Impact Acceleration, Kinematic and Training-related Risk Factors of Running Injuries: A Prospective Trial

Aoife Burke [B.Sc.]

A thesis submitted for the award of Doctor of Philosophy

September 2022

Supervisors: Prof. Kieran Moran, Dr. Siobhán O'Connor

School of Health and Human Performance
Dublin City University

Declaration

I hereby certify that this material, which I now submit for the 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 of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: Student ID: 57523548 Date: 13/06/2022

Acknowledgements

I would like to take this opportunity to extend my sincere gratitude to the following people, for whom I could not have completed this journey without. Despite having developed my writing skills over the past number of years, I will struggle to find words that are strong enough to convey my gratuity.

To my supervisors for providing such patience, guidance and support throughout the whole process. To Kieran, thank you for your invaluable insight and thought provoking conversations, but most importantly thank you for backing me from day one. To Siobhán, my appreciation and admiration for your work ethic and leadership is unrivalled, something I can only try to emulate. To Enda, it has been quite the journey from my early undergraduate days until now, and I will forever be indebted to you for your advice and encouragement. To Shane, thank you so much for your extensive contribution to this journey. Your diligence and attention to detail is unwavering, and I am very fortunate to have learned from you.

To Insight SFI Centre for Data Analytics, thank you for funding this PhD. It has provided me with a magnificent platform to develop as a researcher, but also as a person. Furthermore, a special note of gratitude to the participants who selflessly and voluntarily gave up their time and efforts to take part in this research – I hope that you will ultimately reap the rewards.

To the staff and students in the School of Health and Human Performance, but in particular to Sarahjane, thank you for being so supportive and accommodating the past three years. It is genuinely very much appreciated. And to the Albie Legion, the friendship and laughter will be treasured forever.

Le mo chlanna, de Búrcas ‘s de Hearforts, ach go háirithe mo Mham agus mo Dhaid, go raibh míle míle maith agaibh as do tacaíocht gan teorainn. Táim sách cinnte nach féidir leat do thuismitheoirí a roghnú, ach is cosúil gur bhuaigh mé an chrannchur. Arís, ós bhun mo chroí, mile buíochas.

To Sarah, what can I say! We started out as complete strangers but I genuinely couldn’t have asked for a better friend and partner in crime throughout this whole journey. We shared so many highs and lows, a bond that will never be broken. Your departure to the west will leave a significant void, you’ll be irreplaceable.

Lastly, and by no means least, to Stephen, thank you for everything you do for me. You’ve been by my side through thick and thin, and there’s nobody in this world that compares. I promise to fully support you if you ever take that plunge into research! Mo grá go léir X

Statement of Funding

The studies contained within this thesis were supported by a grant from Insight Science Foundation Ireland Research Centre for Data Analytics (grant number SFI/12/RC/2289), co-funded by the European Regional Development Fund.

The finding to support this research was for two PhD students, and thus, this thesis was conducted in parallel with another PhD thesis (Sarah Dillon). As a result there is sharing of some data. Both reserachers (Aoife Burke and Sarah Dillon) conducted the data collection together but aspects of the data collection were subsequently segregated to inform independent research questions. The focus of my thesis was on impact acceleration and running kinematics (captured at a 9km/hr fixed speed), in addition to training practices of injured and uninjured runners. The forcus of Sarah's thesis was on impact acceleration and running kinematics (captured at a self-selected speed), in addition to clinical measures of strength, mobility and foot posture of injured and uninjured runners. Both reserachers (Aoife Burke and Sarah Dillon) conducted data processing, analyses, literature reviews and thesis write ups independently.

Table of Contents

List of Appendices

List of Tables

List of Figures

List of Abbreviations

A: Acceptable

Asym: Asymptomatic at time of testing

ACWR: Acute chronic workload ratio

ABD: Abduction

ADD: Adduction

AFA: Ankle flexion angle

AIR: Acquired injury resistance

AKP: Anterior knee pain

AT: Achilles tendinopathy

au: arbitrary units

BF: Barefoot

BMI : Body mass index

BW: Bodyweight

BW/s: Bodyweight per second

CI : Confidence interval

cIRD: Cumulative injury risk difference

CSMI: Calf strain muscle injury

COM: Centre of mass

CPD: Contralateral pelvic drop

DF: Dorsiflexion

ER: External Rotation

ERLP: Exercise related leg pain

ES: Effect size

EXT: Extension

F: Force

F/BW: Force normalized to bodyweight

FCA: Foot contact angle

FFS: Forefoot strike

FLX: flexion

FSP: Foot strike pattern

FST: Foot strike technique

Fz1: Initial impact peak

Fz2: Propulsive peak

g: Force in units of gravity

g/s: Rate of force development in units of gravity per second

GRADE: Grading of recommendation, assessment, development and evaluation

GRF: Ground reaction force

h: Hours

hGRF: Horizontal ground reaction force

HO: Heel off

HazR: Hazard ratio

HR: Heart rate

Hx RRI: History of running-related injury

Hz: Hertz

IC: Initial contact

ICC: Intraclass correlations coefficient

IMU: Inertial measurement unit

Inj: Injured

IR: Internal rotation

ITBS: Iliotibial band syndrome

KFA: Knee flexion angle

kg: kilogram

kg/m2: kilogram per metre squared

km: kilometre

km/hr: kilometres per hour

LLSF: Lower limb stress fracture

LR: Loading rate

m: metre

mm: millimetre

ms: millisecond

MS: mid-stance

m/s: metres per second

Max: Maximum

MDC: Minimal detectable change

MFS: Midfoot strike

Min: Minimum

Mjoint: Joint moment

MS: Minimalist shoe

MSK: Musculoskeletal

MSP: Medial shin pain

MTSS: Medial tibial stress syndrome

N: Novice runner

N/A: Not applicable

NI: Never injured

NIoP: Negative impact on performance

Nm: Newton metre

Nm/kg: Newton metre per kilogram

N/R: Not reported

NRFS: Non-rearfoot strike

NS: No significant findings

NSF: Navicular stress fracture

O: Overground

O_{Peak}: Overground peak

O_{Rate}: Overground rate

OR: Odds ratio

OT: Outdoor track

p: Alpha level of significance

PB: Personal best

$Peak_{accel}$: Peak acceleration

PF: Plantarflexion

PFJRF: Patellofemoral joint reaction force

PFPS: Patellofemoral pain syndrome

PPA: Peak positive acceleration

PRISMA: Preferred reporting items for systematic reviews and meta-analyses

PT: Patellar tendinopathy

R: Recreational runner

$Rate_{accel}$: Rate of acceleration

RCT: Randomised controlled trial

RE: Rearfoot eversion

Ref: Reference

RI: Recently injured

RISS: Running injury severity score

RFS: Rearfoot strike

RPE: Rating of perceived exertion

RR: Relative risk

RRI: Running-related injury

s: second

SD: Standard deviation

SEM: Standard error of measurement

SH: Shod

SI: Strike index

SF: Stress fracture

SS: Self-selected

SSP: Self-selected pace

Sym: Symptomatic at time of testing

T : Treadmill

TFJ: Tibiofibular joint

TL : Time-loss

TO : Toe off

TRIPP : Translating research into injury prevention practice

TS: Traditional shoe

TSF: Tibial stress fracture

TSS: Tibial stress syndrome

U: Unacceptable

Uninj: Uninjured

vGRF: Vertical ground reaction force

VAP: Vertical active peak

VALR: Vertical average loading rate

VILR: Vertical instantaneous loading rate

VIP: Vertical impact peak

VO_2 max: Maximal aerobic capacity

Y: Yes

2D: Two dimensional

3D: Three dimensional

List of Publications

Journal Articles

Published

- **Burke, A**., Dillon, S., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Relative and absolute reliability of shank and sacral impact accelerations over a short- and long-term time frame. Sports Biomechanics (Accepted for Publication, 31/05/2022).

- **Burke, A**., Dillon, S., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2021. Risk factors for injuries in runners; A systematic review of foot strike technique and its classification at impact. Orthopaedic Journal of Sports Medicine, 9 (9).

- Dillon, S., **Burke, A**., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2021. Do injury-resistant runners have distinct differences in clinical measures compared with recently injured runners? Medicine and Science in Sport and Exercise, 53 (9).

Under Review

- **Burke, A**., Dillon, S., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Comparison of impact accelerations between injury-resistant and recently injured recreational runners. Plos One (Accepted for publication August 2022).

- **Burke, A**., Dillon, S., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Training related factors that differentiate between the recently injured, injury-resistant and never injured runner – A retrospective study. [Journal of Strength and Conditioning] (Awaiting decision).

- Dillon, S., **Burke, A**., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Are peak and rate of acceleration during treadmill running representative of those produced overground? Gait and Posture (Awaiting decision).

- Dillon, S., **Burke, A**., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2022. Are there differences in impact accelerations between recently injured and injury resistant runners? Scandinavian Journal of Medicine and Science in Sport (Awaiting decision).

<u>Conference Proceedings</u>

Oral Presentations

- **Burke, A**., Dillon, S., O'Connor, S., Whyte, E., Gore, S., Moran, K., 2019*. "A novel comparison of impact accelerations between prospectively injured runners and runners with and without a history of injury". IOC World Conference on Prevention of Injury & Illness in Sport. Monaco. *Re-scheduled due to Covid-19.

- **Burke, A**., O'Connor, S., Whyte, E., Dillon, S., Gore, S. and Moran, K., 2019. Impact accelerations in recreational runners with and without a history of injury. ECSS Congress Prague, Czech Republic.

- Dillon, S., Whyte, E., **Burke, A**., O'Connor, S., Gore, S. and Moran, K., 2019. A prospective investigation of the association between isometric muscle strength and running-related Injury among novice and recreational runners. ECSS Congress Prague, Czech Republic

- **Burke, A**., O'Connor, S., Whyte, E., Dillon, S., Gore, S., Moran, K., 2019. An Injury Profile of Irish Recreational Runners. All Ireland Postgraduate Conference in Sport Science, Physical Activity and Physical Education, Athlone, Ireland.

- Dillon, S., Whyte, E., **Burke, A**., O'Connor, S., Gore, S. and Moran, K., 2019. The differences in isometric muscle strength between recreational runners with and without a history of running-related injury. All Ireland Postgraduate Conference in Sport Science, Physical Activity and Physical Education. Athlone, Ireland.

- **Burke, A**., O'Connor, S., Whyte, E., Dillon, S., Gore, S., Moran, K., 2018. The development of the RISC prospective injury surveillance research project. Faculty of Sports and Exercise Participation, Optimising Health for Sport and Exercise Participation. Limerick, Ireland.

Poster Presentations

- Dillon, S., Whyte, E., **Burke, A**., O'Connor, S., Gore, S. and Moran, K., 2019. “Are lower limb isometric muscle torque and dorsiflexion range of motion associated with calf and Achilles tendon injuries among runners? A prospective study”. IOC World Conference on Prevention of Injury and Illness in Sport. Monaco.

- Dillon, S., Whyte, E., **Burke, A**., O'Connor, S., Gore, S. and Moran, K., 2019. Is Navicular Drop Associated with Running Related Injuries?. Insight student conference, Galway, Ireland.

- **Burke, A**., O'Connor, S., Whyte, E., Dillon, S., Gore, S., Moran, K., 2018. Running related injuries in Irish runners. Return to Play. Dublin, Ireland.

Abstract

Title Impact Acceleration, Kinematic and Training-related Risk Factors of Running Injuries: A Prospective Trial

Name Aoife Burke

Running-related injuries (RRIs) are a prevelant and challenging issue for runners and clinicians alike, fundamentally attributed to excessive overload on the body. The proposed aetiology of RRIs is vast, with several factors thought to be influential, including but not limited to a multifactorial myriad of impact loading, running technique, training practices and previous injury. This thesis applied a unique dual approach of risk factor identification by taking a retrospective and prospective vantage of RRIs on a large sample size of recreational runners. Retrospectively, high rates of acceleration at the sacrum were found to distinguish recently injured from never injured and acquired injury resistance runners. This is a promising finding for clinicians as accelerometer devices are readily usable outside of the laboratory, and thus may inform injury rehabilitation practices. Elsewhere, recently injured runners were found to exhibit riskier training practices such as high speeds, hill runs, changes of gradient and running with a niggle than their injury resistant counterparts, all factors which are easily modifiable for injury avoidance. Prospectively, risk factors for injury included a non-rearfoot strike pattern, lesser knee valgus, greater knee rotation, greater thorax drop to the contralateral side, marathon training, previous injury and frequent changes of footwear. Contrary to the hypothesis, baseline measures of impact loading and training were not found to predict injury. This suggests the need for more frequent assessments of internal and external loads. Although the findings from the retrospective and prospective studies differ, this highlights the value of both vantages, affording researchers and clinicians the opportunity to determine the potential causes and effects of RRIs with greater confidence than looking at either retrospective or prospective injury mechanisms in isolation. Future studies may benefit from a more continuous measure of loading, technique and training practices in order to further develop our understanding of RRI development.

Chapter 1 Introduction

Recreational running is now one of the top three most popular sports in Ireland, with participation levels growing from 6% to 10% in recent years (Sports Monitor Report Ireland 2021). Although this rise in participation has several health benefits including improvements to body composition, cardiovascular health, mental health and musculoskeletal health (Fries *et al*., 1994), running-related injuries (RRIs) are a significant issue. A recent prospective study reported prevalence rates of 66% in recreational runners, with 56% of participants suffering multiple RRIs (Messier *et al*., 2018). This high prevalence rate poses considerable challenges to the aforementioned health benefits, bringing physical and emotional stress to runners, as well as financial strain to both the runner and the healthcare system (Hespanhol Junior *et al*., 2016). Unfortunately, treatment may sometimes only relieve symptoms temporarily and the underlying causes of RRIs do not always get addressed (Messier *et al*., 2018). The aetiological factors of RRIs appear to be multifactorial in nature and have largely been attributed to impact loading (Van Der Worp, Vrielink and Bredeweg, 2016), running technique (Noehren *et al*., 2007; Kuhman *et al*., 2016; Dudley *et al*., 2017; Messier *et al*., 2018; Shen *et al*., 2019), training behaviour (Hreljac, 2005; Nielsen *et al*., 2014; Saragiotto, Yamato and Lopes, 2014) and previous injury history (van der Worp *et al*., 2015).

Taking a biomechanical model of injury, RRIs, like all injuries, are generally produced by relative excessive loading (i.e. high loading relative to tissue strength) (Hreljac, 2000). Studies investigating the biomechanical causes of RRIs have frequently focused their attention on loading through analysis of the ground reaction force (GRF) curve at impact (Figure 2.4.5). While there has been greater evidence that rate of loading may be related to RRIs, research findings on both rate and magnitude of GRF loading have been very mixed (van der Worp *et al*., 2016), which may in part be explained by whole body GRFs failing to account for the distribution of load at a segmental level (van der Worp *et al*., 2016). More recently, wearable accelerometer sensors have received support for potential load analysis as they provide a low cost, light weight, localised segmental analysis (F = m.a) and user-friendly alternative to force plates and instrumented treadmills (Auvinet *et al*., 2002; Laughton *et al*., 2003; Dufek *et al*., 2009). Although some studies have investigated the magnitude of loading of the lower limb through tibial accelerations, there has been no prospective research in this area, and very few retrospective studies conducted thus far. Given that lower limb injuries account for up to 73% of all RRIs (Messier *et al*., 2018), analysing load through tibial accelerations appears to be a justified exploration. Additionally, with lower back injuries making up 16% of RRIs (Ellapen *et al*., 2013), it may also be insightful to explore sacral loading local to this region. Only two studies have investigated the magnitude of sacral accelerations to date with only one of these being prospective in nature, demonstrating that this is a largely understudied area. Sacral acceleration has been found to be somewhat reflective of vGRF loading (LeBlanc *et al*., 2021), and so it may provide for a very useful transition towards an ecologically valid and clinically useful measure of loading. In addition, despite some research identifying the rate of loading from the vGRF curve to be related to injury (Ferber *et al.*, 2002; Milner *et al.*, 2006; Ribeiro *et al.*, 2015; Altman and Davis, 2016; Bigouette *et al.*, 2016), no studies investigating running load through accelerometers to date have explored the loading rate (rate of acceleration). This may provide an additional insight into the segment specific loading and injury relationship.

Elsewhere in the literature, authors have explored the role of running technique in RRI development. Similar to the analysis of impact loading, there has been mixed findings with respect to the role of technique at the foot, knee and hip in RRI development (Noehren *et al*., 2007; Kuhman *et al*., 2016; Dudley *et al*., 2017; Messier *et al*., 2018; Shen *et al*., 2019). This is likely because the majority of studies have been retrospective in nature, and so it is difficult to know whether the differences in technique between injured and uninjured runners is as a result of the injury, or if it is a cause of the injury. One area of technique and injury which has drawn greater interest is the relationship between foot strike and injury. Foot strike technique has been classified into distinct patterns, denoted by the part of the foot which makes initial contact with the ground first, such as rear-foot, mid-foot and fore-foot strike patterns (Daoud *et al*., 2012). It has been widely speculated that landing more dominantly with one pattern over another may have distinct effects on the loading and kinematics of the more superior segments to the foot (Goss, 2012; Kulmala *et al.*, 2013; Hamill and Gruber, 2017). However, the research has provided mixed findings regarding its relationship with injury, with retrospective study analysis and arbitrary foot strike assessment strategies being some of the potential reasons for this (Daoud, 2012; Goss, 2012; Mann *et al*., 2015; Warr *et al*., 2015). Elsewhere in the kinematic chain, little attention has been given to the relationship between pelvis and trunk kinematics and RRIs, highlighting the need for further research in this area. As the trunk weighs up to 60% of total body weight (Ford *et al*., 2013), movement at this segment likely influences the movement of more distal segments such as the pelvis, hips and knees in efforts to control centre of mass displacement during running. Therefore, it is imperative to consider the full kinematic chain, including the trunk, as it may assist in explaining the various pathological patterns of injury.

In addition to the internal load endured by runners, several authors have speculated that external loading in the form of training load, may also be linked to RRIs (Hreljac, 2005; Nielsen *et al*., 2014; Saragiotto, Yamato and Lopes, 2014). It has been hypothesized that injury may occur when cumulative training loads exceed a runner's capacity for tissue-repair adaptations (Damsted *et al*., 2018). Training load has been explored through several variables including running distance, speed and volume (frequency of sessions). A systematic review found low level evidence to support a relationship between training load and RRIs (Damsted *et al.*, 2018), but studies were limited by short follow-up periods. This clearly needs further investigation within a multifactorial approach.

Despite biomechanical loads and training loads receiving significant attention in the research of RRIs, with mixed findings prevalent, one risk factor which has consistently been reported to relate to prospective running injuries is a history of previous injury (van der Worp *et al*., 2015). It is thought that a history of previous injury may lead to re-injuries due to an uncorrected biomechanical problem and/or incomplete healing and rehabilitation of the original injury (van der Worp *et al.*, 2015). Additionally, runners may adopt a new biomechanical pattern or technique following return from previous injury, in an attempt to execute a protective strategy of the injured structure. This may overload a new joint or segment, and ultimately lead to further injuries (Saragiotto *et al.*, 2014). Despite previous injury history having strong links with prospective injury occurrence, there seems to be a gap in the research in the exploration of the amount of time between previous injuries and prospective injuries. While some studies have reflected upon the relationship between very recent (0-3 months) and less recent (4 – 12 months) time periods between previous injuries and prospective injuries (van der Worp *et al*., 2016; Leppe and Besomi, 2018), no studies have investigated the relationship between previous injuries that have occurred over a longer timeframe (> 2 years). By introducing a longer continuum for which previous injuries are explored, we may increase our understanding of how the body adapts to previous injury over time, and how this may affect impact loading and technique upon return to participation. In addition, runners who have no history of injury, the "never injured" runners, have rarely been investigated. This is important and possibly very insightful, as these never injured runners may have specific injury-resistant mechanics which can be of significant interest to runners, biomechanists and healthcare professionals. To date only two studies have investigated this specific group, looking directly at impact loading (Zifchock *et al*., 2008; Davis, Bowser and Mullineaux, 2016). These studies had low sample sizes however (n = 20), and did not consider other injurious factors such as training practices, thus highlighting the need for further research in this area.

Overall, while there has been some research into RRIs with respect to loading, technique, training practices and previous injury history, the majority of studies have been retrospective in nature and may have only explored one variable in isolation with respect to injury. Given the multifactorial nature of injuries, a multifactorial approach is warranted. Additionally, while retrospective studies are easier to implement and provide a more cost effective means of conducting research in comparison to prospective studies, the results of these studies may have restricted applicability. Ultimately, prospective research of multiple aetiological factors with large sample sizes and long-term surveillance periods will provide greater insight into the cause of RRIs.

Aims and objectives of the thesis

The overall aim of this research project was to conduct a large scale 12 month prospective trial, with the study being one of the largest of its kind with respect to segmental load analysis. A multifactorial approach was undertaken where several aetiological factors of RRIs were explored, including impact load analysis (accelerations across multiple segments), technique analysis (foot, ankle, knee, hip, pelvis and trunk), previous injury history, and training practice variables. In addition, investigations into never injured runners was undertaken to further the research in this novel and insightful group.

Finally, to be able to achieve the above, relative and absolute reliability of impact accelerometers of the tibia and sacrum was determined over short- and long-term time periods, to ensure they were appropriate for use in the injury surveillance studies.

Objectives:

1. To investigate the relative and absolute reliability of tibial and sacral impact accelerometers over a short- and long-term time frame (Chapter 3).

2. To investigate the differences in tibial and sacral impact accelerations between recently injured runners, runners who have acquired injury resistance and never injured runners (Chapter 4).
3. To investigate the differences in training practices between recently injured runners, runners who have acquired injury resistance and never injured runners (Chapter 5).
4. To investigate the aetiological factors of prospective running-related injuries, with consideration of impact acceleration, kinematics and training practices (Chapter 6).

In addition, to evaluate the relationship between foot strike technique and running-related injuries, a systematic review was completed and published (*Appendix A*).

Chapter 2 Literature Review

2.1 Introduction

The aim of this review is to critically appraise the literature surrounding running-related injuries (RRIs) and associated risk factors. The review will address 5 major areas: definition of RRIs, epidemiology of RRIs, intrinsic risk factors for RRIs, extrinsic risk factors for RRIs (training load factors, impact loading, running kinematics), and how technique affects impact loading.

2.2 Definition of running-related injury

Prevalence rates of RRIs range from 16% to 66% within the literature. This wide range may be due to differences in running populations studied and varying methods of acquiring RRI information such as self-reporting surveys, emails and medical reviews (Bredeweg *et al.*, 2013; Yamato *et al.*, 2015; Messier *et al.*, 2018). Ultimately, the definitions of RRIs within the running literature are widely varying, and this is a considerable factor underlying why prevalence rates have such a broad range across running populations (Yamato *et al.*, 2015). RRI definitions within the literature are summarized in Table 2.2.1. For the purpose of this review, only studies which have investigated RRIs in recreational running populations were included. In order to compare the definitions across the studies, the definition of RRI was broken up into four sub-categories (physical complaint, specified region, training disruption and medical attention).

With respect to physical complaint, the key descriptor term used to define physical complaint was analysed. Of the seventeen prospective and eight retrospective studies identified in this review, all studies reported at least one key descriptor of physical complaint in their definition of RRI. Pain was the most commonly reported key descriptor, with 44% of studies defining this as their physical complaint. Other descriptors found in RRI definitions included injury (28%), complaint (8%), symptom (8%), disorder (4%), distress or agony (4%) and problem (4%).

Specified region was also noted with respect to anatomical location of the RRI. Eleven studies stated a specified region in their definition, with “lower extremity or back” being defined by 64% of these studies.

With regards to training disruption, definitions were classified as having a "negative impact on performance" (NIoP) and/or time-loss (TL) criteria. Negative impact on performance covered terms used to describe when a RRI impacted negatively on training performance, whereby speed, distance, intensity, frequency, volume and/or duration of running was affected by the physical complaint. Time-loss refers to a minimum amount of time that running participation or performance was affected (e.g. one day, three sessions, one week). Twenty-two studies of the twenty-five reviewed specified a negative impact on performance as a criteria for injury, with twelve of these studies detailing the time-loss required for this negative impact on performance. However, as can be seen from the table, minimum time-loss values range from one day to one week, making it difficult to compare.

Lastly, RRI definitions were screened for medical attention criteria, whereby runners who sought attention from a medical professional for a physical complaint, irrespective of having training disruption, were included in RRI analyses. Only seven studies had specified this criterion in their definition.

In recognition of the problem regarding wide variances in RRI definition, Yamato *et al.*, (2015) conducted a systematic review. The authors demonstrated that a definition of RRI with little to no time-loss stated could yield RRI prevalence rates of up to 84.9% (Bovens *et al.*, 1989), while more specific time-loss (e.g. 7 days) definitions demonstrated much lower prevalence rates (24%) (Blair, Kohl and Goodyear, 1987) in similar running populations (Yamato *et al.*, 2015). This highlights the need to have consistency when defining RRI, and the authors concluded that a definition with a time-loss element would be more stringent in determining the burden of injury. Thus, a consensus definition was developed based on the approval of thirty-eight experts (Yamato *et al.*, 2015). RRI was 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 requires the runner to consult a physician or other health professional" (Yamato *et al.*, 2015). Going forward, all research concerning RRIs should strive to utilize this definition, or at the very least, utilize a definition with clear and specific physical complaint descriptors, regions of interest, details of training disruptions (negative impact on performance and/or time-loss), and details of medical attention being sought.

Table 2.2.1 Definition of running-related injury in the literature.

Study	**Population**	**Methods**	**Definition of RRI**			
Prospective	*Recreational (R)*	*Methods*	*Physical Complaint*	*Specified Region*	*Training Disruption*	*Medical Attention*
Lun *et al*., (2004)	n = 87 (44 ♂, 43 ♀)	Online training log	Symptom	-	NIoP	-
Gerlach *et al*., (2005)	n = 87 (0 ♂, 87 ♀)	Survey	Injury	Lower Extremity or Back	NIoP	Y
Van Middelkoop *et al*., (2008)	n = 694 (694 ♂, 0 ♀)	Survey	Injury	Lower Extremity	NIoP	-
Hendricks *et al*., (2013)	n = 50 (34 ♂, 16 ♀)	Survey	Injury	Lower Extremity	NIoP & TL	Y
Altman *et al*., (2015)	n = 201 (153 ♂, 48 ♀)	Survey	Injury	Lower Extremity or Back	-	Y
Malisoux *et al*., (2015)	n = 264 (195 ♂, 69 ♀)	Online training log	Pain or Complaint	-	NIoP & TL (1 day)	-
Davis *et al*., (2016)	n = 249 (0 ♂, 249 ♀)	Online training log	Pain	-	NIoP	Y
Van der Worp *et al*., (2016)	n = 417 (0 ♂, 417 ♀)	Survey	Pain	Lower Extremity or Back	NIoP & TL (1 day)	-
Messier *et al*., (2018)	n = 300 (172 ♂, 128 ♀)	Survey	Symptom	-	NIoP	-
Napier *et al*., (2018)	n = 65 (0 ♂, 65 ♀)	Survey	Pain	Lower Extremity or Back	NIoP & TL (3 sessions)	-
Dallinga *et al*., (2019)	n = 678 (347 ♂, 331 ♀)	Survey	Complaint	-	NIoP & TL (1 week)	-
Franke *et al*., (2019)	n = 161 (90 ♂, 71 ♀)	Survey	Complaint	-	NIoP (1 session)	-
Winter *et al*., (2020)	n = 76 (45 ♂, 31 ♀)	Physical Examination	Pain	-	NIoP & TL (1 session)	Y
Desai *et al*., (2021)	n = 224 (135 ♂, 89 ♀)	Physical Examination	Pain	Lower Extremity or Back	NIoP & TL (2 weeks)	Y
Taunton *et al*., (2003)	n = 840 (205 ♂, 635 ♀)	Survey	Pain	-	NIoP	-
Chorley *et al*., (2002)	n = 1548 (577 ♂, 968 ♀)	Survey	Disorder	-	NIoP	-
Buist *et al*., (2008)	n = 629 (207 ♂, 422 ♀)	Training Diary	Pain	Lower Extremity or Back	NIoP & TL (1 day)	-
Retrospective	*Recreational*	*Methods*	*Physical Complaint*	*Specified Region*	*Training Disruption*	*Medical Attention*
Williams *et al*., (2001)	n = 40 (18 ♂, 22 ♀)	Survey	Injury	Lower Extremity	NIoP & TL (1 week)	-

Taunton *et al*., (2002)	n = 2002 (926 ♂, 1076 ♀)	Medical Review	Pain or Symptom	-	NIoP	-
Hespanhol *et al*., (2012)	n = 200 (146 ♂, 54 ♀)	Survey	Pain	-	NIoP & TL (1 session)	-
Vadeboncoeur *et al*., (2012)	n = 194 (55 ♂, 139 ♀)	Survey	Injury	Hip or Below	-	-
Ellapen *et al*., (2013)	n = 200 (120 ♂, 80 ♀)	Survey	Distress or Agony	-	NIoP & TL (1 day)	-
Besomi *et al*., (2018)	n = 4380 (N/R ♂, N/R ♀)	Survey	Injury	-	NIoP & TL (1 week)	-
Linton *et al*., (2018)	n = 1145 (504 ♂, 641 ♀)	Survey	Problem	-	NIoP	-
Hollander *et al*., (2020)	n = 550 (277 ♂, 273 ♀)	Physical Examination	Pain	Lower Extremity or Back	-	Y

RRI: Running-related injury; n: sample size; N & R: novice and recreational running populations combined; NIoP: negative impact on performance; TL: Time-loss; Y: Yes, medical attention was a stated criteria in the definition; -: variable not stated in definition; N/R: not reported.

2.3 Epidemiology of injury

2.3.1 Prevalence and incidence of injury

Running-related injuries are a well-known burden of the sport (Hespanhol Junior *et al.*, 2016). However, quantifying this burden has proven difficult, with injuries reported in varying ways across studies. To date, injuries have been reported as both prevalence and incidence measures. Prevalence refers to the proportion of a population who have an injury at a particular point in time, while incidence refers to the number of injuries occurring during the specified period of time in a study (Knowles, Marshall and Guskiewicz, 2006). Typically, prevalence has been reported as a percentage. While incidence per 1,000 hours has been highlighted as an important measure of injury (Jakobsen *et al.*, 1994), it seems that not all epidemiology studies have applied this metric to their analyses.

With respect to epidemiological studies on RRIs (Table 2.3.1), all studies have reported the prevalence of RRI, with recreational runners reported to have a prevalence range of 14-90%. These ranges are quite wide mainly due to methodological differences between studies, including varying definitions of injury, durations of injury surveillance, as well as methods of surveillance.

In terms of injury incidence, only five of twenty studies reported incidence rates. Of these studies, it was found that the incidence rate in recreational runners ranged from 5.2 – 10.0 injuries per 1,000 hours. The limited reporting of incidence rates throughout the literature is likely due to the challenges of tracking training hours on an ongoing basis.

Table 2.3.1 Prevalence and incidence of RRIs in recreational runners.

Study	***Sample size***	***Duration of surveillance***	***Methods of surveillance***	***RRI Definition***	***Prevalence***	***Incidence (per 1000h)***
Recreational Runners						
Ellapen *et al*., (2013)	200 (120 ♂, 80 ♀)	1 year	Survey Self-documented RRI	Experience of as a sensation of distress or agony, and which prevented them from physical activity for a minimum of 24 hours.	90%	-
Franke *et al*., (2019)	n = 161 (90 ♂, 71 ♀)	4 months	Survey	Any self-reported complaint involving muscles, tendons, and/or bones deemed by the runner to be caused by running.	89%	-
Lun *et al*., (2004)	87 (44 ♂, 43 ♀)	6 months	Monthly training log Self-documented RRI	Any musculoskeletal symptom of the lower limb that required a reduction or stoppage of normal training.	79% (79% ♂, 79% ♀)	-
Jakobsen *et al*., (1994)	41 (37 ♂, 4 ♀)	1 year	Weekly training log Self-documented RRI	Any injury to the musculoskeletal system that was incurred during running and prevented training or competition.	76%	6.9
Messier *et al*., (2018)	252 (172 ♂, 128 ♀)	2 years	Bi-weekly email RRI consultation	Overuse running injuries were graded as: grade 1, maintained full activity in spite of symptoms; grade 2, reduced weekly mileage; and grade 3, interrupted all training for at least 2 weeks.	66% (62% ♂, 73% ♀)	-
Di Caprio *et al*., (2010)	166 (86 ♂, 80 ♀)	5 years	N/R	Non-traumatic foot and lower limb diseases resulting in a minimum rest period of two weeks.	59%	-
Davis *et al*., (2016)	249 (0 ♂, 249 ♀)	2 years	Monthly training log RRI consultation	Injuries that did not resolve on their own and led the runner to seek medical attention.	58%	-
Winter *et al*., (2020)	n = 76 (45 ♂, 31 ♀)	1 year	Training diary	Any pain of musculoskeletal origin attributed to running by the runner themselves and severe enough to prevent the runner from performing or completing at least 1 training session.	51%	-
Desai *et al*., (2021)	n = 224 (135 ♂, 89 ♀)	1 year	N/R	A running-related musculoskeletal pain in the lower limbs or back that causes restriction of running (distance, speed, duration or training) in more than 66% of all training sessions in 2 consecutive weeks or in more than 50% of all training sessions in 4 consecutive weeks, or that requires the runner to consult a physician or other health professional.	50%	-
Malisoux *et al*., (2015)	264 (195 ♂, 69 ♀)	5 months	Training log Self-documented RRI	A physical pain or complaint located at the lower limbs or lower back region, sustained during or as a result of running practice and impeding planned running activity for at least 1 day.	33%	8.0
Hendricks *et al*., (2013)	50 (34 ♂, 16 ♀)	4 months	Weekly visit to club RRI consultation	Any reported muscle, joint or bone problem /injury of the back or lower extremity (i.e. hip, thigh, knee, shin, calf, ankle, foot) resulting from running in a practice or meet and requiring the runner to be removed from the practice or meet or to miss a subsequent one. Furthermore, the running injury should be severe enough to require medication, injection into the painful muscle, joint or tendon, surgery, physiotherapy, rehabilitative treatment, braces or orthotics.	32%	-
Dallinga *et al*., (2019)	678 (347 ♂, 331 ♀)	1 year	Survey Self-documented RRI	Every physical complaint that resulted in at least 1 week of training loss.	32%	-
Junior *et al*., (2013)	191 (141 ♂, 50 ♀)	3 months	Bi-monthly survey Self-documented RRI	Any pain of musculoskeletal origin attributed to running and severe enough to prevent the runner from performing at least one training session.	31% (35% ♂, 18% ♀)	10.0

Taunton *et al*., (2003)	844 (205 ♂, 635 ♀)	13 weeks	Monthly survey Self-documented RRI	Running injuries were graded as 1, pain only after exercise; 2, pain during exercise, but not restricting distance or speed; 3, pain during exercise and restricting distance and speed; 4, pain preventing all running.	30%	-
Theisen *et al*., (2014)	247 (136 ♂, 111 ♀)	5 months	Weekly training log Self-documented RRI	Physical pain or a complaint sustained during or as a result of running practice and impeding normal running activity for at least 1 day.	28%	-
Junior *et al*., (2016)	89 (68 ♂, 21 ♀)	3 months	Bi-monthly survey Self-documented RRI	Any pain of musculoskeletal origin attributed to running and severe enough to prevent the runner from performing at least one training session.	27%	7.7
Van Der Worp *et al*., (2016)	417 (0 ♂, 417 ♀)	3 months	Monthly email Self-documented RRI	Running-related pain of the lower back and/or the lower extremity that restricted running for at least 1 day.	26%	-
Ogwumike *et al*., (2013)	920 (856 ♂, 64 ♀)	2 events	RRI consultation	N/R	17%	-
Van Middelkoop *et al*., (2008)	694 (694 ♂, 0 ♀)	1 month	Survey Self-documented RRI	Injury on muscles, joints, tendons and/or bones of the lower extremities (hip, groin, thigh, knee, lower leg, ankle, foot, and toe) that the participant attributed to running.	16%	-
Van Mechelen *et al*., (1993)	167 (167 ♂, 0 ♀)	4 months	Monthly training log RRI consultation	Any injury that occurred as a result of running and caused one or more of the following: 1) the subject had to stop running, 2) the subject could not run on the next occasion, 3) the subject could not go to work the next day, 4) the subject needed medical attention, or 5) the subject suffered from pain or stiffness during 10 subsequent days while running.	14%	5.2

RRI: Running-related injury; ♂: male; ♀: female; RRI consultation: running-related injuries were diagnosed by medical professionals; Self-documented RRI: running-related injuries were documented and reported by the runners themselves; -: not reported; 95% CI: 95% confidence intervals.

