: knee pain (13%), calf strain (9.6%), MTSS (9.2%), ITBS (7.3%), Achilles tendinopathy (5.8%) |
| **49** | Toresdahl *et al*. (2022) | NR | NR | NR | NR | NR | NR | NR |
| **50** | Stenerson *et al*. (2023) | - | 18% | - | 22% | 16% | 31% | NR |
| **51** | Van Der Does, Kemler and Gouttebarge (2023) | NR | NR | NR | NR | NR | NR | NR |
| **52** | Wiegand *et al*. (2023) | NR | NR | NR | NR | NR | NR | NR |
| **53** | Zapata-Rodrigo *et al*. (2023) | - | 17% | 8% | 8% | 8% | 58% | NR |
| **54** | Viljoen *et al*. (2024) | - | 12% | 6% | 28% | 17% | 27% | Muscle injury (31%), tendinopathy (25%), joint sprain (11%), fracture (6%), cartilage (6%). |

* Indicates that figures represent a breakdown of the locations of the total number of injuries, not the incidence rate per location. NR: not reported; MTSS: medial tibial stress syndrome; PFPS: patellofemoral pain syndrome; ITBS: iliotibial band syndrome, SS: standard shoe, MCS: motion control shoe, SfS: soft shoe, HC: hard shoe.

*Appendix C10 Risk factors investigated across studies (n=35)*

| | **Training-related (n=29 factors)** | **Biomechanical (n=20 factors)** | **Socio-demographics (n=14 factors)** | **Health-related (n=10 factors)** | **Psychosocial (n=5 factors)** | **Sport history (n=3 factors)** |
|---|---|---|---|---|---|---|
| **1** | Weekly mileage (51%, n=18) * | Q angle (11%, n=4) | Height (57%, n=20) | Previous injury (63%, | Behaviour type | Other sport |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | n=22) | (3%, n=1) | participation * (14%, n=5) |
| **2** | Running experience (46%, n=16) * | Foot arch type (9%, n=3) | Weight (57%, n=20) | Current injury (11%, n=4) | Personality type (3%, n=1) * | Cross-training (11%, n=4) |
| **3** | Running shoes (43%, n =15) * | Hip ROM (6%, n=2) | Sex (57%, n=20) * | Illness history (9%, n=3) | Self-efficacy (3%, n=1) * | Strength training (9%, n=3) |
| **4** | Session frequency (34%, n=12) * | Ankle ROM (6%, n=2) | Age (23%, n=8) * | Chronic disease (6%, n=3) * | Satisfaction with life (3%, n=1) * | |
| **5** | Terrain (38%, n=11) * | Foot strike (6%, n=2) | Alcohol use (14%, n=5) | Injury type (3%, n=1) | Anxiety (3%, n=1) | |
| **6** | Average pace (17%, n=6) * | Impact transient peak force (6%, n=2) | BMI (14%, n=5) * | Missed work (3%, n=1) | | |
| **7** | Stretching (17%, n=6) * | Dynamic balance (3%, n=1) * | Smoking status (11%, n=4) | Blood pressure (3%, n=1) | | |
| **8** | Weekly running duration (17%, n=6) | Knee genu varum (3%, n=1) | Type of work (6%, n=2) * | Medication use (6%, n=2) | | |
| **9** | Marathon experience (9%, n=3) | Leg length (3%, n=1) | Ethnicity (3%, n=1) | Treatment of previous injury (3%, n=1) | | |
| **10** | Race experience (9%, n=3) | Rearfoot & forefoot valgus (3%, n=1) | Drug use (3%, n=2) | Medical consultations (3%, n=1) | | |
| **11** | Type of training (6%, n=3) * | Standing pronation (3%, n=1) | Diet (3%, n=1) | | | |
| **12** | Orthotics (6%, n=2) | Navicular drop (3%, n=1) * | Food supplements (3%, n=1) | | | |
| **13** | Motivation (6%, n=2) * | Hamstring flexibility (3%, n=1) | Sleep quality (3%, n=1) | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **14** | Perceived exertion (6%, n=2) | Ankle flexibility (3%, n=1) | Contraceptive use (3%, n=1) | | | |
| **15** | Session GPS data (6%, n=2) | Knee strength (3%, n=1) | | | | |
| **16** | Following a training plan (6%, n=2) | Ankle strength (3%, n=1) | | | | |
| **17** | Speed training (6%, n=2) | Hip strength (3%, n=1) | | | | |
| **18** | Weather (3%, n=1) | Gait analysis (3%, n=1) | | | | |
| **19** | Temperature (3%, n=1) | Knee stiffness (3%, n=1) * | | | | |
| **20** | Injury prevention completion (3%, n=1) | Centre of mass acceleration (3%, n=1) | | | | |
| **21** | Recovery routines (3%, n=1) | | | | | |
| **22** | Warm-up/Cool-down (3%, n=1) | | | | | |
| **23** | Rest days (3%, n=1) | | | | | |
| **24** | Goal pace (3%, n=1) | | | | | |
| **25** | Competition distance (3%, n=1) | | | | | |
| **26** | Competition frequency (3%, n=1) | | | | | |
| **27** | Trail running experience (3%, n=1) | | | | | |
| **28** | Longest monthly run (3%, n=1) | | | | | |
| **29** | Use of a heart rate monitor (3%, n=1) | | | | | |

Notes: * : indicates statistical significance; GPS: global positioning system;, ROM: range of motion; BMI: body mass index.

## 10.4 Appendix D. Study 3: The Running Injury Continuum: A qualitative examination of recreational runners' description and management of injury

*Appendix D1: Focus group schedule*

| Domain | Sample dialogue |
|---|---|
| Introduction & aims of study | Hi everyone. Thank you for coming and for being involved in this study. I am conducting some research on runners' description and management of injury, and the aim of this study is to gather your thoughts on running-related injuries. Please go into as much detail as you can, ask each other questions, and agree or disagree on any points raised, but please respect everyone's opinion. If you have any questions, please ask at any point. |
| Sample questions | How would you define injury? |
| | How would you describe injury? |
| | Based on your descriptions of injury and the terms you have used, could you elaborate on these on the whiteboard? |
| | How would you manage injuries? |

*Appendix D2: Standards for reporting qualitative research checklist (O'Brien et al., 2014)*

| Topic | Page # |
|---|---|
| **Title and Abstract** | |
| **Title -** Concise description of the nature and topic of the study. Identifying the study as qualitative or indicating the approach (e.g., ethnography, grounded theory) or data collection methods (e.g., interview, focus group) is recommended | 188 |
| **Abstract** - Summary of key elements of the study using the abstract format of the intended publication; typically includes background, purpose, methods, results, and conclusions | 188-189 |
| **Introduction** | |
| **Problem formulation -** Description and significance of the problem/phenomenon studied; review of relevant theory and empirical work; problem statement | 189 |
| **Purpose or research question -** Purpose of the study and specific objectives or questions | 191 |
| **Methods** | |
| **Qualitative approach and research paradigm -** Qualitative approach (e.g., ethnography, grounded theory, case study, phenomenology, narrative research) and guiding theory if appropriate; identifying the research paradigm (e.g., postpositivist, constructivist/ interpretivist) is also recommended; rationale** | 191-192 |
| **Researcher characteristics and reflexivity -** Researchers' characteristics that may influence the research, including personal attributes, qualifications/experience, relationship with participants, assumptions, and/or presuppositions; potential or actual interaction between researchers' characteristics and the research questions, approach, methods, results, and/or transferability | xxv |
| **Context** - Setting/site and salient contextual factors; rationale** | 192 |
| **Sampling strategy –** How and why research participants, documents, or events were selected; criteria for deciding when no further sampling was necessary (e.g., sampling saturation); rationale** | 192 |
| **Ethical issues pertaining to human subjects -** Documentation of approval by an appropriate ethics review board and participant consent, or explanation for lack thereof; other confidentiality and data security issues | 193 |
| **Data collection methods -** Types of data collected; details of data collection procedures including (as appropriate) start and stop dates of data collection and analysis, iterative process, triangulation of sources/methods, and modification of procedures in response to evolving study findings; rationale** | 193-194 |

| | |
|---|---|
| **Data collection instruments and technologies -** Description of instruments (e.g., interview guides, questionnaires) and devices (e.g., audio recorders) used for data collection; if/how the instrument(s) changed over the course of the study | 193-194 |
| **Units of study -** Number and relevant characteristics of participants, documents, or events included in the study; level of participation (could be reported in results) | 192 |
| **Data processing -** Methods for processing data prior to and during analysis, including transcription, data entry, data management and security, verification of data integrity, data coding, and anonymization/de-identification of excerpts | 195 |
| **Data analysis -** Process by which inferences, themes, etc., were identified and developed, including the researchers involved in data analysis; usually references a specific paradigm or approach; rationale** | 195-196 |
| **Techniques to enhance trustworthiness -** Techniques to enhance trustworthiness and credibility of data analysis (e.g., member checking, audit trail, triangulation); rationale** | 196-197 |
| **Results/Findings** | |
| **Synthesis and interpretation –** Main findings (e.g., interpretations, inferences, and themes); might include development of a theory or model, or integration with prior research or theory | 198-218 |
| **Links to empirical data –** Evidence (e.g., quotes, field notes, text excerpts, photographs) to substantiate analytic findings | 207-218 |
| **Discussion** | |
| **Integration with prior work, implications, transferability, and contribution(s) to the field -** Short summary of main findings; explanation of how findings and conclusions connect to, support, elaborate on, or challenge conclusions of earlier scholarship; discussion of scope of application/generalizability; identification of unique contribution(s) to scholarship in a discipline or field | 218-227 |
| **Limitations –** Trustworthiness and limitations of findings | 228 |
| **Other** | |
| **Conflicts of interest –** Potential sources of influence or perceived influence on study conduct and conclusions; how these were managed | NA |
| **Funding –** Sources of funding and other support; role of funders in data collection, interpretation, and reporting | vi |

## 10.5 Appendix E. Study 4: A qualitative examination of the factors affecting the adoption of injury focused wearable technologies in recreational runners