2.3.2 Location of injury

Twenty-five studies have reported on the location of RRIs and are outlined in Table 2.3.2. The knee is the most commonly cited location of injury with 8% - 42% of all RRIs in recreational runners. This is followed by the foot/ankle with prevalence rates of up to 36%, and lower leg/calf rate up to 28%. Whilst some studies found the hip and upper leg to have high prevalence rates (32%), this has not been a common trend throughout the literature.

2.3.3 Type of injury

As noted from the previous section, the knee, foot, ankle and lower leg are amongst the highest reported sites of injury in running. However, knowing the type of injury that occurs at various locations may be useful in order to identify risk factors for injury or develop targeted preventative strategies. However, not all epidemiology studies reported the type of injury, with only twelve of the twenty-five reviewed studies reporting this (Table 2.3.3). Of the studies that have reported the type of injury, authors have utilised two methods to do so, making comparison across studies difficult. Some authors have reported on the type of injury in terms of anatomical structure injured (e.g. muscle, tendon, ligament) (Van Mechelen *et al.*, 1993; Hespanhol Junior, Pena Costa and Lopes, 2013; Theisen *et al.*, 2014; Malisoux *et al.*, 2015; Davis, Bowser and Mullineaux, 2016; Hespanhol Junior *et al.*, 2016), whilst other authors have reported the diagnosis of the injury (Lysholm and Wiklander, 1987; Bovens *et al.*, 1989; Jakobsen *et al.*, 1994; Di Caprio *et al.*, 2010; Napier *et al.*, 2018).

With regards to the anatomical structure of injury, muscle and tendon are the most commonly reported structures involved in RRIs, with prevalence ranging between 23% - 70% (Van Mechelen *et al.*, 1993; Hespanhol Junior, Pena Costa and Lopes, 2013; Theisen *et al.*, 2014; Malisoux *et al.*, 2015; Davis, Bowser and Mullineaux, 2016; Hespanhol Junior *et al.*, 2016). This range is quite wide as three studies combined muscle and tendon pathologies and reported them together as one metric (Theisen *et al.*, 2014; Malisoux *et al.*, 2015; Smits *et al.*, 2016). Other anatomical structures which have high prevalence rates in RRIs include ligaments (8% - 23%) (Theisen *et al.*, 2014; Malisoux *et al.*, 2015; Davis, Bowser and Mullineaux, 2016), joints (21%) (Van Mechelen *et al.*, 1993) and bone (14%) (Davis, Bowser and Mullineaux, 2016). With respect to the diagnoses of RRIs, Achilles tendonitis (9-32%) (Lysholm and Wiklander, 1987; Jakobsen *et al.*, 1994; Di Caprio *et al.*, 2010), plantar fasciitis (7-31%) (Lysholm and Wiklander, 1987; Jakobsen *et al.*, 1994; Di

Caprio *et al.*, 2010) and medial tibial stress syndrome (15-26%) (Jakobsen *et al.*, 1994; Napier *et al.*, 2018) are the three highest reported diagnoses of injury in recreational runners. Of the studies which reported RRI diagnoses specifically, none of them identify knee pathologies as their number one reported diagnoses, which is surprising as it is the most common location of injury across multiple studies.

It seems that the literature is lacking in this area. Given the extent of kinetic and kinematic research which has been targeted at runners with specific injuries such as patellofemoral pain syndrome, anterior knee pain and tibial stress fractures, it is unusual that these injuries have not proven to be as prevalent in the epidemiology studies reviewed. While location of injury is well reported in the literature, future research should report on the type of injury and the diagnosis of injury where applicable to further our understanding of common RRIs in recreational and novice runners.

Table 2.3.2 Top five most commonly reported locations of RRIs.

Study	***Sample size***	***Location 1***		***Location 2***		***Location 3***		***Location 4***		***Location 5***	
Recreational Runners											
Taunton *et al*., (2002)	2002 (926 ♂, 1076 ♀)	Knee	42%	Ankle/Foot	17%	Lower leg	13%	Hip/Pelvis	11%	Achilles/Calf	6%
Taunton *et al*., (2003)	844 (205 ♂, 635 ♀)	Knee	34%	Shin	16%	Foot	14%	Ankle	10%	Achilles/Calf	9%
Rasmussen *et al*., (2013)	662 (531 ♂, 131 ♀)	Knee	32%	Ankle/Foot	32%	Lower leg	18%	Thigh	6%	Lower back	4%
Buist *et al*., (2010)	629 (207 ♂, 422 ♀)	Knee	31%	Lower leg	34%	Other	11%	Hip/Groin	7%	Ankle	6%
Van Middelkoop *et al*., (2008)	694 (694 ♂, 0 ♀)	Knee	29%	Calf	27%	Thigh	16%	N/R	-	N/R	-
Messier *et al*., (2018)	252 (172 ♂, 128 ♀)	Knee	28%	Foot	21%	Hip	13%	Ankle	12%	Lower leg	12%
Desai *et al*., (2021)	n = 224 (135 ♂, 89 ♀)	Knee	27%	Achilles/Calf	25%	Foot/Ankle	20%	Hip/Pelvis	15%	Lower leg	7%
Walter *et al*., (1989)	1281 (980 ♂, 301 ♀)	Knee	27%	Foot	16%	Foot	15%	Lower back	11%	Hip	9%
Hollander *et al*., (2020)	n = 550 (277 ♂, 273 ♀)	Knee	26%	Lower leg	22%	Foot/Toes	16%	Hip/Groin	13%	N/R	-
Ellapen *et al*., (2013)	200 (120 ♂, 80 ♀)	Knee	26%	Tibia/Fibula	22%	Lower back/Hip	16%	Thigh	14%	Ankle	10%
Van Mechelen *et al*., (1993)	167 (167 ♂, 0 ♀)	Knee	25%	Calf	14%	Pelvis/Groin	14%	Posterior Thigh	14%	Foot	14%
Theisen *et al*., (2014)	247 (136 ♂, 111 ♀)	Knee	25%	Lower leg	22%	Thigh	17%	Trunk	10%	Foot	10%
Williams *et al*., (2001)	40 (18 ♂, 22 ♀)	Knee	23%	Foot	18%	Ankle	17%	Lower leg	16%	Back	5%
Dallinga *et al*., (2019)	678 (347 ♂, 331 ♀)	Knee	22%	Lower leg	15%	Achilles	10%	N/R	-	N/R	-
Malisoux *et al*., (2015)	264 (195 ♂, 69 ♀)	Knee	20%	Lower leg	20%	Thigh	18%	Ankle	16%	Lower back/Pelvis	10%
Junior *et al*., (2013)	191 (141 ♂, 50 ♀)	Knee	19%	Foot/Toe	17%	Lower leg	14%	Lower back	14%	Thigh	14%
Junior *et al*., (2016)	89 (68 ♂, 21 ♀)	Knee	15%	Achilles	15%	Lower back	7%	Foot	7%	Shin	7%
Winter *et al*., (2020)	n = 76 (45 ♂, 31 ♀)	Achilles/Calf	28%	Lower leg/Ankle	15%	Hip/Pelvis	15%	Hamstring	13%	Knee	13%

Van Der Worp *et al*., (2016)	376 (0 ♂, 376 ♀)	Lower leg (5k) Knee (10k)	N/R	Hip/Groin (5k) Thigh (10k)	N/R	Foot (5k) Hip/Groin (10k)	N/R	Ankle (5k) Lower leg (10k)	N/R	Thigh (5k) Ankle (10k)	N/R
Vadeboncoeur *et al*., (2012)	194 (55 ♂, 139 ♀)	Hip/Upper leg	32%	Foot/Ankle	26%	Knee	19%	Lower leg	16%	Other	7%
Di Caprio *et al*., (2010)	166 (86 ♂, 80 ♀)	Foot	31%	Achilles	24%	Knee	14%	Lower leg	10%	Toe	7%
Davis *et al*., (2016)	249 (0 ♂, 249 ♀)	Foot/Ankle	24%	Lower leg	21%	Knee	21%	Thigh	18%	Hip	12%
Lun *et al*., (2004)	87 (44 ♂, 43 ♀)	Foot	15%	Thigh	9%	Lower Leg	9%	Knee	8%	Hip/Groin	5%
Hendricks *et al*., (2013)	50 (16 ♂, 34 ♀)	Calf	20%	Knee	18%	Lower back	18%	Ankle	8%	Hamstring	8%
Ogumike *et al*., (2013)	920 (856 ♂, 64 ♀)	Thigh	32%	Ankle	18%	Calf	17%	Knee	14%	Foot	14%

RRI: Running-related injury; Location 1 – 5: locations of running-related injuries are ranked from highest to lowest in terms of percentage of total running-related injuries reported in that study; ♂: Male; ♀: female; N/R: not reported; (5k): most commonly reported injury in recreational runners running a 5km event; (10k): most commonly reported injury in recreational runners running a 10km event.

Table 2.3.3 Top five most commonly reported anatomical structures and diagnoses of RRI.

Study	***Sample size***	***Type 1***		***Type 2***		***Type 3***		***Type 4***		***Type 5***	
Recreational Runners											
Van Mechelen *et al*., (1993)	167 (167 ♂, 0 ♀)	Muscle	25%	Tendon	21%	Joint	21%	Tendon-muscle	18%	Tendon-bone	9%
Theisen *et al*., (2014)	247 (136 ♂, 111 ♀)	Muscle & Tendon	70%	Capsule & Ligament	16%	Fracture or Bone Trauma	4%	Contusion	3%	Nervous system	3%
Malisoux *et al*., (2015)	264 (195 ♂, 69 ♀)	Muscle & Tendon	68%	Capsule & Ligament	23%	Contusion	3%	N/R	-	N/R	-
Junior *et al*., (2013)	191 (141 ♂, 50 ♀)	Muscle	30%	Lower back pathology	14%	Tendon	12%	Fascia	8%	Meniscus	7%
Davis *et al*., (2016)	249 (0 ♂, 249 ♀)	Muscle	23%	Tendon	19%	Fracture or Bone Trauma	19%	Tendon-bone	11%	Ligament	8%
Junior *et al*., (2016)	89 (68 ♂, 21 ♀)	Tendon	30%	Lower back pathology	7%	Fascia	7%	Tendon-bone	7%	N/R	-
Dallinga *et al*., (2019)	678 (347 ♂, 331 ♀)	Tendon	20%	Muscle	17%	N/R	-	N/R	-	N/R	-

Study	***Sample size***	***Diagnosis 1***		***Diagnosis 2***		***Diagnosis 3***		***Diagnosis 4***		***Diagnosis 5***	
Recreational Runners											
Lysholm *et al*., (1987)	60 (44 ♂, 16 ♀)	MTSS	15%	Hamstring Strain	11%	Ankle Sprain	11%	Achilles Tendonitis	9%	Planter Fasciitis	7%
Jakobsen *et al*., (1994)	41 (37 ♂, 14♀)	Achilles Tendonitis	32%	MTSS	26%	Ankle Sprain	16%	PFPS	13%	Plantar Fasciitis	10%
Williams *et al*., (2001)	40 (18 ♂, 22 ♀)	Plantar Fasciitis	10%	Patellar Tendinitis	7%	Lateral Ankle Sprain	7%	ITBS	6%	Tibial Stress Fracture	5%
Di Caprio *et al*., (2010)	166 (86 ♂, 80 ♀)	Plantar Fasciitis	31%	Achilles Tendinopathy	24%	Knee Flexor	14%	Stress Fracture	10%	Metatarsalgia	7%
Napier *et al*., (2018)	55 (0 ♂, 55 ♀)	MTSS	27%	ITBS	14%	Tendonitis	14%	Muscle strain	14%	Piriformis Syndrome	9%

RRI: Running-related injury; Type 1 – 5: anatomical structures of running-related injuries are ranked from highest to lowest in terms of percentage of total running-related injuries reported in that study Diagnosis 1 – 5: diagnoses of running-related injuries are ranked from highest to lowest in terms of percentage of total running-related injuries reported in that study; ♂: Male; ♀: female; N/R: not reported; MTSS: medial tibial stress syndrome; PFPS: patellofemoral pain syndrome; ITBS: iliotibial band syndrome.

2.3.4 Severity of injury

The severity of injury is important as it can provide an additional perspective to the negative consequence that injury has (Junge and Dvorak, 2000). Severity of injury has typically been reported in terms of the duration of incapacity that results from injury (Junge and Dvorak, 2000), however, similar to the disparities relating to the definition of RRIs, there too seems to be a lack of consensus in methods of reporting severity (Van Gent *et al.*, 2007). In running literature, injury severity is typically reported through negative impact on performance and quantitative time-loss methods. Although, medical attention and cost methods have been used to determine severity in other sports (Knowles *et al.*, 2007), this is not as evident in running epidemiological studies and so for the purpose of this review, severity has been explored under the two sub-categories previously mentioned: negative impact on performance and quantitative time-loss (Table 2.3.4).

With respect to negative impact on performance, three studies have applied this severity classification method to determine the consequence of injury (Marti *et al.*, 1988; Lun *et al.*, 2004; Messier *et al.*, 2018). Two studies in particular utilised a grading system to quantify severity where a low grade (Grade 1) injury reflected maintenance of full training activity, moderate grade (Grade 2) injuries were those that caused a reduction in training, and high grade (Grade 3) injuries indicated complete interruption or stoppage of training activity (Marti *et al.*, 1988; Messier *et al.*, 2018). Lun *et al.*, (2004) also applied a grading method to the classification of injury severity, but their system differed to that of Marti *et al.*, (1988) and Messier *et al.*, (2018) in that they split restriction (R) and stoppage (S) of training into two separate scales. The scales defined severity by the time for which restriction or stoppage of training was affected, whereby R1, R2, R3 and S1, S2, S3 denoted restrictions and stoppages in running training for 1, 2-7 and 7+ days respectively (Lun *et al.*, 2004). Although, this grading system is a bit more insightful as it reflects how long the runner suffered from a negative impact on performance, the grading system fails to capture the severity of longer and potentially more significant injuries which may have negative consequences to performance for up to 6 months.

In the studies outlined above, it was reported that high grade injuries accounted for 20%-38% of RRIs (Marti *et al.*, 1988; Lun *et al.*, 2004), and moderate grade injuries accounted for 29-36% of RRIs (Marti *et al.*, 1988; Lun *et al.*, 2004). Interestingly, 28%-38% of RRIs were low grade injuries, meaning that the runner was able to maintain their weekly training despite having pain (Marti *et al.*, 1988; Lun *et al.*, 2004; Messier *et al.*, 2018). This is quite striking as it demonstrates that runners persist to train even through adversity. In doing so, runners may be running with impaired function and tissue damage, potentially leading to significant overuse injuries (Lopes *et al.*, 2011).

Elsewhere in the running literature, severity of injury has been reported through means of quantitative time-loss. Four studies have reported the number of days, weeks or training sessions missed through injury (Hespanhol Junior, Pena Costa and Lopes, 2013; Warr *et al.*, 2015; Hespanhol Junior *et al.*, 2016; Dallinga *et al.*, 2019). Although the periods of surveillance vary from 3 -12 months, the range in time-loss due to RRI is 3 – 8 weeks (Hespanhol Junior, Pena Costa and Lopes, 2013; Hespanhol Junior *et al.*, 2016; Dallinga *et al.*, 2019). This range appears to be quite wide, and in part may be explained by differences in sample size studied, period of surveillance, definition of injury and types of injuries sustained. Nevertheless, a time-loss of up to 8 weeks due to injury is concerning for runners, medical professionals and biomechanists alike. In order to gain further understanding of injury epidemiology in running, severity of injury should be reported consistently throughout the literature. A method of including both negative impact on performance and quantitative time-loss would be most insightful. Researchers should also pay particular attention to documenting the effect of injury on the runner's ability to maintain full training. As highlighted earlier, up to 38% of runners continued full training despite having persistent pain. Should the function of the painful tissue be impaired throughout the training, the body may find strategies to compensate for this, thus potentially affecting the kinetics and kinematics elsewhere in the musculoskeletal chain.

Table 2.3.4 Severity of RRIs in recreational runners.

Study	***Sample size***	***Duration of surveillance***	***Methods of surveillance***	***Severity classification***	***Severity definition***	***Severity reported***
Negative impact on performance						
Recreational Runners						
Marti *et al*., (1988)	4358 (4358 ♂, 0 ♀)	1 year	Survey Self-documented RRI	Grade 1	Maintenance of full training activity	28%
				Grade 2	Reduction in training activity	29%
				Grade 3	Involuntary complete interruption of running of at least 2 weeks duration	20%
Messier *et al*., (2018)	252 (172 ♂, 128 ♀)	2 years	Bi-weekly email RRI consultation	Grade 1	Maintain weekly mileage	38%
				Grade 2 & 3	Altered or discontinued training	41%
Lun *et al*., (2004)	87 (44 ♂, 43 ♀)	6 months	Monthly training log Self-documented RRI	R1	Restriction for 1 day	7%*
				R2	Restriction for 2-7 days	19%*
				R3	Restriction for 7 days +	10%*
				S1	Stoppage for 1 day	5%*
				S2	Stoppage for 2-7 days	9%*
				S3	Stoppage for 7 days +	24%*
Quantitative time-loss						
Recreational Runners						
Junior *et al*., (2013)	191 (141 ♂, 50 ♀)	3 months	Bi-monthly survey Self-documented RRI	No classification	Duration of RRI in weeks	3 ± 2 weeks
					Training sessions per week missed	4 ± 3 sessions/week
Junior *et al*., (2016)	53 (22 ♂, 31 ♀)	18 weeks	Bi-monthly survey Self-documented RRI	No classification	Duration of RRI in weeks	4 weeks
Dallinga *et al*., (2019)	678 (347 ♂, 331 ♀)	1 year	Survey Self-documented RRI	No classification	Duration of RRI in weeks	8 ± 8 weeks
Warr *et al*., (2015)	341 (341 ♂, 0 ♀)	1 year	Survey Self-documented RRI	No classification	Days of modified training	18 days ± 64 days

♂: males; ♀: females; RRI: running-related injury; R1, R2, R3: restriction in running training for 1, 2-7 and 7+ days respectively; S1, S2, S3: stoppage in running training for 1, 2-7 and 7+ days respectively;

**percentages are estimated from a bar graph figure as actual figures are not reported in text; Kee and Seo pain-rating scale: 1 = uncomfortable, 2 = mild, 3 = moderate, 4 = severe, 5 = worst experienced.*

2.4 Risk factors for running-related injuries

In order to review risk factors for running-related injuries (RRIs), it is important to consider both intrinsic and extrinsic risk factors. When reviewing the literature, evidence for a relationship with various factors was synthesized using the following criteria:

Strong evidence: ≥75% of studies found a significant effect between risk factor and RRI.
Limited evidence: 50-74% of studies found a significant effect between risk factor and RRI.
Little evidence: <50% of studies found a significant effect between risk factor and RRI.
Conflicting evidence: Findings of evidence were in multiple directions, but number of studies finding an effect > number of studies finding no effect.

Finch (2006) established a framework for research in injuries (translating research into injury prevention practice: TRIPP), whereby in order to prevent injuries occurring, there are a series of important steps to consider within research. The first of which is establishing injury surveillance, followed by establishing the aetiology and mechanisms of injury. Following this, injury preventative measures could be introduced and efficacy of the prevention methods could be assessed thereafter. Although the framework is well known within the injury research field, there is little detail given towards establishing the aetiology and mechanisms of injury. However, Meeuwisse *et al.*, (2007) proposed a dynamic, recursive model of sports injury very shortly after the TRIPP framework was released, and this will inform the structure of this following literature review section. With reference to the dynamic, recursive model of sports injury as outlined by Meeuwisse *et al.*, (2007) (Figure 2.4.1), a person's risk for injury is dynamic, whereby one's exposure to a potentially injurious event may change frequently depending on the interplay of intrinsic and extrinsic factors (Meeuwisse *et al.*, 2007). With each athletic exposure, intrinsic risk factors may be minimized as the runner adapts to the demands placed on the body, subsequently lowering their predisposition to injury (Meeuwisse *et al.*, 2007). In contrast, each athletic exposure could equally produce asymptomatic microtrauma and as a result may lower the strength or neuromuscular control of the runner, increasing their susceptibility to a prospective injury (Meeuwisse *et al.*, 2007). Although exposure to extrinsic risk factors may be identical between two athletic events, failure of the body to adapt to the asymptomatic microtrauma might result in an injury, and pending the recovery of this injury, time-loss from running may ensue. With respect to the dynamic, recursive model of sports injury by Meeuwisse *et* *al.*, (2007), important aspects pertinent to prospective RRI occurrence includes analysis of both intrinsic (sex, age, running experience, previous injury and anthropometrics) and extrinsic (training-related characteristics, surface and footwear) risk factors, and the potential interplay between the two in prospective RRI occurrence. Both intrinsic and extrinsic risk factors will be reviewed in the proceeding sections.

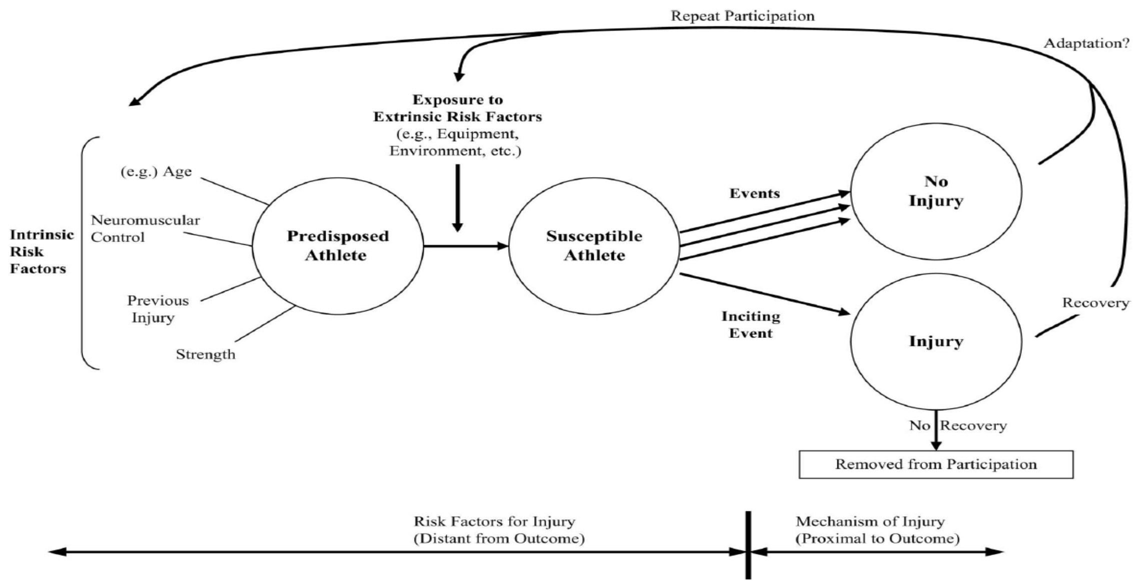

Figure 2.4.1 The dynamic, recursive model of injury (Meeuwisse et al., 2007).

2.4.1 Intrinsic risk factors

2.4.1.1 Sex

Fifteen studies have sought to explore the differences in risk between males and females. Of these, 7 were prospective and 8 were retrospective in nature, with prospective findings suggesting conflicting evidence and retrospective findings suggesting little evidence for sex as a risk factor for RRIs (Table 2.4.1). A distinction should be made here however, as some studies explored general overuse injuries collectively whilst others investigated the effect of sex on specific injuries. With respect to general overuse RRIs, there was mixed findings with a very slight tendency for males to be at greater risk of general overuse RRIs than females. Prospectively, 1 of 3 studies found male recreational runners to be at greater risk of RRIs compared to females [HazR: 1.42] (Buist *et al.*, 2010), whilst another found the contrary where female recreational runners were at greater risk to general overuse RRIs (Messier *et al.*, 2018). One prospective study found no effect of sex on general overuse RRIs (Theisen *et al.*, 2014). Retrospectively, 2 of 5 studies reported male masters

runners [OR: 1.28] (McKean, Manson and Stanish, 2006), and recreational runners to be at greater risk of general overuse RRIs than females [OR: 1.45] (Linton and Valentin, 2018). Opposing this however, Lopes *et al.*, (2011) reported female recreational runners to be at greater risk than males [Relative Risk (RR): 1.35]. An additional 2 retrospective studies found no effect of sex on RRIs (Jacobs and Berson, 1986; Ramskov *et al.*, 2013).

Interestingly, when RRIs were explored by specific injury, there were findings distributed in three directions. (male being prone, females being more prone, no effect). Two prospective study and two retrospective studies focused on specific injuries, with 1 of 4 prospective studies finding both males and females to be at risk for specific injuries (Satterthwaite *et al.*, 1999), 1 of 2 retrospective studies similarly finding males and females to be more at risk for specific RRIs (Taunton *et al.*, 2002), and 2 studies (1 prospective (Hirschmüller *et al.*, 2012) and 1 retrospective (Messier *et al.*, 1995)) finding no effect of sex on specific RRIs. Where effects were observed, males were found to have significantly greater risks of sustaining plantar fasciitis [8% difference], patellar tendinopathy [38% difference], Achilles tendinopathy [14% difference] and meniscal injuries [16% difference] (Taunton *et al.*, 2002), as well as hamstring [OR: 1.60] and calf injuries [OR: 1.86] (Satterthwaite *et al.*, 1999). In contrast to this, females were found to be at significantly greater risk of sustaining hip injuries [Odds Ratio (OR): 1.88] (Satterthwaite *et al.*, 1999), patellofemoral pain syndrome [30% difference], iliotibial band syndrome [30% difference] and gluteus muscle injuries [52% difference] than males (Taunton *et al.*, 2002). It appears that sex is not a significant risk factor for exercise related leg pain, as demonstrated by Reinking *et al.*, (2007) and Bennett, Reinking and Rauh, (2012).

Some disparities exist between studies finding significance for specific RRIs and others not, with Taunton *et al.*, (2002) documenting females to be at greater risk of iliotibial band syndrome, while Messier *et al.*, (1995) found no evidence of sex as a risk factor for this same injury. This may be due to an uneven distribution of males and females in both the injured and uninjured groups, and perhaps the imbalance lacked enough power for detecting significance. In addition, another finding of Taunton *et al.*, (2002) reported males to be at greater risk of Achilles tendinopathy than females, while Hirschmüller *et al.*, (2012) found no such differences (Hirschmüller *et al.*, 2012). It seems that Achilles tendinopathies are more prevalent in older male running populations however (Taunton *et al.*, 2002) (Section 2.3.3), and the interplay of age and sex together may be more insightful than looking at sex alone in this case (Hirschmüller *et al.*, 2012). Nevertheless, where differences are evident due to sex it has been speculated that it may be due to differences in anatomical (femoral inclination and femoral anteversion) (Eckhoff *et al.*, 1994; Heiderscheit, Hamill and Caldwell, 2000; Powers, 2003a), physiological (heart and lung size and capacity) (Boles and Ferguson, 2010) and biomechanical (joint kinematics and landing strategies) (Souza and Powers, 2009; Baggaley *et al.*, 2015; Gaitonde, Ericksen and Robbins, 2019) characteristics; however the basis for such differences is largely theoretical to date. Despite this, it does appear that both males and females may be at greater risk of specific injuries. Future studies should analyse sex as a risk factor for specific injuries as this may provide more insight when developing injury prevention programmes.

Table 2.4.1 Studies investigating sex as a risk factor for RRI.

Study	***Population***	***Injury type***	***Unit Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Prospective						
Satterthwaite *et al*., (1999)	875 recreational runners	Hamstring (Inj: 212; Uninj: 663) Calf (Inj: 396; Uninj: 479)	♀ is ref	OR: 1.60 (1.04 to 2.47) OR: 1.86 (1.29 to 2.68)	P = 0.03* P = 0.0008*	♂ ↑ risk of hamstring injury ♂ ↑ risk of calf injury
Buist *et al*., (2010)	629 recreational runners (Inj: 163; Uninj: 466)	General RRIs	♀ is ref	HazR: 1.42 (1.02 to 1.99)	P = 0.04*	♂ ↑ risk of RRI
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	♀ : ♂	Inj 2.2 : 1.0 Uninj 2.0 : 1.0	P > 0.05	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	♂ is ref	HazR: 1.04	P = 0.880	-
Satterthwaite *et al*., (1999)	875 recreational runners	Hip (Inj:124; Uninj:751)	♂ is ref	OR: 1.88 (1.15 to 3.06)	P = 0.01*	♀ ↑ risk of hip injury
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	♀ : ♂	Inj 73 : 62 Uninj 27 : 38	P = 0.05*	♀ ↑ risk of RRI
Retrospective						
Taunton *et al*., (2002)	2002 recreational runners (Inj:2002; Uninj: 0)	PF Meniscus PT AT Calf injuries	♀ : ♂	46% : 54% 31% : 69% 43% : 57% 42% : 58% 30% : 70%	P < 0.05*	♂ ↑ risk of PF injury ♂ ↑ risk of meniscus injury ♂ ↑ risk of PT injury ♂ ↑ risk of AT injury ♂ ↑ risk of calf injury
McKean *et al*., (2006)	2825 Masters runners (Inj: 1309; Uninj; 1516)	General RRIs	♀ is ref	<40yrs : OR: 1.28 (1.06 to 1.54) >40yrs : OR: 1.10 (0.83 to 1.46)	P = 0.01* P = 0.50	♂ ↑ risk of RRI
Linton *et al*., (2018)	1145 novice and recreational runners (Inj: 567; Uninj: 578)	General RRIs	♀ is ref	OR: 1.45 (1.13 to 1.84)	P = 0.003*	♂ ↑ risk of RRI
Jacobs & Berson (1986)	451 recreational runners (Inj: 210; Uninj: 241)	General RRIs	N/R	N/R	P > 0.05	-
Messier *et al*., (1995)	126 recreational and competitive runners	ITBS	♀ : ♂	Inj 33 : 23 Uninj 53 : 17	P > 0.05	-

	(Inj: 56; Uninj: 70)					
Rasmussen *et al*., (2013)	662 recreational runners (Inj: 68; Uninj: 594)	General RRIs	♀ : ♂	RR: 0.77 (0.46 to 1.31)	P = 0.34	-
Taunton *et al*., (2002)	2002 recreational runners (Inj:2002; Uninj: 0)	PFPS ITBS Glute injuries	♀ : ♂	62% : 32% 62% : 32% 76% : 24%	P < 0.05*	♀ ↑ risk of PFPS injury ♀ ↑ risk of ITBS injury ♀ ↑ risk of Glute injury
Lopes *et al*., (2011)	1049 recreational runners (Inj: 227; Uninj: 822)	General RRIs	♂ is ref	RR: 1.35 (1.05 to 1.72)	P < 0.05*	♀ ↑ risk of RRI

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; ERLP, exercise-related leg pain; ITBS, iliotibial band syndrome; PF: plantar fasciitis; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.1.2 Age

Fifteen studies investigated age as a risk factor, 9 of which were prospective and 6 retrospective in design, with conflicting evidence for a relationship (Table 2.4.2). Where significance was reported, there are mixed findings for both greater age and lesser age to be a risk. Once again, some studies explored the risk of age with respect to general overuse RRIs whilst others focused on specific injuries. With reference to general overuse RRIs, 1 out of 5 prospective studies reported a greater age to be a significant risk factor [RR:1.92] (Taunton *et al.*, 2003), with 0 of 2 retrospective studies finding *greater* age to be a significant risk factor. Meanwhile 1 of 8 prospective studies and 2 of 2 retrospective studies reported a younger age to be a significant risk factor [HazR range: 0.63 to 0.81; RR: 2.31] (Hootman *et al.*, 2002; Buist *et al.*, 2010; Rasmussen *et al.*, 2013). Two prospective studies found no effect of age on RRIs (Theisen *et al.*, 2014; Messier *et al.*, 2018).

When RRIs are explored by specific injuries, 2 of 3 prospective and 1 of 3 retrospective studies found older runners to be at an increased risk of Achilles tendinopathies (Taunton *et al.*, 2002; Hirschmüller *et al.*, 2012) [OR: 0.36], plantar fasciitis [OR : 0.39] meniscal injuries [OR range : 0.22 to 0.44] (Taunton *et al.*, 2002), and front of thigh injuries [OR: 1.83] (Satterthwaite *et al.*, 1999). Contrarily, 1 of 3 prospective and 2 of 3 retrospective studies reported younger age to be a significant risk factor for calf injuries [OR: 0.40] (Satterthwaite *et al.*, 1999), patellofemoral pain syndrome [OR range : 1.90 to 2.16] (Taunton *et al.*, 2002), stress fractures in female runners (Grimston *et al.*, 1991), and iliotibial band syndrome [OR: 2.77], patellar tendinopathies [OR: 4.21] and tibial stress syndrome [OR: 4.58] in male runners (Taunton *et al.*, 2002). One prospective (Wen, Puffer and Schmalzried, 1998) and one retrospective (Messier *et al.*, 1995) study found no effect of age on knee injuries, exercise-related leg pain and iliotibial band syndrome.

It has been reported that the musculoskeletal system undergoes significant changes with increased age, including deficits to flexibility, strength, bone density and proprioception, as well as joint degeneration becoming more apparent over time (McKean, Manson and Stanish, 2006). These physiological changes along with a reduced capacity for healing and recovery would suggest an increase in susceptibility to prospective injuries for an older athlete (Marti *et al.*, 1988; McKean, Manson and Stanish, 2006), and although some studies found greater age to be a significant risk factor for injury, this does not explain why more studies found younger age to be a risk factor for injury. Suggestions have been made regarding the study of age as a risk factor, with numerous compounding factors being thought to weigh heavily on the relationship, such as: running experience or lack thereof (Marti *et al.*, 1988; van Mechelen, 1992), previous injury (Marti *et al.*, 1988) and training related characteristics (Marti *et al.*, 1988; van Mechelen, 1992). It has been proposed that running experience may help older runners to avoid potential training errors through familiarization alone (van Mechelen, 1992) and in this light, younger runners or runners with relatively low experience may not have the same familiarity with training, and therefore may have an increased susceptibility to training errors and subsequent injuries. However, age as a risk factor is inherently complex, and may be subject to selection bias whereby there is reduced participation with increasing age (Fries *et al*., 1996). The participation of older runners may therefore demonstrate a natural decrease due to drop-out from the activity for reasons such as arthritis, bone density changes, and other illnesses. As a result, studies examining older runners may only be capturing the older runners who have not been affected by age or activity-related injuries, and thus may not be truly reflective of how age affects injury risk within this population (Fries *et al*., 1996).

Although there was demonstration of moderate evidence for age as a risk factor for RRIs, comparison between the studies is difficult as the unit reference point and grouping of ages varies across the literature. As indicated in Table 2.4.2, conflicting directions of findings for age as a risk factor for RRIs were apparent. Future studies may need to include other potential compounding factors in age analyses, such as running experience, previous injuries and training-related characteristics in the investigation of age as a potential risk factor for injury.

Table 2.4.2 Studies investigating age as a risk factor for RRI.