*Appendix E1: Standards for reporting qualitative research checklist (O'Brien et al., 2014)*

| Topic | Page # |
|---|---|
| **Title and Abstract** | |
| **Title -** Concise description of the nature and topic of the study. Identifying the study as qualitative or indicating the approach (e.g., ethnography, grounded theory) or data collection methods (e.g., interview, focus group) is recommended | 231 |
| **Abstract -** Summary of key elements of the study using the abstract format of the intended publication; typically includes background, purpose, methods, results, and conclusions | 231-232 |
| **Introduction** | |
| **Problem formulation -** Description and significance of the problem/phenomenon studied; review of relevant theory and empirical work; problem statement | 232-234 |
| **Purpose or research question -** Purpose of the study and specific objectives or questions | 234 |
| **Methods** | |
| **Qualitative approach and research paradigm -** Qualitative approach (e.g., ethnography, grounded theory, case study, phenomenology, narrative research) and guiding theory if appropriate; identifying the research paradigm (e.g., postpositivist, constructivist/ interpretivist) is also recommended; rationale** | 234-235 |
| **Researcher characteristics and reflexivity -** Researchers' characteristics that may influence the research, including personal attributes, qualifications/experience, relationship with participants, assumptions, and/or presuppositions; potential or actual interaction between researchers' characteristics and the research questions, approach, methods, results, and/or transferability | xxv |
| **Context** - Setting/site and salient contextual factors; rationale** | 235 |
| **Sampling strategy –** How and why research participants, documents, or events were selected; criteria for deciding when no further sampling was necessary (e.g., sampling saturation); rationale** | 235 |
| **Ethical issues pertaining to human subjects -** Documentation of approval by an appropriate ethics review board and participant consent, or explanation for lack thereof; other confidentiality and data security issues | 235 |
| **Data collection methods -** Types of data collected; details of data collection procedures including (as appropriate) start and stop dates of data collection and analysis, iterative process, triangulation of sources/methods, and modification of procedures in response to evolving study findings; rationale** | 236-237 |
| **Data collection instruments and technologies -** Description of instruments (e.g., interview guides, questionnaires) and devices (e.g., audio recorders) used for data collection; if/how the instrument(s) changed over the course of the study | 236-237 |
| **Units of study -** Number and relevant characteristics of participants, documents, or events included in the study; level of participation (could be reported in results) | 235 |
| **Data processing -** Methods for processing data prior to and during analysis, including transcription, data entry, data management and security, verification of data integrity, data coding, and anonymization/de-identification of excerpts | 237 |
| **Data analysis -** Process by which inferences, themes, etc., were identified and developed, including the researchers involved in data analysis; usually references a specific paradigm or approach; rationale** | 237-238 |
| **Techniques to enhance trustworthiness -** Techniques to enhance trustworthiness and credibility of data analysis (e.g., member checking, audit trail, triangulation); rationale** | 238 |
| **Results/Findings** | |

| | |
|---|---|
| **Synthesis and interpretation –** Main findings (e.g., interpretations, inferences, and themes); might include development of a theory or model, or integration with prior research or theory | 239-255 |
| **Links to empirical data –** Evidence (e.g., quotes, field notes, text excerpts, photographs) to substantiate analytic findings | 243-255 |
| **Discussion** | |
| **Integration with prior work, implications, transferability, and contribution(s) to the field -** Short summary of main findings; explanation of how findings and conclusions connect to, support, elaborate on, or challenge conclusions of earlier scholarship; discussion of scope of application/generalizability; identification of unique contribution(s) to scholarship in a discipline or field | 255-265 |
| **Limitations –** Trustworthiness and limitations of findings | 265-266 |
| **Other** | |
| **Conflicts of interest –** Potential sources of influence or perceived influence on study conduct and conclusions; how these were managed | NA |
| **Funding –** Sources of funding and other support; role of funders in data collection, interpretation, and reporting | NA |

*Appendix E2: Focus group introduction, aims, schedule domains, and sample questions*

| Domain | Sample questions |
|---|---|
| Sample brief introduction/Aims of study | Hi everyone. I am conducting research on the use of wearable technologies to monitor running-related injuries. The aims of this focus group are to gather your thoughts on the important metrics to monitor for running-related injuries using wearable technologies. We will also have a discussion on injury focused technologies and why you would or would not use them. If you have any questions at any point, please let me know. |
| Conversation openers | Can you tell me about the types of technologies you use while running? |
| Perceived barriers to the use of injury-focused technologies | Would anything discourage you from engaging with an injury-focused application? |
| | Would anything discourage you from wearing an injury-focused device or sensor? |
| Perceived facilitators to the use of injury-focused technologies | Would anything encourage you to engage with an injury-focused application? |
| | Would anything encourage you to wear an injury-focused device or sensor? |
| Metrics perceived as important for monitoring RRI risk | What are the risk factors for injury that you think should be monitored with wearable technologies? |

*Appendix E3: Pre-focus group questionnaire*

Section 1: Participant Demographics

1. What is your age (in years)? _____________
2. What is your gender?
    a. Male
    b. Female
    c. Non-binary/third gender
    d. Prefer not to say

Section 2: Running Habits & Training History

3. Is running your main sport or activity?
    a. Yes
    b. No
    c. Unsure
4. When did you start running?
    a. Less than 6 months ago
    b. 6-12 months ago
    c. 1-3 years ago
    d. 4-5 years ago
    e. More than 5 years ago
    f. Other. Please specify _______
    g. Unsure
5. How often do you run?
    a. Less than once a week
    b. Once a week
    c. 2-3 times a week
    d. 4-6 times a week
    e. Everyday
    f. Non-consistent routine
    g. Other. Please specify _________
6. Do you take part in organised running events?
    a. Yes
    b. Sometimes
    c. No
    d. Unsure
7. What is your preferred running distance for organised events? Please select all that apply.
    a. Less than 5km
    b. 5km
    c. 10km
    d. Half marathon (21.1km)
    e. Marathon (42.2km)
    f. Ultramarathon (i.e., anything longer than a marathon)
    g. Triathlon
    h. Non-specific
    i. Unsure
    j. Other. Please specify ____________
8. In a typical 12-month period, how many organised running events would you normally take part in?
    a. One event
    b. 2-4 events
    c. 5 events or more
    d. Unsure
    e. Other. Please specify _________

9. What is your average weekly training mileage?
    a. Less than 10km per week
    b. 10-20km per week
    c. 21-30km per week
    d. 31-40km per week
    e. 41-50km per week
    f. More than 50km per week
    g. Unsure
    h. Other. Please specify ____________
10. In which setting do you normally run? Please select the best fit.
    a. Mainly or solely on my own
    b. Mainly or solely with friends, colleagues, or small groups
    c. Mainly or solely with a running club

Section 3: Technology Use

11. What type(s) of running technologies do you use? Please select all that apply.
    a. I do not use any type of running technology
    b. Mobile phone and application (e.g., iPhone & Strava)
    c. GPS watch (e.g., Garmin)
    d. Heart rate monitor
    e. Smartwatch (e.g., Apple Watch)
    f. Wristband activity Tracker (e.g., Fitbit)
    g. Foot pod
    h. Body worn sensor
    i. Other. Please specify ___________

Section 4: Running-Related Injuries

12. Have you had any previous running-related injuries? A running-related injury is any muscle, bone, joint, tendon or ligament pain in the lower back/lower limb(s) that caused you to stop running or restricted your running (either your distance, speed or duration of training)

    **AND**

    a) That lasted at least 7 days or 3 consecutive scheduled training sessions

    **OR**

    b) That required you to consult a health care professional

    a. Yes, I have had a previous running-related injury
    b. No, I have not had a previous running-related injury

13. Thinking of your worst running-related injury, did you miss any training because of it?
    a. I did not miss any training
    b. I missed less than one week
    c. I missed 7-10 days
    d. I missed 2-3 weeks
    e. I missed 4-6 weeks
    f. I missed more than 6 weeks

g. Other. Please specify _______________

14. How many running-related injuries have you had in the past 12 months?
    a. I have not had a running-related injury in the last 12 months
    b. 1 running-related injury
    c. 2 running-related injuries
    d. 3 running-related injuries
    e. 4 running-related injuries
    f. 5 running-related injuries
    g. More than 5 running-related injuries
15. How important is injury prevention to you for running?
    a. Not at all important
    b. Slightly important
    c. Moderately important
    d. Very important
    e. Extremely important

*Appendix E3. Pre-focus group questionnaire*

Section 1: Participant Demographics

16. What is your age (in years)? _____________
17. What is your gender?
    a. Male
    b. Female
    c. Non-binary/third gender
    d. Prefer not to say

Section 2: Running Habits & Training History

18. Is running your main sport or activity?
    a. Yes
    b. No
    c. Unsure
19. When did you start running?
    a. Less than 6 months ago
    b. 6-12 months ago
    c. 1-3 years ago
    d. 4-5 years ago
    e. More than 5 years ago
    f. Other. Please specify _______
    g. Unsure
20. How often do you run?
    a. Less than once a week
    b. Once a week
    c. 2-3 times a week
    d. 4-6 times a week
    e. Everyday
    f. Non-consistent routine
    g. Other. Please specify _________
21. Do you take part in organised running events?
    a. Yes
    b. Sometimes
    c. No
    d. Unsure

22. What is your preferred running distance for organised events? Please select all that apply.
    a. Less than 5km
    b. 5km
    c. 10km
    d. Half marathon (21.1km)
    e. Marathon (42.2km)
    f. Ultramarathon (i.e., anything longer than a marathon)
    g. Triathlon
    h. Non-specific
    i. Unsure
    j. Other. Please specify ____________
23. In a typical 12-month period, how many organised running events would you normally take part in?
    a. One event
    b. 2-4 events
    c. 5 events or more
    d. Unsure
    e. Other. Please specify _________
24. What is your average weekly training mileage?
    a. Less than 10km per week
    b. 10-20km per week
    c. 21-30km per week
    d. 31-40km per week
    e. 41-50km per week
    f. More than 50km per week
    g. Unsure
    h. Other. Please specify ____________
25. In which setting do you normally run? Please select the best fit.
    a. Mainly or solely on my own
    b. Mainly or solely with friends, colleagues, or small groups
    c. Mainly or solely with a running club