Study	***Population***	***Injury type***	***Unit Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Prospective						
Satterthwaite *et al*., (1999)	875 recreational runners	Front Thigh (Inj:526; Uninj: 349)	<25 years	>30-34 years OR: 1.83 (1.04 to 3.22)	P = 0.01*	↑ risk of front of thigh RRI in 30-34 year olds
Taunton *et al*., (2003)	844 recreational runners (Inj: 249; Uninj: 595	General RRIs	Age (Years)	♀ RR: 1.92 (1.11 to 3.33)	P < 0.05*	♀ Higher age ↑ risk of RRI
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	Age (years)	Inj 48.1 : Uninj 42.8	P < 0.05*	Higher age ↑ risk of AT injury
Wen *et al*., (1998)	255 recreational runners (Inj: 90; Uninj: 165)	Knee injuries	1 Year	RIR: 2.09 (0.95 to 4.58)	P > 0.05	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	1 year	HazR: 0.97	P = 0.731	-
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	Age (years)	Inj 42.3 : Uninj 40.0	P = 0.06	-
Satterthwaite *et al*., (1999)	875 recreational runners	Calf (Inj: 396; Uninj: 479)	<25 years	>40 years OR: 0.40 (0.23 to 0.73)	P = 0.001*	Higher age ↓ risk of calf RRI
Buist *et al*., (2010)	629 recreational runners (Inj: 163; Uninj: 466)	General RRIs	10 years	♂ HazR: 0.63 (0.48 to 0.82) ♀ HazR: 0.82 (0.66 to 1.02)	P = 0.001* P = 0.069	♂ Lower age ↑ risk of RRI
Retrospective						
Taunton *et al*., (2002)	2002 recreational runners (Inj:2002; Uninj: 0)	PF Meniscus Meniscus AT	<34 years	♂ OR: 0.39 (0.19 to 0.78) ♂ OR: 0.22 (0.08 to 0.57) ♀ OR: 0.44 (0.20 to 0.98) ♂ OR: 0.36 (0.16 to 0.78)	P < 0.05*	♂ Higher age ↑ risk of PF ♂ & ♀ Higher age ↑ risk of meniscus ♂ Higher age ↑ risk of AT
Messier *et al*., (1995)	126 recreational and competitive runners (Inj: 56; Uninj: 70)	ITBS	Age (Years)	Inj 35.0 : Uninj 33.9	P > 0.05	-
Hootman *et al*., (2002)	3090 recreational runners	General RRIs	10 Years	♂ HazR: 0.88 (0.86 to 0.91)	P = 0.0002*	♂ & ♀ Higher age ↓ risk of RRIs

	(Inj: 1207; Uninj: 1883)			♀ HazR: 0.74 (0.69 to 0.80)	P = 0.0001*	
Taunton *et al*., (2002)	2002 recreational runners (Inj:2002; Uninj: 0)	ITBS PFPS PFPS PT TSS	<34 years	♂ OR: 2.77 (1.72 to 5.40) ♂ OR: 1.90 (1.15 to 3.14) ♀ OR: 2.16 (1.33 to 3.49) ♂ OR: 4.21 (1.97 to 8.89) ♂ OR: 4.58 (1.77 to 11.81)	P < 0.05*	♂ Lower age ↑ risk of ITBS ♂ & ♀ Lower age ↑ risk of PFPS ♂ Lower age ↑ risk of PT ♂ Lower age ↑ risk of TSS
Grimston *et al*., (1991)	14 female runners (Inj: 6; Uninj: 8)	Stress fracture	Age (Years)	Inj 26.9 : Uninj 32.8	P < 0.05*	♀ Lower age ↑ risk of stress fractures
Rasmussen *et al*., (2013)	662 recreational runners (Inj: 68; Uninj: 594)	General RRIs	35-50 years	<35 years RR: 2.31 (1.44 to 3.73) >50 years RR: 0.82 (0.38 to 1.75)	P < 0.01* P = 0.60	Runners < 35 years ↑ risk of RRI

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; ERLP, exercise-related leg pain; ITBS, iliotibial band syndrome; TSF: tibial stress fracture; PT: patellar tendinopathy; PF: plantar fasciitis; TSS: tibial stress syndrome; PFPS: patellofemoral pain syndrome; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.1.3 Running experience

Nine prospective and 6 retrospective studies have explored running experience with little evidence to suggest it is a risk factor of RRIs (Table 2.4.3). There was a similar quantity of findings in both directions and so there is no strong tendency for either low experience or high experience to weigh more heavily on RRI prevalence. Looking at general overuse RRIs directly, 1 of 9 prospective and 1 of 3 retrospective studies found higher running experience to be a significant risk factor [RIR: 1.88 (Wen, Puffer and Schmalzried, 1998); HazR range: 1.03 to 1.18 (Hootman *et al.*, 2002)], with 1 of 9 prospective and 2 of 3 retrospective studies finding low experience to be influential [HazR range: 2.13 to 2.61 (Satterthwaite *et al.*, 1999; Buist *et al.*, 2010); OR range: 0.51 to 0.71 (Linton and Valentin, 2018); RR: 0.46 (Rasmussen *et al.*, 2013)]. However, 4 prospective studies found no effect of running experience on RRI risk (Van Middelkoop *et al.*, 2008; Hespanhol Junior, Pena Costa and Lopes, 2013; Theisen *et al.*, 2014; Messier *et al.*, 2018).

Focusing on specific injuries, 1 of 3 prospective and 2 of 3 retrospective studies reported having greater experience to be associated with an increased risk of plantar fasciitis, stress fractures, metatarsalgia (Di Caprio *et al.*, 2010) and Achilles tendon injuries (McCrory *et al.*, 1999; Knobloch, Yoon and Vogt, 2008; Di Caprio *et al.*, 2010). Meanwhile 1 of 3 prospective and 0 of 3 retrospective studies reported runners with lower experience to be a greater risk for knee injuries [OR: 1.66] (Satterthwaite *et al.*, 1999), with 1 prospective and 1 retrospective study finding no effect on specific RRIs such as stress fractures (Grimston *et al.*, 1991), and Achilles tendinopathy (Hirschmüller *et al.*, 2012). Some disparities within the literature exist, with some contrasting findings for specific injuries evident. With reference to hamstring injuries in particular, one study found greater experience to be a significant risk factor [OR: 1.21] (Di Caprio *et al.*, 2010) and another study found low experience to be a significant risk factor [OR: 1.55] (Satterthwaite *et al.*, 1999). A potential reason for this disagreement may be due to the definition of experience, with Di Caprio *et al.*, (2010) referring to experience as years of running in recreational and competitive runners while Satterthwaite *et al.*, (1999) defines experience as whether the recreational runners are doing their first marathon or not. This inconsistency in running experience definition was evident throughout the literature with measures used to define experience ranging from absolute and cumulative monthly or annual units of running, to number of races, events or competitions.

It appears that running experience as a variable can be quite complex, and therefore difficult to define as it is likely influenced by both age and previous injury (van der Worp *et al.*, 2015). In addition, experience in other sports which have high running demands may also contribute towards "running experience" and perhaps researchers need to clarify if running experience is exposure solely to running (unidirectional axial loading) or if exposure to sports of multi-directional axial loading counts as running experience too. Without consideration and clarity of other potential confounding factors (age, previous injury, exclusive participation in unidirectional axial loading activities), the investigation into running experience as a risk factor for RRIs will remain a challenge (Rasmussen *et al.*, 2013; Linton and Valentin, 2018).

Table 2.4.3 Studies investigating running experience as a risk factor for RRI.

Study	***Population***	***Injury type***	***Unit Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Prospective						
Wen *et al*., (1998)	255 recreational runners (Inj: 90; Uninj: 165)	General RRIs	Previous experience	RIR: 1.88 (1.16 to 3.05)	P < 0.05*	High experience ↑ risk of RRI
Di Caprio *et al*., (2012)	166 recreational and competitive runners (Inj: 98; Uninj: 68)	PF AT Hamstring Stress fracture Metatarsalgia	Years running	Inj 12 : Uninj 8.7 Inj 13.8 : Uninj 8.4 Inj 12.4 : Uninj 9.3 Inj: 13.6 : Uninj 9.3 Inj 15.3 : Uninj 9.3	P = 0.002* P = 0.005* P = 0.03* P = 0.03* P = 0.008*	High experience ↑ risk of PF, AT, hamstring, stress fractures and metatarsalgia injuries
Van Middelkoop *et al*., (2008)	694 male recreational runners (Inj:195; Uninj: 499)	General RRIs	4-10 years	0-3 years OR: 1.21 (0.79 to 1.85) >11 years OR: 1.47 (0.96 to 2.24)	P = 0.39 P = 0.08	-
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	Years running	Inj 12.7 : Uninj 9.3	P > 0.05	-
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Previous experience	OR: 0.99 (0.94 to 1.03)	P = 0.60	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	1 year	HazR: 1.00	P = 0.69	-
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	Years running	Inj 10.5 : Uninj 11.9	P = 0.24	-
Satterthwaite *et al*., (1999)	875 recreational runners	Hamstring (Inj: 212; Uninj: 663) Knee (Inj:224; Uninj:651)	First marathon	OR: 1.55 (1.08 to 2.22) OR: 1.66 (1.16 to 2.38)	P = 0.02* P = 0.005*	Low experience ↑ risk of hamstring injury Low experience ↑ risk of knee injury
Buist *et al*., (2010)	629 recreational runners (Inj: 163; Uninj: 466)	General RRIs	Previous experience	♂ HazR: 2.61 (1.23 to 5.53) ♀ HazR: 2.14 (1.24 to 3.70)	P = 0.012* P = 0.007*	No experience ↑ risk of RRI
Retrospective						

McCrory *et al*., (1999)	89 recreational and competitive runners (Inj: 31; Uninj: 58)	AT	Years running	Inj 11.9 : Uninj 9.6	P < 0.05*	High experience ↑ risk of AT
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Number of races	♂ HazR: 1.03 (1.00 to 1.06) ♀ HazR: 1.18 (1.07 to 1.31)	P = 0.04* P < 0.001*	♂ & ♀ Higher number of races ↑ risk of RRIs
Knobloch *et al*., (2008)	291 masters runners (815 injuries)	Back AT	<10 years	RR: 3.30 (1.16 to 4.57) RR: 1.60 (1.02 to 2.76)	P = 0.015* P = 0.041*	High experience ↑ risk of back and AT injuries
Grimston *et al*., (1991)	14 female runners (Inj: 6; Uninj: 8)	Stress fracture	Years running	Inj 7.2 : Uninj 6.6	P > 0.05	-
Rasmussen *et al*., (2013)	662 recreational runners (Inj: 68; Uninj: 594)	General RRIs	First marathon	RR: 0.46 (0.29 to 0.72)	P < 0.01*	Runners doing first marathon ↑ risk of RRI

Linton *et al*., (2018)	1145 novice and recreational runners (Inj: 567; Uninj: 578)	General RRIs	< 6 months experience	6-12 months OR: 1.00 (0.62 to 1.64) 1-2 years OR: 0.71 (0.45 to 1.13) 2-5 years OR: 0.65 (0.43 to 0.99) 5-10 years OR: 0.51 (0.31 to 0.81) >10 years OR: 0.58 (0.38 to 0.89)	P = 0.10 P = 0.14 P = 0.14* P = 0.005* P = 0.012*	Low experience (<2 years) ↑ risk of RRI

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; ERLP, exercise-related leg pain; PF: plantar fasciitis; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.1.4 Previous injury

Previous injury appears to be the strongest intrinsic risk factor related to RRIs, with strong evidence of an association (Table 2.4.4). Nine out of 10 prospective studies [HazR range: 1.74 to 2.64 (Buist *et al*., 2010; Theisen *et al*., 2014); OR range: 1.67 to 3.80 (Van Middelkoop *et al.*, 2008; Hirschmüller *et al.*, 2012; Hespanhol Junior, Pena Costa and Lopes, 2013; Besomi *et al*., 2019; Dallinga *et al.*, 2019; van Poppel *et al*., 2018); RIR: 2.02 (Wen, Puffer and Schmalzried, 1998)], and 3 out of 3 retrospective studies found a positive association [OR range: 1.44 to 2.81 (Hootman *et al.*, 2002; Linton and Valentin, 2018); RR: 2.30 (Rasmussen *et al.*, 2013)]. Only one study found no effect of previous injury on subsequent injury risk (Messier *et al.*, 2018).

While most of the studies refer to previous injuries in the year preceding RRI surveillance (Hootman *et al.*, 2002; Van Middelkoop *et al.*, 2008; Rasmussen *et al.*, 2013; Theisen *et al.*, 2014; Linton and Valentin, 2018; van Poppel *et al.*, 2018; Besomi *et al.*, 2019; Dallinga *et al.*, 2019), some studies do not specify the timeframe over which previous injuries were analysed (Wen, Puffer and Schmalzried, 1998; Kelsey *et al.*, 2007; Reinking *et al.*, 2007; Buist *et al.*, 2010; Hirschmüller *et al.*, 2012; Hespanhol Junior, Pena Costa and Lopes, 2013), and so it is difficult to determine how lasting the effects of previous injuries are.

There are multiple reasons suggested as to why a previous injury may be a significant risk factor to further injuries. Firstly, there may be incomplete healing of the original injury (van der Worp *et al.*, 2015). If previous lower limb injuries have healed completely and the athlete has returned to pre-injury levels of strength, range of motion and proprioception, the risk of a subsequent injury should not be high (Hootman *et al.*, 2002). However, if runners adopt a new biomechanical pattern following the return from previous injury, in an attempt to execute a protective (compensatory) strategy of the injured structure, this may overload structures, and ultimately lead to a new injury or a recurrence of a previous injury (Saragiotto *et al.*, 2014). Secondly, if the previous injury caused permanent and long-lasting structural (e.g. tendon disrepair) or biomechanical (e.g. high impact loading) mal-adaptations, the chances of subsequent re-injuries become much greater (Van Der Worp *et al.*, 2012). Finally, to compound these factors, if rehabilitation was insufficient in terms of addressing intrinsic (strength, mobility, flexibility, impact loading) and extrinsic (surface, footwear, training characteristics) risk factors for the injury, or if rehabilitation had poor adherence, the return to full participation may be at a compromised level resulting in potentially dysfunctional movement and coordination strategies (Drew, Cook and Finch, 2016; Toohey *et al.*, 2017). This too may overload previously vulnerable or weak structures and tissue failure may result (Saragiotto *et al.*, 2014). For these reasons, examining recently injured runners in addition to runners who have recovered without becoming re-injured may prove insightful in determining factors which should be targeted within rehabilitation and return to participation programmes. Furthermore, the never injured runner provides a unique insight into what factors may protect them from injury.

Table 2.4.4 Studies investigating previous injury as a risk factor for RRI.

Study	Population	Injury type	Unit Reference	Estimate (95% CI)	Significance	Interpretation
Prospective						
Wen *et al*., (1998)	255 recreational runners (Inj: 90; Uninj: 165)	General RRIs	Previous injury	RIR: 2.02 (1.27 to 3.21)	P < 0.05*	Previous injury ↑ risk of RRI
Van Middelkoop *et al*., (2008)	694 male recreational runners (Inj:195; Uninj: 499)	General RRIs	Previous injury (1 year)	OR: 2.62 (1.82 to 3.78)	P = 0.00*	Previous injury ↑ risk of RRI
Buist *et al*., (2010)	629 recreational runners (Inj: 163; Uninj: 466)	General RRIs	Previous injury (Ever)	♂ < 1 year HazR: 2.64 (1.32 to 5.30) ♂ > 1 year HazR: 2.14 (1.05 to 4.35)	P < 0.05* P < 0.05*	♂ Previous injury ↑ risk of RRI
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	Previous AT injury	OR: 3.80 (1.70 to 8.50)	P = 0.001*	Previous AT injury ↑ risk of AT injury
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Previous injury	OR: 1.88 (1.01 to 3.51)	P = 0.05*	Previous injury ↑ risk of RRI
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Previous injury (1 year)	HazR: 1.74 (1.04 to 2.90)	P = 0.005*	Previous injury ↑ risk of RRI
Besomi *et al*., (2018)	4380 recreational runners (Inj: 623; Uninj: 3757)	General RRIs	Previous injury (1 year)	OR: 2.06 (1.72 to 2.47)	P < 0.01*	Previous injury ↑ risk of RRI
Dallinga *et al*., (2019)	706 recreational runners (Inj: 142; Uninj: 654)	General RRIs	Previous injury (1 year)	OR: 1.67 (1.14 to 2.44)	P < 0.05*	Previous injury ↑ risk of RRI
Van Poppel *et al*., (2018)	2369 recreational runners (Inj: 709; Uninj: 1660)	General RRIs	Previous injury (1 year)	OR: 3.70 (3.00 to 4.50)	P < 0.05*	Previous injury ↑ risk of RRI
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	% with a previous injury	Injured 74% : Uninjured 65%	P = 0.10	-
Retrospective						
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Previous injury (1 year)	♂ OR: 2.09 (1.63 to 2.68) ♀ OR: 2.81 (1.68 to 4.71)	P = 0.0001* P = 0.0001*	♂ & ♀ Previous injury ↑ risk of RRI
Rasmussen *et al*., (2013)	662 recreational runners (Inj: 68; Uninj: 594)	General RRIs	Previous injury (1 year)	RR: 2.30 (1.45 to 3.66)	P < 0.01*	Previous injury ↑ risk of RRI
Linton *et al*., (2018)	1145 recreational runners (Inj: 567; Uninj: 578)	General RRIs	Previous injury (1 year)	OR: 1.44 (1.08 to 1.92)	P = 0.014*	Previous injury ↑ risk of RRI

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; ERLP: exercise related leg pain; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.1.5 Anthropometry

Body mass index (BMI) is used to assess weight relative to height (Pescatello, Riebe and Thompson, 2014). Normal BMI for males and females is categorized as 18.6 – 24.9kg/m^2, with results greater than 30kg/m^2 identified as obese (Pescatello, Riebe and Thompson, 2014). Ten prospective and four retrospective studies have investigated the association of BMI with RRIs, with only limited evidence to suggest BMI as a risk factor for injury (Table 2.4.5). Although there was a tendency for the limited evidence findings to lean towards greater BMI as a risk factor for general overuse RRIs, lower BMI was also found to be related to stress fracture type injuries. Of the prospective studies, 2 of 7 found greater BMI to be a significant risk factor for general overuse RRIs [HazR range: 1.13 to 1.14] (Buist *et al.*, 2010; Theisen *et al.*, 2014) and hamstring injuries (Di Caprio *et al.*, 2010) in recreational runners. Contrarily, 2 of 10 prospective studies found a lower BMI to increase the risk of general overuse RRIs in male recreational runners [RR: 0.41] (Taunton *et al.*, 2003) and of stress fractures in recreational and competitive runners (Di Caprio *et al.*, 2010). Five prospective and three retrospective studies found no effect of BMI on RRIs.

Retrospectively, 1 of 4 studies reported a lower BMI to significantly increase the risk of tibial stress fractures [OR: 2.43] and spinal injuries [OR: 4.98] in female recreational runners (Taunton *et al.*, 2002). Knowing that RRIs can result from excessive loading or forces (Hreljac, 2004), and looking at the formula to calculate force (F = m.a), it may be reasonable to assume that mass plays a role in RRI occurrence. Thus, it has been speculated that a greater BMI may be a risk factor of RRI due to the association with increased loading on the lower extremities (Manek *et al.*, 2003). Interestingly, where Di Caprio *et al.*, (2010) also found an increased BMI to be a significant risk factor for RRI, this was related to hamstring injuries specifically. Whilst the mechanism of injury for these hamstring injuries was not documented, perhaps the acceleration or deceleration of higher mass was excessive in this group and maybe helps to explain the association of BMI as a risk factor for this injury. In contrast, where a lower BMI was found to be a significant risk factor for general overuse RRIs (Taunton *et al.*, 2003), stress fractures (Taunton *et al.*, 2002; Di Caprio *et al.*, 2010) and spinal injuries (Taunton *et al.*, 2002), it has been speculated that low BMI may increase the risk of injury due to insufficient lean body mass and the knock on effect that this has on attenuating the stresses of running (Taunton *et al.*, 2002; Knapik, 2015).

Nevertheless, there appears to be limited evidence with respect to BMI as a risk factor for RRIs.

In summary, previous injury appears to have the strongest predictive value as a potential intrinsic risk factor for RRI occurrence. Sex, age, running experience and BMI each have relatively limited evidence with conflicting findings to warrant significant attention in risk factor analysis. Future studies should perhaps avoid investigating intrinsic risk factors in isolation, given the potential inter-play of these risk factors with each other.

Table 2.4.5 Studies investigating BMI as a risk factor for RRI.

Study	*Population*	*Injury type*	*Unit Reference*	*Estimate (95% CI)*	*Significance*	*Interpretation*
Prospective						
Buist *et al*., (2010)	629 recreational runners (Inj: 163; Uninj: 466)	General RRIs	Per 1 kg/m^2 ↑	♂ HazR: 1.14 (1.05 to 1.25)	P < 0.05*	♂ Higher BMI ↑ risk of RRI
Di Caprio *et al*., (2012)	166 recreational runners (Inj: 98; Uninj: 68)	Hamstring	Inj vs Uninj	Inj 21.7 kg/m^2 : Uninj 20.4 kg/m^2	P = 0.002*	Higher BMI ↑ risk of hamstring RRI
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Per 1 kg/m^2 ↑	HazR: 1.13 (1.03 to 1.23)	P < 0.05*	Higher BMI ↑ risk of RRI
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	Inj vs Uninj	Wald X^2: 0.69	P = 0.041	-
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Inj vs Uninj	Inj 24.5 kg/m^2 : Uninj 24.4 kg/m^2	P = 0.83	-
Besomi *et al*., (2018)	4380 recreational runners (Inj: 623; Uninj: 3757)	General RRIs	Inj vs Uninj	Inj 24.5 kg/m^2 : Uninj 24.5 kg/m^2	P = 0.51	-
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	Inj vs Uninj	Inj 23.9 kg/m^2 : Uninj 24.5 kg/m^2	P = 0.16	-
Dallinga *et al*., (2019)	706 recreational runners (Inj: 142; Uninj: 654)	General RRIs	Per 1 kg/m^2 ↑	OR: 1.05 (0.98 to 1.13)	P > 0.05	-
Taunton *et al*., (2003)	844 recreational runners (Inj: 249; Uninj: 595)	General RRIs	>26.0 1 kg/m^2	♂ RR: 0.41 (0.21 to 0.79)	P < 0.05*	♂ Higher BMI ↓ risk of RRI
Di Caprio *et al*., (2012)	166 recreational runners (Inj: 98; Uninj: 68)	Stress fracture	Inj vs Uninj	Inj 19.4 kg/m^2 : Uninj 20.7 kg/m^2	P = 0.011*	Lower BMI ↑ risk of stress fracture RRI
Retrospective						
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Inj % vs Uninj %	>25 kg/m^2 ♂ Inj 52.6% : Uninj 54.1% >25 kg/m^2 ♀ Inj 10.9% : Uninj 7.5%	P > 0.05	-
Ribeiro *et al*., (2011)	105 recreational runners (Inj: 45; Uninj: 60)	PF	Current PF vs Uninj	Current PF: 24.3 : Uninj: 22.5	P = 0.30	-
Rasmussen *et al*., (2013)	662 recreational runners (Inj: 68; Uninj: 594)	General RRIs	> 25 kg/m^2 vs < 25 kg/m^2	RR: 0.88 (0.47 to 1.68)	P = 0.70	-
Taunton *et al*., (2002)	2002 recreational runners (Inj:2002; Uninj: 0)	TSF Spinal injuries	Normal BMI	♀ OR: 2.43 (0.99 to 5.94) ♀ OR: 4.98 (1.36 to 18.27)	P < 0.05*	♀ Lower BMI ↑ risk of TSF ♀ Lower BMI ↑ risk of spinal injuries

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; ERLP, exercise-related leg pain; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; TSF: tibial stress fracture; PF: plantar fasciitis; TSF: tibial stress fracture; PFPS patellofemoral pain syndrome; OR, odds ratio; RR, relative risk; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.1.6 Muscle Activation Patterns

Abnormal muscle activation patterns are an intrinsic factor that may overload various joints or segments through the body, and thus can potentially contribute to running-related injuries (Willson *et al*., 2011). These activation patterns have largely been studied with respect to specific RRIs such as Achilles tendinopathies, medial tibial stress syndrome and patellofemoral pain syndrome.

With regards to Achilles tendinopathies, differences in muscle activation patterns of the gastrocnemius and soleus have been found to influence non-uniform loading within the Achilles tendon (Finni *et al*., 2018; Handsfield *et al*., 2017). It has been speculated that running kinematics such as knee flexion and rearfoot eversion likely contribute to these altered muscular contractions and resultant tendon displacements (Hérbert-Losier *et al*., 2012; Vieira *et al*., 2013).

Medial tibial stress syndrome is a condition that affects the posteromedial border of the tibia, and while the exact pathology of the injury is still debated within medicine, it is thought to be a fascial traction injury or a bone overload injury (Saxena, O Brien and Bunce, 1990; Beck and Osternig, 1994). As this has been known to be an overuse injury, researchers have hypothesised that abnormal activation of tibialis posterior, flexor digitorum loingus and soleus to cause increased tension through the crural fascia, and that this is possibly caused by increased rearfoot eversion during running (Bramah *et al*., 2020).

With respect to patellofemoral pain syndrome, this injury is thought to be a result of increased patellofemoral joint stress which then increases the stress on underlying chondral surfaces, subchondral bones and the infrapatellar fat pad (Powers *et al*., 2017; Besier *et al*., 2008). Research has suggested that abnormal activity of the vastus lateralis may cause a lateral tracking of the patella within the trochlear groove, and that this increases the stress on the joint (Ng, Zhang and Li, 2008). Delayed gluteus medius activity has also been found to be influential, as delayed control of hip adduction and hip internal rotation causes increased stress through the patellofemoral joint (Willson *et al*., 2011).

As has been observed above, muscle activation patterns are inherently related to running kinematics, and thus play a contributory role to RRI risk. However, electromyography of muscle activation is beyond the scope of this thesis due to the breath of impact acceleration and running kinematics being investigated.

2.4.2 Extrinsic risk factors

As previously mentioned, the aetiology of RRIs is multi-factorial in nature with many proposed intrinsic and extrinsic risk factors. Coaches, runners and researchers have given some focus to readily modifiable extrinsic risk factors such as training load, surface, footwear, stretching, warm-ups and cool downs in efforts to limit RRI incidence. Each of these factors will be reviewed with respect to RRIs below.

2.4.2.1 Training load

Training load is an external load to the body, and has been described as a quantification of workload external to the athlete (Drew and Finch, 2016; Soligard *et al.*, 2016). In a recent International Olympic Committee consensus statement, various measures of external load were identified including: training or event frequency, speed, duration and distance (Soligard *et al.*, 2016). Through application of appropriate external load, a stimulation of homeostatic responses and accompanying adaptations of the human body results, ultimately with the objective of improving fitness and performance (Figure 2.4.2) (Viru and Viru, 2000; Brooks, Fahey and Baldwin, 2004).

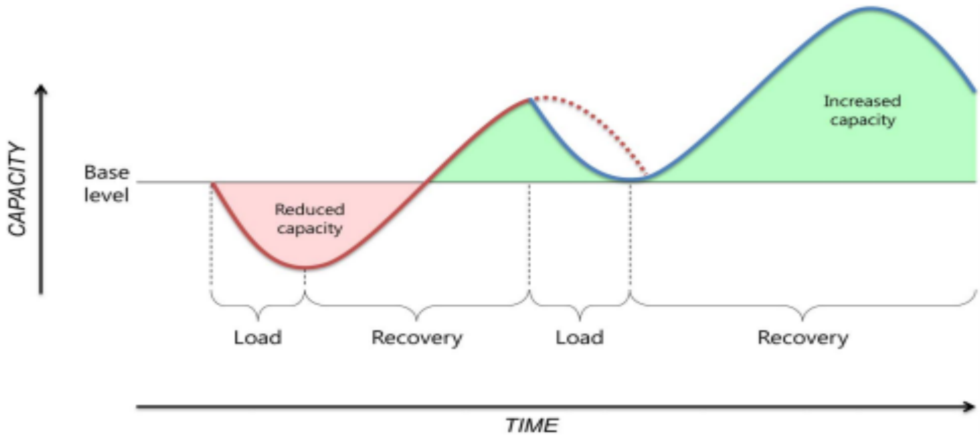

Figure 2.4.2 Biological adaptations observed with cycles of loading and recovery (Soligard et al.*, 2016).*

However, excessive external loading and a poor balance with recovery may result in prolonged fatigue, maladaptation to training, and an increased risk of injury (Figure 2.4.3) (Drew and Finch, 2016; Schwellnus *et al.*, 2016). With this in mind, the literature will be reviewed in the context of exploring training load (distance, frequency, speed, duration) as a potential risk factor for RRIs.

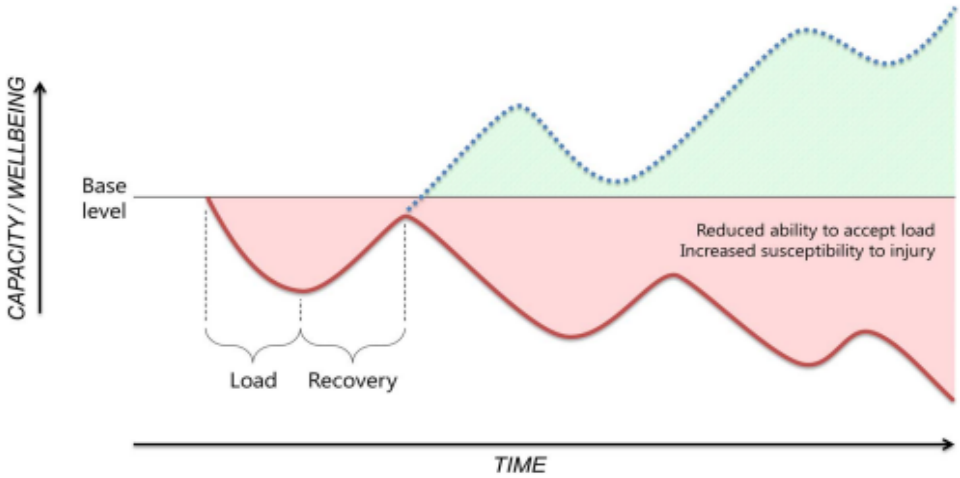

Figure 2.4.3 Biological maladaptation observed with excessive loading and/or inadequate recovery (Schwellnus *et al.*, 2016).

An aspect of training load which has received significant attention is distance, with only limited evidence to suggest this as a compelling risk factor in RRI development (Table 2.4.6). Where significant findings were reported, it seems that results lean towards greater distance in training being a risk for injury. Prospectively, only 4 of 14 studies found significantly higher daily (Ferreira *et al.*, 2012) and weekly [OR range: 1.07 to 1.11] (Wen, Puffer and Schmalzried, 1998; Satterthwaite *et al.*, 1999; Di Caprio *et al.*, 2010) distances in runners who went on to sustain RRIs. In contrast however, 2 of the 14 prospective studies reported weekly distance [OR: 1.13] (Satterthwaite *et al.*, 1999; Di Caprio *et al.*, 2010) to be significantly lower in those who became injured, with 7 prospective studies finding no effect of distance on RRIs. One prospective study found lower acute chronic workload ratios to increase the risk of RRIs (Nakaoka *et al.*, 2021). Retrospectively, 5 of 13 studies recorded significantly greater distances per session (Jacobs and Berson, 1986), per week (McQuade, 1986; Haglund-Åkerlind and Eriksson, 1993; Messier *et al.*, 1995) and per season [RR: 2.00] (Knobloch, Yoon and Vogt, 2008) in runners with a history of injury compared to those who had experienced no injuries. Opposing this, 2 of 13 studies reported the contrary where significantly lower weekly distances were observed in runners with a history of injury (Messier *et al.*, 1991; Hootman *et al.*, 2002), with an additional 6 retrospective studies finding no effect of distance on RRIs.

Interestingly, it appears that there is more evidence for distance as a potential risk factor of RRI when specific injuries are analyzed as opposed to analysis of general overuse

RRIs collectively. Eight of thirteen studies focusing on specific injuries found evidence of distance as a risk factor, with 5 studies (3 prospective and 2 retrospective) finding significantly greater weekly distance in runners who had sustained hamstring [OR range: 1.07 to 1.11] (Wen, Puffer and Schmalzried, 1998; Satterthwaite *et al.*, 1999), plantar fasciitis (Di Caprio *et al.*, 2010), Achilles tendinopathy (Haglund-Åkerlind and Eriksson, 1993; Di Caprio *et al.*, 2010), stress fractures (Di Caprio *et al.*, 2010), chronic anterior compartment syndrome (Di Caprio *et al.*, 2010) and iliotibial band syndrome (Messier *et al.*, 1995) injuries. Three studies (2 prospective and 1 retrospective) found results in the opposite direction, whereby significantly lower distances were recorded in runners who had experienced non-specific knee injuries [OR: 1.13] (Satterthwaite *et al.*, 1999), patellofemoral pain syndrome (Messier *et al.*, 1991) and hamstring injuries (Di Caprio *et al.*, 2010). It is unusual that studies found contrasting results for hamstring injuries in particular (Wen, Puffer and Schmalzried, 1998; Satterthwaite *et al.*, 1999; Di Caprio *et al.*, 2010) and reasons for this difference are difficult to determine. In general, hamstring injuries are often associated with explosive type movements such as those demonstrated with speed or interval training (Liu *et al.*, 2012). However, the studies above did not analyze speed or type of training and so it cannot be confirmed if this was the reason why some studies found greater weekly distance and another found lower weekly distance in those who sustained hamstring injuries. Nevertheless, there appears to be only limited evidence to suggest distance as a risk factor for RRIs. It seems that there may be a fine balance between overuse and under-conditioning in runners (Satterthwaite *et al.*, 1999), and perhaps this helps to explain the opposing directions of significant findings.

Despite the quantity of studies exploring distance as a risk factor for RRI, there are disparities in the literature with respect to the means of quantifying distance. Whilst some studies dichotomized and categorized absolute distance measures, other studies compared absolute daily, weekly and season mileage. Although absolute comparison of load can detect potential relationships between high and low loads with RRIs, this means of assessing load fails to consider the rate of load application. In this light, high absolute loads may not be the enemy *per se*, but rather the excessive or sharp increase in load relative to what the runner is prepared for (Soligard *et al.*, 2016). Gabbett et al., (2016) have introduced a training load concept that models the relationship between training load and injury risk, and has been referred to as the acute: chronic workload ratio (ACWR). This model maps the acute load (e.g. training load in the past week) as a ratio to chronic load (e.g. rolling average of training load in the past 4 weeks) (Gabbett, 2016). Thus, if there is a rapid increase or spike in training load in one week, that is not reflective of the training load over the past 4 weeks, the runner may be at an increased risk of maladaptation and/or injury. Validation of this ACWR in team sports has demonstrated that the likelihood of injury is low (<10%) when the ACWR is within a range of 0.8 – 1.3 (Blanch and Gabbett, 2016; Hulin *et al.*, 2016). If however, the ACWR exceeds 1.5 (i.e. the acute load is 1.5 times greater than the chronic load), the likelihood of injury has been shown to more than double in team sport athletes (Figure 2.4.4) (Blanch and Gabbett, 2016; Hulin *et al.*, 2016). Interestingly, only one study has implemented this model on RRIs thus far (Nakaoka *et al.*, 2021), but this may be due to the relatively recent validation and publication of the ACRW concept in running load analysis (Dijkhuis *et al.*, 2020). Nakaoka et al., (2021) reported a higher RRI risk with lower ACRW (< 0.70), indicating that runners who have reduced their acute workload (e.g. reduction in the last week) with respect to their recent chronic workload history (e.g. workload over previous 6 weeks) would be more susceptible to RRIs. Perhaps runners should avoid drastic changes in workload from week to week if possible. In light of this, future studies should consider investigating distance as a measure that is relative to the runner, rather than in absolute values, if we are to determine distance as a compelling risk factor for RRI development.

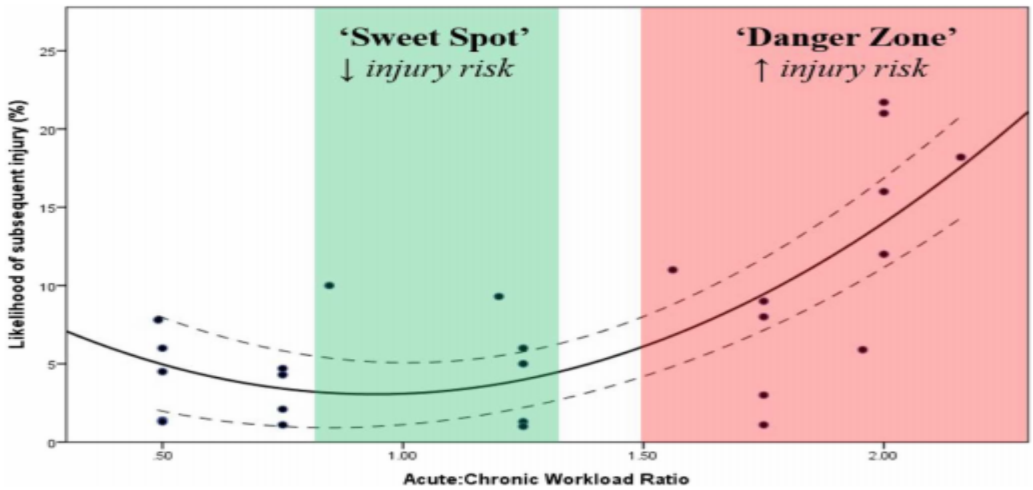

Figure 2.4.4 Acute Chronic Workload Ratio model of injury likelihood (Gabbett, 2016).

Table 2.4.6 Studies investigating distance as a risk factor for RRI.

Study	Population	Injury type	Unit Reference	Estimate (95% CI)	Significance	Interpretation
Prospective						
Wen *et al*., (1997)	304 experienced runners (Inj: 136; Uninj: 168)	Hamstring	N/R	OR: 1.11	P = 0.005*	Higher weekly distance ↑ risk of hamstring injury
Satterthwaite *et al*., (1999)	875 recreational runners (Inj: 212; Uninj: 663)	Hamstring	Per 10km ↑	OR: 1.07 (1.02 to 1.13)	P = 0.008*	Higher weekly distance ↑ risk of hamstring injury.
Di Caprio *et al*., (2010)	166 recreational runners (Inj: 98; Uninj: 68)	PF AT Stress fracture CACS	Average weekly distance Inj vs Uninj	Inj 61.1 : Uninj 41.1 Inj 63.5 : Uninj 42.2 Inj 84.4 : Uninj 43.4 Inj 67.0 : Uninj 46.1	P = 0.0005* P = 0.0005* P = 0.0005* P = 0.005*	Higher weekly distance in runners sustaining PF, AT, stress fracture and CACS injuries.
Ferreira *et al*., (2012)	100 recreational runners (Inj: 40; Uninj: 60)	General RRIs	Average daily distance Inj vs Uninj	Inj 7.0km : Uninj 5.5km	P = 0.004*	Higher daily distance in injured runners
Van Middelkoop *et al*., (2008)	694 male recreational runners (Inj:195; Uninj: 499)	General RRIs	Long distance training	OR: 0.76 (0.54 to 1.07	P = 0.12	-
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	Weekly distance Inj vs Uninj	Inj 35.3km : Uninj 33.8km	P > 0.05	-
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Per 1km ↑	OR: 1.00 (0.99 to 1.01)	P = 0.92	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Weekly mean distance	HazR: 0.97	P > 0.05	-
Besomi *et al*., (2019)	4380 recreational runners (Inj: 623; Uninj: 3757)	General RRIs	Average weekly distance Inj vs Uninj	Inj 21.0km : Uninj 25.0km	P = 0.05	-
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	Average weekly distance Inj vs Uninj	Inj 32.8km : Uninj 32.0km	P = 0.75	-
Dallinga *et al*., (2019)	706 recreational runners (Inj: 142; Uninj: 654)	General RRIs	Average weekly distance (>30km)	<5km OR: 2.03 (0.87 to 4.70) 5-10km OR: 1.85 (0.92 to 3.69) 10-20km OR: 1.24 (0.65 to 2.38) 20-30km OR: 1.29 (0.65 to 2.59)	P > 0.05	-

Satterthwaite *et al*., (1999)	875 recreational runners (Inj:224; Uninj:651)	Knee	Per 10km ↓	OR: 1.13 (1.04 to 1.23)	P = 0.003*	Lower weekly distance ↑ risk of knee injury.
Di Caprio *et al*., (2010)	166 recreational runners (Inj: 98; Uninj: 68)	Hamstring	Average weekly distance Inj vs Uninj	Inj 29.6 : Uninj 50.4	P < 0.0005*	Lower weekly distance in runners who sustained hamstring injuries.
Nakaoka *et al*., (2021)	435 recreational runners (Inj: N/R; Uninj: N/R)	General RRIs	ACWR	OR: 0.13 (0.04 to 0.45)	p < 0.05*	Lower ACWR ↑ risk of RRIs
Retrospective						
Jacobs & Berson (1986)	451 recreational runners (Inj: 210; Uninj: 241)	General RRIs	Run > 48km per week Inj % vs Uninj%	Inj ~68% : Uninj ~49%	P < 0.001*	Higher % of injured runners ran greater distances in training
McQuade *et al*., (1986)	155 recreational runners (Inj: 96; Uninj: 59)	General RRIs	Average weekly distance Inj vs Uninj	Inj 32.2km : Uninj 24.1km	P < 0.02*	Higher weekly distance in injured runners
Haglund-Akerlind *et al*., (1993)	46 male recreational runners (Inj: 28; Uninjured: 18)	AT	Average weekly distance Inj vs Uninj	Inj 106.2km : Uninj 85.8km	P < 0.05*	Higher weekly distance in injured runners
Messier *et al*., (1995)	126 recreational runners (Inj: 56; Uninj: 70)	ITBS	Average weekly distance Inj vs Uninj	Inj 50.4km : Uninj 42.5km	P = 0.01*	Higher weekly distance in injured runners
Knobloch *et al*., (2008)	291 masters runners (815 injuries)	General RRIs	Total distance in season	>2600km RR: 2.00 (1.11 to 3.48)	P = 0.02	Running >2600km per season was an ↑ risk for shin injuries.
Grimston *et al*., (1991)	14 female runners (Inj: 6; Uninj: 8)	Stress Fracture	Average weekly distance Inj vs Uninj	Inj 60.7km : Uninj 57.4km	P > 0.05	-
McCrory *et al*., (1999)	89 recreational runners (Inj: 31; Uninj: 58)	AT	Average weekly distance Inj vs Uninj	Inj 52.1 km : Uninj 44.5 km	P > 0.05	-
Duffey *et al*., (2000)	169 recreational runners (Inj: 99; Uninj: 70)	AKP	Average weekly distance Inj vs Uninj	Inj 40.6km : Uninj 42.7km	P > 0.05	-
McKean *et al*., (2006)	2825 Masters runners (Inj: 1309; Uninj; 1516)	General RRIs	Distance per week	N/R	P > 0.05	-

Miller *et al*., (2007)	16 recreational runners (Inj: 8; Uninj: 8)	ITBS	Weekly distance Inj vs Uninj	Inj 38.1km : Uninj 19.0km	P = 0.06	-
Rasmussen *et al*., (2013)	662 recreational runners (Inj: 68; Uninj: 594)	General RRIs	Longest training distance (above 30km)	25-30 km: RR 1.18 (0.68 to 2.08) <25 km: RR 1.27 (0.71 to 2.26)	P = 0.55 P = 0.42	-
Messier et al., (1991)	36 recreational runners (Inj: 16; Uninjured: 20)	PFPS	Average weekly distance Inj vs Uninj	Inj 33.6km : Uninj 48.8km	P < 0.008*	Lower weekly distance in injured runners
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Distance per week (km) Inj % vs Uninj %	<32 ♂ Inj 76.4% : Uninj 86.2% <32 ♀ Inj 85.3% : Uninj 92.0% >32 ♂ Inj 23.6% : Uninj 13.8% >32 ♀ Inj 14.7% : Uninj 8.0%	P < 0.05*	Higher weekly distance ↓ risk of RRI

*Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; CACS: chronic anterior compartment syndrome; ERLP, exercise-related leg pain; TSF: tibial stress fracture; PF: plantar fasciitis; TSF: tibial stress fracture; PFPS patellofemoral pain syndrome; ACWR: acute chronic workload ratio; OR, odds ratio; RR, relative risk; N/R: not reported; CI, confidence interval; HazR, hazard ratio; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference; For randomised controlled trials, results presented are for whole population studied, irrespective of intervention groups -unless stated otherwise in table.*

Another aspect of training load which has received some attention is the duration of running, with little evidence suggesting a relationship between session duration and RRIs (Table 2.4.7). Five prospective studies and three retrospective studies explored this variable with a slight tendency for higher durations to relate to RRI, but the evidence is limited largely by retrospective rather than prospective findings. One of five prospective studies found significantly higher session durations to increase the risk of general overuse RRIs in recreational runners [OR: 1.01] (Hespanhol Junior, Pena Costa and Lopes, 2013). Four prospective studies found no effect of duration on RRIs (Ferreira *et al.*, 2012; Hirschmüller *et al.*, 2012; Theisen *et al.*, 2014; Dallinga *et al.*, 2019).

Retrospectively, all three studies found duration to be a risk factor for injury but findings were mixed. One study found a higher duration of weight-bearing physical activity per week to increase the risk of general overuse RRIs in recreational runners [OR: 1.11] (Hootman *et al.*, 2002). In contrast, another study reported significantly lower weekly activity (<5 hours) in female recreational runners who had a history of patellofemoral pain syndrome [OR: 0.54] (Taunton *et al.*, 2002). The third retrospective study reported mixed findings for duration as a risk factor, with higher session duration (>60 minutes) associated with an increased risk of foot pain [OR: 3.04], but a decreased risk of hip pain [OR: 0.34] when compared to lower session durations (< 30 minutes) (Chang, Shih and Chen, 2012). Authors of this study suggested that high session durations may lead to fatigue and overload of the lower limb structures, potentially exposing runners to increased risks of RRI. Chang, Shih and Chen, (2012) did not discuss why one body part could have an increased risk of RRI and another body part could have a decreased risk of RRI with longer session durations. On observation, given that the foot is the first segment in contact with the ground, perhaps the impact loading is greatest at this point, and with fatigue, the foot becomes less efficient at managing this load. With the hip placed more proximally up the kinetic chain, perhaps this joint is more protected from impact loading. Chang, Shih and Chen, (2012) did not explore impact loading or joint kinematics however, and so this is only speculation.

In conclusion, there is little prospective evidence to suggest training duration as a risk factor for RRI. Although this review noted findings in both directions, the differences between studies such as session vs weekly duration of training, and the lack of clarity between running duration and duration of physical activity or weight-bearing activity may play a role here. It is quite likely that duration as a risk factor is somewhat dependent and related to other training load variables such as distance, intensity, speed and frequency. Future studies should account and explore all aspects of training loads rather than each in isolation.

Frequency of running (number of sessions per week/days of running per week) is another training related risk factor which has been explored with respect to RRIs, with little evidence suggesting frequency of training as a confounding risk factor for RRIs (Table 2.4.8). Where studies have found significance, they are largely in agreement with higher frequencies of training relating to RRIs. Prospectively, there are findings in both directions with 2 out of 6 studies reporting higher frequencies of training (days per week) to be a significant risk factor for front of thigh injuries [OR: 1.19] (Satterthwaite *et al.*, 1999) and plantar fasciitis [OR: 2.59] (Di Caprio *et al.*, 2010). Conversely, Taunton *et al.*, (2003) reported a significantly greater risk of general overuse RRIs in female recreational runners who had lower training frequencies [OR: 3.65]. Three prospective studies found no effect of frequency on RRIs (Ferreira *et al.*, 2012; Hespanhol Junior, Pena Costa and Lopes, 2013; Theisen *et al.*, 2014).

Retrospectively, findings are more consistent in direction with 3 of 6 studies finding a greater risk of general overuse RRIs in recreational (Jacobs and Berson, 1986) and master runners [OR range: 1.28 to 2.30] (McKean, Manson and Stanish, 2006; Knobloch, Yoon and Vogt, 2008) with higher frequencies of training (days per week). Three retrospective studies found no effect (Haglund-Åkerlind and Eriksson, 1993; Hootman *et al.*, 2002; Lopes *et al.*, 2011). Proposed reasons for why frequency of training may be related to RRI development include the lack of recovery occurring in the runners who train more frequently (Soligard *et al.*, 2016). As is evident from Figure 2.4.3, recovery is necessary following the application of training load in order for biological adaptation to occur. However, when recovery is suboptimal or compromised, the risk of maladaptation, overuse and injury ensues (Soligard *et al.*, 2016). Although there is more agreement amongst the findings of this training variable in comparison to some other training load variables, more prospective research is required that is cognizant of how frequency may change from week to week and month to month. In addition, the frequency of training may be influenced by the intensity and type of sessions, and so these factors should be considered together rather than alone.

Table 2.4.7 Studies investigating duration as a risk factor for RRI.

Study	***Population***	***Injury type***	***Unit Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Prospective						
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Mean session duration (Per 10 min ↑)	OR: 1.01 (1.00 to 1.02)	P = 0.017*	Higher session duration ↑ risk of RRI
Ferreira *et al*., (2012)	100 recreational runners (Inj: 40; Uninj: 60)	General RRIs	Mean session duration Inj vs Uninj	Inj 54.3 min : Uninj 50.3 min	P = 0.29	-
Hirschmüller *et al*., (2012)	427 recreational runners (Inj: 61; Uninj: 366)	AT	Training volume (Hr/week) Inj vs Uninj	Inj 3.6 : Uninj 3.4	P > 0.05	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Mean session duration (Per 1 min ↑)	HazR: 0.99	P = 0.34	-
Dallinga *et al*., (2019)	706 recreational runners (Inj: 142; Uninj: 654)	General RRIs	Training hours (Reference not defined)	OR: 1.00 (0.99 to 1.00)	P > 0.05	-
Retrospective						
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Weight-bearing physical activity per week (Hours per week)	OR: 1.11 (1.06 to 1.17)	P = 0.0001*	Higher duration of weight-bearing physical activity per week ↑ risk of RRI
Chang *et al*., (2012)	893 recreational runners (Inj: 396; Uninj: 497)	Foot pain	Mean session duration (<30 min)	30-60min OR: 1.43 (0.73 to 2.83) >60min OR: 3.04 (1.47 to 6.28)	P = 0.30 P = 0.003*	Higher duration ↑ risk of foot pain.
Taunton *et al*., (2002)	2002 recreational runners (Inj:2002; Uninj: 0)	PFPS	Weekly activity hours (<5 hours)	♀ OR: 0.54 (0.34 to 0.84)	P < 0.05*	♀ Lower weekly activity ↓ risk of PFPS
Chang *et al*., (2012)	893 recreational runners (Inj: 396; Uninj: 497)	Hip pain	Mean session duration (<30 min)	30-60min OR: 1.10 (0.38 to 3.16) >60min OR: 0.34 (0.13 to 0.86)	P = 0.86 P = 0.02*	Higher duration ↓ risk of hip pain.

Inj: injured; Uninj: uninjured; Hr: hour: min: minutes; RRIs: running-related injuries; PFPS patellofemoral pain syndrome; OR, odds ratio; RR, relative risk; CI, confidence interval; HazR, hazard ratio; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

Table 2.4.8 Studies investigating frequency of training as a risk factor for RRI.

Study	*Population*	*Injury type*	*Unit Reference*	*Estimate (95% CI)*	*Significance*	*Interpretation*
Prospective						
Satterthwaite *et al*., (1999)	875 recreational runners	Front thigh (Inj: 526; Uninj: 349)	↑ 1 day/week	OR: 1.19 (1.05 to 1.34)	P = 0.008*	Higher frequency ↑ risk of front thigh injury.
Di Caprio *et al*., (2010)	166 recreational runners (Inj: 98; Uninj: 68)	PF	Days of training per week	OR: 2.59 91.68 to 3.99)	P < 0.0005*	Higher frequency ↑ risk of PF injury.
Ferreira *et al*., (2012)	100 recreational runners (Inj: 40; Uninj: 60)	General RRIs	Days of training per week Inj vs Uninj	Inj 3.7 : Uninj 3.7	P = 0.77	-
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Days of training per week	OR: 1.01 (0.87 to 1.18)	P = 0.86	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Weekly mean distance	HazR: 0.97	P > 0.05	-
Taunton *et al*., (2003)	844 recreational runners (Inj: 249; Uninj: 595)	General RRIs	1 day per week	♀ OR: 3.65 (1.08 to 12.29)	P < 0.05*	Lower frequency ↑ risk of RRI.
Retrospective						
Jacobs & Berson (1986)	451 recreational runners (Inj: 210; Uninj: 241)	General RRIs	Run > 5 days per week Inj % vs Uninj%	Inj ~50% : Uninj ~32%	P < 0.001*	Higher % of injured runners ran more than 5 times per week.
McKean *et al*., (2006)	2825 Masters runners (Inj: 1309; Uninj; 1516)	General RRIs	Days of training per week (1-3 days per week)	4-5 days per week <40 years OR: 1.32 (1.07 to 1.62) >40 years OR: 1.28 (0.95 to 1.74) 6+ days per week <40 years OR: 1.77 (1.25 to 2.53) >40 years OR: 2.24 (1.46 to 3.45)	P = 0.009* P = 0.002* P = 0.110 P < 0.001*	Greater risk of RRI with higher frequency of training.
Knobloch *et al*., (2008)	291 masters runners (815 injuries)	General RRIs	Run > 4 days per week	OR: 2.30 (1.09 to 4.96)	P = 0.025*	Running >4 days per week ↑ risk of RRI.

Haglund-Akerlind *et al*., (1993)	46 male recreational runners (Inj: 28; Uninjured: 18)	AT	Days of training per week Inj vs Uninj	Inj 7.9 : Uninj 7.0	P > 0.05	-
Lopes *et al*., (2011)	1049 recreational runners (Inj: 227; Uninj: 822)	General RRIs	Running 3 days per week	N/R	P = 0.793	-
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Workouts per week Inj % vs Uninj %	<6 ♂ Inj 83.3 : Uninj 87.5% <6 ♀ Inj 85.3% : Uninj 90.2% 6+ ♂ Inj 16.7% : Uninj 12.5% 6+ ♀ Inj 14.7% : Uninj 9.8%	P > 0.05	-

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; PF: plantar fasciitis; TSF: tibial stress fracture; OR, odds ratio; CI, confidence interval; HazR, hazard ratio; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

Two final areas of training load which have been investigated as potential risk factors for RRIs are speed and interval training. These factors are closely related due to the similar demands they place on the anaerobic energy and neuromuscular systems of the body (Buchheit and Laursen, 2013). Regarding speed, there is only limited evidence in support of this training variable as a risk factor for RRIs, but there is consistency in the direction of those with significant findings, with injured runners having a tendency to train at greater speeds than uninjured runners (Table 2.4.9). Prospectively, no studies found training speed to relate to RRI. (Theisen *et al.*, 2014; Messier *et al.*, 2018) Retrospectively, 2 of 3 studies looking at general overuse RRIs found that runners trained at significantly faster speeds than uninjured runners (Jacobs and Berson, 1986; Hootman *et al.*, 2002). When focusing on specific RRIs, there was no prospective research in this area. With reference to retrospective studies, 1 of 5 studies found runners with a history of Achilles tendon injuries (McCrory *et al.*, 1999) to train at significantly faster speeds than those who were uninjured. It does not appear that speed is a confounding risk factor for anterior knee pain (Duffey *et al.*, 2000), iliotibial band syndrome (Messier *et al.*, 1995; Miller *et al.*, 2007) or patellofemoral pain syndrome (Messier *et al.*, 1991). There are a limited number of studies in this area however, and more research is needed.

Regarding speed work in training, only one study has assessed this factor, with authors noting greater risk for RRIs [OR: 1.46] if there was a higher frequency of speed sessions per week (Hespanhol Junior, Pena Costa and Lopes, 2013).

Similar to speed, few studies have explored interval training as a potential risk factor of RRI, with little evidence that interval training may be a risk factor for RRIs (Table 2.4.9). Prospectively, 1 out of 2 studies found interval training to be a significant risk factor for general overuse RRIs, with Hespanhol Junior, Pena Costa and Lopes (2013) reporting a greater amount of interval sessions per week to be a protective factor for RRI [0.61]. There were no retrospective studies that explored interval training as a risk factor for general overuse RRIs. With reference to specific RRIs, only 1 prospective study looked at this with Wen, Puffer and Schmalzried, (1998) reporting significantly greater interval based training in recreational runners who sustained shin injures compared to their uninjured counterparts [RIR: 14.89]. Retrospectively, 1 of 2 studies found interval training to relate to specific injuries, with findings in support of Wen, Puffer and Schmalzried (1998), where runners who had a history of shin injuries performed more interval based training than those who had no history of injury [OR: 55.91] (Wen, Puffer and Schmalzried, 1997). In conclusion, although it does appear that greater speeds and greater percentages of speed/interval training may predispose to specific injuries, there are not enough studies in this area to definitively conclude speed and interval training as a compounding risk factor. Most of the studies to date have captured self-reported mean training speeds and this may be affected by recall bias. The use of technological global positioning system (GPS) trackers and/or smartphone applications may prove to be a more accurate reflection of mean speed, in addition to the range of speeds reached per session.

Some RRIs have been suggested as speed-related injuries (Nielsen *et al.*, 2013), with these injuries typically affecting posterior chain structures (plantar fasciitis, gastrocnemius strain, Achilles tendon injuries, tibial stress fractures hamstring strains) (Nielsen *et al.*, 2014). A possible explanation for this could be the greater loading seen at the ankle joint with faster speeds in comparison to the knee joint (Nilsson and Thorstensson, 1989; Bredahl *et al.*, 2013; Petersen *et al.*, 2014; de David, Carpes and Stefanyshyn, 2015). Perhaps studying RRIs collectively clouded any potential relationships in the studies reviewed here, and going forward research may need to explore RRI risk factors with respect to specific joints or pathologies if there are sufficient numbers of various pathologies to power a statistical analysis.

In summary of training load factors, there appears to be limited evidence for a relationship between distance, duration, frequency, and training speed as risk factors for RRIs. This is largely due to the lack of prospective research in this area, and the univariate approach to analyses. Future research should therefore seek to investigate these factors prospectively with a multifactorial approach.

Table 2.4.9 Studies investigating speed and interval training as a risk factor for RRI.

Study	***Population***	***Injury type***	***Unit Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Training Speed						
Prospective						
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Mean speed (km/hr)	HazR: 0.91	P = 0.30	-
Messier *et al*., (2018)	300 recreational runners (Inj: 199; Uninj: 101)	General RRIs	Training pace (km/hr) Inj vs Uninj	Inj 10.6 : Uninj 10.9	P = 0.20	-
Retrospective						
Jacobs & Berson (1986)	451 recreational runners (Inj: 210; Uninj: 241)	General RRIs	Run faster than 12km/hr Inj % vs Uninj%	Inj ~54% : Uninj ~47%	P < 0.05*	Higher % of injured runners ran a faster pace than uninjured runners.
McCrory *et al*., (1999)	89 recreational runners (Inj: 31; Uninj: 58)	AT	Training pace (km/hr) Inj vs Uninj	Inj 12.9 : Uninj 12.5	P < 0.05*	Injured runners trained at a faster pace than uninjured runners.
Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	General RRIs	Training pace (km/hr) Inj vs Uninj	<15 ♂ Inj 89.9 : Uninj 80.1% <15 ♀ Inj 73.0% : Uninj 54.8% 15+ ♂ Inj 10.1% : Uninj 19.9% 15+ ♀ Inj 27.0% : Uninj 45.2%	P < 0.05*	Injured runners trained at a faster pace than uninjured runners.
Duffey *et al*., (2000)	169 recreational runners (Inj: 99; Uninj: 70)	AKP	Training pace (km/hr) Inj vs Uninj	Inj 12.0 : Uninj 12.0	P > 0.05	-
Miller *et al*., (2007)	16 recreational runners (Inj: 8; Uninj: 8)	ITBS	5km race time (min) Inj vs Uninj	Inj 23.4 : Uninj 22.9	P = 0.84	-
Messier *et al*., (1991)	36 recreational runners (Inj: 16; Uninjured: 20)	PFPS	Training pace (km/hr) Inj vs Uninj	Inj 11.6 : Uninj 12.4	P > 0.05	-

Messier *et al*., (1995)	126 recreational runners (Inj: 56; Uninj: 70)	ITBS	Training pace (km/hr) Inj vs Uninj	Inj 12.1 : Uninj 14.1	P > 0.05	-
McQuade *et al*., (1986)	155 recreational runners (Inj: 96; Uninj: 59)	General RRIs	Training pace (km/hr) Inj vs Uninj	Inj 12.5 : Uninj 12.5	P > 0.05	-
Speed based training						
Prospective						
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Type of training (per 1 day a week ↑)	OR: 1.46 (1.02 to 2.10)	P = 0.039*	Higher frequency of speed training ↑ risk of RRI.
Interval based training						
Prospective						
Wen *et al*., (1998)	255 recreational runners (Inj: 90; Uninj: 165)	Shin	% training was interval	RIR: 14.89 (0.50 to 147.33)	P < 0.05*	Runners with shin injuries performed more interval based training.
Van Middelkoop *et al*., (2008)	694 male recreational runners (Inj:195; Uninj: 499)	General RRIs	Interval training (Always)	OR: 0.76 (0.54 to 1.07)	P = 0.12	-
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Type of training (per 1 day a week ↑)	Interval OR: 0.61 (0.43 to 0.88)	P = 0.008*	Higher frequency of interval training ↓ risk of RRI.
Retrospective						
Wen *et al*., (1997)	304 experienced runners (Inj: 136; Uninj: 168)	Shin	% training was interval	OR: 55.91	P = 0.04*	Runners with shin injuries performed more interval based training.
Haglund-Akerlind *et al*., (1993)	46 male recreational runners (Inj: 28; Uninjured: 18)	AT	Intervals per week (km) Inj vs Uninj	Inj 12.3 : Uninj 10.2	P > 0.05	-

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; PF: plantar fasciitis; TSF: tibial stress fracture; OR, odds ratio; CI, confidence interval; HazR, hazard ratio; (-) not reported/statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.2.2 Surface

It has been proposed in a recent systematic review that impact loading, joint kinematics and muscle activity during running differ between various surfaces (Van Hooren *et al.*, 2020). Given the relationship between particular RRIs and both impact loading (Section 2.4.3) and joint kinematic variables (Section 2.4.4), it is not surprising that running surface has been investigated as a potential extrinsic risk factor in RRI development. Runners may choose a range of surfaces to train or compete on depending on the event, their accessibility and their personal preference. Surfaces which runners typically run on include the road, footpaths, treadmills, synthetic track, asphalt, grass, trails, dirt, cross-country and sand. To date, 7 prospective and 6 retrospective studies have explored surface as a risk factor for RRIs with little evidence to suggest that any one surface is more injurious than another (Table 2.4.10).

Prospectively, 1 of 5 studies found surface to be associated with injury, where an increased risk of Achilles tendon injuries was observed on an athletic track compared to road and field surfaces [OR: 5.25] (Di Caprio *et al.*, 2010). Four prospective studies found no effect of surface on RRIs. Retrospectively, 3 of 6 studies found a link between surface and injury (Messier *et al.*, 1995; Knobloch, Yoon and Vogt, 2008; Fonseca *et al.*, 2015). One of these studies documented an increased risk of iliotibial band injury in recreational and competitive runners with more time spent training on an athletic track compared to asphalt and dirt surfaces (Messier *et al.*, 1995). Another study found the risk of general overuse RRIs in male recreational runners to decrease with predominant use of a treadmill in training compared to asphalt, track, dirt and sand (Fonseca *et al.*, 2015). Lastly, the third study reporting specifically on Achilles tendon injuries noted an increased risk of injury with sand running [OR: 10.00] compared to trails and asphalt, and a decreased risk of injury with asphalt running [OR: 0.47] compared to trails and sand in masters runners (Knobloch, Yoon and Vogt, 2008). Despite these findings, several studies found no relationship between surface and RRI development whatsoever (Wen, Puffer and Schmalzried, 1998; J. McCrory *et al.*, 1999; Duffey *et al.*, 2000; Taunton *et al.*, 2003; Lopes *et al.*, 2011; Hespanhol Junior, Pena Costa and Lopes, 2013; Theisen *et al.*, 2014).

It has been proposed that each surface may demonstrate different compliance and so, this may have direct implications for various tissues (Moore, 2016). On a surface with greater compliance or cushioning properties (e.g. sand), it has been assumed that peak impact loading would be reduced (Dixon, Collop and Batt, 2000), and thus the risk of overuse RRIs would be reduced too. However, multiple studies have found no differences in peak impact loading across surfaces of various compliance (Feehery, 1986; Nigg and Yeadon, 1987; Wilson, Rochelle and Bischoff, 1997). It has since been proposed that the maintenance of similar impact loading across various surfaces is accomplished by running technique adjustments made by the runner, such as changes in foot contact angle (De Wit and De Clercq, 1997) or knee angle (Derrick, 2004) at impact. Perhaps this may explain why there is little evidence to suggest surface as a compounding risk factor for RRIs, as runners tend to adapt their technique to various surfaces, negating any potential injury risk thought to be associated with greater or lesser surface compliance.

Table 2.4.10 Studies investigating surface as a risk factor for RRI.

Study	***Population***	***Injury type***	***Surfaces Studied***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Prospective						
Di Caprio *et al*., (2010)	166 recreational runners (Inj: 98; Uninj: 68)	AT	Athletics Track ; Street ; Field	OR: 5.25 (1.26 to 21.84)	P = 0.023*	↑ risk of AT RRI with athletic track surface
Wen *et al*., (1998)	255 recreational runners (Inj: 90; Uninj: 165)	General RRIs	Concrete; Asphalt	N/R	P > 0.05	-
Junior *et al*., (2013)	191 recreational runners (Inj: 60; Uninj: 131)	General RRIs	Hard; Soft; Treadmill; Other	Hard OR: 1.06 (0.86 to 1.31) Other OR: 0.25 (0.05 to 1.25)	P = 0.59 P = 0.09	-
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69)	General RRIs	Hard surfaces	HazR: 1.00	P = 0.663	-
Taunton *et al*., (2003)	844 recreational runners (Inj: 249; Uninj: 595	General RRIs	Road; Trail; Grass; Treadmill	N/R	P > 0.05	-
Retrospective						
Messier *et al*., (1995)	126 recreational runners (Inj: 56; Uninj: 70)	ITBS	Athletics Track; Asphalt; Dirt	Synthetic Track Inj 5.4 : Uninj 1.4 Asphalt Inj 75.9 : Uninj 74.5 Dirt Inj 7.2 : 9.8	P = 0.007* P > 0.05 P > 0.05	↑ risk of RRI with greater times on track
Knobloch *et al*., (2008)	291 masters runners (815 injuries)	AT	Sand	OR: 10.00 (1.12 to 92.80)	P = 0.011*	↑ risk of AT injury on sand
McCrory *et al*., (1999)	89 recreational runners (Inj: 31; Uninj: 58)	AT	Not reported	N/R	P > 0.05	-
Duffey *et al*., (2000)	169 recreational runners (Inj: 99; Uninj: 70)	AKP	Asphalt; Dirt; Cross-country; Composition track; Cinder Track; Crowned roads; Trails	N/R	P > 0.05	-
Lopes *et al*., (2011)	1049 recreational runners (Inj: 227; Uninj: 822)	General RRIs	Asphalt; Treadmill; Sand/Grass/Clay	N/R	P > 0.05	-
Knobloch *et al*., (2008)	291 masters runners (815 injuries)	AT	Asphalt	OR:0.47 (0.25 to 0.89)	P = 0.019*	↓ risk of AT injury on asphalt
Fonsenca *et al*., (2015)	121 male recreational runners (Inj: 40; Uninj: 81)	General RRIs	Treadmill	N/R	P = 0.043*	↓ risk of RRI with treadmills

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AT, Achilles tendinopathy; AKP: anterior knee pain; ERLP, exercise-related leg pain; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-): statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; N/R: not reported; ref: reference.

2.4.2.3 Footwear

It has been speculated that various types of footwear may affect impact loading (Shorten and Mientjes, 2011; Theisen *et al.*, 2014) and joint kinematics (Lieberman *et al.*, 2010; Lohman *et al.*, 2011) during landing and mid-stance in running. These effects on technique have thus led some runners and researchers to believe that footwear may play a determining role in the development of RRIs (Theisen, Malisoux and Gette, 2016). With this, the relationship between footwear and RRI has been explored mainly by comparing injury rates across various shoe types (traditional shod, minimalist, barefoot, hard sole, soft sole), and to a lesser extent through differences in shoe age and single vs multiple shoe use. For this reason, each aspect of footwear and RRI will be discussed separately with reference to studies included in Table 2.4.11.

With respect to shoe type, there is only limited evidence to suggest footwear as a risk factor for RRI. Six randomized controlled trials (RCTs) explored the differences in injury rates between various shoe types (traditional shod, neutral, minimalist and hard and soft soles), with mixed findings apparent. One of the six RCTs found an increased risk with partial [RR: 3.10] and full minimalist footwear [RR: 1.60] compared to a neutral shoe (Ryan *et al.*, 2014). Interestingly, the risk was higher in partial minimalist footwear than in full minimalist footwear and authors speculated that this may have been due to compromised shock attenuation with the partial minimalist shoe (Ryan *et al.*, 2014), although shock attenuation was not directly measured in this study. Another RCT found the opposite however, with an increased risk of RRI noted with traditional shod use compared to a motion control shoe [RR: 0.59], suggesting that the motion control feature may have limited the degree of foot pronation thereby decreasing the risk of RRI (Malisoux *et al.*, 2016a). As these studies were intervention studies, participants may not have been familiar with the new shoe type, thereby increasing their risk of RRI due to unfamiliar loading. Four of the remaining six RCTs found no differences in injury rate between hard sole and soft sole shoes (Theisen *et al.*, 2014), traditional and minimalist shoes (Dubois *et al.*, 2015; Fuller *et al.*, 2017), and between 0mm, 6mm and 10mm drop shoes (Malisoux *et al.*, 2016b).

Prospectively, only one study explored footwear as a potential risk factor for RRI with Altman and Davis, (2016) reporting an increased risk of RRI in traditional shod footwear compared to barefoot [1.66 RRIs/runner in shod vs 1.17 RRIs/runners in barefoot].

Interestingly, this result became insignificant when results were normalized to mileage of the runners. This highlights the importance of controlling for mileage and other potential risk factors in the analysis of footwear and RRIs. Three of the RCTs implemented standardized training programmes with the various shoe types (Ryan *et al.*, 2014; Dubois *et al.*, 2015; Fuller *et al.*, 2017), whilst the other three normalized for mileage in the analysis (Theisen *et al.*, 2014; Malisoux *et al.*, 2016a; Malisoux *et al.*, 2016b). However, in the only retrospective study investigating footwear as a risk factor for RRI, Goss and Gross (2012) did not account for mileage in their analysis. Despite authors reporting an increased risk for RRI with traditional shod footwear compared to minimalist footwear [traditional 46.7% RRI prevalence vs minimalist 13.7% RRI prevalence], making traditional shod wearers over 3 times more likely to have reported a RRI, the results of this study should be taken with caution (Goss and Gross, 2012). One strength of this study (Goss and Gross, 2012) and the study by Altman and Davis, (2016) however, is that the runners analysed had reported to be using their 'natural footwear', and so would be very familiar with the shoe type. Due to the nature of a randomised controlled trial, not all subjects would be familiar with the assigned shoe type and this may have an effect on running technique such as foot contact angle and stride rate, and subsequently influence RRI development (Dubois *et al.*, 2015).