Section 3: Technology Use

26. What type(s) of running technologies do you use? Please select all that apply.
    a. I do not use any type of running technology
    b. Mobile phone and application (e.g., iPhone & Strava)
    c. GPS watch (e.g., Garmin)
    d. Heart rate monitor
    e. Smartwatch (e.g., Apple Watch)
    f. Wristband activity Tracker (e.g., Fitbit)
    g. Foot pod
    h. Body worn sensor
    i. Other. Please specify ___________

Section 4: Running-Related Injuries

27. Have you had any previous running-related injuries? A running-related injury is any muscle, bone, joint, tendon or ligament pain in the lower back/lower limb(s) that caused you to stop running or restricted your running (either your distance, speed or duration of training)

**AND**

a) That lasted at least 7 days or 3 consecutive scheduled training sessions

**OR**

b) That required you to consult a health care professional

   c. Yes, I have had a previous running-related injury
   d. No, I have not had a previous running-related injury

28. Thinking of your worst running-related injury, did you miss any training because of it?
    a. I did not miss any training
    b. I missed less than one week
    c. I missed 7-10 days
    d. I missed 2-3 weeks
    e. I missed 4-6 weeks
    f. I missed more than 6 weeks
    g. Other. Please specify _______________
29. How many running-related injuries have you had in the past 12 months?
    a. I have not had a running-related injury in the last 12 months
    b. 1 running-related injury
    c. 2 running-related injuries
    d. 3 running-related injuries
    e. 4 running-related injuries
    f. 5 running-related injuries
    g. More than 5 running-related injuries
30. How important is injury prevention to you for running?
    a. Not at all important
    b. Slightly important
    c. Moderately important
    d. Very important
    e. Extremely important

*Appendix E4: 'Order of themes'*

| **1. Metrics perceived as important to monitor for injury risk** | | |
|---|---|---|
| **Core categories** | **Themes** | **Sub-themes** |
| 1.1 Overtraining | 1.1.1 Excessive loading | 1.1.1.1 High accumulative load |
| | | 1.1.1.2 High intensity training |
| | | 1.1.1.3 In-session fatigue |
| | | 1.1.1.4 Lower running experience |
| | 1.1.2 Inadequate recovery | 1.1.2.1 Fatigue and poor sleep |
| | | 1.1.2.2 Insufficient rest days |
| | | 1.1.2.3 Poor nutrition |
| | | 1.1.2.4 High stress |
| 1.2 Training-related risk factors | 1.2.1 Running environment | 1.2.1.1 Terrain |
| | | 1.2.1.2 Weather |
| | 1.2.2 Training activities | 1.2.2.1 Current training activities |
| | | 1.2.2.2 Historic training activities |
| | 1.2.3 Running technique | 1.2.3.1 Foot strike |
| | | 1.2.3.2 Cadence |
| | | 1.2.3.3 Bilateral asymmetry |
| | 1.2.4 Footwear | 1.2.4.1 Infrequent changing of footwear |
| | | 1.2.4.2 Type of footwear |
| | 1.3.1 Injury history | 1.3.1.1 Ongoing niggle |

| | | |
|---|---|---|
| 1.3 Individual related risk factors | | 1.3.1.2 Previous injury |
| | 1.3.2 Demographic information | 1.3.2.1 Age |
| | | 1.3.2.2 Body mass index |
| | | 1.3.2.3 Sub-optimal biomechanics |
| | 1.3.3 Type of runner | 1.3.3.1 Preferred distance/event |
| | 1.3.4 Psychological parameters | 1.3.4.1 Mood |
| | | 1.3.4.2 Perception of run |
| | | 1.3.4.3 Psychological readiness to run |

**2. Barriers to the use of injury focused running technologies**

| **Core categories** | **Themes** | **Sub-themes** | **Secondary sub-themes** | **Tertiary sub-themes** |
|---|---|---|---|---|
| 2.1 Difficult to use | 2.1.1 Device design | 2.1.1.1 Specifications of device | 2.1.1.1.1 Bulky | |
| | | | 2.1.1.1.2 Large | |
| | | 2.1.1.2 Application method | 2.1.1.2.1 Time consuming set up | |
| | | | 2.1.1.2.2 Adapting clothing/Extra clothing | |
| | | | 2.1.1.2.3 Belt mechanism | 2.1.1.2.3a Irritating/Uncomfortable |
| | | | | 2.1.1.2.3b Not secure |
| | | 2.1.1.3 Location | 2.1.1.3.1 Lower back/Waist | 2.1.1.3.1a Uncomfortable/ Irritating |
| | | | | 2.1.1.3.1b Not secure |
| | | | 2.1.1.3.2 Uncomfortable/Irritating (non-specific location) | |
| | | | 2.1.1.3.3Wrist/Arm | 2.1.1.3.3a Uncomfortable/ Irritating |
| | | | | 2.1.1.3.3b Not secure |
| | | | 2.1.1.3.4 Obvious/Noticeable to others (non-specific location) | |
| | | | 2.1.1.3.4 Foot/Shoe | 2.1.1.3.4a Inconvenient |

| | | | | |
|---|---|---|---|---|
| | | | 2.1.1.3.5 Chest/Torso | 2.1.1.3.5a Uncomfortable/ Irritating |
| | | | | 2.1.1.3.5b Not secure |
| | | 2.1.1.4 Technical issues | 2.1.1.4a Frequent charging of device | |
| | | | 2.1.1.4b Bluetooth connection issues | |
| | | | 2.1.1.4c Broken device | |
| | | | 2.1.1.4d Unclean device | |
| | 2.1.2 Application design | 2.1.2.1 Data input | 2.1.2.1a Time consuming | |
| | | | 2.1.2.1b High quantity of questions | |
| | | | 2.1.2.1c Repetitive/Irrelevant data required | |
| | | | 2.1.2.1d High text input | |
| | | 2.1.2.2 Data use | 2.1.2.2a Ambiguity of data use | |
| 2.2 Feedback | 2.2.1 Irrelevant feedback | | | |
| | 2.2.2 Too much data | | | |
| | 2.2.2 Inaccurate feedback | | | |
| | 2.2.3 Feedback delivery | 2.2.3.1 Email | | |
| **3 Facilitators to the use of injury-focused running technologies** | | | | |
| 3.1 Ease of use | 3.1.1 Application design | 3.1.1.1 User-friendly system | 3.1.1.1a Quick input session | |
| | | | 3.1.1.1b Multiple choice questions | |
| | | | 3.1.1.1c Synced with other applications/devices | |
| | | | 3.1.1.1d Notification reminders | |
| | | | 3.1.1.1e Automatic downloading of data from sensor | |
| | | 3.1.1.2 Current usage habits | 3.1.1.2a Fits with current usage habits | |
| | 3.1.2 Device design | 3.1.2.1 Application method | 3.1.2.1.1 Comfortable (non-specific application method) | |
| | | | 3.1.2.1.2 Discrete (non-specific application method) | |
| | | | 3.1.2.1.3 Convenient (non-specific application method) | |
| | | | 3.1.2.1.4 Belt mechanism | 3.1.2.1.4a Convenient |

| | | | | |
|---|---|---|---|---|
| | | | | 3.1.2.1.4b Stable |
| | | | 3.1.2.1.5 Clip mechanism | 3.1.2.1.5a Convenient |
| | | 3.1.2.2 Location | 3.1.2.2.1 Lower back/Waist | 3.1.2.2.1a Convenient |
| | | | | 3.1.2.2.1b Discrete |
| | | | | 3.1.2.2.1c Comfortable |
| | | | | 3.1.2.2.1d Stable |
| | | | 3.1.2.2.2 Wrist/Arm | 3.1.2.2.2a Convenient |
| | | | | 3.1.2.2.2b Stable |
| | | | 3.1.2.2.3 Chest/Torso | 3.1.2.2.3a Convenient |
| | | | | 3.1.2.2.3b Stable |
| | | | 3.1.2.2.4 Foot/Shoe | 3.1.2.2.4a Convenient |
| | | | | 3.1.2.2.4b Stable |
| | | | 3.1.2.2.5 Ankle | 3.1.2.2.5a Convenient |
| | | | | 3.1.2.2.5b Discrete |
| | | | 3.1.2.2.6 Thigh | 3.1.2.2.6a Thigh |
| | | 3.1.2.3 Specifications of sensor | 3.1.2.3a Small | |
| | | | 3.1.2.3b Lightweight | |
| | | 3.1.2.4 Good technical features | 3.1.2.4a Infrequent charging of device | |
| | | | 3.1.2.4b Strong Bluetooth connection | |
| 3.2 Feedback received | 3.2.1 Injury-related feedback | 3.2.1.1 Reduce injury risk | | |
| | | 3.2.1.2 Understand injury mechanisms | | |
| | | 3.2.1.3 Monitor rehabilitation from injury | | |
| | | 3.2.1.4 Advice/Recommendations | | |
| | | 3.2.1.5 Comparison to cohort | | |
| | | 3.2.1.6 Extend running career | | |
| | 3.2.2 Enhanced data | 3.2.2.1 Performance insights | 3.2.2.1a Performance progressions | |
| | | | 3.2.2.1b Optimizing performance | |

| | | | |
|---|---|---|---|
| | 4 focus groups | 3.2.2.2 Additional data | 3.2.2.1a Cadence/Stride information |
| | | | 3.2.2.1b Technique |
| | | | 3.2.2.1c Power |
| | | | 3.2.2.1d Comparison to cohort |
| | | | 3.2.2.1feMonitor recovery from training |
| | 3.2.3 Feedback delivery | 3.2.3.1 Choice of feedback delivery | |
| | | 3.2.3.2WhatsApp/Text | |

*Appendix E5: Exemplary quotes*

Exemplary quotes of running-related injury risk factors perceived as important to monitor using wearable technology devices by recreational runners

| **Theme** | **Sub-theme** | **Exemplary quotes** |
|---|---|---|
| Excessive loading | High accumulative load | M1: *"the single biggest injury I had was the stress fracture. And the cause of that is load… if you're going from 20 miles one week to 50 miles the next week, and yoyo-ing like that constantly… the kind of loads that that places on the body, especially… if you're including in that speed work, is inevitably going to lead to injury"* |
| | High intensity training | F2: *"a lot of people don't leave a gap between their hard runs and you're not getting the… difference… Every run shouldn't be the same… In terms of injury… if you're doing three hard runs in a row and just doing one long easy one, then maybe your training isn't improving and… the injury could be getting into it"* |
| | In-session fatigue | M7: *"… The more tired I get, the heart rate goes up, and if I try and stick to a particular pace, the whole form goes out. And for me, I would think that would lead to more injuries in that regard....Particularly on a long run, I suppose everybody notices that you start to slump that bit more, the form goes… and that's one thing I'm very, very wary of"* |
| | Less running experience | M9: *"somebody maybe not that experienced reads something decides to change how they run… and then that leads to an injury. As opposed to a more experienced runner who will… be very careful about things that they change and are less likely to get injured"* |
| Inadequate recovery | Fatigue & poor sleep | F4: *"I just think fatigue sometimes too… like you're not sleeping properly"* |
| | Poor nutrition | M1: *"I'm always interested in how nutrition and iron and that kind of thing affect the body, and how we look after ourselves. You know, we forget that there's a huge amount of work and there's a huge amount of energy involved in running. And we don't fuel ourselves and look after ourselves in general. You learn too late that you've probably done damage already"* |
| | Insufficient rest days | F3: *"if you're over running? Because there's a lot of people that… probably are injured because they're not actually taking rest days and they're… going out every day"* |
| | High stress | F12: *"my Garmin probably has this kind of thing on it… stress levels or how much sleep you got… Because I find, I don't know whether it's the PhD, I find like my recovery's really slow at the moment, which probably isn't good for injuries. So I'd be really interested in seeing… if you're injured when I'm not sleeping well, when I'm stressed about other things"* |

| | | |
|---|---|---|
| Training activities | Concurrent training activities | M2: *"very important to take into account what other sports they're doing… If you're playing golf you're obviously predisposed... to knee problems and lower back problems… If you're doing other track events, like javelin or shot put or something, it's different rotational movements. So I think important to take into account or to track other sporting activity to see if it's an injury related to running, versus... related to something else, or the compound of both"* |
| | Previous training activities | M9: "*... we were saying that people that had taken up running later in life, without doing any major sports before that, tended to have less injuries. Whereas people like us, that played… soccer, Gaelic, whatever… tended to pick up more injuries because they were running after having all these injuries in the other sports as well… I think our history is… a little bit of a factor as well…. all my problems are as a result of injuries from a previous sport… whereas other people will have a sort of blank slate coming into it, and you might say 'oh God… they must be doing everything right because they're not getting injured', ehm, but they also haven't put their body through… 10 years of hard slog in another sport as well"* |
| Running technique | Foot strike | M13: *"If you could see some… asymmetry in the heel strike or ground contact time… one side or the other... Like vertical oscillation or like, some sort of orientation of the feet, you know, or pelvis or hips, with respect to one another as you move"* |
| | Cadence | M1: *"... to understand why maybe a foot strike issue or an alignment issue might be coming in… your cadence and the amount of which your foot strike goes out of sync as you go into the longer distances… Your cadence rate drops or increases to try and keep with a pace, when your foot strike is wrong… when you're trying to sprint and over-stride"* |
| | Bilateral limb differences | M7: *"whether you're landing heavier left or right foot… I'm sort of conscious of that… I have a raised arch on my right foot… so that leads to me having to occasionally be wary of that… I see if I notice that I'm tending to favour… my left over my… right. That means I probably heading towards something going wrong with the right foot"* |
| Running environment | Terrain | F12: *"I actually thought of this because I have a little injury at the moment, it's like a flare up of an old injury…. anecdotally, everyone will be like 'you know concrete is really bad'. Because I found… I did like a race thing on concrete, and I wouldn't normally run on concrete, but I don't know if it was the race, or if it was the concrete, but I have like a flare up from an injury, from that"* |
| | Weather | M4: *"I think maybe the temperature of the run. Because on a… cold day you might be more susceptible to getting injured than a hot day"* |

| | | |
|---|---|---|
| Footwear | Infrequent changing of footwear | F11: *"... footwear. I feel like so many people don't change their runners often enough and I really think that's a huge factor in injuries… some people only change their runners every year, and they might be running every day"* |
| | Type of footwear | M10: *"... what runners people wear… I'd kind of be particular with what kind of runners I wear… spikes for the track, or flats…if I was running a race I'd be wearing… Vaporfly's… if I was running on wet ground I'd wear my trail runners… taking into account what runners people wear"* |
| Injury status & history | Ongoing niggle | F1: *"... say if you're after coming back from running and you're like 'oh my knee is a little bit sore'. You're not injured, but there could be little tweaks that may lead to other injuries… like there's always something sore after a run, so it's tracking the little niggles that might actually lead to something"*<br>F2: "*... And we don't always remember those little niggles"*<br>F1: *"... until you're halfway through the next run and you're like 'Oh, this is sore again remember this was sore"*<br><br>M7: *I'd be intrigued to know… all of us have the little niggles and aches and stuff like that… are they precursors to an injury or are they just the little aches and pains that we all get? Because I tend to, if I get an ache or pain or a niggle, I tend not to ignore it and I wait until it goes away… but by virtue of the fact that I quit when I do, is that what has kept me injury free? As opposed to, some people tend to run through these things, they'll run it off. I keep hearing that expression from other people, 'actually you can run that off', or something like that… I'd be intrigued to know is that the niggles that all of us have, can you ignore them as opposed to them turning into an injury"* |
| | Previous injury | M9: *"The chronic injuries I have, more or less, have been there since before I took up running… I actually don't get a lot of injuries from running, it's more about trying to manage the old ones… I've actually had very, very few running injuries, but all my problems are as a result of injuries from a previous sport"* |
| Population characteristics | Age | M8: "when you're getting older, you're probably going to get more injury prone as well" |
| | Body mass index | M8: "the more you weigh I'd say that the higher your impact forces, and I guess that will be at a straight impact.. on the risk factors" |
| | Sub-optimal biomechanics | M7: *"I have a natural claw foot… I have a raised arch on my right foot… so that leads to me having to occasionally be wary of that"* |

| | | |
|---|---|---|
| Type of runner | Preferred distance/event | M4: *"the type of runner… is it a hill runner or is it a 5km park runner, a very fast 5km park runner, or a marathon runner, or a 10 km runner. Because I presume all those different types, would have different injuries and susceptibility to injury as well"* |
| Psychological parameters | Mood | F5: *"... motivation levels on a day. Because some days I'll go out and I'll be like really energized for a run, and some days I'd be like 'oh I don't want to run', but I know I have to run. So you run the 5km both days, but like if you're not motivated, you might not be watching the way you run, or you might not be taking care of a pre-existing injury"* |
| | Perception of run | F14: *"how the run felt, like exertion and then fatigue in general… like the pace in terms of how they're feeling. Was it a really hard run"* |
| | Psychological readiness to run | F5: *"... mental tiredness… if you have a heavy day at work"* |

Exemplary quotes of perceived barriers to the use of injury-focused running technologies

| **Sub-theme** | **Secondary sub-theme** | **Exemplary quotes** |
|---|---|---|
| Attachment method | Time consuming | F11: *"I wouldn't want it to take too long to have to set up and get in place… It might kind of put you off actually going on the run… I think if you're doing that every run you went on, you kind of get fed up of it fairly quickly"* |
| | Adapting/Additional clothing required | M8: *"If I need to wear some contraption or something, I probably wouldn't be much in favour of it… As long as it doesn't rub… that's the main thing… if it's rubbing against your skin and getting a bit sore or something like that, that would be my, my issue"* |
| | Belt mechanism | M1: *"anything like a… belt. You see people wearing belts with water holders and stuff like that… in particular for marathons and longer runs, I've always struggled with those. I find them uncomfortable, and the wearing for the most part, unnecessary"* |
| Technical issues | Frequent charging | F3: *"The charging will be important, because I find… with the watch, you know, it can put me off, like if the battery is low on it… you need it to be easy to charge and that it doesn't need to be charged too frequently"* |
| | Bluetooth connection issues | F3: *" I have earphones that are wireless… they do disconnect quite frequently which can be quite frustrating during the middle of a run… just to try and make sure that whatever way that that's set up right"* |
| | Broken device | F11: *"it just depends how sturdy they are, but I could definitely imagine… one falling off during a run and me like breaking it or something"* |
| | Unclean device | F11: *"how to clean them… nobody wants to be putting on the same sweaty sensor"* |

| | | |
|---|---|---|
| User input requirement | Time consuming | F11: *"say you're going on a run like three times a week and you just kind of, input it straight after it, and then it's kind of done. Once… you don't have to be going back… later that night… I think once you can… do your run and do the app, then you'd be fine… Just kind of get it over and done with… Once you don't have to be spending too much time"* |
| | High quantity of questions | M12: *"things that would put me off would be off, asking for the whole session… exercises from 12345… And then rest periods or tempos… because that would just be a bit tedious"* |
| | Repetitive/Irrelevant data required | M11: *"It just gets a bit tedious… basically it'd ask you loads of questions, and it's like the same questions over and over"* |
| | High text input requirement | M8: *"if you had to write half an essay every time, I think that gets old very quickly"* |
| Data use | Ambiguity of data use | F8: *"be very clear on the data and what the data is being used for… people… can be a little bit funny about… where the data is actually being used. So just that it's very clear that whatever they're signing up for they know where the data is going to be used"* |
| Attachment method | Uncomfortable/Irritating | M8: *"if it's rubbing against your skin and getting a bit sore or something… that would be my issue… that would be my main concern, if it starts rubbing against your skin and the skin gets rubbed, then that's an issue"* |
| | Time consuming | F11: *"I wouldn't want it to take too long to have to set up and get in place… It might kind of put you off actually going on the run… I think if you're doing that every run you went on, you kind of get fed up of it fairly quickly"* |
| | Adapting/Additional clothing required | M8: *"If I need to wear some contraption or something, I probably wouldn't be much in favour of it… As long as it doesn't rub… that's the main thing… if it's rubbing against your skin and getting a bit sore or something like that, that would be my, my issue"* |
| | Belt mechanism | M1: *"anything like a… belt. You see people wearing belts with water holders and stuff like that… in particular for marathons and longer runs, I've always struggled with those. I find them uncomfortable, and the wearing for the most part, unnecessary"* |