Table 2.4.11 Studies investigating footwear as a risk factor for RRI.

Study	***Population***	***Footwear type***	***Unit/ Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Shoe Type						
Randomised Controlled Trial						
Malisoux *et al*., (2016)a	372 recreational runners (Inj: 93; Uninj: 279) 6 month follow-up	TS: 185 (Inj: 60) MCS: 187 (Inj: 33)	TS	RR: 0.55 (0.36 to 0.85)	P < 0.05*	↑ risk of RRI with TS compared to MCS
Theisen *et al*., (2014)	215 recreational runners (Inj: 146; Uninj: 69) 5 month follow-up	Hard sole: 113 (Inj: 32) Soft sole: 134 (Inj: 37)	Hard sole	HazR: 0.92	P = 0.731	-
Dubois *et al*., (2015)	24 recreational runners (Inj: 6; Uninj: 14) 4 month follow-up	TS: 12 (Inj: 3) MS: 12 (Inj: 3)	TS vs MS	RRI prevalence 25% vs 25%	P = 1.00	-
Malisoux *et al*., (2016)b	553 recreational runners (Inj: 136; Uninj:417) 6 month follow-up	10mm drop TS: 176 (Inj: 38) 6mm drop TS: 190 (Inj: 52) 0mm drop TS: 187 (Inj: 46)	10mm drop TS	6mm drop TS HazR: 1.29 0mm drop TS HazR: 1.21	P = 0.239 P = 0.392	-
Fuller *et al*., (2017)	61 male distance runners (Inj: 27; Uninj: 34) 6 month follow-up	TS: 30 (Inj: 11) MS: 31 (Inj: 16)	TS	HazR: 1.64 (0.63 to 4.27)	P = 0.31	-
Ryan *et al*., (2014)	99 recreational runners (Inj: 23; Uninj: 76) 3 month follow-up	Neutral: 32 (Inj: 4) Partial MS: 32 (Inj: 12) Full MS: 35 (Inj: 7)	Neutral	Partial MS: RR 3.10 (1.12 to 8.57)% Full MS: RR 1.60 (0.52 to 4.96)%	P < 0.05*	↑ risk of RRI with minimalist footwear.
Prospective						
Altman *et al*., (2016)	201 recreational runners (Inj: 114; Uninj:87) 12 month follow-up	Shod: 94 (Inj: 58) Barefoot: 107 (Inj: 56)	MSK RRIs/runner	Shod 1.66 RRIs/runner Barefoot 1.17 RRIs/runner	P = 0.05	↑ risk of RRI in shod runner, but this became insignificant when normalised for mileage
Retrospective						
Goss & Gross (2012)	888 recreational runners 12 month history	TS: 662 MS: 226	Injury prevalence TS vs MS	TS: 46.7% vs MS: 13.7% $X_2 = 77.4$	P < 0.001*	Runners wearing TS were 3.41 times more likely to have reported a RRI compared to MS wearers
Shoe Age						
Prospective						
Taunton *et al*., (2003)	844 recreational runners (Inj: 249; Uninj: 595)	Running shoe age	1 – 3 months	♀ RR: 0.61 (0.38 to 0.99)	P < 0.05*	Wearing newer running shoes decreased the risk for RRI in females

Kluitenberg *et al*., (2015)	1696 novice runners (Inj: 185; Uninj: 1511)	Running shoe age	< 3 months	3-12 months HazR: 0.90 (0.62 to 1.31) >12 months HazR: 0.80 (0.5 to 1.13)	P = 0.585 P = 0.212	-
Retrospective						
Messier *et al*., (1995)	126 recreational and competitive runners (Inj: 56; Uninj: 70)	Footwear usage (miles)	Inj vs Uninj	Inj 559.5 miles : Uninj 730.8 miles	P > 0.05	-
Wen *et al*., (1997)	304 experienced runners (Inj: 136; Uninj: 168)	Duration of shoe wear (months)	Inj vs Uninj	Inj 7.0 months : Uninj 10.8 months	P = 0.016*	Injured runners had lower miles per shoe than uninjured runners
Duffey *et al*., (2000)	169 recreational and competitive runners (Inj: 99; Uninj: 70)	Footwear usage (miles)	Inj vs Uninj	Inj 536.0 miles: Uninj 693.0 miles	P = 0.003*	Injured runners had lower miles per shoe than uninjured runners
Single vs Multiple Shoe Use						
Randomised Controlled Trial						
Malisoux *et al*., (2015)	264 amateur runners (Inj: 87; Uninj: 177)	Single shoe use: 116 (Inj: N/R) Multiple shoe use: 148 (Inj: N/R)	Multiple shoe use	HazR: 0.45	p < 0.036*	↑ risk of RRI with single shoe use compared to multiple shoe use

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; TS: traditional shoe; MS: minimalist shoe; MCS: motion control shoe; MSK: musculoskeletal; CI, confidence interval; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-): statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; ~: estimate from graph; N/R: not reported; ref: reference.

With respect to shoe age, research is lacking with only 4 studies in this area (1 prospective and 3 retrospective). Although mixed findings are apparent, results tend to lean very slightly in the direction of injured runners having lower mileage per shoe than uninjured, which is somewhat counterintuitive, but this finding is solely retrospective in nature. Prospectively, 1 of 2 studies found a reduced risk of RRI in female recreational runners who had newer running shoes (1-3 months old), compared to runners who were wearing older shoes [RR: 0.61] (Taunton *et al.*, 2003). Authors suggested that newer shoes tend to have greater cushioning and supportive qualities, and this may have played a role in the lower rate of injuries seen in runners with relatively new and less worn shoes (Taunton *et al.*, 2003). However, these properties were not assessed as part of the study and are thus only speculative (Taunton *et al.*, 2003).

Retrospectively, 2 out of 3 studies found the opposite, where significantly lower mileage [Injured: 536 miles vs Uninjured: 693 miles] (Messier *et al.*, 1995) and duration of shoe wear [Injured: 7.0 months vs Uninjured: 10.8 months] (Duffey *et al.*, 2000) was reported in recreational runners with a history of RRI compared to those who were injury free. Authors proposed that injured runners may have replaced their shoes sooner than uninjured runners due to the discomfort experienced with injury (Duffey *et al.*, 2000). In addition, it was thought that the reduced shock attenuation capacity of older or worn shoes may have prompted injured runners to change their shoes more often due to the increased sensation of impact loading (Duffey *et al.*, 2000). The mixed direction of findings between prospective and retrospective research, as well as the opposing rationales for such findings make this a challenging area to summarize. With the diverse range of footwear available to runners, it can be difficult to compare one brand or model with another due to variations in shoe quality, and variations in the environment in which shoes are used (surface and weather conditions). If shoe age is a metric to be analyzed as a risk factor for injury, perhaps future studies should look to explore other related factors in determining how shoe age might relate to RRIs.

Finally, only one study explored single vs multiple shoe use and RRI, finding a significantly greater risk of RRI with single shoe use compared to those with multiple shoe use [HazR: 0.45] (Malisoux *et al.*, 2015). The authors of this study speculated that given the repetitive nature of running as an activity, and the associated injuries that occur with cumulative micro-trauma, cycling through multiple shoes may vary the stress applied to the body, and as a result would eliminate the cumulative micro-trauma to specific structures (Malisoux *et al.*, 2015). Authors did not measure stress or trauma at any specific site and so this speculation has not been supported by physical evidence.

In conclusion, it appears that there is very little evidence to suggest footwear as a risk factor for RRI. There does not appear to be one particular type of shoe that is more injurious than another, especially when mileage and training load is controlled for. Regarding shoe age, there is relatively little research in this area with mixed findings apparent. Lastly, only one study has explored the area of shoe rotation and injury, and so it cannot be concluded that this is a risk factor for RRI.

2.4.2.4 Stretching, warm-ups and cool-downs

Stretching, warm-ups and cool-downs have been commonly observed as pre and post-participation practices across multiple sports globally, with well documented performance benefits (McGowan *et al.*, 2015). It is a popular belief amongst runners that stretching may help to prevent RRIs (Saragiotto, Yamato and Lopes, 2014), despite the actual benefits of stretching, warm-ups and cool-downs with respect to RRIs being poorly understood (Yeung, Yeung and Gillespie, 2011). Within the literature, relatively few studies have investigated stretching, warm-ups and cool-downs as potential risk factors for RRIs, with limited evidence to suggest a relationship with injury and findings of mixed directions apparent (Table 2.4.12). One RCT compared injury rates between male recreational runners who were educated on and implemented a standardized warm-up, stretching and cool-down programme with a control group who did not receive any education or training, finding no significant difference in injury incidence rate per 1000 hours between the groups [Intervention: 5.5 injuries/1000 hours; Control: 4.9 injuries/1000 hours] (Van Mechelen *et al.*, 1993).

Prospectively, only 1 of 5 studies found significance, where runners who stretched sometimes were at greater risk of RRI compared to runners who always stretched [RR range: 1.56 to 1.78] (Walter *et al.*, 1989). In the same study, authors also found male runners who sometimes warmed-up to be at significantly greater risk of RRI compared to males who always warmed-up [RR: 1.30]. Retrospectively, there were contrasting findings with 1 of 4 studies reporting significantly greater risk of injury in recreational runners who did not stretch [RR: 2.0] (McQuade, 1986), while two other studies reported the contrary whereby injured runners were found to spend significantly more time stretching than uninjured runners (Jacobs and Berson, 1986; Duffey *et al.*, 2000).

Comparison across the literature in this area is challenging as few studies detail the parameters and characteristics of the stretching, warm-up and cool-down protocols. The discussion of these results is therefore compromised as it is difficult to establish the type (static, dynamic, jog, cycle, etc.), frequency (repetitions), duration (seconds, minutes) and intensity (slow, moderate, fast, ballistic) of stretches, warm-ups and cool-downs employed in the majority of these studies. A systematic review investigating the effects of pre-participation stretching and warm-ups in sport have found some evidence of injury-prevention potential, but this potential is largely based on the reduction of muscle strains (McHugh and Cosgrave, 2010). These proposed benefits have been suggested to increase muscle-tendon unit compliance (Toft *et al.*, 1989) and thus may allow for greater force production at longer muscle lengths (McHugh and Nesse, 2008). However, given the relatively low incidence rate of muscle strain injuries in recreational running, this may explain the lack of findings in relation to stretching and injury prevention in this particular area. Recreational running by default engages the lower limbs in a largely cyclical and repetitive motion at submaximal intensity, and so the benefits of stretching mentioned above may not be applicable to the nature of this activity (Witvrouw *et al.*, 2004). It appears that team sports have had greatest success with injury prevention when adapting sport specific and standardized warm-ups (Sadigursky *et al.*, 2017; Kelly and Lodge, 2018), and perhaps this is an area that needs more attention in running.

Table 2.4.12 Studies investigating stretching, warm-ups and cool-downs as a risk factor for RRI.

Study	***Population***	***Stretching, Warm-up, Cool-down Parameters***	***Unit Reference***	***Estimate (95% CI)***	***Significance***	***Interpretation***
Randomised Controlled Trial						
Van Mechelen *et al*., (1993)	327 male recreational runners (Int: 159; Control: 168) (Inj: 49; Uninj: 278)	Warm-up: Running exercises x 6 min, loosening exercises x 3 min. Stretching: static stretching x 10 min. Cool-down: Inverse of warm-up.	Control vs Intervention (Warm-up, cool-down and stretching)	IIR: 4.9 vs 5.5 per 1000 hours (3.1 – 7.4 vs 3.6 – 8.0) RR: 1.12 (0.56 to 2.72)	P > 0.05	-
Prospective						
Walter *et al*., (1989)	1265 recreational runners (Inj: 637; Uninj: 628)	Stretching (not defined) Warm-up (not defined)	Always stretches Always warm-up	♂ Sometimes RR: 1.56 (1.10 to 2.21) ♀ Sometimes RR: 1.78 (0.91 to 3.53) ♂ Sometimes RR: 1.30 (0.87 to 1.93) ♀ Sometimes RR: 0.95 (0.47 to 1.96)	P < 0.05*	Runners who sometimes stretch are at greater risk of injury than those who always stretch. Male runners who sometimes warm-up are at greater risk of injury than those who always warm-up.
Van Middelkoop *et al*., (2007)	165 recreational runners (Inj: 165; Uninj: 0)	Cool-down (not defined)	Never cooling-down	OR: 0.51 (0.21 to 1.26)	P = 0.14	-
Van Middelkoop *et al*., (2008)	694 male recreational runners (Inj:195; Uninj: 499)	Warm-up (not defined)	Always warming-up before a race	OR: 0.79 (0.55 to 1.12)	P = 0.18	-
Van Poppel *et al*., (2018)	2369 recreational runners (Inj: 709; Uninj: 1660)	Warm-up (not defined) Stretching (not defined) Cool-down (not defined)	Warming-up pre training Stretching pre training Cool-down post training Stretching post training	N/R	N/R	-
Hofstede *et al*., (2020)	161 recreational runners (Inj: 71; Uninj: 90)	Warm-up (not defined) Stretching (not defined) Cool-down (not defined)	Warm-up, cool-down and stretching Injured vs Uninjured	Warm-up solely 4.2% : 2.2% Cool-down solely 2.8% : 1.1% Stretching solely 15.5% : 14.4% Warm-up + cool-down + stretching 45.1% : 46.7%	P = 0.655 P = 0.583 P = 0.853 P = 0.840	-
Retrospective						
McQuade *et al*., (1986)	155 recreational runners (Inj: 96; Uninj: 59)	Stretching (not defined)	No stretching	RR: 2.0 (1.07 to 3.80)	P = 0.03*	Greater risk of injury in runners who did not stretch

Hootman *et al*., (2002)	3090 recreational runners (Inj: 1207; Uninj: 1883)	Stretching (not defined)	Stretching twice per week	N/R	N/R	-
Jacobs & Berson (1986)	451 recreational runners (Inj: 210; Uninj: 241)	Stretching (not defined)	Stretching before a run Injured vs Uninjured	Injured ~89% Uninjured ~79%	P < 0.025*	Higher percentage of injured runners stretched before a run than uninjured runners
Duffey *et al*., (2000)	169 recreational runners (Inj: 99; Uninj: 70)	Time spent stretching (stretching not defined)	Time spent stretching (minutes) Injured vs Uninjured	Injured 7 minutes Uninjured 5 minutes	P = 0.042*	Runners with AKP spent significantly more time stretching than uninjured runners

Inj: injured; Uninj: uninjured; RRIs: running-related injuries; AKP: anterior knee pain; CI, confidence interval; cIRD, cumulative injury risk difference; HazR, hazard ratio; OR, odds ratio; RR, relative risk; (-): statistically insignificant; ↑, increase; ↓, decrease; *: statistically significant; ♀: female; ♂: male; ~: estimate from graph; N/R: not reported; ref: reference.

2.4.3 Impact loading and injury

According to Lieberman *et al*. (2010), runners strike the ground over 600 times per km, each resulting in impact GRFs on the body. During rearfoot strike running in particular, the curve depicting the vertical GRF (vGRF) shows two distinctive peaks; the impact (passive) peak and the propulsive (active) peak (Figure 2.4.5) (Van Der Worp, Vrielink and Bredeweg, 2016). The initial impact peak (1.5 to 3.5 times the body weight of the runner) typically occurs within the first 30ms of contact with the ground, with its magnitude being determined largely by foot position and the centre of mass (COM) velocity (Hreljac, 2004), along with variables such as surface, soft tissue strength, speed, and stride length (Hreljac, 2004; Goss and Gross, 2012). The active or propulsive peak of the vGRF generally occurs in the latter stage of the vGRF curve, through the mid-stance phase of the gait cycle, and lasts approximately 200ms (Hreljac, 2004). This peak is reflective of the generation of force by the muscles in accelerating the body forward (Grabowski and Kram, 2008). As this force is applied over a longer space of time, the active peak is considered to be the lower frequency element of the GRF (Hreljac, 2004), and may be less related to injury, especially when compared to the short duration of the passive impact peak which is of a higher frequency generally (Shorten and Mientjes, 2011). For the purpose of this review, a focus will be placed on the impact peak as injuries are most associated with this phase of impact. The loading rate of the vGRF is depictive of the speed at which force is applied to the body, and this is derived from the gradient of the initial impact peak. Loading rate has been reported mainly in two forms; vertical average loading rate (VALR), and vertical instantaneous loading rate (VILR).

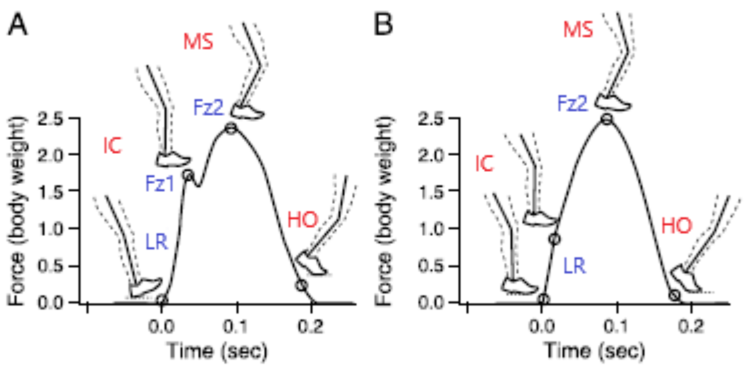

Figure 2.4.5 Phases of vertical ground reaction force (vGRF).

A: Rearfoot strike pattern, B: Forefoot strike pattern, IC: Initial Contact, MS: Mid-stance, HO: Heel Off, LR: Loading Rate, Fz1: Initial impact peak (passive peak), Fz2: Propulsive peak (active peak). Adapted from Daoud et al. (2012).

2.4.3.1 Ground reaction force and injury

Loading and its relationship with injury has been researched extensively with respect to various components of the GRF curve (Figure 2.4.5). Specific areas of interest have included the vertical impact peak (VIP) (Table 2.4.13), average loading rate (VALR) (Table 2.4.14), and instantaneous loading rate (VILR) (Table 2.4.15). Despite this area being relatively well researched, there seems to be mixed findings. Trends are evident which show a moderate relationship between the rate of loading and RRI, but it is less clear if impact and active peaks relate to RRI.

With regard to the vGRF impact peak (VIP), five prospective and fifteen retrospective studies have investigated its relationship with RRIs (Table 2.4.13). Prospectively, one study found female recreational runners who had sustained a RRI to have significantly greater VIPs compared to runners who remained injury-free ($p < 0.05$) (Davis, Bowser and Mullineaux, 2016). These results from Davis, Bowser and Mullineaux, (2016) were attributable to the sub-group analysis of never injured and injured for the first time, rather than to injured vs un-injured runners collectively. Four prospective studies found no effect of VIP on RRI.

Retrospectively, there are mixed findings with three authors reporting VIP to be significantly greater (12.7 – 21.0%) in runners who had a history of chronic ankle instability (Bigouette *et al.*, 2016), lower limb stress fracture (Grimston *et al.*, 1991) and RRIs to the knee or below the knee (Hreljac, Marshall and Hume, 2000), eleven studies finding no effect, and one study reporting VIPs to be significantly lower (4.6%) in runners with anterior knee pain (Duffey *et al.*, 2000) compared to uninjured controls. Again, it may be the case that having a symptomatic knee injury causes an adaptive gait to reduce the pain and potential load going through the knee. Although the runners with chronic ankle instability were also symptomatic while being tested in the study by Bigouette *et al.*, (2016), the long-lasting mechanical and functional insufficiencies associated with the nature of this condition may limit the body's ability to tolerate VIP loads effectively (Hiller, Kilbreath and Refshauge, 2011; Liu, Uygur and Kaminski, 2012).

Table 2.4.13 Vertical impact peak and RRI

Study	***Population****	***Injury***	***Methods***	***Instrument & Sampling Rate***	***Injured Group*** ***Mean ± SD (BW)***	***Uninjured Group*** ***Mean ± SD (BW)***	***Significance*** ***(p value & ES)***	***% difference***
Prospective								
Davis *et al*., (2016) (subgroup)	RRI: 11, Control: 21 (♀)	2 years	O : 3.5m/s	Force plate (1080Hz)	1.7 ± 0.2	1.5 ± 0.2	P = 0.013* ES : Large	13.9%
Davis *et al*., (2016)	RRI: 144, Control: 105 (♀)	2 years	O : 3.5m/s	Force plate (1080Hz)	1.7 ± 0.3	1.7 ± 0.3	P = 0.883 ES : Small	0.6%
Gerlach *et al*., (2005)	RRI: 48, Control: 39 (♀)	1 year	O : 5km race pace	Instrumented treadmill (520Hz)	1.9 ± 0.1	1.9 ± 0.1	P = 0.84	-1.1%
Bredeweg *et al*., (2013)	RRI: 34, Control: 176	9 weeks	T : 2.5m/s	Instrumented treadmill (1000Hz)	1.3 ± 0.2	1.3 ± 0.2	P > 0.05	-3.7%
Messier *et al*., (2018)	RRI: 199, Control: 101	2 years	O : SS	Force plate (480Hz)	1.5 ± 0.3	1.5 ± 0.3	P = 0.74	-4.6%
Retrospective								
Bigouette *et al*., (2016)	CAI: 11, Control: 13	Symptomatic	T l: 3.3m/s	Instrumented treadmill (1200Hz)	2.1 ± 0.2 (Sym)	1.7 ± 0.2	P = 0.001*	21.0%
Grimston *et al*., (1991)	LLSF: 6, Control: 8 (♀)	N/R	O : 4.04m/s	Force plate (1000Hz)	2.1 ± 0.1 (Asym)	1.9 ± 0.1	P < 0.05*	13.0%
Hreljac *et al*., (2000)	Knee & LL: 20, Control: 20	> 3 months RTR	O : 4.0m/s	Force plate (480Hz)	2.4 ± 0.4 (Asym)	2.1 ± 0.4	P < 0.05*	12.7%
Milner *et al*., (2006)	TSF: 20, Control: 20 (♀)	35 ± 28 months	O : 3.7m/s	Force plate (960Hz)	1.8 ± 0.2 (Asym)	1.7 ± 0.3	P = 0.057	8.3%
Pohl *et al*., (2009)	PF: 20, Control: 20 (♀)	2.8 ± 2.4 years	O : 3.7m/s	Force plate (960Hz)	1.8 ± 0.3 (Asym)	1.7 ± 0.3	P = 0.093	8.3%
Azevedo *et al*., (2009)	AT: 21, Control: 21	Symptomatic	O : SS	Force plate (1000Hz)	1.5 ± 0.2 (Sym)	1.3 ± 0.2	P = 0.14	7.5%
McCrory *et al*., (1999)	AT: 31, Control: 58	Symptomatic	O : SS	Force plate (500Hz)	1.8 ± 0.1 (Sym)	1.7 ± 0.0	P > 0.05	4.6%
Esculier *et al*., (2016)	PFPS: 21, Control: 21	Symptomatic	T : SS	Instrumented treadmill (1000Hz)	3.0 ± 0.4 (Sym)	3.1 ± 0.3	P = 0.339	-3.1%
Crossley *et al*., (1999)	TSF: 23, Control: 23 (♂)	1.9 ± 1.3 years	O : 4.0m/s	Force plate (500Hz)	1.9 ± 0.39 (Asym)	2.0 ± 0.3	P > 0.05	-4.1%
Bischof *et al*., (2010)	MTSF: 9, Control: 15 (♀)	N/R	O : 3.3m/s	Force plate (1200Hz)	2.4 ± 0.2 (Asym)	2.5 ± 0.1	P > 0.05	-4.4%
Messier *et al*., (1995)	ITBS: 56, Control: 70	Symptomatic	O : SS	Force plate (500Hz)	1.6 ± 0.0 (Sym)	1.8 ± 0.0	P > 0.05	-6.2%
Bennell *et al*., (2004)	TSF: 13, Control: 23 (♀)	1.6 ± 1.0 years	O : 4.0m/s	Force plate (500Hz)	1.9 ± 0.3 (Asym)	2.1 ± 0.4	P = 0.32	-6.7%
Messier *et al*., (1991)	PFPS: 16, Control: 20	Symptomatic	O : SS	Force plate (500Hz)	1.7 ± 0.1 (Sym)	1.8 ± 0.1	P > 0.05	-7.9%
Baur *et al*., (2004)	Chronic AT: 8, Control: 14	Symptomatic	O : 3.33m/s	Force plate (N/R)	N/R (Sym)	N/R	P > 0.05	N/R
Duffey *et al*., (2000)	AKP: 99, Control: 70	Symptomatic	O : 3.35m/s	Force plate (500Hz)	1.7 ± 0.3 (Sym)	1.7 ± 0.0	P < 0.05*	-4.6%

Population: Population is mixed gender unless males (♂) or females (♀) are stated specifically.^^: Authors used accelerometery data to estimate vGRF; BW: body weight; RRI: running-related injury; TSF: tibial stress fracture; MTSF: metatarsal stress fracture; PF: plantar fasciitis; AT: Achilles tendinopathy; LLSF: lower limb stress fracture; AKP: anterior knee pain; SF: stress fracture; ITBS: iliotibial band syndrome; MTSS: medial tibial stress syndrome; Knee & LL: Injuries to the knee and lower limb below the knee; PFPS: patellofemoral pain syndrome; O: over-ground running; T: treadmill running; SS: self-selected pace; m/s: metres per second; (Asym): asymptomatic at time of testing; (Sym): symptomatic at time of testing; ES: effect size; N/R: not reported;* * Significance at p ≤ 0.05.

Looking specifically at VALR (Table 2.4.14), three prospective and six retrospective studies have investigated its relationship with RRI. Prospectively, only one study found significance where Davis *et al.*, (2016) reported that a sub-group of female runners who had sustained their first RRI to have significantly greater (29%) VALR compared to runners who had never been injured, with a large effect size (d = 1.42, p = 0.001). Retrospectively, four out of six studies found runners with a history of tibial stress fracture (Ferber *et al.*, 2002; Milner *et al.*, 2006), plantar fasciitis (Ribeiro *et al.*, 2015) and chronic ankle instability (Bigouette *et al.*, 2016) have significantly greater VALR than uninjured controls, with moderate to large effect sizes reported (d = 0.56 - 1.26, g = 1.49, $p < 0.05$). Differences between injured and uninjured groups ranged from 18.7% to 52.1% (Ferber *et al.*, 2002; Milner *et al.*, 2006; Ribeiro *et al.*, 2015; Bigouette *et al.*, 2016).

With respect to VILR (Table 2.4.15), seven prospective and ten retrospective studies have explored its relationship with RRI. Prospectively, two sub-group studies found VILR to be significantly greater in both male (Bredeweg *et al.*, 2013) and female runners (Davis, Bowser and Mullineaux, 2016) who sustained a RRI compared to runners who remained injury-free ($p < 0.05$), with differences of 20.5 - 31.4% between the injured and uninjured. Interestingly, before injured runners were divided into sub-groups for analysis by gender (Bredeweg *et al.*, 2013) or by never injured vs injured for the first time (Davis, Bowser and Mullineaux, 2016), no significant findings were reported ($p > 0.05$). Six prospective studies found no effect of VILR on RRI.

Retrospectively, there are mixed findings with four studies reporting VILR to be significantly greater (16.2 – 46%) in runners who had a history of tibial stress fracture (Ferber *et al.*, 2002; Milner *et al.*, 2006), plantar fasciitis (Pohl, Hamill and Davis, 2009) and RRIs to or below the knee (Hreljac, Marshall and Hume, 2000); five studies finding no effect and one study finding significantly lower (8.9%) VILR in runners who had been suffering with anterior knee pain (Duffey *et al.*, 2000) when compared with uninjured controls. Of note, the studies which reported significantly greater VILR had all tested subjects in an asymptomatic phase of injury whilst Duffey *et al.*, (2000) had tested subjects who were still symptomatic of anterior knee pain (Hreljac, Marshall and Hume, 2000; Ferber *et al.*, 2002; Milner *et al.*, 2006; Pohl, Hamill and Davis, 2009). Perhaps the findings of Duffey *et al.*, (2000) are in contrast to the results of the other studies as the subjects with ongoing anterior knee pain may have adapted a compensative running strategy due to pain, thus protecting themselves from high loading rates (Van Der Worp, Vrielink and Bredeweg, 2016). This may be supported by the findings of Messier *et al*., (1991) and McCrory *et al*., (1991) who had similar magnitudes for the uninjured participants, but the values for the injured runners were much lower for Duffey *et al*., (2000). Of note, three of the four studies finding significantly higher VILR in runners with a history of RRI had populations that were exclusively female (Ferber *et al.*, 2002; Milner *et al.*, 2006; Pohl, Hamill and Davis, 2009), and perhaps this reinforces previous findings that females tend to have poorer landing mechanics in comparison to males, and therefore are at an increased risk of injury (Sinclair and Selfe, 2015).

Table 2.4.14 Vertical average loading rate and RRI

Study	***Population****	***RRI Timeframe***	***Methods***	***Instrument & Sampling Rate***	***Injured Group Mean ± SD (BW/s)***	***Uninjured Group Mean ± SD (BW/s)***	***Significance (p value & ES)***	***% difference***
Prospective								
Davis *et al*., (2016) (subgroup)	RRI: 11, Control : 20 (♀)	2 years	O: 3.5m/s	Force plate (1080Hz)	78.2 ± 11.1	60.7 ± 12.8	P = 0.001* ES : Large	29%
Dudley *et al*., (2017)	RRI : 12, Control : 19	14 weeks	T : SS	Force plate (2400Hz)	68.3	58.1	P = 0.313 ES : Small	17.5%
Davis *et al*., (2016)	RR1: 144, Control : 105 (♀)	2 years	O : 3.5m/s	Force plate (1080Hz)	71.3 ± 18.7	73.6 ± 20.7	P = 0.357 ES : Small	-3.1%
Napier *et al*., (2018)	RRI: 22, Control : 33 (♀)	15 weeks	T : SS	Instrumented treadmill (2400Hz)	N/R	N/R	P > 0.05	N/R
Retrospective								
Ferber *et al*., (2002)	TSF:10, Control: 10 (♀)	No access	O: 3.5m/s	No access	117.9 ± 29.4 (Asym)	77.5 ± 29.4	P = 0.03*	52.1%
Ribeiro *et al*., (2015)	Chronic PF: 15, Control: 30	Symptomatic	O: 3.5m/s	N/R	64.4 ± 19.5 (Sym)	38.7 ± 9.7	P = 0.034* ES : Large	39%
Bigouette *et al*., (2016)	CAI: 11, Control: 13	Symptomatic	O: 3.5m/s	Instrumented treadmill (1200Hz)	93.8 ± 0.9 (Sym)	77.8 ± 10.0	P = 0.001* ES : Moderate	20.7%
Milner *et al*., (2006)	TSF: 20, Control: 20 (♀)	35 ± 28 months	O: 3.7m/s	Force plate (960Hz)	79.0 ± 25.0 (Asym)	66.3 ± 19.5	P = 0.041* ES : Moderate	19%
Ribeiro *et al*., (2015)	Acute PF: 30, Control: 30	Symptomatic	O: 3.5m/s	N/R	52.9 ± 13.9 (Sym)	38.7 ± 9.7	P = 0.001* ES : Moderate	18.7%
Esculier *et al*., (2016)	PFPS: 21, Control: 21	Symptomatic	T : SS	Instrumented treadmill (1000Hz)	68.0 ± 17.3 (Sym)	69.7 ± 21.8	P = 0.78	-2.4%
Popp *et al*., (2022)	BSI: 16, Control: 14 (♀)	Asymptomatic for 6 months	T : 2.7m/s	Instrumented treadmill (1500Hz)	83.0 (Asym)	88.2	P = 0.42	-5.9%

Population∗: Population is mixed gender unless males (♂) or females (♀) are stated specifically. BW/s: body weight per second; RRI: running-related injury; TSF: tibial stress fracture; PF: plantar fasciitis; CAI: chronic ankle instability; PFPS: patellofemoral pain syndrome; BSI: bone stress injury; O: over-ground running; T: treadmill running; SS: self-selected pace; m/s: metres per second; (Asym): asymptomatic at time of testing; (Sym): symptomatic at time of testing; ES: effect size; N/R: not reported; * Significance at $p \leq 0.05$

Table 2.4.15 Vertical instantaneous loading rate and RRI

Study	Population*	RRI Timeframe	Methods	Instrument & Sampling Rate	Injured Group Mean ± SD (BW/s)	Uninjured Group Mean ± SD (BW/s)	Significance (p value & ES)	% difference
Prospective								
Bredeweg *et al*., (2013) (subgroup)	RRI: 11, Control: 66 (♂)	9 weeks	T : 2.8m/s	Instrumented treadmill (1000Hz)	127.0 ± 39.7	96.7 ± 30.8	P < 0.05*	31.4%
Davis *et al*., (2016) (subgroup)	RRI: 11, Control: 20 (♀)	2 years	O : 3.5m/s	Force plate (1080Hz)	88.0 ± 13.9	73.1 ± 15.9	P = 0.01* ES : Large	20.5%
Dudley *et al*., (2017)	RRI: 12, Control: 19	14 weeks	T : SS	Force plate (2400Hz)	123.4	109.5	P = 0.24 ES : Small	13.1%
Gerlach *et al*., (2005)	RRI: 48, Control: 39 (♀)	1 year	O : 5km race pace	Instrumented treadmill (520Hz)	124.8 ± 5.8	117.4 ± 0.4	P = 0.46	6.3%
Bredeweg *et al*., (2013)	RRI: 34, Control: 176	9 weeks	T : 2.5m/s	Instrumented treadmill (1000Hz)	101.0 ± 28.4	96.3 ± 29.0	P > 0.05	5.2%
Davis *et al*., (2016)	RRI: 144, Control: 105 (♀)	2 years	O : 3.5m/s	Force plate (1080Hz)	81.1 ± 20.4	85.2 ± 22.7	P = 0.14 ES : Small	-4.8%
Kuhman *et al*., (2016)	RRI: 10, Control: 9	1 season	O : 4.0-4.5m/s	Force plate (1200Hz)	93.5 ± 30.3	100.3 ± 19.9	P = 0.65 ES : Small	-6.8%
Napier *et al*., (2018)	RRI: 22, Control: 33 (♀)	15 weeks	T : SS	Instrumented treadmill (2400Hz)	N/R	N/R	P > 0.05	N/R
Retrospective								
Ferber *et al*., (2002)	TSF: 10, Control: 10 (♀)	No access	O : 3.5m/s	No access	158.6 ± 41.8 (Asym)	108.9 ± 41.8	P = 0.03*	46.0%
Hreljac *et al*., (2000)	Knee & LL: 20, Control: 20	> 3 months RTR	O : 4.0m/s	Force plate (480Hz)	93.1 ± 23.8 (Asym)	76.6 ± 19.5	P = 0.00*	21.5%
Pohl *et al*., (2009)	PF: 25, Control: 25 (♀)	2.8 ± 2.4 years	O : 3.7m/s	Force plate (960Hz)	100.5 ± 36.0 (Asym)	82.9 ± 18.7	P = 0.04* ES : Small	21.2%
Milner *et al*., (2006)	TSF: 20, Control: 20 (♀)	35 ± 28 months	O : 3.7m/s	Force plate (960Hz)	92.6 ± 24.7 (Asym)	79.7 ± 18.8	P = 0.036* ES : Moderate	16.2%
Messier *et al*., (1991)	PFPS: 16, Control: 20	Symptomatic	O : SS	Force plate (500Hz)	56.5 ± 4.5 (Sym)	53.9 ± 3.1	P > 0.05	4.8%
Azevedo *et al*., (2009)	AT: 21, Control: 21	Symptomatic	O : SS	Force plate (1000Hz)	44.8 ± 11.3 (Sym)	42.9 ± 9.3	P = 0.58	4.5%
McCrory *et al*., (1999)	AT: 31, Control: 58	Symptomatic	O : SS	Force plate (500Hz)	55.5 ± 2.7 (Sym)	54.9 ± 1.7	P > 0.05	1.1%
Esculier *et al*., (2016)	PFPS: 21, Control: 21	Symptomatic	T : SS	Instrumented treadmill (1000Hz)	81.4 ± 15.0 (Sym)	83.1 ± 15.1	P = 0.72	-2%
Popp *et al*., (2022)	BSI: 16, Control: 14 (♀)	Asymptomatic for 6 months	T : 2.7m/s	Instrumented treadmill (1500Hz)	96.1 (Asym)	104.9	P = 54	-8.4%
Duffey *et al*., (2000)	AKP: 99, Control: 70	Symptomatic	O : SS	Force plate (500Hz)	50.0 ± 1.7 (Sym)	54.9 ± 1.8	P < 0.05*	-8.9%

Population: Population is mixed gender unless males (♂) or females (♀) are stated specifically. BW/s: body weight per second; RRI: running-related injury; TSF: tibial stress fracture; PF: plantar fasciitis; AT: Achilles tendinopathy; AKP: anterior knee pain; Knee & LL: Injuries to the knee and lower limb below the knee; PFPS: patellofemoral pain syndrome; BSI: bone stress injury; O: over-ground running; T: treadmill running; SS: self-selected pace; m/s: metres per second; (Asym): asymptomatic at time of testing; (Sym): symptomatic at time of testing; ES: effect size;* > 3 months RTR *: runner had returned to running at least 3 months before testing; N/R: not reported;* * Significance at p ≤ 0.05

In summary, it appears that vertical average loading rate (VALR) and vertical instantaneous loading rate (VILR) have the strongest relationship with RRI, particularly with respect to stress fractures and plantar fasciitis, with larger rates of loading being associated with these types of injury. Prospectively, there has been few significant findings and this may be due to the fact that prospective studies have looked at RRIs collectively, potentially masking the more localized relationship that loading rates may have with specific types and regions of RRI, such as stress fractures and plantar fasciitis. VIP does not seem to have a strong relationship with RRI. Future directions for kinetic research should aim to study large populations prospectively. Initially, RRIs should be studied collectively, before delving deeper into the analysis of sub-groups based on gender, location of RRI and type of RRI. In addition to this, a largely under-studied area is the analysis of kinetics in the never injured and injured for the first time running populations. It was only when Davis et al., (2016) did a more in-depth analysis of their injured and un-injured group, that significant differences were identified, highlighting the need to thoroughly explore our never injured population. This sub-group of runners may provide a valuable adjunct to our understanding of why some runners get injured whilst others remain injury-free.