| | | |
|---|---|---|
| Location | Low back | M2: *"I've had those fuel belts for the marathons… you just can't wait to throw it away… just gets annoying after a while"* |
| | Wrist/Arm | M3: *"I'm not a big fan of the… arm monitors… but I haven't used one for a while and I don't know how big this is"* |
| | Obvious/Noticeable to others | F11: *"I also wouldn't like it if was very obvious…That I was going by with this… fluorescent thing hanging around my waist, and people are like 'what is that?'"* |
| | Foot/Shoe | M8: *"If it's a sensor on the shoe, like if you have to tie your shoelaces it's a bit awkward because… I rotate my shoes, and I would have to change it every single time I go running"* |
| | Chest/Torso | M4: *"I definitely wouldn't like one strapped around the chest… I got a heart rate monitor before with the Garmin and I just couldn't run with it. So I ran about twice with it and it's in a press ever since"* |
| Specifications of device | Bulky | F9: *"something that's not too heavy or not too bulky or something, that, that it would impact their running"* |
| | Large | M1: *"if it's something larger than mobile phones…that's… different"* |
| Technical issues | Frequent charging | F3: *"The charging will be important, because I find… with the watch, you know, it can put me off, like if the battery is low on it… you need it to be easy to charge and that it doesn't need to be charged too frequently"* |
| | Bluetooth connection issues | F3: *" I have earphones that are wireless… they do disconnect quite frequently which can be quite frustrating during the middle of a run… just to try and make sure that whatever way that that's set up right"* |
| | Broken device | F11: *"it just depends how sturdy they are, but I could definitely imagine… one falling off during a run and me like breaking it or something"* |
| | Unclean device | F11: *"how to clean them… nobody wants to be putting on the same sweaty sensor"* |
| Useless feedback | Irrelevant feedback | M11: *"when I was using the Whoop… I stopped using it because… it tells you recovery scores, and all this sort of thing… You'd wake up in the morning and it would tell you how you're feeling, and then that would… determine how you felt… I just stopped using it because… I don't really want to know if I got bad sleep, because… I feel like I had bad sleep all day"* |

| | | |
|---|---|---|
| | Too much feedback | M13: *"all these diet apps, that are… tracking your calories in and calories out… there's just too much in those. And I'm like 'oh God, I can't use this this, this is annoying me'"* |
| | Inaccurate feedback | F2: *"I was getting rid of the watch when I was injured or not running well so… you're not becoming consumed by the data like you do with the watches"* |
| | Feedback delivery | F14: *"I get lost in the amount of emails I get from college, and on top of that you have your private one then… I see emails all the time and I'm just like 'ugh, what is this now?'... it's nearly like a negative thing attached with emails"* |

Exemplary quotes of perceived facilitators to the use of injury-focused technologies

| Sub-theme | Secondary sub-theme | Exemplary quotes |
|---|---|---|
| User friendly system | Quick input session | F8: *"I think once it wasn't too onerous… if it was just like asking for three or four questions… that are related to the injury then I certainly wouldn't see an issue with it… once it's very user friendly and that it doesn't take a lot of time"* |
| | Multiple choice questions | M9: *"... I'd be more encouraged to do it if there's a lot more, you know, tick the box, rate the scale type things, as opposed to having to type in on your phone… Just tick the box or rate it one to five, as opposed to having to write in stuff"* |
| | Synced with other applications/devices | F9: *"If you could connect to some of the other Apps that we're using, like the Garmin one or something for your sleep. Because the Garmin can track your sleep, or if you're using, like My Fitness Pal, if you were inputting your data for… what you're eating there, it'd be very handy, because then you can just go straight across like… it has all the information"* |
| | Notification reminders | F9: *"a reminder as well to do it, like a notification coming up… is really handy, because it's easy forget"* |
| | Automatic downloading of data from device | M5: *"I suppose that the less that data we have to put in, the better"*<br>…<br>M3: *"I think you're right M5, especially if the information is already there, maybe you can get it from Strava and tie it in"* |
| Current habits | Fits with current usage habits | F14: *"I suppose it is a good window because you're looking at Strava, you're looking at what you're doing, so you're kind of in the running zone… after your run could be a good time to input some data.. I definitely would have the time then"* |
| Location | Low back/Waist | F1: *"I have one of them now and it just has one zip on it, and if I'm going for… a long run, I put my phone in it… my phone sits… on my lower back. And it doesn't bother me at all"* |
| | Wrist/Arm | M11: *"I've also used… a wristband… and… you just don't notice that… So the wrist isn't a bad spot for an extra monitor"* |

| | | |
|---|---|---|
| | Chest/Torso | M2: *"the chest strap obviously is very fine, so if it could be integrated into the chest strap… no problem"* |
| | Foot/Shoe | M9: *"I'd actually... be much more likely to use the one on the shoe. Because… sometimes I'm running from home, sometimes I'm running for work, sometimes I'm running from the gym… sometimes I have a bag with me, sometimes I have a different bag, I'm gonna forget it some days. I'm not going to use it... But if it's on my runners… I'm much more likely to just leave it there and make sure that it's there for everything, rather than forget about it… Whereas at least… if it's on the runners, they're the one thing I always have with me"* |
| | Ankle | F11: *"Could you attach it around your ankle or something?.. I don't think I'd mind that too much… because you could even wear slightly longer socks to cover it"* |
| | Thigh | F8: *"Could you wear them like a strap around your quad, your thigh, under your shorts?... f it was around… your thigh, say… the shorts come over it, you mightn't notice"* |
| Attachment method | Discrete | M2: *"definitely something that is easy. That you can put it on and forget about it… just to be enjoyable and not interfere with what you're doing"* |
| | Comfortable | F12: "*the main thing would be as long as the sensor is comfortable to run with"* |
| | Convenient | F4: *"It'd have to be something easily either worn or attached to you"* |
| | Belt mechanism | F14: *"that's very easy to wear… So it… ticks lots of boxes"* |
| | Clip mechanism | M2: *"it has to be very easy to clip to a shoe or… just small clip on the back of the shorts"* |
| Specifications of sensor | Small | M4: *"small enough so it seems easy to have.. in your kit bag if you're going for a run"* |
| | Lightweight | F9: *"really small and… really light… so you wouldn't really notice you're wearing them"* |
| Good technical features | Infrequent charging of device | F1: *"that it has a good battery life… because that's sometimes… I'd be here working and I'd be like… 'I never put my watch on charge'... but… I shouldn't be worrying about that too much"* |
| | Strong Bluetooth connection | F1: *"Strong Bluetooth connection"* |

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|---|---|---|
| Injury-related feedback | Reduce injury risk | M1: *"in terms of looking at injury prevention… I'm at a stage where the injuries are becoming more frequent, and what I can do to avoid them, I'm happy to do it…For most people the thing that stops them from running is injury… if you're running and you're enjoying it, the one thing that's going to stop you is pain…Anything we can learn in terms of telling people how to avoid injuries is best because you keep them involved in it and it's the same the myself"* *I'm 53 now, if I can stay around for another 10 years I'll be happy. Ehm, I'd, I'd, I'd prefer not to, to wind up finishing up as a lot of people do when they get back into it in the sort of mid-life, in the mid 40s, they end up finishing by the time they're 55 or 56.* |
| | Understand injury mechanisms | M4: *"I'd just be interested in how injuries happen, and tell us how some people could go years without, without an injury running the same way, and then some people have injury after injury, and… what's the cause of it, and if it can be stopped"* |
| | Monitor rehabilitation from injury | F9: *"I presume they want to see how they're improving along the way. Like they start with an injury, they want to see improvements. Like you don't want to stay injured forever, so… you'd want to be able to see where you were, like three months ago, to where you are now, to where you should be… when you'll be able to get back to doing your normal running… You'd like to see… progression as well… Might be interesting… to be able to see that kind of an improvement"* |
| | Comparison to others | M13 - *"it would be interesting to know… injury reportage… If you could say… 'in our group of 30-39 year olds, 4% have experienced a tendo-Achilles pain in the last week, and their volume of running was 30-40 kilometres' then… I'd be like 'oh that's interesting information'"* |
| | Advice/Recommendations | F6: *"for example…'I went for a run today'... And then I come back and I'm like 'Okay, I feel like I pulled… my hamstring', and then if I was go onto the app, 'what should I do in the case of this?' So maybe if it's like ice, or if it's rest for three days, and then consult your Physio or whatever… like immediate advice to… prevent the injury developing further"* |

| | | |
|---|---|---|
| | Extend running career | M1: *"if I can stay around for another 10 years I'll be happy…I'd prefer not to wind up finishing up, as a lot of people do when they get back into it in the sort of mid-life, in the mid 40s, they end up finishing by the time they're 55 or 56"* |
| Enhanced data | Performance progressions | M1: *"whatever would improve me as a runner… Everything is about trying to be better than I can be, in my times… it's more about what I could get out of it to see how can I change my running to be better"* |
| | Optimizing performance | F2: *"performance, optimizing performance… Everyone's looking for the edge"* |
| | Cadence/Stride information | M12: *I suppose cadence… I suppose stride length as well… if you can see how long you are striding and notice any differences at the start. Are you longer and then as you fatigue, you shorten up, or vice versa. Just to see if there's any differences as a run progresses, does your stride length change"* |
| | Technique | M13: *"If you're talking about a device that measures a specific… aspect of my running that's not currently measured, like biomechanics or whatever, that would be interesting. And then if it's to just reaffirm some data that I'm collecting already, then that's also cool"* |
| | Power | M1: *"I don't know much about running power, I haven't really looked into it too much… but you know, it'd be interesting to see additional information as well … power one would be interesting"* |
| | Comparison to others | M12: *"if you said 'oh here's the 20-29 year old data of 20 runners we have, you are below the mean for your average… distance, but your pace is above average', that would be interesting, just to see how you stack up in your age range… or demographic if you do it by height and weight… it would be interesting to see how you can stack up again to the mean"* |

## 10.6 Appendix F. Study 5: Recruitment and retention of recreational runners in prospective injury research: A qualitative study

*Appendix F1: Standards for reporting qualitative research checklist (O'Brien et al., 2014)*

| Topic | Page # |
|---|---|
| **Title and Abstract** | |
| **Title -** Concise description of the nature and topic of the study. Identifying the study as qualitative or indicating the approach (e.g., ethnography, grounded theory) or data collection methods (e.g., interview, focus group) is recommended | 269 |
| **Abstract -** Summary of key elements of the study using the abstract format of the intended publication; typically includes background, purpose, methods, results, and conclusions | 269-270 |
| **Introduction** | |
| **Problem formulation -** Description and significance of the problem/phenomenon studied; review of relevant theory and empirical work; problem statement | 270-272 |
| **Purpose or research question -** Purpose of the study and specific objectives or questions | 272 |
| **Methods** | |
| **Qualitative approach and research paradigm -** Qualitative approach (e.g., ethnography, grounded theory, case study, phenomenology, narrative research) and guiding theory if appropriate; identifying the research paradigm (e.g., postpositivist, constructivist/ interpretivist) is also recommended; rationale** | 272-273 |
| **Researcher characteristics and reflexivity -** Researchers' characteristics that may influence the research, including personal attributes, qualifications/experience, relationship with participants, assumptions, and/or presuppositions; potential or actual interaction between researchers' characteristics and the research questions, approach, methods, results, and/or transferability | xxv |
| **Context** - Setting/site and salient contextual factors; rationale** | 272-273 |
| **Sampling strategy** – How and why research participants, documents, or events were selected; criteria for deciding when no further sampling was necessary (e.g., sampling saturation); rationale** | 273 |
| **Ethical issues pertaining to human subjects -** Documentation of approval by an appropriate ethics review board and participant consent, or explanation for lack thereof; other confidentiality and data security issues | 273 |
| **Data collection methods -** Types of data collected; details of data collection procedures including (as appropriate) start and stop dates of data collection and analysis, iterative process, triangulation of sources/methods, and modification of procedures in response to evolving study findings; rationale** | 274-27527<br>4-275 |
| **Data collection instruments and technologies -** Description of instruments (e.g., interview guides, questionnaires) and devices (e.g., audio recorders) used for data collection; if/how the instrument(s) changed over the course of the study | 274-275 |
| **Units of study -** Number and relevant characteristics of participants, documents, or events included in the study; level of participation (could be reported in results) | 275 |
| **Data processing -** Methods for processing data prior to and during analysis, including transcription, data entry, data management and security, verification of data integrity, data coding, and anonymization/de-identification of excerpts | 275 |
| **Data analysis -** Process by which inferences, themes, etc., were identified and developed, including the researchers involved in data analysis; usually references a specific paradigm or approach; rationale** | 275 |
| **Techniques to enhance trustworthiness -** Techniques to enhance trustworthiness and credibility of data analysis (e.g., member checking, audit trail, triangulation); rationale** | 276 |
| **Results/Findings** | |

| | |
|---|---|
| **Synthesis and interpretation –** Main findings (e.g., interpretations, inferences, and themes); might include development of a theory or model, or integration with prior research or theory | 276-294 |
| **Links to empirical data –** Evidence (e.g., quotes, field notes, text excerpts, photographs) to substantiate analytic findings | 284-294 |
| **Discussion** | |
| **Integration with prior work, implications, transferability, and contribution(s) to the field -** Short summary of main findings; explanation of how findings and conclusions connect to, support, elaborate on, or challenge conclusions of earlier scholarship; discussion of scope of application/generalizability; identification of unique contribution(s) to scholarship in a discipline or field | 294-302 |
| **Limitations –** Trustworthiness and limitations of findings | 303 |
| **Other** | |
| **Conflicts of interest –** Potential sources of influence or perceived influence on study conduct and conclusions; how these were managed | NA |
| **Funding –** Sources of funding and other support; role of funders in data collection, interpretation, and reporting | vi |

*Appendix F2: Focus group introduction, aims, schedule domains, and sample questions*

| **Domain** | **Sample questions** |
|---|---|
| Brief Introduction/Aims of study | Hi everyone. Thank you for coming and being involved in this study. I am conducting some research on the reason recreational runners would or would not be involved in a long-term research project, involving running technologies. The aims of the focus group are to gather your thoughts on what would encourage you and discourage you from being involved in such a study. If you have any questions at any point, please let me know. |
| Conversation openers | Firstly, can you tell me about your running and your use of running technologies? |
| Perceived facilitators to participation in prospective, longitudinal, RRI research involving wearable technologies | Would anything encourage you to be involved in a long-term, running-related injury research project, involving running technologies? |
| Perceived barriers to participation in prospective, longitudinal, RRI research involving wearable technologies | Would anything discourage you to be involved in a long-term, running-related injury research project, involving running technologies? |

*Appendix F3: Pre-focus group questionnaire*

Section 1: Participant demographics

1. What is your age (in years)?
2. What is your gender?
    a. Male
    b. Female
    c. Non-binary/third gender
    d. Prefer not to say

Section 2: Running Habits & Training History

3. Is running your main sport or activity?

   a. Yes
   b. No
   c. Unsure
4. When did you start running?
   a. Less than 6 months ago
   b. 6-12 months ago
   c. 1-3 years ago
   d. 4-5 years ago
   e. More than 5 years ago
   f. Other. Please specify _______
   g. Unsure
5. How often do you run?
   a. Less than once a week
   b. Once a week
   c. 2-3 times a week
   d. 4-6 times a week
   e. Everyday
   f. Non-consistent routine
   g. Other. Please specify _________
6. Do you take part in organised running events?
   a. Yes
   b. Sometimes
   c. No
   d. Unsure
7. What is your preferred running distance for organised events? Please select all that apply.
   a. Less than 5km
   b. 5km
   c. 10km
   d. Half marathon (21.1km)
   e. Marathon (42.2km)
   f. Ultramarathon (i.e., anything longer than a marathon)
   g. Triathlon
   h. Non-specific
   i. Unsure
   j. Other. Please specify ____________
8. In a typical 12-month period, how many organised running events would you normally take part in?
   a. One event
   b. 2-4 events
   c. 5 events or more
   d. Unsure
   e. Other. Please specify _________
9. What is your average weekly training mileage?
   a. Less than 10km per week
   b. 10-20km per week
   c. 21-30km per week
   d. 31-40km per week
   e. 41-50km per week
   f. More than 50km per week
   g. Unsure
   h. Other. Please specify ____________

10. In which setting do you normally run? Please select the best fit.
    a. Mainly or solely on my own
    b. Mainly or solely with friends, colleagues, or small groups
    c. Mainly or solely with a running club

Section 3: Technology Use

11. What type(s) of running technologies do you use? Please select all that apply.
    a. I do not use any type of running technology
    b. Mobile phone and application (e.g., iPhone & Strava)
    c. GPS watch (e.g., Garmin)
    d. Heart rate monitor
    e. Smartwatch (e.g., Apple Watch)
    f. Wristband activity Tracker (e.g., Fitbit)
    g. Foot pod
    h. Body worn sensor
    i. Other. Please specify ___________

12. Do you carry your mobile phone while running?
    a. Yes
    b. No
    c. Sometimes

13. If so, where do you carry your mobile phone while running?
    a. Arm
    b. Lower back/Waist
    c. Chest/Torso
    d. Other. Please specify ___________

14. For the purpose of a research project, would you be willing to carry your mobile phone while running?
    a. Yes
    b. No
    c. Maybe
    d. Unsure

15. If so, where would you be willing to carry your mobile phone? Please select all that apply.
    a. Arm
    b. Lower back/Waist
    c. Chest/Torso
    d. Other. Please specify ___________

Section 4: Running-Related Injuries

16. Have you had any previous running-related injuries? A running-related injury is any muscle, bone, joint, tendon or ligament pain in the lower back/lower limb(s) that caused you to stop running or restricted your running (either your distance, speed or duration of training)

    **AND**

    a) That lasted at least 7 days or 3 consecutive scheduled training sessions

**OR**

b) That required you to consult a health care professional

e. Yes, I have had a previous running-related injury
f. No, I have not had a previous running-related injury

17. Thinking of your worst running-related injury, did you miss any training because of it?
    a. I did not miss any training
    b. I missed less than one week
    c. I missed 7-10 days
    d. I missed 2-3 weeks
    e. I missed 4-6 weeks
    f. I missed more than 6 weeks
    g. Other. Please specify _______________
18. How many running-related injuries have you had in the past 12 months?
    a. I have not had a running-related injury in the last 12 months
    b. 1 running-related injury
    c. 2 running-related injuries
    d. 3 running-related injuries
    e. 4 running-related injuries
    f. 5 running-related injuries
    g. More than 5 running-related injuries
19. How important is injury prevention to you for running?
    a. Not at all important
    b. Slightly important
    c. Moderately important
    d. Very important
    e. Extremely important

Section 5: Experience with Research

20. Have you previously participated in any form of research project?
    a. Yes
    b. No
    c. Unsure

*Appendix F4: Exemplary quotes*

<u>Exemplary quotes of perceived facilitators of recreational runners to their involvement in prospective running related research</u>

| Theme | Sub-theme | Secondary/Tertiary sub-theme | Exemplary Quotes |
|---|---|---|---|
| **Incentives** | | | |
| Study outputs | Type of output | Interpreted individual metrics | F10: *"some kind of a performance report that can be linked to the likelihood or less likelihood of an injury. So I think some kind of report each quarter would definitely keep you interested"* |
| | | Analysed group/individual findings | M8: *"I'd be really interested in the results of the study, so I'd be really curious. And if you can give a promise to share the results with us or give whatever you found. I'd definitely be very much inclined to take part, I'd be really curious myself on that"* |
| | | Basic individual metrics | F9: *"it would be interesting from our point of view if there was a little feedback we could even see, not even that we need you to explain it, but do you know like on a GPS watch or something, you can see heart rates, it'd be good if there was kind of some sort of tracking that we could see"* |
| | Topic of feedback | Identify how to reduce injury risk | M3: *"it will be really interesting to see can you measure the sort of impact, is there a device that you can put in your back pocket that that will measure when you're putting your body under a level of stress that is likely to cause an injury. And that's going to be great, you know"* |
| | | Monitor rehab from injury | M4: *"something… whilst you're injured, you might be doing other stuff… if you're just swimming to just to give your leg or whatever's injured, ehm rest, and still doing your gym work whilst injured, just to capture the recovery as well"* |
| | | Advice/Recommendations on managing injuries | F5*: "Advice maybe? Like obviously… it's very personal so it's very different for everyone, but if there's like generic exercises you should be doing that could tie into your stretching… If you had like little guides, so say for example, like you could have "I have a knee injury, I have a shoulder injury, I have an ankle injury", and you can just have a little guides with all the very beginner level strength and conditioning stuff that people should be doing to improve those injuries"* |
| | | Identify how to extend running career | F4: *"I hope to just continue running for as long as I can… like I have friends who… started and stopped and… it's pain or doing too much at the beginning and then giving* |