2.4.3.2 Acceleration and injury

Although vertical ground reaction force (vGRF) and loading rates (vertical average loading rate and vertical instantaneous loading rate) in particular have been shown by some studies to have links with RRIs (Van Der Worp, Vrielink and Bredeweg, 2016), the use of vGRF may not be sensitive enough to identify risk factors at a segmental level as vGRF represent a gross measure of loading on the body as a whole. More recently, wearable accelerometer sensors have received support as an estimate of localised loading during gait analysis (Sheerin, Reid and Besier, 2019), as it has the ability to give tri-axial acceleration components, and therefore can quantify very specific loading values for body segment accelerations that occur during movement. With accelerometers being a low cost, light weight, and user friendly alternative to force plates and instrumented treadmills, their use in RRI research has increased greatly in the past decade (Norris, Kenny and Anderson, 2016).

Tibial acceleration in particular has been the most popular focus of segmental load analysis to date when exploring the relationship between impact acceleration and RRIs, and these studies have been summarised in Table 2.4.16. To date, there has been only one prospective study[1] (Winter *et al.*, 2020) examining the relationship between peak axial impact acceleration ($Peak_{accel}$) and RRI. While two prospective studies have been published as abstracts from conference proceedings (Bowser, Hamill and Davis, 2010; Davis, Bowser and Mullineaux, 2010), these studies will not be included in this review as they have not been through a rigorous peer review process and they do not provide sufficient detail for inclusion in this literature review. Winter *et al*., (2020) found no significant differences in sacral $Peak_{accel}$ between runners who sustained a RRI and those who remained injury free within the 12 month prospective analysis (Table 2.4.16). Six retrospective studies have explored the relationship between $Peak_{accel}$ and RRI, with two studies finding tibial $Peak_{accel}$ to be significantly greater (22.0 – 32.8%) in female runners with a history of stress fracture compared to controls ($p < 0.05$) (Ferber *et al.*, 2002; Milner *et al.*, 2006). Although Zifchock *et al*., (2006) and (2008) did not find significant differences between injured and uninjured runners, a sub-group analysis of the involved and uninvolved limbs of the injured groups found runners with a history of tibial stress fracture and general overuse RRIs to have significantly greater tibial $Peak_{accel}$ in their injured limb compared to the uninjured limb ($p < 0.05$). Runners who had a history of RRI had a 14.6 % difference between limbs, with this

[1] With full publications.

demonstrating a moderate effect size (d = 0.59) (Zifchock *et al.*, 2008), whilst runners with a history of tibial stress fracture having a difference of 15.8% between limbs (Zifchock, Davis and Hamill, 2006).

In summary, it appears that female runners with a history of stress fracture may demonstrate greater $Peak_{accel}$ when compared to healthy controls (Ferber *et al.*, 2002; Milner *et al.*, 2006). Additionally, runners with a history of injury also tend to have greater $Peak_{accel}$ in their affected side post injury (Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008). However, as the research is largely limited to retrospective analysis to date, we are unable to determine if $Peak_{accel}$ is the cause of injury or an effect of injury in these cases. There is quite clearly a lack of research in this area, particularly prospective studies and studies looking at the $Peak_{accel}$ of multiple segments and RRIs. To date, only two studies were found to have explored $Peak_{accel}$ at the sacrum (Schütte *et al.*, 2018; Winter *et al.*, 2020), with all other studies reviewed looking solely at the tibia. Given that hip and lower back injuries account for up to 27% of all RRIs in recreational shod runners (Altman and Davis, 2016), the exploration of impact acceleration at this region may provide an insight into the potential overload being experienced at this site and thus broaden our understanding of the aetiology of hip and lower back injuries in this population. Further studies should strive to explore the differences between injured and uninjured limbs, as well as the differences in $Peak_{accel}$ between injured runners and runners who have never sustained a RRI. Interestingly, despite the rate of vGRF loading being more related to RRI than peak vGRF (Section 2.4.3.1) the relationship between the rate of impact acceleration and RRI does not appear to have been examined. This may provide a further valuable insight into RRIs when assessed at a segmental level.

If such injury-related research is to be realised, it is essential to know how consistent (reliable) impact acceleration measures from the tibia and the sacrum are over short- and long-term time frames. If impact accelerations taken at baseline remain consistent over the course of a prospective trial, then only baseline assessment would be required, thereby reducing cost and participant recruitment challenges. However, if impact accelerations change over time, for example due to natural changes in technique or changes in trained status, then there will be a need for more frequent assessment up to the point of injury. Currently, there is a scarcity of research on the reliability of such accelerometer devices

(Sheerin *et al.*, 2018), especially in relation to both the sacrum and the rate of acceleration, highlighting the need for further research in this area.

Table 2.4.16 Studies investigating peak positive acceleration and RRI.

Study	***Population****	***RRI Timeframe***	***Methods***	***Accelerometer Position & Sampling Rate***	***Injured Group Mean ± SD***	***Uninjured Group Mean ± SD***	***Significance (p value & ES)***	***% difference***
Prospective								
Winter *et al.*, (2020)	RRI: 39, Control: 37	12 months	O : 3.6m/s	Sacrum (250Hz)	4.2 ± 0.8g (Asym)	4.3 ± 1.1g	p > 0.05	2.4%
Retrospective								
Milner *et al., (*2006)	TSF: 20, Control: 20 (♀)	35 ± 28 months	O : 3.7m/s	Tibia (960Hz)	7.7 ± 3.2g (Asym)	5.8 ± 1.7g	p = 0.014* ES: Moderate	32.8%
Ferber *et al., (*2002)	SF: 10, Control: 10 (♀)	SF	O : 3.7m/s	Tibia (N/R)	9.3g (Asym)	7.2g	p = 0.05*	22.0%
Schutte *et al., (*2018)	MTSS: 14, Control: 16	N/R	OT: 3.2km fatiguing run	Tibia & Sacrum (1024Hz)	2.2 ± 1.0g Sacrum (Asym) 6.6 ± 1.2g Tibia (Asym)	2.0 ± 1.2g Sacrum 6.4 ± 1.5g Tibia	p = 0.24 ES: Moderate P = 0.14 ES: Moderate	Trunk 10% Tibia 3.1%
Zifchock *et al., (*2006)	TSF: 24, Control: 25 (♀)	N/R	O : 3.7m/s	Tibia (960Hz)	N/R (Asym)	N/R	p = 0.70	N/R
Zifchock *et al., (*2008)	RRI: 20, Control: 20	> 4 months RTR	O : 3.7m/s	Tibia (1080Hz)	5.1 ± 1.7g (Asym)	5.2 ± 2.4g	p = 0.20 ES: Small	-1.9%
Popp *et al.*, (2022)	BSI: 16, Control: 14 (♀)	Asymptomatic for 6 months	T : 2.7m/s	Tibia (1000Hz)	11.8g (Asym)	12.8g	P = 0.51	-7.8%
Injured group sub-analysis -								
Retrospective								
					Involved Limb Mean ± SD	***Uninvolved Limb Mean ± SD***		
Zifchock *et al., (*2006)	TSF: 24, Control: 25 (♀)	N/R	O : 3.7m/s	Tibia (960Hz)	N/R (Asym)	N/R	P = 0.02*	15.8%
Zifchock *et al., (*2008)	RRI: 20, Control: 20	> 4 months RTR	O : 3.7m/s	Tibia (1080Hz)	5.5 ± 2.2g (Asym)	4.8 ± 1.6g	P = 0.05* ES: Moderate	14.6%

Population: Population is mixed gender unless males (♂) or females (♀) are stated specifically.*

*TSF: tibia stress fracture; MTSS: medial tibial stress syndrome; SF: stress fracture of the lower extremity; RRI: running-related injuries collectively; O: over-ground run in laboratory; OT: outdoor track run; > 4 months RTR: returned to running at least 4 months before testing; PPA: peak positive acceleration; m/s: metres per second; (Asym): asymptomatic at time of testing; g: g-force; ES: Effect size; N/R: not reported; * Significance at p ≤ 0.05.*

2.4.4 Technique and injury

The following section will review the relationship between running technique and RRIs, with a specific focus on foot, knee, hip, pelvis and trunk kinematics. A brief description of normal kinematics during rearfoot strike running will be provided at the beginning of each subsection, before the relationship with injury is discussed. References will be made to Figure 2.4.6 where relevant.

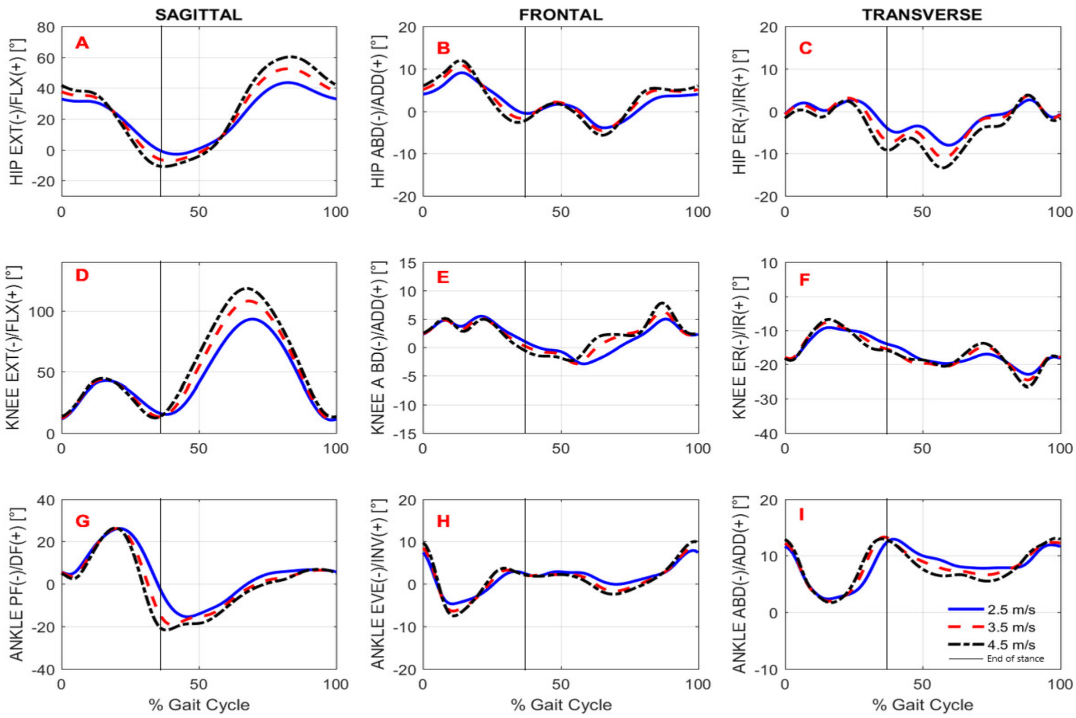

Figure 2.4.6 Joint angles of the lower limb during the running gait cycle.

Joint angles are shown in the sagittal, frontal and transverse planes for the hip, knee and ankle joints at 2.5m/s (blue line), 3.5m/s (broken red line) and 4.5m/s (broken black line). EXT: Extension, FLX: Flexion, ADD: Adduction, ABD: Abduction, IR: Internal rotation, ER: External rotation, °: degrees, m/s: metres per second. Adapted from Fukuchi et al. (2017).

2.4.4.1 Foot strike and injury

Within the foot and ankle, the talocrural joint allows movement in the sagittal plane through plantarflexion and dorsiflexion, while the subtalar joint allows frontal plane movement through inversion and eversion. Within the transverse plane, abduction and adduction occur. There are three general categories of foot strike: rear-foot strike (RFS), in which the heel is the first point of contact, mid-foot strike (MFS), in which there is a simultaneous landing of the heel and the ball of the foot, and fore-foot strike (FFS), in which the ball of the foot contacts the ground before the heel (Daoud *et al.*, 2012). For RFS, at

initial contact, it has been reported that the talocrural joint moves from approximately 5 degrees of plantarflexion or neutral to about 10 degrees of dorsiflexion as the heel approaches the ground (Loudon, Manske and Reiman, 2013). The foot then goes from a slightly supinated position at ground contact to a pronated position, assisting in shock absorption (Dugan and Bhat, 2005). The subsequent propulsive mechanism occurs through the latter stance phase, which ensues with external tibial rotation and subtalar joint supination (Dugan and Bhat, 2005). Momentum then carries the body forward causing the heel to lift and consequently the foot moves into a plantarflexed position. Once the heel is off the ground, supination of the mid and forefoot creates a rigid lever of the stance leg and allows for efficient propulsion of the body in a forward motion. The foot then reaches an approximate angle of 25 degrees of plantarflexion at toe-off (Figure 2.4.6).

As the foot is the first point of ground contact during landing, the strike technique can influence both the kinetics and kinematics experienced by the runner (Goss and Gross, 2012). To date, multiple studies have investigated foot strike amongst elite, recreational and military runners, with RFS being the most common (mean = 71%, range = 31-95%), followed by MFS (mean = 17%, range = 0-43%) and FFS (mean = 16%, range = 1-31%) (Table 2.4.17). For recreational runners alone the RFS pattern is also by far the most common (RFS mean = 68%, range = 31 – 95%). The conflicting percentages and broad ranges may be due to contrasting technologies used in foot strike analysis (Hasegawa *et al.*, 2007; Larson *et al.*, 2011; Daoud *et al.*, 2012; Goss, 2012; Mann *et al.*, 2015; Warr *et al.*, 2015; Paquette, Milner and Melcher, 2017). It is unclear if foot strike technique differs between males and females, years of running experience or between middle and long distance runners. Although one study has found no difference between gender (Larson *et al.*, 2011), and one study found no difference between middle or long distance runners (Daoud *et al.*, 2012) in terms of foot strike pattern, more studies are needed to confirm if these factors may influence foot strike technique. Some authors do suggest that the type of shoe worn or not worn (cushioned vs minimalist vs barefoot) may have an effect on foot strike technique, and this should be taken into account when comparing various foot strike techniques across running populations (Portefaix and Simon, 2016). It is thought that barefoot runners and runners who wear minimalist footwear often land with a forefoot strike pattern, but may sometimes land with a flat mid-foot strike pattern too. In contrast, runners who wear cushioned shoes often land with a rearfoot strike pattern (Portefaix and Simon, 2016).

Table 2.4.17 Foot strike pattern predominance in running.

Study	***Population****	***Methods***	***Classification***	***Surface***	***RFS***	***MFS***	***FFS***	***Non-RFS***
Fukusawa *et al*., (2020)	122 Recreational runners	2D visual observation: film rate 300Hz. 10 foot strikes.	RFS: Heel clearly makes IC. Non-RFS: Ball of foot at IC or, heel and ball of foot contact simultaneously.	Overground	95.2%			4.8%
Mann *et al.,* (2015)	40 Recreational runners (♂)	Pressure-sensitive insoles: acquired at 247Hz. ~161 foot strikes.	Strike index	Treadmill	93.3%			6.7%
Larson *et al.,* (2010)	286 Recreational runners	2D visual observation: film rate 300Hz.	RFS: Heel or rear third IC. MFS: Midfoot or entire sole IC. FFS: Forefoot or front half of sole IC.	Overground	89.9%	3.4%	1.8%	
Warr *et al.,* (2015)	341 Military recruits (♂)	2D visual observation: HD film rate 30Hz. 2 foot strikes.	RFS: Heel clearly makes IC. Non-RFS: Ball of foot at IC or, heel and ball of foot contact simultaneously.	Overground	87.0%			13.0%
Hasegawa *et al.,* (2007)	283 Elite runners	2D visual observation: $250s^{-1}$ shutter speed, film rate 120Hz.	RFS: Heel or rear third IC. MFS: Midfoot or entire sole IC. FFS: Forefoot or front half of sole IC.	Overground	74.9%	23.7%	1.4%	
Hollander *et al*., (2020)	550 Recreational runners	2D visual observation: film rate 125Hz. 10 foot strikes.	RFS: Heel contacts the ground first. MFS: Heel and ball contact simultaneously. FFS: Ball of foot contacts first.	Treadmill	71.0%	10.0%	19.0%	
Daoud *et al.,* (2012)	52 Cross country runners	2D visual observation: film rate 500Hz. 3 foot strikes.	RFS: Positive plantar angle at IC. MFS: Simultaneous landing of heel and ball of foot at IC. FFS: Negative plantar angle at IC.	Treadmill (n=31), Overground (n=28), Both (n=7)	69.0%	0.0%	31.0%	
Sugimoto *et al*., (2019)	70 Recreational runners	2D visual observation: film rate 300Hz.	RFS: Heel contacts the ground first. MFS: Heel and ball contact simultaneously. FFS: Ball of foot contacts first.	Treadmill	59.0%	20.0%	21.0%	

Paquette *et al.,* (2017)	44 Recreational runners	3D motion analysis: film rate 240Hz. 5 consecutive foot strikes.	RFS: FCA >8°. Non-RFS: FCA <8°.	Treadmill	36.0%			64.0%
Goss e*t al*., (2012)	904 Recreational runners	Self-report via survey.	Not reported.	N/A	31.0%	43.0%	20.0%	
					RFS	MFS	FFS	Non-RFS
Average					*70.6%*	*16.7%*	*15.7%*	*22.1%*
Range					*31.0-95.2%*	*0.0-43.0%*	*1.4-31.0%*	*4.8-64.0%*

Population∗: Population is mixed gender unless males (♂) or females (♀) are stated specifically.
RFS: Rear-foot strike; MFS: Mid-foot strike; FFS: Fore-foot strike; Non-RFS: non rearfoot strike; FCA: Foot contact angle; IC: Initial contact; n: number; N/A: Not applicable.

As aforementioned, one of the main reasons for exploring foot strike pattern is to understand how the foot contact inherently affects the kinematics and kinetics of the whole lower extremity (Goss and Gross, 2012). Kinematically, a RFS runner will typically land with a somewhat extended knee and with an inverted, abducted and dorsiflexed ankle. This pattern can place high demands on the knee extensors which must act eccentrically to attenuate the resulting vGRF, with RFS exhibiting up to 12% greater extensor moments than their FFS counterparts (Kulmala *et al.*, 2013). Increased knee extensor activation may then heighten tibio-femoral joint loading as well as almost 16% greater patellofemoral compression forces (Goss, 2012; Kulmala *et al.*, 2013). In contrast to this, FFS runners will typically land with a more flexed knee and plantarflexed ankle, increasing the load by as much as 19% on the plantarflexor muscles and Achilles tendon (Goss, 2012; Kulmala *et al.*, 2013; Hamill and Gruber, 2017). MFS kinematics are generally intermediate of RFS and FFS patterns (Daoud *et al.*, 2012). Kinetically, a review paper by Hamill and Gruber (2017) stated that a RFS pattern appears to result in both impact and passive peaks being visible in the vGRF component, while the impact peak is substantially diminished or visually obscured by the active peak with MFS and FFS patterns (Figure 2.4.5). Although it has been speculated that reducing these impact peaks may help in preventing RRIs, there is not enough conclusive evidence to confirm that impact peaks cause injury (Section 2.4.3.1), and for this reason, it is difficult to determine the optimal foot-strike pattern for injury resilience.

To date, three prospective (Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Messier *et al.*, 2018) and ten retrospective (Donoghue *et al.*, 2008; Daoud *et al.*, 2012; Goss and Gross, 2012; Mann *et al.*, 2015; Warr *et al.*, 2015; Paquette, Milner and Melcher, 2017; Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020) studies have investigated the relationship between foot strike technique at initial contact and the incidence of RRIs (Table 2.4.18), with the findings suggesting very low evidence of a relationship. Prospectively, despite all three studies employing 3D motion analysis methodologies, none of the authors classified runners into foot strike pattern groups. Instead, continuous measures of foot strike technique were compared via foot strike index values (Kuhman *et al.*, 2016b; Messier *et al.*, 2018) and foot contact angle values (Dudley *et al.*, 2017) between injured and uninjured runners, through which no significant differences were found. Retrospectively, five of thirteen studies reported significant findings with Goss (2012), Daoud (2012) and Sugimoto *et al.*, (2019) finding RFS runners to have greater previous RRI incidence rates than MFS and FFS runners. Goss (2012) reported that RFS recreational runners had a significantly ($p < 0.001$) higher injury incidence (52.4%) compared to MFS (34.7%) and FFS runners (22.8%) (Goss and Gross, 2012), whilst Sugimoto *et al*., (2019) found 74% of runners with a history of hamstring injury to have demonstrated a RFS pattern and 43% of runners with no history of injury to use a RFS pattern ($p < 0.05$). Similarly, Daoud (2012) found RFS collegiate cross country runners to have had more than twice the injury rate of FFS runners (RFS: 8.15 RRIs per 10,000km, FFS: 3.28 RRIs per 10,000km, $p < 0.05$) (Daoud *et al.*, 2012). Authors speculated that this higher incidence rate in RFS runners was due to the rate and magnitude of initial impact peaks that are seen in rearfoot strikers, but are not as evident in forefoot strikers, or that occur later in the vGRF time domain (Daoud *et al.*, 2012) (Figure 2.4.5). However, none of the authors mentioned above measured vGRF, and so they cannot definitively say that this was the reason for the differences reported.

In contrast, one study found Achilles tendon injuries to be 2.3 times greater in MFS runners compared to RFS and FFS runners, and posterior shank injuries to be 2.6 times greater in FFS runners compared to RFS and MFS runners ($p < 0.05$). Another study found significantly lower foot contact angles (injured: 6.8° vs uninjured: 9.7°) in runners who had current running-related knee injuries compared to uninjured controls ($p < 0.05$) (Dingenen *et al.*, 2019). Caution should be taken when acknowledging these results as the studies are limited by a retrospective study design (Daoud *et al.*, 2012; Goss and Gross, 2012; Sugimoto *et al.*, 2019; Hollander *et al.*, 2020), low subject numbers of a homogenous population (Daoud *et al.*, 2012; Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019), and methodological foot strike categorisation limitations (Goss and Gross, 2012).

As part of this thesis, a full systematic review has been completed and published in the area of foot strike technique and RRIs, concluding that there is low level evidence for a relationship (*Appendix A*). A variation in foot strike defining methodologies, injury definitions and categorisations, as well as large variations in participant subgroup numbers compounds the inconclusive nature of results across the literature (Daoud *et al.*, 2012; Goss and Gross, 2012; Mann *et al.*, 2015; Warr *et al.*, 2015; Paquette, Milner and Melcher, 2017). This highlights the need for further large-scale prospective studies to be conducted, which utilizes a standardised, validated and reliable method of foot strike pattern determination.

Table 2.4.18 The relationship between foot strike technique and RRI.

Study	***Variable***	***Population****	***RRI Timeframe***	***Methods***	***Instrumentation & Sampling Rate***	***Significance & Effect Size***	***Significant Findings***
Prospective							
Continuous Measures							
Messier *et al.,* (2018)	SI	RRI: 300, Control: 101	2 years	O : SS	3D (200Hz) FP (480Hz)	P = 0.44	N/A
Kuhman *et al.,* (2016)	SI	RRI: 10, Control: 9	3 months	O : 4.5m/s ♂ O : 4.0m/s ♀	3D (240Hz) FP (480Hz)	P = 0.64	N/A
Dudley *et al.,* (2017)	FCA	RRI: 12, Control: 20	14 weeks	O : SS	3D (240Hz) FP (2400Hz)	P = 0.94	N/A
Retrospective							
Continuous Measures							
Donoghue *et al*., (2008)	AFA	AT: 11, Control: 11	1 year	T : SS	3D (200Hz)	P > 0.05	N/A
Paquette *et al.,* (2017)	FCA	RRI: 23, Control: 21	1 year	T : 75% 10km pace	3D (240Hz)	P = 0.66	N/A
Dingenan et al., (2019)	FCA	Knee injury (S): 18, Control: 24	2 years	T : SS	2D (120Hz)	P = 0.031*	Greater foot inclination angle in uninjured runners (9.8°) compared to injured runners (6.8°)
Categorical Measures							
Goss *et al.,* (2012)	FSP	RRI: 369, Control: 352	1 year	Survey	Self-report Survey	P < 0.001*	RFS IIR : 52.4% MFS IIR : 34.7% FFS IIR : 22.8%
Daoud *et al.,* (2012)	FSP	RRI: 44, No Control Group (RFS: 69%, FFS: 31%)	9 months	T : 3.0 – 5.0m/s OT : SS	2D (500Hz)	P < 0.05*	RFS: 8.15 RRIs per 10,000km FFS: 3.28 RRIs per 10,000km
Sugimoto *et al*., (2019)	FSP	Hamstring RRI: 35, Control: 35	N/R	T : 1.8 – 2.2m/s	2D (300Hz)	P = 0.004*	74% of runners with hamstring injuries demonstrated a RFS pattern, vs 43% RFS in healthy controls

Mann *et al.,* (2015)	FSP	RRI: 44, Control: 46	1 year	T : 80 – 120% SS	Pressure-sensitive insoles (247Hz)	P = 0.21	N/A
Warr *et al.,* (2015)	FSP	RRI: 194, Control: 147	Lifetime	O : SS	2D (50Hz)	P = 0.51	N/A
Fukusawa *et al*., (2020)	FSP	AKP: 60, Control: 62	3 months	O : SS	2D (300Hz)	P > 0.05	N/A
Hollander *et al*., (2020)	FSP	RRI: 550, No Control Group	7 years	T : SS	2D (125Hz)	P = 0.04* P = 0.004*	Runners with a MFS pattern were at 2.27 times greater odds of sustaining an Achilles tendon injury Runners with a FFS pattern were at 2.6 times greater odds of sustaining a posterior shank injury

Population∗: Population is mixed gender unless males (♂) or females (♀) are stated specifically.
AT: Achilles tendinopathy; (S): symptomatic knee injury at time of testing; AKP: anterior knee pain; SI: strike index; FCA: foot contact angle; AFA: ankle flexion angle; FSP: foot-strike patterns; O: over-ground run in a laboratory; T: treadmill run; OT: outdoor track run; SS: self-selected speed; 3D: 3D motion capture analysis; FP: force-plate analysis; m/s: metres per second; RFS: Rear-foot strike; MFS: Mid-foot strike; FFS: Fore-foot strike; RRI: running related injury; IIR: injury incidence rate in previous 12 months; N/R: not reported; N/A: not applicable

2.4.4.2 Knee kinematics and injury

During the initial contact phase, the knee is flexed between 15 and 25 degrees (Buczek and Cavanagh, 1990; Dugan and Bhat, 2005). Although some studies report differing contact angles for the knee (Derrick, Dereu and McLean, 2002; Kulmala *et al.*, 2013), Novacheck (1998) documented that increased knee flexion at foot strike is essential in assisting with shock attenuation. Following on to the mid-stance phase, the knee reaches approximately 38-45 degrees of flexion (Pink *et al.*, 1994; Novacheck, 1998). As the body's centre of mass translates forward over the stance limb, the knee begins to straighten and reaches 13 degrees of flexion at toe-off (Pink *et al.*, 1994). This action of knee extension helps to propel the body forwards into the float phase. Researchers have hypothesized that movements occurring in the sagittal, frontal and transverse planes at the knee joint may have profound effects on landing strategies at ground contact, potentially contributing to RRIs (Ireland *et al.*, 2003; Lee, Morris and Csintalan, 2003a; Powers, 2003a). Whilst peak angles and initial contact angles have been explored in the sagittal plane, only peak angles have been investigated in the frontal and transverse planes. Studies exploring knee kinematics and RRIs are summarized in Table 2.4.19.

With reference to the sagittal plane, knee flexion has been an area of interest with knee flexion angles calculated from full extension, with lesser flexion angles demonstrating a knee that is closer to extension (Figure 2.4.7). Only one prospective (Noehren, Davis and Hamill, 2007) and four retrospective (Milner, Hamill and Davis, 2007; Bramah *et al.*, 2018, 2021; Luginick *et al.*, 2018) studies have analysed knee flexion angles at initial contact, with Bramah *et al*., (2018) and Luginick *et al*., (2018) finding significantly lesser knee flexion angles (3.2 – 4.2°) at foot-strike in runners who had retrospectively sustained a RRI compared to their uninjured counterparts. It has been speculated that landing with a more extended knee may lead to greater impact forces and compression at the patellofemoral joint, which may help with explaining why Bramah *et al*., (2018) noted significantly lesser knee flexion angles at contact in injured runners (Powers, 2000; Derrick, 2004; Wille *et al.*, 2014).

Studies exploring the relationship between RRI and knee flexion are more plentiful when investigating the peak values of knee flexion, rather the initial contact values, with two prospective studies (Hein *et al.*, 2014; Messier *et al.*, 2018) and ten retrospective studies evident to date (Azevedo *et al.*, 2009; Ferber *et al.*, 2010; Grau *et al.*, 2011; Loudon and Reiman, 2012; Wirtz *et al.*, 2012; Bazett-jones *et al.*, 2013; Bramah *et al.*, 2018, 2021; Luginick *et al.*, 2018; Haghighat *et al.*, 2021). It would appear that there is little to no relationship between RRI and peak knee flexion as no significant differences were reported between injured and uninjured runners in both prospective studies (Hein *et al.*, 2014; Messier *et al.*, 2018). There are limited findings retrospectively, with only two studies reporting statistically significant findings (Loudon and Reiman, 2012; Luginick *et al.*, 2018). These studies found runners who had a history of medial shin pain and iliotibial band syndrome to demonstrate peak knee flexion that was 6-10% greater than in controls. It has been thought that having less peak knee flexion may lead to lesser shock attenuations by the runner, and this may be a precursor to RRI (Souza, 2016).

One final variable of knee flexion which has been investigated with respect to RRI is knee flexion excursion. This is the difference between peak and initial contact values. Only one study has looked at this prospectively, finding no difference between runners who sustained an Achilles tendon injury and those who remained injury-free (Hein *et al.*, 2014). Retrospectively, only one of three studies found significance, where Azevedo *et al.*, (2009) found runners who had Achilles tendon injuries to have 16.5% lesser excursions than controls. It is thought that greater knee flexion excursions help reduce peak vertical forces of the lower limb by increasing the time by which the velocity of the centre of mass is brought to zero (Milner, Hamill and Davis, 2007).

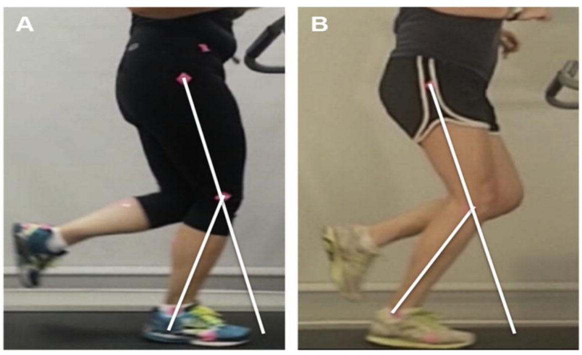

Figure 2.4.7 Knee Flexion Angle Calculation (Souza, 2016).

A demonstrates a lesser flexion angle, while B demonstrates greater flexion angle.

Table 2.4.19 The relationship between knee kinematics and RRIs.