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|---|---|---|---|
| | | | *up… and I just think it's one thing you just stick on your runners and head out your door… like I'm always trying to encourage my daughter to do, because I just think it's one of those things… once you… keep it consistent it is something you can do hopefully for life"* |
| | | Cadence/Stride information | M12: *"stride length as well… that's kind of tied with cadence, but if you tie it in with M13, if you can see how long you are striding and notice any differences at the start; are you longer and then as you fatigue, you shorten up, or vice versa. Just to see if there's any differences as a run progresses, does your stride length change"* |
| | Frequency received | Regular feedback (weekly/monthly) | F1: *"if you're doing some small every week, but maybe then like at the end of the month… if you have all, whoever's doing it, their email, not necessarily a personalized email, but like just a little 'thanks for the involvement, here's a summary of your month'. If there was anything that you noticed… even like just a little snippet maybe at the end of the month"* |
| | | Summary data on finish of study | M10: "*then just at the end, just a general overview of what you concluded from you study"* |
| | | Quarterly/Biannually | F9: *"some kind of a performance report that can be linked to the likelihood or less likelihood of an injury or whatever. So I think some kind of report each quarter would definitely keep you interested"* |
| | Mode of delivery | Notification from app | F8: "*So if it was something that was simple, that it gave you a notification, because what that does is it notifies you, it comes up as a little notification at the top of your phone, and you can click into it and gives all the stats"* |
| | | Email | |
| Provision of evidence-based information | Type of information | Injury prevention advice | F8: *"showing people this is the optimum way to recover, this is the optimum way to stretch, this is the way that you'll most help yourself prevent injury"* |
| | | Stretches/Strength and conditioning | F8: *"I think maybe around the kind of stretching and your active recovery kind of sessions, and that kind of thing in order to prevent injuries. I think they'd be the two key areas that I'd be interested in"* |
| | | Injury rehabilitation advice | F10: *"showing people this is the optimum way to recover, this is the optimum way to stretch, this is the way that you'll most help yourself prevent injury"* |
| | | Recovery strategies | F9: *"… nutrition I think it's really important there, and definitely prevention for future injuries, as well… If you could see the impact of somebody who is trying to recover or to rehab and doesn't get enough sleep, and then maybe versus somebody who does, and see how it impacts. Or somebody who follows nutrition plans, or whatever, or does their stretches. It would just be interesting to see"* |

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|---|---|---|---|
| Lab testing | VO2 max test | | F6: *"like your whole body check, I can't remember what it was called… like your lung capacity or whatever, those type of things, like maybe halfway through the year… say at the start of it and then halfway through, and at the end or something like that, that you could monitor across and see like overall improvement and stuff, that that would be quite motivating"* |
| | Body composition | | F8: *"a DEXA scan, I'd love to get a DEXA scan… that's a massive factor in terms of recovery and stuff like, you know your bone density, your muscle mass, ehm, all that sort stuff, so absolutely"* |
| | Gait analysis | | F6: *"anything I guess maybe related to your injuries… if you monitored what you're like starting off with on this… your running style or something, and then if there was any change, even six months, and then a year down the line"* |
| | Experience of lab testing | | F10: *"being brought up to DCU, like the High Performance Centre to get tested then… like runners, they love talking about running. Like I'm sure loads of them, 'like Jesus this is great', like 'I get to go up'… even if it the test wasn't outrageously amazing, but even to experience what it's like in the lab"* |
| Prize/Draw | | | F12: *"I don't know if you're allowed do some sort of like incentive. So say if… everyone who after three months, six months point, would you be able to say, like anyone who's stayed up to that point… could you like get something small… or have even like a raffle for a t-shirt of something?"* |
| **Suitable participants** | | | |
| Personal interest | Running injuries | Prevent personal injury | F3: *"people who are running… there's like always that chance that you're going to get injured. Ehm, so yeah I think it like, I don't know all of us, anyway, would happily do it because I think we've all had our fair share of niggles and injuries that you'd rather not have"* |
| | | Prevent injury in others | M2: *"… happy to be contributing to that to improve injury prevention for other runners"* |
| | | Extend running career | M2: *"Running for me is also you know very like F1 said about the mental health aspect of it, especially during lockdown, great to get out and get the fresh air. And my friends who haven't been running, you know, you can see that they're annoyed by it and if I couldn't run every day I'd be definitely pissed off half of the time. Ehm, so anything that will keep you running for healthier for longer I'm happy to look at and contribute to"* |
| | | Understand mechanisms of injury | M4: *"I find it interesting, but I also try to prevent myself from getting back into that situation of going from one injury to, to another. Ehm, and anything that -- it just piques my interest, how or why we get injured"* |

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|---|---|---|---|
| | | Understand impact of injury on performance | F11*: "I think every recreational runner has a certain amount of performance* [focus]… *everyone does want to improve a bit and I suppose injuries are going to set them back so much that they should care about how often they're going to get injured or not"* |
| | | Monitor rehabilitation from injury | M12: *"Yeah if it* [the sensor] *can track other forms of training or anything like that, or even… if I can't run and can only walk, I'll happily track walks or whatever. Whatever I could do with the injury, I'd happily track it"* |
| | Assisting with research | | M2: *"assisting with the research. Ehm, I studied science when I was in college, so you know, obviously very important to have real world evidence, ehm, so happy to be contributing to that to improve injury prevention for other runners"* |
| | Performance insights | Enhance performance | F2: *"performance, optimizing performance… Everyone's looking for the edge"* |
| | | Receiving additional data | M2: *"to get the data for myself out of it… To whatever would improve me as a runner"* |
| Daily schedule | Fits with current technology habits | | M2: *"as soon as I come in I just edit all of them very quickly, so I'd have no problem doing you know 5-10 minutes after the run… every run. I'd be recording it anyway, so to add in something small, it'd be no problem for me to be doing it every day for a couple of minutes after each run"* |
| | Fits with running schedule | | M1: *"… as I said, I'm sticking to it a plan anyway for this year and I have an idea of what I intend to do next year, so, the kind of running that I am doing has nothing to do with the study that you're doing. I'm more than happy to give the information but, ehm, if you're studying interferes with my running, I won't be involved in your study. That would be my way of looking at it. I'm happy to give the information, but my focus is on what I'm doing, and what you get out of it that's to your benefit, happy days, no problem with that. Ehm, but I'll be sticking with what I intend to anyway"* |
| **Ease of use of running technologies** | | | |
| User-friendly application | Quick input sessions | | F9: *"Something not too long, like just a couple of questions on it, like I don't think it'd be an issue like"*<br><br>F3: *"It needs to be succinct"* |
| | Question format | | M9: "I know that I'd be more encouraged to do it if there's a lot more, you know tick the box, rate the scale type things, as opposed to having to type in on your phone" |
| | Synced to other apps | | M5: *"whatever you can take from any of the apps, all the better"* |
| | Notifications reminders | | F12: *"say for the app, do you have like a reminder every day to fill it in?.. I think it would be* [important]… *do you know the Covid contact tracing app? I've completely forgotten about it until this moment. Ehm, I used to fill it in at the start, but even… if* |

| | | | |
|---|---|---|---|
| | | | *that came up every day, just a reminder, and you could just go into it easily, then that would be helpful, yeah"* |
| | Automatics downloading of data | | M5: *"I suppose that the less that data we have to put in the better. You know anything that updates automatically, great… Whether that be GPS, or your location, or the weather or any of these. Like I would use Strava.. and that kind of pulls all the stuff in… The less data you need to put in the better, I would say all and round"* |
| Sensor design | Location | Lower back/Waist | F5: *"I don't think I would notice it really because I'm used to having something around my waist anyway"* |
| | | Foot/Shoe | M9: *"I'd be much more likely to use the one on the shoe. Because again, like physically in the wintertime, you know sometimes I'm running from home, sometimes I'm running for work, sometimes I'm running from the gym, if it's in the bag, sometimes I have a bag with me, sometimes I have a different bag, I'm gonna forget it some days, I'm not going to use it. But if it's on my runners… I'm much more likely to just leave it there and make sure that it's there for everything, rather than forget about it… But I know if it's something like that, and it has to be in my gear bag, I guarantee there's going to be days that I forget and it don't use it, you know. I'll have left the gear bag in a locker in work or something, ehm and I'm running from home, whereas at least if it's on the runners, they're the one thing I always have with me"* |
| | | Wrist/Arm | M11: *"I've also used… a wristband thing… you just don't notice that either. So the wrist isn't a bad spot for an extra monitor"* |
| | | Chest/Torso | M1: *"Like a chest strap, fine… they don't bother me much… if it's a chest strap… or something that's easily worn and not bouncing about for want of a better description, I'd have no problem with it"* |
| | Attachment method | Discrete | M1: *"as long as it's easy to, it's easy to wear, and it's not incumbering you, in any way… as long as it's not a cumbersome thing that's interfering with the running, I've no problem wearing it"* |
| | | Secure | M8: *"Obviously needs to be secure"* |
| | | Convenient | M3: *"I think key is where this device goes, ehm and how, how easy it is. If it goes on a shoe, can it be moved from shoe to shoe, from different pairs of shoes. If it goes on, on, on the back of your shorts, how easy is to get on and off"* |
| | | Comfortable | M8: *"As long as it doesn't rub… that's the main thing. So if it's reasonably comfortable to wear, that's fine by me"* |
| | | Belt mechanism | F8: *"the most straightforward way is definitely the one strap around the waist or chest"* |