Study	***Population∗***	***RRI Timeframe***	***Injured Group: Mean ± SD***	***Uninjured Group: Mean ± SD***	***Significance***	***Absolute difference***
Knee Flexion at IC						
Prospective						
Noehren *et al*., (2007)	ITBS:18, Control: 18 (♀)	2 years	11.8 ± 4.8° (Asym)	14.4 ± 6.0°	P = 0.18	-2.6°
Retrospective						
Milner *et al*., (2007)	TSF: 23, Control: 23 (♀)	N/R	13.7 ± 6.0° (Asym)	11.9 ± 6.5°	P = 0.35 ES: Small	1.8°
Bramah *et al*., (2021)	CMSI: 15, Control: 15	12 months	5.4 ± 5.2° (Asym)	6.3 ± 5.4°	P = 0.17	-0.9°
Luiginick *et al*., (2018)	ITBS: 30, Control: 30	N/R	15.0 ± 4.8° (Sym)	18.2 ± 4.3°	P < 0.05* ES: Medium	-3.2°
Bramah *et al*., (2018)	RRI: 72, Control: 36	Symptomatic	6.0 ± 4.9° (Sym)	10.2 ± 4.8°	P < 0.01* ES: Large	-4.2°
Peak Knee Flexion						
Prospective						
Messier *et al*., (2018)	RRI: 199, Control: 101	2 years	40.0 ± 5.3° (Asym)	40.1 ± 4.7°	P = 0.82	-0.1°
Hein *et al*., (2014)	AT: 10, Control: 10	1 year	37.0 ± 7.0° (Asym)	41.0 ± 4.0°	N/R	-4.0°
Retrospective						
Wirtz *et al*., (2012)	PFPS: 20, Control: 20 (♀)	Symptomatic	43.9 ± 5.0° (Sym)	41.8 ± 4.1°	P = 0.16 ES: Moderate	2.1°
Grau *et al*., (2011)	ITBS: 18, Control: 18	Symptomatic	38.0 ± 4.0° (Sym)	37.0 ± 7.0°	P > 0.05	1.0°
Bramah *et al*., (2021)	CMSI: 15, Control: 15	12 months	33.4 ± 5.1° (Asym)	33.0 ± 2.8°	P = 0.09	0.4°
Ferber *et al*., (2010)	ITBS: 35, Control: 35 (♀)	N/R	45.3 ± 4.5° (Asym)	45.2 ± 5.0°	P = 0.95	0.1°
Bramah *et al*., (2018)	RRI: 72, Control: 36	Symptomatic	32.3 ± 5.0° (Sym)	32.7 ± 4.9°	P = 0.56 ES: Small	-0.4°
Azevedo *et al.,* (2009)	AT: 21, Control: 21	Symptomatic	42.2 ± 4.8° (Sym)	42.8 ± 8.6°	P = 0.80	-0.6°
Haghighat *et al*., 2021	PFPS: 17, Control: 17 (♀)	Symptomatic	40.2 ± 4.7° (Asym)	41.4 ± 4.9°	P = 0.52	-1.2°
Luiginick *et al*., (2018)	ITBS: 30, Control: 30	N/R	45.0 ± 4.5° (Sym)	48.0 ± 4.9°	P < 0.05* ES: Large	-3.0°
Loudon *et al*., (2012)	MSP: 14, Control: 14	2 years	37.1 ± 5.4° (Asym)	42.1 ± 4.8°	P = 0.02*	-5.0°
Bazett-Jones *et al.,* (2013)	PFPS:19, Control: 19	Symptomatic	41.6 ± 5.4° (Sym)	54.1 ± 4.8°	P > 0.05	-12.5°
Knee Flexion Excursion						

Prospective						
Hein *et al.,* (2014)	AT: 10, Control : 10	1 year	26.0 ± 4.0° (Asym)	26.0 ± 3.0°	N/R	0.0°
Retrospective						
Grau *et al.,* (2011)	ITBS: 18, Control: 18	Symptomatic	24.0 ± 4.0° (Sym)	26.0 ± 6.0°	P > 0.05	-2.0°
Milner *et al.,* (2007)	TSF: 23, Control: 23 (♀)	N/R	14.4 ± 4.0° (Asym)	16.0 ± 5.3°	P = 0.35 ES: Moderate	-1.6°
Azevedo *et al*., (2009)	AT: 21, Control: 21	Symptomatic	22.0 ± 5.5° (Sym)	26.3± 3.9°	P = 0.01*	-4.3°
			Peak Knee Adduction			
Retrospective						
Willy *et al.,* (2012)	PFPS: 18 (♂), Control: 18 (♂) PFPS: 18 (♀), Control: 18 (♂)	Symptomatic	5.7 ± 1.0° (Sym) 2.2 ± 4.0° (Sym)	2.7 ± 3.2° 2.7 ± 3.2°	P = 0.03* P = 0.02*	3.0° -0.5°
Luz *et al*., (2018)	PFPS:27, Control: 27	Symptomatic	5.9 ± 1.96° (Sym)	5.3 ± 2.21°	P = 0.32	0.6°
Bramah *et al*., (2018)	RRI: 72, Control: 36	Symptomatic	2.0 ± 3.5° (Sym)	1.9 ± 3.1°	P = 0.79 ES: Small	0.1°
Pohl *et al.,* (2008)	TSF: 30, Control: 30 (♀)	N/R	2.0 ± 5.0° (Asym)	2.5 ± 5.0°	P > 0.05 ES: Small	-0.5°
			Peak Knee Abduction			
Prospective						
Dudley *et al.,* (2017)	RRI: 12, Control: 19	14 weeks	3.5° (Asym)	4.3°	P = 0.46 ES: Small	-0.8°
Retrospective						
Bazett-Jones *et al*., (2013)	PFPS:19, Control: 19	Symptomatic	3.4 ± 2.6° (Sym)	1.6 ± 2.7°	P = 0.029*	1.8°
Noehren *et al.,* (2012)	PFPS: 15, Control: 15 (♀)	Symptomatic	4.1 ± 4.1° (Sym)	4.4 ± 3.3°	P > 0.05	-0.3°
Haghighat *et al*., (2021)	PFPS: 17, Control: 17 (♀)	Symptomatic	3.1 ± 5.0° (Asym)	3.5 ± 2.6°	P = 0.69	-0.4°
			Peak Knee IR			
Prospective						
Noehren *et al.,* (2007)	ITBS:18, Control: 18 (♀)	2 years	3.9 ± 3.7° (Asym)	0.0 ± 4.6°	P = 0.01*	3.9°
Retrospective						
Ferber *et al*., (2010)	ITBS: 35, Control: 35 (♀)	N/R	1.8 ± 5.9° (Asym)	-1.2 ± 5.0°	P = 0.03*	3.0°
Foch *et al*., (2015)	ITBS: 9 (Sym), Control: 9 (♀) ITBS: 9 (Asym), Control: 9 (♀)	Symptomatic > 1 month RTR	3.9 ± 6.4°(Sym) 5.9 ± 6.4°(Asym)	3.2 ± 5.4° 3.2 ± 5.4°	P = 0.60	0.7° 2.7°
Luz *et al*., (2018)	PFPS:27, Control: 27	Symptomatic	1.2 ± 4.2° (Sym)	0.4 ± 6.0°	P = 0.59	0.8°
Pohl *et al*., (2008)	TSF: 30, Control: 30 (♀)	N/R	3.7 ± 5.1° (Asym)	2.6 ± 6.8°	P > 0.05 ES: Small	1.1°

Bazett-Jones *et al*., (2013)	PFPS:19, Control: 19	Symptomatic	2.0 ± 5.1° (Sym)	3.0 ± 5.0°	P > 0.05	-1.0°
Haghighat *et al*., (2021)	PFPS: 17, Control: 17 (♀)	Symptomatic	3.0 ± 7.3° (Asym)	1.7 ± 5.2°	P = 0.61	-1.2°
Wirtz *et al*., (2012)	PFPS: 20, Control: 20 (♀)	Symptomatic	2.3 ± 9.6° (Sym)	4.3 ± 7.5°	P = 0.48 ES: Small	-2.0°
Peak Knee ER						
Retrospective						
Bramah *et al*., (2018)	RRI:72, Control: 36	Symptomatic	7.1 ± 6.9° (Sym)	6.7 ± 5.5°	P = 0.62 ES: Small	0.4°
Noehren *et al*., (2012)	PFPS: 15, Control: 15 (♀)	Symptomatic	1.1 ± 4.9° (Sym)	1.7 ± 4.2°	P > 0.05	-0.6°

Population: Population is mixed gender unless males (♂) or females (♀) are stated specifically.*

IR; internal rotation: ER: external rotation; PFPS: Patellofemoral pain syndrome; AT: Achilles tendon injury; ITBS: Iliotibial band syndrome; TSF: tibial stress fracture; MSP: medial shin pain; CMSI: calf muscle strain injury; RRI: Running related injuries collectively; IC: initial contact; (Asym): Asymptomatic at time of testing; (Sym): Symptomatic at time of testing; N/R: Not reported; (°): degrees; ES: effect size; Nm: Newton Meter; Nm/kg: Newton Meter per kilogram; >1 month RTR: runners had returned to pain-free running for more than 1 month; All peak values are taken during the stance phase unless otherwise stated; *Significance at $p \leq 0.05$.

In relation to frontal plane kinematics, research has explored the relationship between both peak knee adduction and peak knee abduction with RRIs. With regards to peak knee adduction, only retrospective studies have been undertaken, with four authors investigating this variable (Pohl *et al.*, 2008; Willy *et al.*, 2012; Bramah *et al.*, 2018; Luz *et al.*, 2018). The results are contrasting, with one author finding peak knee adduction to be significantly greater (111.1%) in male runners who had suffered from patellofemoral pain syndrome when compared to uninjured controls (Willy *et al.*, 2012). In the same study, he also found the contrary with respect to females, where female runners with a history of patellofemoral pain syndrome demonstrated significantly lesser peak knee adduction values (by 18.5%) than their uninjured counterparts. It has been suggested that the differences seen in gender could potentially be down to pelvic alignments (Willy *et al.*, 2012), as well as dynamic movement strategies to reduce knee pain (Willy *et al.*, 2012), but due to the retrospective nature of this study, we are unable to determine cause or effect. Three other retrospective studies found no significant differences between injured runners and controls (Pohl *et al.*, 2008; Bramah *et al.*, 2018; Luz *et al.*, 2018).

With regards to peak knee abduction, Dudley *et al*., (2017) was the only author to prospectively investigate its relationship with RRI, finding no significant differences between injured and uninjured runners. Retrospectively, one of three studies found significance, where runners with patellofemoral pain demonstrated significantly greater peak knee abduction values compared to uninjured controls (Bazett-jones *et al.*, 2013). Authors speculated that greater knee abduction may contribute to patellofemoral pain by causing a dynamic valgus stress to the knee and potentially increasing the lateral forces acting on the patella, ultimately resulting in injury (Bazett-jones *et al.*, 2013).

When looking at transverse plane kinematics, only one prospective study has explored the relationship between peak knee internal rotation and RRI, finding peak knee internal rotation values to be significantly greater in runners who sustained an injury to their iliotibial band (Noehren, Davis and Hamill, 2007). Seven retrospective studies (Pohl *et al.*, 2008; Ferber *et al.*, 2010; Wirtz *et al.*, 2012; Bazett-jones *et al.*, 2013; Foch *et al.*, 2015; Luz *et al.*, 2018; Haghighat *et al.*, 2021) have explored how knee internal rotation may relate to running injury, with only Ferber *et al*., (2010) finding significantly greater peak knee internal rotation in runners with a history of iliotibial band syndrome compared to uninjured runners. It has been speculated that due to the anatomical insertion of the iliotibial band on the tibia, increases in internal rotation of the knee causes an additional torsional load and greater tissue strain of the iliotibial band (Ferber *et al.*, 2010). With respect to peak knee external rotation, both Bramah *et al*., (2018) and Noehren *et al*., (2012) found no significant differences between retrospectively injured and uninjured runners.

In summary, there are mixed findings with respect to knee kinematics and RRI. There is quite clearly a lack of prospective studies analysing the kinematics of the knee and their relationship with RRI, and although some studies have found knee flexion at initial contact, peak knee flexion, knee flexion excursion and peak knee adduction to be significantly related to RRIs, these significant findings are too inconclusive to really confirm that a relationship exists. More large scale prospective studies may help develop our understanding of whether knee kinematics relate to RRIs. Additionally, it may be useful to investigate how kinematics relate to all RRIs *per se*, before subsequently analysing how kinematics relate to localized regions, segments and specific injuries.

2.4.4.3 Hip kinematics and injury

It has been reported that at initial contact, the hip can be in up to 65 degrees of flexion (Schache *et al.*, 1999). As soon as contact is made, the hip moves into extension and reaches approximately 20 degrees of flexion during mid-stance. The hip continues to go into extension as the body's centre of mass translates forward, reaching approximately 5-11 degrees of extension at toe-off (Franz *et al.*, 2009; Loudon, Manske and Reiman, 2013).

While sagittal plane motion has been well documented through the gait cycle, recent studies have also studied both frontal and transverse plane motion in running. With respect to the frontal plane, Willson *et al.,* (2012) noted approximately 7 degrees of hip adduction in males and 11 degrees in females at initial contact (Willson *et al.*, 2012). The hip then abducts as the stance limb moves from initial contact through to mid-stance, before reaching a position of slight abduction at toe-off. The hip reaches a maximum abduction angle of 8 degrees during the early swing phase, and then reverts back towards neutral as the foot descends for the following ground contact (Willson *et al.*, 2012). In terms of transverse plane motion, Loudon, Manske and Reiman (2013) documented that internal and external hip rotation is small in running. At initial contact the hip begins in slight external rotation before rotating internally at mid-stance. From mid-stance to toe-off the hip internally rotates to a neutral position (Loudon, Manske and Reiman, 2013) (Figure 2.4.6).

It has been proposed that motion at the hip can be as a result of motion that has occurred distally in the lower extremity. With excessive motion at the foot such as rearfoot eversion, the tibia tends to internally rotate, and with associated joint coupling, this could then cause a greater degree of internal rotation at the hip, therefore increasing hip adduction (Tiberio, 1987). It is through these potentially injurious kinematics that researchers have speculated a possible cause of injuries to the knee, such as PFPS and ITBS (Noehren, Davis and Hamill, 2007; Wilson, 2007). With this in mind, research has focused mainly on peak hip adduction and peak hip internal rotation, with less attention given to peak hip flexion, hip flexion at initial contact, hip flexion excursion and hip adduction excursion when investigating the kinematics of RRIs. A summary of studies which have explored this relationship are summarized in Table 2.4.20.

With respect to peak hip adduction, two prospective studies (Noehren, Davis and Hamill, 2007; Dudley *et al.*, 2017) and fifteen retrospective studies (Pohl *et al.*, 2008; Souza and Powers, 2009; Milner, Hamill and Davis, 2010; Ferber *et al.*, 2010; Dierks *et al.*, 2011; Grau *et al.*, 2011; Noehren, Sanchez, *et al.*, 2012; Willy *et al.*, 2012; Bazett-jones *et al.*, 2013; Foch and Milner, 2014; Esculier, Bouyer and Roy, 2015; Foch *et al.*, 2015; Brown *et al.*, 2016; Baker *et al.*, 2018; Luz *et al.*, 2018) have examined its relationship with RRIs. Prospectively, one of two studies found peak hip adduction to be significantly greater (33%) in runners who had sustained an injury to their iliotibial band compared to runners who remained injury-free over a two-year period (Noehren, Davis and Hamill, 2007). Authors speculated that with an increase in hip adduction, there is increased tension on the ITB fibres due to the nature of their anatomical attachment, and this tension may lead to injury (Noehren, Davis and Hamill, 2007). Retrospectively, there were mixed findings. Four authors reported significantly greater (16.0 – 52.0%) peak hip adduction in female runners who either had a history of tibial stress fracture (Pohl *et al.*, 2008; Milner, Hamill and Davis, 2010) and ITBS (Ferber *et al.*, 2010) or were currently symptomatic with PFPS (Noehren, Sanchez, *et al.*, 2012) when compared to uninjured controls, with some large effect sizes demonstrated (d = 0.8 – 0.9).

In contrast to this, three other authors found peak hip adduction to be significantly less (19.3 – 30.8%) in runners who were currently symptomatic of ITBS (Grau *et al.*, 2011) and PFPS (Dierks *et al.*, 2011), and who had a history of ITBS (Foch *et al.*, 2015), compared to injury free controls. Interestingly, Foch *et al*., (2015) did not find any difference in peak hip adduction between runners who were currently symptomatic of ITBS and injury-free runners, and instead reported significantly less hip adduction in the asymptomatic group compared to controls. They hypothesized that the asymptomatic group may have adapted a compensatory running strategy in order to reduce hip adduction, and this may be why their symptoms relieved. This is only speculation however, as the study was a retrospective design. Elsewhere, it is possible that the results of Grau *et al*., (2011) differ in part due to the fact that the population studied was dominated largely by males, and the increase in hip adduction seen by Ferber *et al*., (2010) was demonstrated exclusively by female runners.

Table 2.4.20 The relationship between hip kinematics and RRIs.

Study	***Population****	***RRI Timeframe***	***Injured Group: Mean ± SD***	***Uninjured Group: Mean ± SD***	***Significance***	***% difference***
Peak Hip Adduction						
Prospective						
Noehren *et al*., (2007)	ITBS: 18, Control: 18	2 years	14.1 ± 2.5°	10.6 ± 5.1°	P = 0.01*	3.5°
Dudley *et al*., (2017)	RRI: 12, Control: 19	14 weeks	14.0°	12.7°	P = 0.37 ES: Small	1.3°
Retrospective						
Pohl *et al*., (2008)	TSF: 30, Control: 30 (♀)	N/R	11.7 ± 5.0° (Asym)	7.7 ± 3.8°	P < 0.05* LR ES: Large	4.0°
Milner *et al*., (2010)	TSF: 29, Control: 29 (♀)	N/R	11.6 ± 5.0° (Asym)	8.1 ± 3.7°	P < 0.05* ES: Large	3.5°
Ferber *et al*., (2010)	ITBS: 35, Control: 35 (♀)	N/R	10.4 ± 4.6° (Asym)	7.9 ± 5.8°	P = 0.05*	2.5°
Noehren *et al*., (2012)	PFPS: 15, Control: 15 (♀)	Symptomatic	16.7 ± 3.2° (Sym)	14.4 ± 3.4°	P < 0.05*	2.3°
Willy *et al*., (2012)	PFPS: 36, Control: 18	Symptomatic	12.9 ± 3.4° (♂) (Sym) 19.2 ± 3.0° (♀) (Sym)	11.9 ± 3.0° (♂)	P > 0.05	1.0° 7.3°
Bramah *et al*., (2021)	CMSI: 15, Control: 15	12 months	11.3 ± 3.1° (Asym)	29.2 ± 3.2°	P = 0.07	1.1°
Esculier *et al*., (2015)	PFPS: 21, Control: 20	Symptomatic	12.0 ± 3.4° (Sym)	11.5 ± 2.9°	P > 0.05	0.5°
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	13.2 ± 3.3° (Sym)	12.7 ± 3.6°	P = 0.86	0.5°
Souza *et al*., (2009)	PFPS: 21, Control: 20	Symptomatic	N/R (Sym)	N/R	P = 0.27	-
Brown *et al*., (2016)	ITBS: 12, Control: 20 (♀)	Symptomatic	15.4 ± 4.3° (Sym)	16.8 ± 3.0°	P = 0.27	-1.4°
Foch *et al*., (2014)	ITBS: 17, Control: 17 (♀)	RTR > 1 month	13.1 ± 2.6° (Asym)	15.0 ± 3.3°	P > 0.05 ES: Moderate	-1.9°
Baker *et al*., (2018)	ITBS: 13, Control: 13	Symptomatic	8.93° (Sym)	11.18°	P = 0.129	-2.3°
Luz *et al*., (2018)	PFPS: 27, Control: 27	Symptomatic	2.3 ± 1.7° (Sym)	5.0 ± 2.5°	P = 0.67	-2.7°
Foch *et al*., (2015)	ITBS: 18, Control: 9 (♀)	Symptomatic Asymptomatic [2-96 months]	16.6 ± 2.5° (Sym) 13.4 ± 3.2° (Asym)	16.6 ± 1.9°	P < 0.05 (Asym)*	0.0° (Sym) -3.2° (Asym)
Dierks *et al*., (2011)	PFPS: 20, Control: 20	Symptomatic	8.7 ± 5.2° (Sym)	11.8 ± 3.9°	P < 0.05*	-3.1°
Grau *et al*., (2011)	ITBS: 18, Control: 18	Symptomatic	9.0 ± 4.0° (Sym)	13.0 ± 4.0°	P < 0.05*	-4.0°
Hip Adduction Excursion						
Prospective						
No studies						
Retrospective						

Luz *et al*., (2018)	PFPS: 27, Control: 27	Symptomatic	2.3 ± 1.0° (Sym)	2.3 ± 1.1°	P = 0.79	0.0°
Grau *et al*., (2011)	ITBS: 18, Control: 18	Symptomatic	9.0 ± 4.0° (Sym)	13.0 ± 4.0°	P < 0.05*	-4.0°
Peak Hip IR						
Prospective						
Dudley *et al*., (2017)	RRI: 12, Control: 19	14 weeks	7.51°	4.80°	P = 0.29 ES: Moderate	2.7°
Retrospective						
Souza *et al*., (2009)	PFPS: 21, Control: 20	Symptomatic	7.6 ± 7.0° (Sym)	1.2 ± 3.8°	P < 0.05*	6.4°
Noehren *et al*., (2012)	PFPS: 15, Control: 15	Symptomatic	9.7 ± 3.9° (Sym)	5.1 ± 3.9°	P < 0.05*	4.6°
Willy *et al*., (2012)	PFPS: 36, Control: 18	Symptomatic	6.9 ± 4.6° (♂) (Sym) 19.0 ± 4.8° (♀) (Sym)	6.0 ± 3.8° (♂)	P > 0.05	0.9° 13.0°
Loudon *et al*., (2012)	MSP: 14, Control: 14	MSP within previous 2 years	13.91 ± 6.4° (♂) (Asym) 9.65 ± 3.4° (♀) (Asym)	10.23 ± 6.8° (♂) 6.88 ± 2.6° (♀)	P = 0.13 P = 0.22	3.7° 2.8°
Esculier *et al*., (2015)	PFPS: 21, Control: 20	Symptomatic	7.9 ± 5.5° (Sym)	8.2 ± 5.5°	P > 0.05	-0.3°
Luz *et al*., (2018)	PFPS: 27, Control: 27	Symptomatic	10.3 ± 3.7° (Sym)	11.1 ± 4.4°	P = 0.49	-0.8°
Dierks *et al*., (2011)	PFPS: 20, Control: 20	Symptomatic	5.1 ± 6.8° (Sym)	6.0 ± 5.4°	P > 0.05	-0.9°
Milner *et al*., (2010)	TSF: 29, Control: 29 (♀)	N/R	6.6 ± 5.0° (Asym)	8.5 ± 6.1°	P = 0.22 ES: Small	-1.9°
Brown *et al*., (2016)	ITBS: 12, Control: 20 (♀)	Symptomatic	3.6 ± 6.9° (Sym)	5.6 ± 8.3°	P = 0.44	-2.0°
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	3.03 ± 4.2° (Sym)	6.33 ± 4.5°	P = 0.09	-3.3°
Peak Hip Flexion						
Retrospective						
Grau *et al*., (2011)	ITBS: 18, Control: 18	Symptomatic	31.0 ± 4.0° (Sym)	32.0 ± 6.0°	P > 0.05	-1.0°
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	30.4 ± 6.8° (Sym)	35.8 ± 8.4°	P = 0.73	-5.4°
Hip Flexion at IC						
Retrospective						
Bramah *et al*., (2021)	CMSI: 15, Control: 15	12 months	26.3 ± 3.9° (Asym)	21.8 ± 3.5°	P < 0.01*	4.5°
Hip Flexion Excursion						
Retrospective						
Grau *et al*., (2011)	ITBS: 18, Control: 18	Symptomatic	44.0 ± 3.0° (Sym)	45.0 ± 5.0°	P > 0.05	-1.0°

Population∗: Population is mixed gender unless males (♂) or females (♀) are stated specifically.

IR; internal rotation, ER; external rotation, PFPS; Patellofemoral pain syndrome, AT; Achilles tendon injury, ITBS; Iliotibial band syndrome, TSF; tibial stress fracture, MSP; medial shin pain, RRI; Running related injuries collectively, IC; initial contact, (Asym); Asymptomatic at time of testing, (Sym); Symptomatic at time of testing, N/R; Not reported, (°); degrees, ES; effect size, Nm; Newton Meter, Nm/kg; Newton Meter per kilogram, >1 month RTR; runners had returned to pain-free running for more than 1 month, All peak values are taken during the stance phase unless otherwise stated; *Significance at p ≤ 0.05.

Very few studies have looked at hip adduction excursion and RRI, with no prospective studies and only two retrospective studies evident (Grau *et al.*, 2011; Luz *et al.*, 2018). Retrospectively, one study found hip adduction excursion to be significantly less in runners who were currently suffering with ITBS, with a difference of 30.8% seen between injured and uninjured runners (Grau *et al.*, 2011). It has been proposed that this may be as a result of injured runners having irritation at the insertion of the ITB (Grau *et al.*, 2011), and perhaps runners with symptomatic ITB syndrome reduced their hip adduction excursion in order to reduce pain during running.

When exploring the relationship between peak hip internal rotation and RRI, only one prospective study exists (Dudley *et al.*, 2017), with ten retrospective studies (Souza and Powers, 2009; Milner, Hamill and Davis, 2010; Dierks *et al.*, 2011; Loudon and Reiman, 2012; Noehren, Sanchez, *et al.*, 2012; Willy *et al.*, 2012; Bazett-jones *et al.*, 2013; Esculier, Bouyer and Roy, 2015; Brown *et al.*, 2016; Luz *et al.*, 2018). Prospectively, no significant results were reported (Dudley *et al.*, 2017). Although runners who sustained a RRI did not have significantly greater peak hip internal rotation, a moderate effect was observed (d = 0.42) and authors acknowledged that their study may have been underpowered in this instance (Dudley *et al.*, 2017). Meanwhile, two retrospective studies did find peak hip internal rotation to be significantly greater in runners who were symptomatic of PFPS (Souza and Powers, 2009; Noehren, Sanchez, *et al.*, 2012), with Souza and Powers (2009) reporting injured runners to have peak values of over six times that of the uninjured runners. It has been speculated that an increase in hip internal rotation may cause an increase in patellofemoral joint contact pressure and thus pain at the joint ensues (Souza and Powers, 2009).

Peak hip flexion, hip flexion at initial contact and hip flexion excursion have not been the focus of much RRI research, with no prospective and only three retrospective studies apparent (Grau *et al.*, 2011; Bazett-jones *et al.*, 2013; Bramah *et al.*, 2021). One study found significantly greater hip flexion at initial contact in runners with a history of multiple calf strain injuries compared to uninjured controls, with a large effect size (d = 1.20) (Bramah *et al.*, 2021). Authors suggested that the increase in hip flexion at initial contact may be linked with an over-stride, thus placing more demand on the calf complex in efforts to re-accelerate the centre of mass at toe-off. No significant findings were reported with respect to peak hip flexion or hip flexion excursion in runners who had ITBS and PFPS compared to uninjured controls (Grau *et al.*, 2011; Bazett-jones *et al.*, 2013).

In summary, the relationship between hip kinematics and RRI is not very clear, as demonstrated by the mixed findings. Prospective studies have been limited in number as well as being limited by low sample sizes. Future research should endeavour to prospectively analyse injuries throughout the kinetic chain in large subject numbers. Kinematics of proximal and distal joints may also help in the explanation of findings thereafter.

2.4.4.4 Pelvis kinematics and injury

With reference to the sagittal plane, the pelvis sits in a slight posterior tilt at initial contact. As the body moves forward into the mid-stance phase, the pelvis starts to rotate anteriorly, reaching its maximum point of anterior pelvic tilt at toe-off (Schache *et al.*, 1999). During the swing phase, the pelvis begins to rotate slightly into a posterior direction, before reverting anteriorly again for foot descent. It has been documented that the total anterior/posterior tilt that occurs during one cycle is 10-15 degrees (Novacheck, 1998). When addressing the frontal plane kinematics, pelvic motion in this plane is termed lateral pelvic tilt (Loudon, Manske and Reiman, 2013). A neutral pelvic tilt in this plane is relatively horizontal. However, contralateral pelvic tilt, or sometimes referred to as pelvic drop, refers to when the side opposite of the stance limb drops below neutral (*Figure 2.4.8*). As the foot strikes the ground, the pelvis is said to be level. The contralateral pelvis of the stance leg drops to a maximum of 5-8 degrees by the time toe-off occurs. The pelvis then returns to neutral during the swing phase which assists in foot clearance of the ground below (Loudon, Manske and Reiman, 2013).

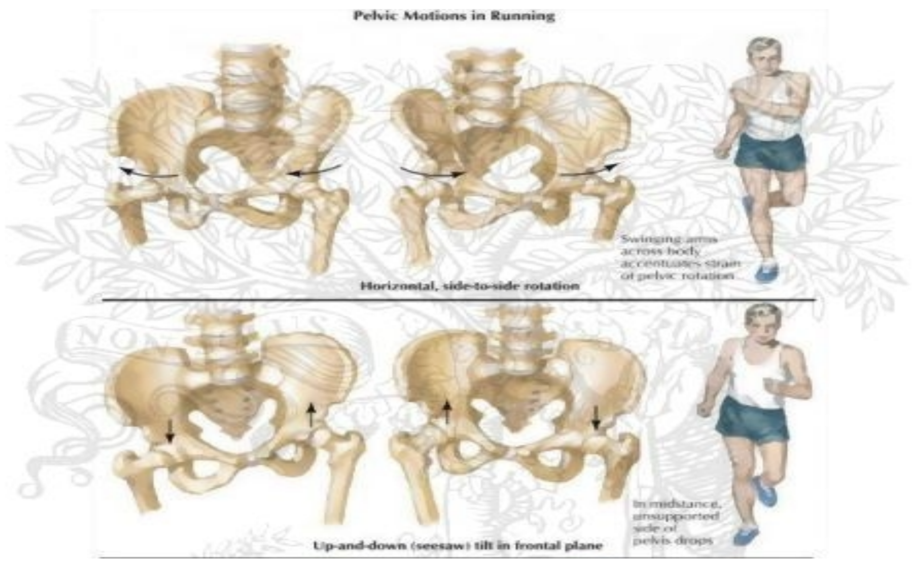

Figure 2.4.8 Pelvic motion in running (Netter Images, Elsevier).

Although it is well understood that movement around the pelvis is a normal component of the running gait cycle (Loudon, Manske and Reiman, 2013), it has been thought that excessive motion of the pelvis, particularly frontal plane contralateral pelvic tilt/drop (*Figure 2.4.8*), may lead to the onset of low back pain in runners (Schache, Blanch and Murphy, 2000). Additionally, motion which occurs around the pelvis may cause sequential movements at the hip and knee, potentially having a knock-on effect down the kinetic chain (Loudon and Reiman, 2012). Studies which have explored pelvic kinematics and RRI are summarized in Table 2.4.21. Unfortunately, studies to date are very limited, with only five studies examining sagittal plane motion (four of which are retrospective), and no studies examining transverse plane motion. Frontal plane motion appears to have received the greatest degree of attention, but this has not been studied prospectively.

With respect to frontal plane contralateral pelvic drop (CPD), no prospective studies have looked at this variable in a RRI context. Retrospectively, ten studies have explored this variable and its potential relationship with RRIs (Loudon and Reiman, 2012; Noehren, Sanchez, *et al.*, 2012; Bazett-jones *et al.*, 2013; Foch and Milner, 2014; Esculier, Roy and Bouyer, 2015; Foch *et al.*, 2015; Bramah *et al.*, 2018, 2021; Haghighat *et al.*, 2021). Three studies reported significantly greater (38.6 – 46.1%) CPD in injured runners compared with uninjured controls (Loudon and Reiman, 2012; Bramah *et al.*, 2018, 2021). Loudon and Reiman, (2012) hypothesized that an increase in CPD may cause an increase in valgus moments at the knee, and this in turn adds stress to the medial shin, while Bramah *et al.*,

(2021) suggest that there may be a deficit in neuromuscular function of the gluteus medius, placing greater demand on the calf complex. However, due to the retrospective nature of these studies, we are unable to really determine if the CPD was a precursor to the shin/calf pain or a result of the injury itself. In addition to CPD, five studies looked at anterior pelvic tilt as a potential link to RRI. Bramah et al., (2021) and Luginick *et al*., (2018) found significantly greater (14.6 - 37.4%) anterior pelvic tilt in runners with a history of multiple calf strains and iliotibial band syndrome respectively compared to controls. Again, authors eluded to a potential deficiency in gluteal muscle activity, resulting in ineffective vertical support and propulsion from the hip, and subsequent increases in muscular demand are placed on the calf complex (Bramah *et al.*, 2021). However, Shen *et al*., (2019), Bazett-Jones *et al*., (2013), and Haghighat *et al.*, (2021) found no significant differences between runners who were symptomatic of ITBS or PFPS and those who were injury-free.

In summary, there is clearly a lack of prospective research around pelvic kinematics and RRIs, and so it is currently not possible to say that pelvic kinematics relate to running injuries comprehensively. Studies to date have been very limited in number, with population sizes being relatively small also. Future research should aim to explore pelvic kinematics on a larger sample size, as well as in a prospective nature in order to give a better understanding of the relationship that may exist across all planes of motion.

Table 2.4.21 The relationship between pelvis sagittal and frontal plane kinematics and RRIs.

Study	***Population****	***RRI Timeframe***	***Injured Group: Mean ± SD***	***Uninjured Group: Mean ± SD***	***Significance***	***% difference***
Anterior Pelvic Tilt						
Prospective						
Shen *et al*., (2019)	ITBS: 15, Control: 15 (♂)	8 weeks	N/R	N/R	P > 0.05	-
Retrospective						
Bramah *et al*., (2021)	CMSI: 15, Control: 15	12 months	9.9 ± 3.7° (Asym)	6.2 ± 3.5°	P < 0.01*	37.4%
Luiginick *et al*., (2018)	ITBS: 30, Control: 30	N/R	22.6 ± 4.0° (Sym)	19.3 ± 5.2°	P < 0.01*	14.6%
Haghighat *et al*., (2021)	PFPS: 17, Control: 17 (♀)	Symptomatic	11.9 ± 6.7° (Asym)	12.3 ± 7.1°	P = 0.64	-3.3%
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	7.2 ± 5.1° (Sym)	10.2 ± 5.5°	P = 0.87	-29.4%
Contralateral Pelvic Drop						
Retrospective						
Loudon *et al*., (2012)	MSP: 14, Control: 14	MSP within previous 2 years	8.6 ± 2.2° (Asym)	5.86 ± 1.9°	P = 0.002*	46.1%
Bramah *et al*., (2018)	RRI:72, Control: 36	Symptomatic	6.4 ± 2.1° (Sym)	3.7 ± 1.9°	P < 0.01* ES: Large	40.6%
Bramah *et al*., (2021)	CMSI: 15, Control: 15	12 months	5.7 ± 1.9°	3.5 ± 2.6°	p < 0.01*	38.6%
Noehren *et al*., (2012)	PFPS: 16, Control: 16 (♀)	Symptomatic	8.0 ± 2.7° (Sym)	6.6 ± 2.1°	P = 0.13 ES: Moderate	21.2%
Haghighat *et al*., (2021)	PFPS: 17, Control: 17 (♀)	Symptomatic	4.0 ± 2.5° (Asym)	5.1 ± 2.3°	P = 0.21	21.6%
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	4.7 ± 2.0° (Sym)	4.22 ± 1.9°	P = 0.64	12.3%
Esculier *et al*., (2015)	PFPS: 21, Control: 20	Symptomatic	3.7 ± 1.4° (Sym)	3.5 ± 1.8°	P > 0.05	5.7%
Foch *et al*., (2014)	ITBS: 17, Control: 17 (♀)	RTR > 1 month	3.9 ± 1.9° (Asym)	4.7 ± 2.2°	P = 0.56 ES: Small	-17.0%
Foch *et al*., (2015)	ITBS: 18, Control: 9 (♀)	Symptomatic Asymptomatic [2-96 months]	6.7 ± 2.8° (Sym) 4.8 ± 3.3° (Asym)	6.1 ± 1.7°	P > 0.05	9.8% (Sym) -21.3% (Asym)

Population: Population is mixed gender unless males (♂) or females (♀) are stated specifically.*

PFPS; Patellofemoral pain syndrome, ITBS; Iliotibial band syndrome, CMSI: calf muscle strain injury; MSP; medial shin pain, (Asym); Asymptomatic at time of testing, (Sym); Symptomatic at time of testing, N/R; Not reported, (°); degrees, ES; effect size, RTR >1 month; runners had returned to pain-free running for more than 1 month, All peak values are taken during the stance phase unless otherwise stated; *Significance at p ≤ 0.05.

2.4.4.5 Trunk kinematics and injury

The trunk is made up of the thoracic and lumbar spine, the ribs, the sternum and the supporting muscles and ligaments attached. The muscles of the trunk and core are crucial in helping to absorb and distribute forces upon impact, as well as assisting in the fluent movement of the upper body during running. As the foot contacts the ground, the trunk is in its most erect position (Schache *et al.*, 1999). While the body translates into mid-stance, the trunk begins to flex anteriorly before reaching a maximum flexion angle of 3-13 degrees at toe-off (Schache *et al.*, 1999).

Kinematic analysis at the trunk has not been very well researched with respect to RRIs, with only one prospective and three retrospective studies exploring this area to date, and no evidence for a relationship with RRIs. Studies which have explored trunk kinematics and RRI have looked at peak trunk ipsilateral flexion (greatest degree of frontal plane lateral trunk flexion in the direction of the stance limb) (Noehren, Pohl, *et al.*, 2012; Bazett-jones *et al.*, 2013; Foch and Milner, 2014; Shen *et al.*, 2019), peak trunk contralateral flexion (greatest degree of frontal plane lateral trunk flexion in the direction away from the stance limb) (Bazett-jones *et al.*, 2013; Foch and Milner, 2014; Haghighat *et al.*, 2021), and peak trunk flexion (greatest degree of flexion that occurs in the sagittal plane by the trunk) (Bazett-jones *et al.*, 2013; Haghighat *et al.*, 2021), with all studies focusing on running-related knee injuries (Table 2.4.22). No studies have examined transverse plane kinematics at the trunk.