| | | | |
|---|---|---|---|
| | | Clip mechanism | M2: *"it has to be very easy to clip to a shoe or you know, just a small clip on the back of the shorts or something like that… if it's in the way, it's not going to last the 12 months. You're gonna get rid of it fairly quickly"* |
| | Discrete sensor specifications | Small | M10: *"I suppose the smaller the better"* |
| | | Lightweight | M10: *"maybe the weight. Make sure… that it's light enough, that's not going to ehm, kind of annoy you during the run"* |
| | Good technical features | Infrequent charging of sensor | M11: *"it's very annoying not having things charged, so a good battery life on it would be important, I would think. Because I have, as I said, I have loads of different monitors and they're really annoying when they run out of battery quickly"* |
| **Good communication practices** | | | |
| Check-ins | Reassure valuable involvement | | M2: *"even if they do get injured, you know to say 'look this is part of it, that if you get injured, we still need to track you even if you're not able to run every day', and that it's not a negative that they get injured, and then they say 'well, I can't be a participate anymore, because I'm injured', but you just say that that is equally as important"* |
| | Reminders to engage with application | | F6: "*maybe even then if you were to say "okay, got injured" and I was told to not run for two weeks, and then maybe in two weeks, you're prompted via the app to say like "How is your injury now? How's your recovery going? Are you ready to run again?", you know, whatever not that many words, but you know, kind of reminding them they're still involved in this program, because if an injury went on for six weeks, they could nearly forget about it maybe"* |
| | Reminder of community of runners/participants | | F8: But I do think a lot of them that are in those kind of running clubs, they wouldn't mind being in a group setting, I don't think.<br><br>F10: Yeah<br><br>F8: It would almost be like a monthly check in for them, kind of thing.<br><br>F10: It'd be like another version of Strava, that they have that and they can give kudos to each other.<br><br>F8: Another little community, yeah |
| | Trouble-shooting with running technology | | M2: *"just to make sure that everybody is, is happy with how it's working"* |

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| Mode of communication | Notifications from app | | F5: *"If it's an APP I'd like prompts… if it was like a little notification"* |
| Frequency of communication | Semi-regular (monthly) | | F10: *"Like be it every four weeks, six weeks, whatever it is, so that it's kind of there to remind you that, like, you're still there and you're not forgetting about them… I'd say that kind of four weeks could be a nice time between things"* |

Exemplary quotes of perceived barriers of recreational runners to their involvement in prospective running related research

| Themes | Sub-themes | Secondary/Tertiary sub-themes | Exemplary quotes |
|---|---|---|---|
| **Difficulty of use of running technologies** | | | |
| Smartphone application design | High user input requirement | Time consuming | M5*: "but realistically it'll be any more than a couple minutes and people get bored… putting in data"* |
| | | High quantity of questions | F14: "*There would be like a consistency issue, long term with the APP I'd say, every morning having to answer a load of questions"* |
| | | Repetitive data required | M11: *"it was fine at the start because you're kind of, you're buzzing about this new APP that you have and you're interested in it, but then after a while it's just gets a bit tedious having to every morning, basically it'd ask you loads of questions, and it's like the same questions over and over"* |
| Wearable sensor design | Attachment method | Irritating/Uncomfortable | F12: *"I think if it's something on people's skin, maybe something that's not gonna irritate the skin over time"* |
| | | Belt mechanism | M1: "*anything like a belt, you see people wearing belts… I've always struggled with those. I find them uncomfortable"* |
| | | Time-consuming set up | F11: *"I wouldn't wanted to take too long to have to set up and get in place… It might kind of put you off actually going on the run… Like once it wasn't more than like a five or 10 minute job… I think if you're doing that every run you went on, you kind of get fed up of it fairly quickly. Like if are wearing it for 12 months, it's a long time"* |
| | Obtrusive sensor | Bulky | F9: *"something that's not too heavy or not too bulky or something, that it would impact their running"* |
| | | Large | M1: *"If it's something larger than mobile phones, that you're having to sit on your waist or your chest or something like that, that's different. I'd try it certainly, but I'm not sure whether I'd persist with it for 12 months"* |
| | Location | Lower back/Waist | M8: *"If you have it on your back it would be slightly more difficult, if it's rubbing against your skin and getting a bit sore or something like that, that would be my issue"* |
| | | Arm/Wrist | F12*: "If there's any way it could go on a wrist or an arm"* |
| | | Obvious/Noticeable to others | F11: *"I also wouldn't like it was very obvious (laughter)… That I was going by with this like fluorescent thing hanging around my waist, and people are like 'what is that?' (laughter)"* |
| | Logistic issues with sensor | Broken/Lost sensor | M3: *"What happens if we just throw the shorts in the washing machine, will it survive, that sort of thing"* |
| | | Frequent charging requirement | F2: *"I would say the charging will be important, because I find like, with the watch… it can put me off like if the battery is low on it… if you have to have it on all the time* |

| | | | |
|---|---|---|---|
| | | | *you need it to be easy to charge and that it doesn't need to be charged too frequently"* |
| Inappropriate feedback from running technology | | | F3: *"obviously if they're just getting that little bit extra feedback… if they're just getting something more than tracking and analysis at the end, like ideally if they're getting something, can be small, but from even each week, or you know analysis of three weeks runs… I think they'll need something to aid it each week rather than at the end, if that make sense?"* |
| **Poor communication practices** | | | |
| Excessive communication | | | M11: *"But not too much either though"*<br><br>F14: *(laughter)*<br><br>M11: *Because then, and I'm serious as well, because not too much, because then you're kind of like, you don't want to be doing so much stuff for it, as well as having to wear it and everything, for a whole year, you know. So, there's a balance I think there, yeah"* |
| Lack of communication | | | M11: *"Maybe if I just didn't hear anything from anyone… I would probably sort of like, I might just forget about it (laughter). Like it's a year, you know"* |
| Mode of communication | Email | | F14: *"Like I get lost in the amount of emails I get from college, and on top of that you have your private one then, and all his stuff coming in… I see emails all the time and I'm just like 'ugh, what is this now?'… Do you know, it's nearly like a negative thing attached with emails"* |
| **Impact to personal schedule** | | | |
| Strict training schedule required | | | F6: *"I think it's like the fact that it's literally just you as you run. Like there's no pressure to do anything, or if you take break for a week at a time or longer, like it's fine, it's just your natural running anyway"*<br><br>F12: *"Once you don't have to change your schedule"* |
| Interference with training schedule | | | M1: *"I'm more than happy to give the information but if your studying interferes with my running, I won't be involved in your study. That would be my way of looking at it. I'm happy to give the information, but my focus is on what I'm doing, and what you get out of it that's to your benefit, happy days, no problem with that, I'll be sticking with what I intend to anyway"* |

## 10.7 Appendix G. Running Injury Surveillance Centre 2 study and app

*Appendix G1. Description of the Running Injury Surveillance Centre study*

The overall objective of the Running Injury Surveillance Centre 2 study is to collaboratively work with experts in sports and health medicine and science to address the challenges of measuring, understanding and influencing behaviour in recreational runners. The objective of the RISC2 app is to objectively, reliably and sensitively measure and understand factors related to RRI development and running performance. Ultimately, through machine learning, this app will be able to predict injury and performance, and provide personalised and adaptive recommendations for changing runners' behaviour to optimize them. Focusing on RRIs, the app aims to showcase the potential of longitudinal, frequent, high-resolution self-monitored data to:

- Enable researchers to identify the complex, multi-factorial causes of injury, through machine learning,
- Empower runners to make better informed decisions on their running, through increased self-awareness,
- Provide recommender prompts/predictions to runners to reduce the likelihood and extent of RRIs.

When signing up for the RISC2 prospective study, runners will register a profile on the RISC2 app. The app will be used to collect, manage, and store all data collected from runners, through a user-friendly interface and comprehensive back-end system. This is a purely observational study in which runners will participate in the normal running schedule, but they will be required to provide several types of data. There will be five primary methods of data collection, some compulsory and some optional.

1. An extensive baseline questionnaire will be issued to capture participant demographics, running habits and history, injury history, general health

history, menstrual cycle and menopause history, lifestyle factors and previous sport history. This data capture will be compulsory; however, data relating to the menstrual cycle and menopause will be optional.

2. Less extensive, albeit thorough monthly questionnaires will be issued to capture the previous month's injury history, management strategies used, general health history, sleep and stress history, running goals achieved and those set for the upcoming month. This data capture will be compulsory; however, data relating to the menstrual cycle and menopause will be optional.
3. Run-by-run/Day-by-day data collection will be captured directly through the RISC2 app. Pre-run questions will examine sleep quality, stress levels, readiness to run, and the planned running session, while post-run questions will examine perceived exertion, perception of session (e.g., harder than expected), session completed, and pain/injury status. As needed, the runner can also input the following information: illness status, menstrual cycle and menopause information (including cycle tracking and symptoms), additional training (not running), unplanned or forced rest taken, and an open-ended 'thoughts' page. This data capture will be compulsory; however, data relating to the menstrual cycle and menopause will be optional.
4. A wearable sensor with an IMU will capture data in relation to impact accelerations during running. It will also be used for a series of home-based clinical tests to assess biomechanics (e.g., single leg balance, tuck jumps). This data capture will be optional.
5. Runners can also share data captured by external devices or health apps that they may use (e.g., Strava, Garmin). This may be in the form of GPS data (e.g., running metrics), physiological data (e.g., heart rate), or sleep data (e.g., duration). This data capture will be optional.

When going for a run, the runner will answer brief pre-run questions as detailed above. If applicable, they will activate the wearable sensor and apply it to their lower back, and go for their run. To capture GPS data, the runner can either carry their smartphone while they run, or share GPS data captured by an external device (e.g., sports watch) afterwards. On finishing their run, runners will answer brief post-run questions, synchronise the wearable sensor and app (if applicable) and any other data that they may have captured from external devices (if applicable). There app will also facilitate communication between the research team and runner, with generic feedback, semi-tailored messaging, and direct messaging if required. A flowchart of the RISC2 app user face is detailed in Appendix G2.

*Appendix G2: Flowchart of the Running Injury Surveillance Centre 2 app interface*