It has been hypothesized that a greater degree of ipsilateral trunk flexion may have increased lateral forces acting on the patella, consequently having detrimental effects on the patellofemoral joint (Nakagawa, Maciel and Serrão, 2015). Although greater ipsilateral trunk flexion has been linked with patellofemoral pain syndrome in runners during a single leg stepping task (Nakagawa, Maciel and Serrão, 2015), no links have been established during a running gait. However, trunk lean has been found to influence motion at the pelvis, the hip and the knee, and thus is important to consider in the development of RRIs (Bramah *et al.*, 2020) (Figure 2.4.9).

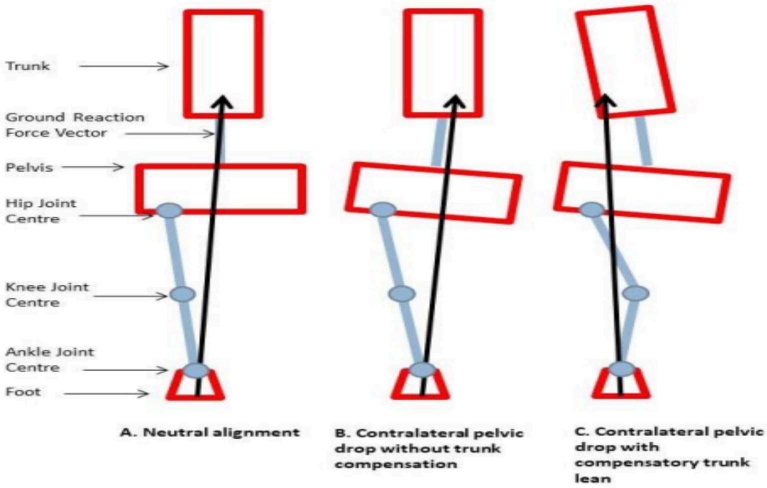

Figure 2.4.9 Trunk kinematics in line with associated and coordinated pelvis and knee kinematic changes (Bramah et al., 2020).

With respect to peak trunk contralateral flexion and RRI, authors have speculated that very little contralateral trunk flexion occurs during running, and previous history of injury does not seem to change this (Foch and Milner, 2014). Lastly, with reference to peak trunk flexion, one prospective (Shen *et al.*, 2019) and three retrospective studies (Bazett-jones *et al.*, 2013; Shen *et al.*, 2019; Haghighat *et al.*, 2021) have explored this variable and its relationship with RRI. Shen *et al.*, (2019) found greater peak trunk flexion among runners when injured with ITBS compared to when these runners were injury-free. An increase in peak trunk flexion may result in greater loading through anterior aspect of the body, and the knee may experience an overload as a result (Figure 2.4.10). The other studies reported no significant differences between runners who had experienced patellofemoral pain syndrome and the control group.

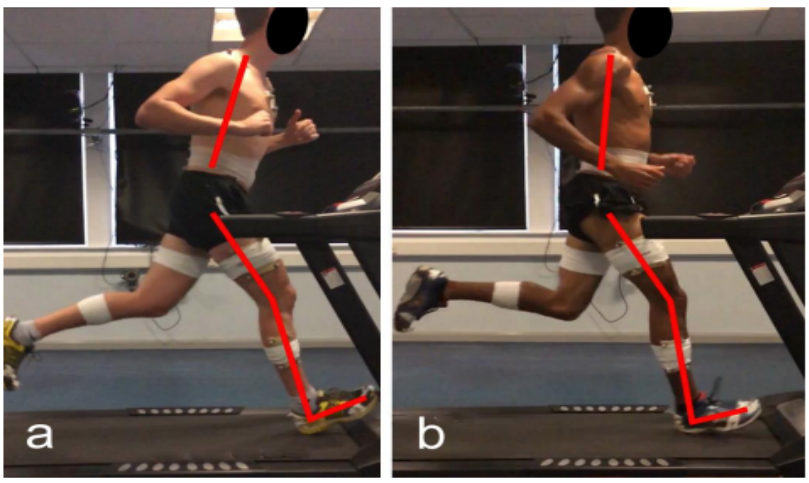

Figure 2.4.10 Forward trunk flexion in injured (a) and uninjured (b) runner (Bramah et al., 2020).

To conclude, it would appear that trunk kinematics do not have a relationship with knee injuries. We are unable to determine if trunk kinematics have a relationship with other injury locations such as the hip or lower back, as these locations have not been investigated yet. Although this area has received very limited research attention to date, running styles aimed at injury prevention such as Chi running and Pose running often still promote “trunk lean” cues (Souza, 2016). As trunk kinematics and RRIs have not been linked prospectively, caution should be taken when adjusting such kinematics for the purpose of injury prevention in running. Further large scale prospective research is needed in the area of trunk kinematics and RRIs, especially studies that are considerate of all three planes of motion.

Table 2.4.22 The relationship between trunk kinematics and RRIs.

Study	***Population****	***RRI Timeframe***	***Injured Group: Mean ± SD***	***Uninjured Group: Mean ± SD***	***Significance***	***Absolute difference***
Peak Trunk Ipsilateral Flexion						
Prospective						
Shen *et al*., (2019)	ITBS: 15, Control: 15 (♂)	8 weeks	9.0 ± 2.4°	9.8 ± 5.3°	P = 0.83 ES: Trivial	-0.8°
Retrospective						
Noehren *et al*., (2012)	PFPS: 16, Control: 16 (♀)	Symptomatic	5.0 ± 1.3° (Sym)	3.5 ± 3.0°	P = 0.07 ES: Large	1.5°
Haghighat *et al*., (2021)	PFPS: 17, Control: 17 (♀)	Symptomatic	3.1 ± 1.6° (Asym)	2.7 ± 1.3°	P = 0.66	0.4°
Foch *et al*., (2014)	ITBS: 17, Control: 17 (♀)	RTR > 1 month	3.7 ± 1.8° (Asym)	3.4 ± 2.2°	P > 0.05 ES: Small	0.3°
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	5.0 ± 3.5° (Sym)	5.1 ± 3.2°	P = 0.62	-0.1°
Peak Trunk Contralateral Flexion						
Retrospective						
Foch *et al*., (2014)	ITBS: 17, Control: 17 (♀)	RTR > 1 month	0.4 ± 2.2° (Asym)	0.1 ± 2.1°	P > 0.05 ES: Small	0.3°
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	2.7 ± 4.1° (Sym)	2.5 ± 2.2°	P = 0.30	0.2°
Peak Trunk Flexion						
Prospective						
Shen *et al*., (2019)	ITBS: 15, Control: 15 (♂)	8 weeks	14.9 ± 4.8°	19.9 ± 13.5°	P > 0.05 ES: Small	-5.0°
Retrospective						
Shen *et al*., (2019)	ITBS: 15, Control: 15 (♂)	N/R	20.9 ± 5.2°	21.1 ± 17.9°	P = 0.02* Large	-0.2°
Bazett-Jones *et al*., (2013)	PFPS: 19, Control: 19	Symptomatic	13.1 ± 6.2° (Sym)	13.9 ± 4.7°	P = 0.88	-0.8°
Haghighat *et al*., (2021)	PFPS: 17, Control: 17 (♀)	Symptomatic	7.4 ± 3.6° (Asym)	8.7 ± 6.9°	P = 0.25	-1.3°

Population: Population is mixed gender unless males (♂) or females (♀) are stated specifically.*

PFPS; Patellofemoral pain syndrome, ITBS; Iliotibial band syndrome, (Asym); Asymptomatic at time of testing, (Sym); Symptomatic at time of testing, N/R; Not reported, (°); degrees, ES; effect size, All peak values are taken during the stance phase unless otherwise stated; *Significance at p ≤ 0.05.

2.4.5 The effect of technique on loading

The biomechanical model of musculoskeletal injury *per se* is largely based on the premise that injuries are caused by excessive forces to the musculoskeletal system (Armstrong, Warren and Warren, 1991). This section of the literature review will aim to examine the role that technique has on loading. The areas to be reviewed include foot strike kinematics (2.4.5.1) and knee kinematics (2.4.5.2) as these have been found to be easily modified in running re-training interventions.

2.4.5.1 Foot orientation and loading

Table 2.4.23 details some of the studies which have looked at how the magnitude and rate of loading differ between foot strike patterns. With regards to the magnitude of the vertical impact peak (VIP) of the vertical ground reaction force (vGRF), there are mixed findings, with some studies reporting VIP to be significantly greater (11-36%) in RFS runners (Kulmala *et al.*, 2013; Mercer and Horsch, 2015; Thompson *et al.*, 2015), other studies reporting the opposite, whereby VIP was significantly lower (6-7%) in RFS runners (Laughton, Davis and Hamill, 2003; Vannatta and Kernozek, 2015; Kuhman, Melcher and Paquette, 2016), and one study reporting no differences (Goss and Gross, 2013). There has been widespread debate about the presence or perceived absence of the VIP in FFS patterned running (Hamill and Gruber, 2017). As mentioned previously (Section 2.4.3), the VIP can often be visually absent when looking at the time-domain of the vGRF. However, when Gruber *et al.*, (2015) analyzed the vGRF of FFS in the frequency domain, they concluded that the VIP was not in fact absent in FFS running, rather it occurred later in the stance phase and was visually obscured by the vertical active peak (VAP).

With respect to the magnitude of the VAP of the vGRF, this did not differ between RFS and non-RFS runners (Nunns *et al.*, 2013; Valenzuela *et al.*, 2015; Sun *et al.*, 2018). Timing of VAP occurrence however was found to be significantly earlier in RFS runners when compared to FFS (Sun *et al.*, 2018). It should be noted that multiple studies imposed a particular foot strike pattern rather than investigating runners with naturally occurring RFS and non-RFS strike patterns. Interestingly, of the studies which found loading to be significantly lower in RFS running, FFS was imposed (Laughton, Davis and Hamill, 2003; Vannatta and Kernozek, 2015; Kuhman, Melcher and Paquette, 2016). This may challenge the validity of the results as the methods are not true to the natural form of the runners.

Regarding vGRF loading rates, the vast majority of studies reported both vertical average loading rate (VALR) (Goss and Gross, 2013; Kulmala *et al.*, 2013; Shih, Lin and Shiang, 2013; Kuhman, Melcher and Paquette, 2016; Yong *et al.*, 2018) and vertical instantaneous loading rate (VILR) (Shih, Lin and Shiang, 2013; Yong *et al.*, 2018) to be significantly greater (VALR: 10-48%, VILR: 27%) with RFS compared to non-RFS running. With reference to impact acceleration, there are conflicting findings with two studies finding peak tibial acceleration to be significantly greater in RFS running (Delgado *et al.*, 2013; Ruder *et al.*, 2017), one study reporting peak acceleration to be significantly lower (21%) in RFS running (Laughton, McClay Davis and Hamill, 2003), and one study finding no difference (Yong *et al.*, 2018). Additionally, it was noted that tibial impact attenuation was significantly greater in RFS running compared to FFS running. However, this was the only study which investigated this metric and their methods involved barefoot running, which may limit the application of their results to the majority of runners who would typically run shod (Delgado *et al.*, 2013).

Additional research has focused specifically at kinetics local to the knee and Achilles in an attempt to gain further understanding of how foot strike kinematics affect loading. It has been reported that a RFS pattern demonstrates greater eccentric quadriceps work during the braking phase of running gait when compared to FFS, therefore placing greater demands on the knee joint (Arendse *et al.*, 2004). It can be seen from Table 2.4.23 that patellofemoral joint stress (Vannatta and Kernozek, 2015; Willson *et al.*, 2015), patellofemoral contact force (Kulmala *et al.*, 2013), patellofemoral joint reaction force (Willson *et al.*, 2015) and tibiofemoral average loading rates (Bowersock *et al.*, 2017) are all significantly greater in RFS running compared to FFS. This is reflected in the knee extensor moments being higher in RFS runners (Kulmala *et al.*, 2013). Elsewhere in the lower extremity, it has been demonstrated that Achilles tendon peak force (Hashizume and Yanagiya, 2017) and time to peak force (Almonroeder, Willson and Kernozek, 2013) is significantly lower in RFS running compared to FFS. These results are also reflected in the ankle plantarflexor moments being higher in FFS runners (Kulmala *et al.*, 2013; Hashizume and Yanagiya, 2017).

In conclusion, it seems evident that loading rates are greater in runners landing with a RFS pattern. It is less clear if peak tibial acceleration and the vertical impact peak are lesser or greater in RFS running when compared to a FFS pattern. Additionally, studies focusing on kinetics that are local to the knee suggest greater loading (joint stress, contact force, joint reaction force, loading rate) with RFS running, whilst loading specific to the ankle joint appears to be lower with RFS running. Future studies should direct their attention towards assessing kinetics, foot strike kinematics and prospective injury simultaneously, thus giving a greater and more rounded analysis of the relationship between foot strike, loading and injury.

Table 2.4.23 Foot strike and loading

Study	***Population***	***Methods***	***Comparisons***	***Variables***	***Significant findings***	***Effect Sizes***
Vertical Impact Peak						
Kulmala *et al*., (2013)	38 ♀	Shod running @ 4m/s (O) 3D motion analysis Force plate	RFS vs FFS (natural strike patterns)	VIP	VIP 26% greater in RFS (P = 0.001)*	ES: 2.43 Large
Mercer *et al*., (2015)	10 ♂	Shod running @ SS (O) Force plate	RFS vs MFS vs FFS (imposed strike patterns)	VIP	VIP greater in RFS than FFS (P < 0.05)*	N/R
Thompson *et al*., (2015)	10 (5 ♂, 5 ♀)	Barefoot & Shod running @ SS (O) 3D motion analysis Force plate	RFS vs NRFS (natural strike patterns)	VIP	VIP greater in RFS (P < 0.05)*	N/R
Goss *et al*., (2013)	44 (18 ♂, 16 ♀)	Shod running @ SS (T) 3D motion analysis Instrumented treadmill 2D video camera	RFS vs Chi (imposed Chi (NRFS))	VIP	P = 0.61	N/R
Vannatta *et al*., (2015)	16 ♀	Shod running @ 3.5m/s – 3.9m/s (O) 3D motion analysis Force plate	RFS vs FFS (imposed FFS)	VIP	Peak vGRF 6.6% lower in RFS (P = 0.000)*	ES: 0.94 Moderate
Kuhman *et al*., (2015)	16 ♂	Shod running @ 3.4m/s & 4.5m/s (O) 3D motion analysis Force plate	RFS vs FFS (imposed FFS)	VIP	Peak vGRF 5.2% lower in RFS (P < 0.001)*	ES: 0.65 Small
Laughton *et al*., (2003)	15 (Gender N/R)	Shod running @ 3.7m/s (O) 3D motion analysis Accelerometer	RFS vs FFS (imposed FFS)	VIP	Lower peak vGRF in RFS (P = 0.0002)*	N/R
Vertical Active Peak						
Nunns *et al*., (2013)	120 (Gender N/R)	Barefoot running @ 3.6m/s (O) 3D motion analysis Pressure Plate	RFS vs MFS vs FFS vs TR (imposed strike patterns)	VAP	P = 0.85	N/R
Valenzuela *et al*., (2015)	21 (11 ♂, 10 ♀)	Shod running @ SS (T) 3D motion analysis Force plate	RFS vs FFS (natural strike patterns)	VAP	P > 0.05	N/R
Sun *et al*., (2018)	12 ♂	Barefoot & Shod running @ 3m/s (O) Force plate Plantar pressure insole	RFS vs FFS (imposed FFS)	VAP	P > 0.05	N/R
				Time of VAP	Time of VAP occurred earlier in RFS shod than FFS shod (P < 0.01)*	N/R
Loading Rates						
Kulmala *et al*., (2013)	38 ♀	Shod running @ 4m/s (O) 3D motion analysis Force plate	RFS vs FFS (natural strike patterns)	VALR	VALR 47% greater in RFS (P = 0.001)*	ES: 2.44 Large
Kuhman *et al*., (2015)	16 ♂	Shod running @ 3.4m/s & 4.5m/s (O) 3D motion analysis Force plate	RFS vs FFS (imposed FFS)	VALR	VALR greater in RFS (P < 0.001)*	ES: 2.09 Large

Goss *et al*., (2013)	44 (18 ♂, 16 ♀)	Shod running @ SS (T) 3D motion analysis Instrumented treadmill 2D video camera	RFS vs Chi (imposed Chi)	VALR	VALR greater in RFS (P < 0.001)*	N/R
Shih *et al*., (2013)	12 ♂	Barefoot & Shod running @ 2.5m/s (T) 3D motion analysis Load-cells	RFS vs FFS (imposed FSS)	VALR	VALR greater in RFS BF & SH (P < 0.000)*	N/R
				VILR	VILR greater in RFS BF & SH (P < 0.000)*	N/R
Yong *et al*., (2018)	17 (6 ♂, 11 ♀)	Shod running @ SS (O) 3D motion analysis Force plate	RFS vs FFS (imposed FFS)	VALR	VALR greater in RFS (P < 0.05)*	N/R
				VILR	VILR greater in RFS (P < 0.05)*	N/R
Laughton *et al*., (2003)	15 (Gender N/R)	Shod running @ 3.7m/s (O) 3D motion analysis Accelerometer	RFS vs FFS (imposed FFS)	VALR	P = 0.99	N/R
Acceleration						
Laughton *et al*., (2003)	15 (Gender N/R)	Shod running @ 3.7m/s (O) 3D motion analysis Accelerometer	RFS vs FFS (imposed FFS)	Tibial PPA	Lower PPA in RFS (P = 0.034)*	N/R
Yong *et al*., (2018)	17 (6 ♂, 11 ♀)	Shod running @ SS (O) 3D motion analysis Force plate	RFS vs FFS (imposed FFS)	Tibial PPA	P > 0.05	N/R
Delgado *et al*., (2013)	43 (24 ♂, 19 ♀)	Barefoot running @ SS (T) Accelerometer	RFS vs FFS (imposed RFS & FFS)	Tibial PPA	Greater PPA in RFS (P < 0.001)*	N/R
				Shock attenuation	Greater shock attenuation in RFS (P < 0.001)*	N/R
Ruder *et al*., (2017)	222 (119 ♂, 103 ♀)	Shod running @ SS (O) 2D video analysis Accelerometer	RFS vs MFS vs FFS (natural strike patterns)	Tibial PPA	PPA greater in RFS & MFS than FFS (P = 0.01)*	N/R
Kinetics localised to the knee						
Vannatta *et al*., (2015)	16 ♀	Shod running @ 3.5m/s – 3.9m/s (O) 3D motion analysis Force plate	RFS vs FFS (imposed FFS)	Peak PFJS	PFJS 27% greater in RFS than FFS (P = 0.000)*	ES: 1.57 Large
Kulmala *et al*., (2013)	38 ♀	Shod running @ 4m/s (O) 3D motion analysis Force plate	RFS vs FFS (natural strike patterns)	PFCF	PFCF 16% greater in RFS (P = 0.01)*	ES: 0.69 Small
Willson *et al*., (2015)	20 (10 ♂, 10 ♀)	Shod running @ SS (T) 3D motion analysis Instrumented treadmill	RFS vs FFS (imposed strike patterns)	Peak PFJRF	PFJRF 13% greater in RFS (P < 0.001)*	N/R
				Peak PFJS	PFJS 12% greater in RFS (P < 0.001)*	N/R
Bowerstock *et al*., (2017)	19 (9 ♂, 10 ♀)	Shod running @ SS (T) 3D motion analysis Instrumented treadmill	RFS vs FFS (imposed FFS)	TFJ VALR	TFJ VALR 18% greater in RFS (P = 0.003)*	N/R
				TFJ peak force	P > 0.05	N/R
Kinetics localised to the Achilles						

Almonroeder *et al*., (2013)	19 ♀	Barefoot running @ 3.5-3.9m/s (O) 3D motion analysis Force plate	RFS vs NRFS (natural strike patterns)	Achilles tendon time to peak force	Time to peak force occurred later in RFS runners (P = 0.007)*	ES: 1.61 Large
				Achilles tendon VALR	P = 0.06	ES: 0.93 Large
				Achilles tendon peak force	P = 0.31	ES: 0.69 Small
				Achilles tendon VILR	P = 0.54	ES: 0.34 Small
Hashizume *et al*., (2017)	10 ♂	Barefoot running @ 3.3m/s (O) 3D motion analysis Force plate	RFS vs MFS vs FFS (imposed strike patterns)	Achilles tendon peak force	Achilles tendon peak force lower in RFS & MFS (P < 0.01)*	ES: 0.79 Moderate

♂: males; ♀: females; *N/R: not reported; (O): over-ground running; (T): treadmill running; SS: self-selected speed; RFS: rear-foot strike; MFS: mid-foot strike; FFS: fore-foot strike; NRFS: non rear-foot strike; PPA: peak positive acceleration; vGRF: vertical ground reaction force; VIP: vertical impact peak; VAP: vertical active peak; VALR: vertical average loading rate; VILR: vertical instantaneous loading rate; BF: barefoot running; SH: shod running; PFJS: patellofemoral joint stress; PFCF: patellofemoral contact force; PFJRF: patellofemoral joint reaction force; TFJ: tibiofemoral joint; (imposed x): strike pattern was imposed by participant; (natural strike patterns): strike patterns were the natural patterns demonstrated by the participants; * P significant at <0.05.*

2.4.5.2 Knee orientation and loading

Following on from foot strike kinematics and loading, this section will give a brief overview of how loading is affected by knee contact angles. Although knee kinematics and loading is a very well-studied area with regard to anterior cruciate ligament injuries and landing in team sports, there does not seem to be a vast quantity of research investigating this relationship directly in running. With respect to acute knee injuries specifically, it was reported in a systematic review, that landing from a jump with reduced knee flexion resulted in a relatively higher ground reaction force (Louw and Grimmer, 2006). One study which did focus on a vertical landing task, similar to that experienced by runners, utilized a swinging pendulum device to replicate foot-strike, where Lafortune, Hennig and Lake, (1996) demonstrated that an increase in knee flexion angle at impact from 0-40°, yielded a reduction in the vertical impact peak by 30%. A subsequent study by Potthast *et al*., (2010), using a similar swinging pendulum device, reported that knee contact angle explained 25% of the impact force. Furthermore, Potthast *et al*., (2010) noted that as knee angle increased from 0-40° of flexion, there was a decrease of 158N in the vertical impact peak. Landing with a more flexed knee angle is thought to provide a larger cushioning effect during initial contact, allowing greater compliance of the lower extremity (Lieberman, 2012), which has been explained by an increase in time by which the vertical velocity of the body's centre of mass is brought to zero (Milner, Hamill and Davis, 2007).

The studies above (Lafortune, Hennig and Lake, 1996; Potthast *et al.*, 2010) also investigated how knee contact angle affected impact acceleration, with contrary findings to how vertical impact peak was affected. Both Lafortune, Hennig and Lake, (1996) and Potthast *et al*., (2010) found greater tibial impact acceleration with increases in knee flexion angle. Lafortune, Hennig and Lake, (1996) in particular demonstrated a 57% increase in tibial impact acceleration as knee flexion increased from 0-40°. In support of this, Potthast *et al*., (2010) reported that tibial impact acceleration increased by up to 46% as knee flexion angle increased from 0-40°. These results are further ratified by Derrick, (2004), who suggested that for every 1° increase in knee flexion angle during heel-toe running, there would be a 0.27g increase in tibial impact acceleration. Interestingly, in a study by Milner, Hamill and Davis, (2007), runners with a history of tibial stress fracture (TSF) tended to land with a more flexed knee angle, which coincided with greater tibial impact acceleration, when compared to the lower knee flexion angles and tibial acceleration demonstrated by the uninjured control group (TSF: 13.7° knee flexion angle, 7.3g tibial impact acceleration vs Control: 11.9° knee flexion angle, 5.9g tibial impact acceleration). This mean difference of a 1.8° decrease in knee flexion angle at contact reflected a mean difference of 1.4g increase in tibial impact acceleration between the groups, which is almost three times the predicted increase that Derrick (2004) had hypothesized. Perhaps a history of injury, and more specifically a history of injury to the tibia, may heighten the influence that knee flexion angle at contact has on tibial impact acceleration. Unfortunately due to the retrospective nature of the study, it is not possible to determine if the kinematics at the knee were present before the injury or if they occurred as a result of the injury. This highlights the importance of conducting a prospective analysis of RRIs in conjunction with both kinematic and kinetic investigations.

2.5 Literature Review Summary

Running-related injuries (RRIs) are prevalent, with rates of 14-90% reported. This wide range is due to the broad heterogeneity of injury definitions, surveillance periods, and sample sizes within the literature. In terms of injury risk factors, both intrinsic and extrinsic risk factors were reviewed. For most factors examined in this review, there was limited and conflicting findings. To compound this further, there was a clear lack of large-scale prospective studies that explored RRI risk factors from a multifactorial perspective.

From an intrinsic point of view, previous injury appears to have the strongest predictive value as a potential intrinsic risk factor for RRI occurrence. Sex, age, running experience and BMI each have relatively limited evidence with conflicting findings to date, but perhaps these factors should be examined with a multifactorial approach, given the potential inter-play of these factors with each other.

Extrinsically, impact loading, running technique and training practices were reviewed. Regarding impact loading, load has been examined predominantly through vGRF analyses which is a measure of whole-body loading. Trends are evident which show a moderate relationship between the rate of loading and RRI (especially where never injured runners are concerned), but it is less clear if impact and active peaks relate to RRI. However, this approach to loading analysis does not reflect the loading on individual segments, because the distribution of loading is unlikely to be equal across segments. Therefore, segmental loading assessment, such as that via accelerometry, may provide greater insight. With reference to impact acceleration, it appears that female runners with a history of stress fracture may demonstrate greater peak tibial acceleration when compared to healthy controls. Additionally, runners with a history of injury also tend to have greater peak tibial acceleration in their affected side post injury. However, as the research is largely limited to retrospective analysis to date, we are unable to determine if peak tibial acceleration is the cause of injury or an effect of injury in these cases. There is quite clearly a lack of research in this area, particularly prospective studies and studies looking at the peak and rate of acceleration of multiple segments and RRIs. Further research is also needed to determine the short- and long-term reliability of these measures, especially at the sacrum and also for the rate of acceleration, as these factors have not been examined previously.

Regarding running kinematics and RRIs, the review suggested low levels of evidence for foot, knee, hip, pelvis and trunk kinematics and their relationship with injury. The overarching theme throughout this area was the lack of prospective research, limited sample sizes and the neglect of various planes (e.g. transverse plane) being studied, especially within the area of foot, pelvis and trunk kinematics. Given the influence that the trunk and pelvis have over the lower limbs, it is critical to consider these segments as part of the whole kinematic chain, and thus it is imperative to include these measures within furture RRI studies.

Lastly, with respect to training-related factors, this review found only limited evidence to suggest distance, duration, frequency and speed as risk factors for injury. The findings were inconsistent in direction with differences in outcome measures making comparisons between studies challenging. These factors are likely all inter-related, and as a result, should be studied simultaneously rather than individually.

Finally, while as stated above, there is a clear need for more prospective studies with large sample sizes, there may be value in undertaking retrospective studies that explore why those who never become injured are so protected from injury. Given the high prevalence of RRIs over a lifetime (90%), this group of runners provide a very unique insight as they possess characteristics that appear to produce a low risk of injury. In addition to this group, runners who do not become re-injured following a recent injury also provide for an insightful perspective on how injury risk can be lowered, especially with previous injury being the most consistent risk factor observed through the research. This group appear to have acquired injury resistance, and have not been studied within the literature previously. Should characteristics between these never injured and acquired injury resistance groups and groups of recently injured runners differ, targeted injury rehabilitation practices will become more effective, ultimately with the aim of preventing injuries over time. The knowledge and insight from this retrospective outlook, combined with the findings from prospective studies, will allow for researchers and clinicians to make more informed judgements on what factors may be cause or effect of RRIs.

Chapter 3 Study 1 - Relative and Absolute Reliability of Shank and Sacral Running Impact Accelerations over a Short- and Long-Term Time Frame

Burke, A., Dillon, S., O'Connor, S., Whyte, E., Gore, G., Moran, K., 2022. Relative and Absolute Reliability of Shank and Sacral Running Impact Accelerations over a Short- nd Long-Term Time Frame. *Sports Biomechanics*. https://doi.org/10.1080/14763141.2022.2086169.
[Link for document when it goes live for publication].

3.1 Abstract

Introduction Whilst running is hugely popular, running-related injuries (RRIs) are prevalent. High impact loading has been proposed to contribute to RRIs, with accelerometers becoming increasingly popular in estimating segmental loading for injury detection and biofeedback training. However, there is a lack of research examining the reliability of measures of impact acceleration across short- and long-term time periods, both prior to and following exerted running. The aim of this study was to assess the absolute and relative reliability of shank and sacral impact accelerations over a short- and long-term time period.

Methods Peak ($Peak_{accel}$) and rate ($Rate_{accel}$) of impact acceleration at the shank and sacrum were assessed in 18 recreational runners over short- and long-term time frames, across fixed and self-selected speeds. The relative and absolute reliability were investigated for pre- and post-exerted states of running.

Results There was high to excellent relative reliability, and predominantly moderate absolute reliability for shank and sacrum $Peak_{accel}$ and $Rate_{accel}$ in the short- and long-term time frames between pre- and post-exerted states.

Conclusion High to excellent relative reliability of $Peak_{accel}$ and $Rate_{accel}$ at the shank and sacrum indicates that these are appropriate and acceptable measures across short- and long-term time frames. These findings were consistent in different levels of speed and exertion. The minimal detectable change % was large for both sensors and associated measurements, indicating that their use may be limited to intervention studies that elicit large change (>30%) in these measures.

3.2 Introduction

Running is a hugely popular form of exercise worldwide with several associated cardiovascular, respiratory and mental health benefits (Hespanhol Junior *et al.*, 2015). However, running has a high prevalence and incidence of running-related injuries (RRIs) (Messier *et al.*, 2018). While the aetiology of RRIs may be multifactorial in nature, high impact loading is frequently hypothesized as a potential risk factor (Milner *et al.*, 2006; Davis, Bowser and Mullineaux, 2010). Studies exploring the relationship between impact loading and RRIs, and how biofeedback on impact loading may reduce the likelihood of RRIs, have predominantly focused on various components of the vertical ground reaction force (vGRF) at impact (Milner *et al.*, 2006; Pohl, Davis and Hamill, 2007; Crowell and Davis, 2011). There are two limitations with the use of vGRF in RRI research however. Firstly, vGRFs reflect loading at a whole-body level, while injuries occur at a localised level. Secondly, vGRF based research is restricted to the laboratory setting, thus restricting its ecological validity.

More recently, wearable accelerometer sensors have been adopted for load analysis at a localised segmental level, as they provide a low cost and user-friendly alternative to force plates and instrumented treadmills (Sheerin *et al.*, 2016). Since force is equal to the product of mass and acceleration, acceleration analysis has been used extensively to infer segmental loading (Van den Berghe *et al.*, 2019). Retrospective studies using accelerometers have found peak axial accelerations at the shank to be significantly greater in injured runners compared to uninjured runners (Ferber *et al.*, 2002; Milner *et al.*, 2006), and in injured limbs compared to uninjured limbs (Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008). However, there is a scarcity of research on the reliability of such accelerometer devices, especially in relation to the sacrum and with regard to fatigue (over long periods of time). If such injury-related research is to be realised, it is essential to know how consistent (reliable) impact acceleration measures from the shank and the sacrum are over short- and long-term time frames. If impact accelerations taken at baseline remain consistent over the course of a prospective trial then only baseline assessment would be required, thereby reducing cost and participant recruitment challenges. However, if impact accelerations change over time, for example due to natural changes in technique or changes in trained status, then there will be a need for more frequent assessment up to the point of injury.

While impact loading has been found to relate to injury, this risk may be further compounded by exertion (Gerlach *et al.*, 2005), with several studies finding impact loading and accelerations to increase following exerted running (Mizrahi *et al.*, 2000; Dierks *et al.*, 2011; Schütte *et al.*, 2018). In one study in particular, shank $Peak_{accel}$ increased by up to 13% following an exertional protocol in runners with patellofemoral pain syndrome, while the uninjured runners demonstrated much smaller changes (2%) in shank $Peak_{accel}$ (Dierks *et al.*, 2011). Interestingly, some studies have found major effects of fatigue on impact acceleration in healthy runners (up to 61%) (Mizrahi *et al.*, 2000; Derrick, Dereu and McLean, 2002), with others finding no major change following exertional protocols (Reenalda *et al.*, 2019; Izquierdo-Renau *et al.*, 2020), which may indicate an issue with reliability. Therefore, it is important to explore not only the reliability of impact acceleration analysis over short- and long-term time frames during non-exerted running, but also following exerted running. To the authors' knowledge, no previous studies have determined the reliability of impact accelerations when in an exerted state.

Thus far, there are relatively few studies which have explored the reliability of impact accelerations during running, with the majority of studies focusing on the magnitude of impact acceleration ($Peak_{accel}$) at the shank (Sheerin *et al.*, 2018; Hughes *et al.*, 2019; Van den Berghe *et al.*, 2019). Only two studies to date have looked at the reliability of shank $Peak_{accel}$ at and beyond one week (Sheerin *et al.*, 2018; Van den Berghe *et al.*, 2019), with only one of those extending to a long-term time frame of six months (Sheerin *et al.*, 2018). The choice of tibial $Peak_{accel}$ is presumably due to the high prevalence of lower limb injuries in running. However, only one study has investigated reliability of $Peak_{accel}$ at the sacrum over a one day period (Lindsay, Yaggie and McGregor, 2016), despite more proximal injuries being common in running (e.g. lower back injuries) (Ellapen *et al.*, 2013). As sacral accelerations have been found to be reflective of vGRF loading (LeBlanc *et al.*, 2021), inertial measurement devices worn at this location may therefore provide for a very useful transition towards an ecologically valid and clinically useful measure of loading.

To compound the paucity of research in this area further, no studies have examined the reliability of the rate of acceleration ($Rate_{accel}$) for the shank or sacrum. As stated previously, force is the product of mass and acceleration, thus acceleration is directly proportional to force. Given that the rate of force development has been shown to be more related to RRI than the peak (Van Der Worp, Vrielink and Bredeweg, 2016), there is possibly a need to examine the rate of acceleration (technically referred to as *jerk*) in RRI research. This study referred to jerk as $Rate_{accel}$ so that there is better alignment and ease of interpretation. First and foremost however, it is imperative to investigate the consistency of impact accelerations over both short- (e.g. 1 week) and long-term (e.g. 6 months) time frames.

Two important aspects of reliability are relative and absolute reliability (Atkinson and Nevill, 1998). If impact accelerations have high relative reliability the rank ordering of the runners within the population group will remain consistent over time. This would be important when examining the relationship between impact accelerations examined at baseline and prospective injuries which occur at a later time point, and provides confidence in the instrument being used (i.e. impact accelerometer). Therefore, for repeated measurements on a continuous scale whereby the objective concerns the distinction of people, relative reliability has been reported to be the most appropriate parameter (de Vet *et al*., 2006). Absolute reliability refers to the degree of consistency in measures of individuals (Weir, 2005) and are particularly important when a person's results are being compared to determine a change in health status, for example due to injury, and in gait re-training or biofeedback interventions (Cheung and Davis, 2011).

The primary objective of this study was therefore to assess the relative and absolute reliability of shank and sacral impact accelerations (both peak and rate) over the course of a short-term (1 week) and long-term (6 month) time period. Additionally, a secondary aim was to determine if the impact acceleration measures are consistent while in an exerted state over the same time periods. We hypothesize that there will be good relative and absolute reliability of the shank and sacrum over the course of a short- and long-term time period.

3.3 Methods

3.3.1 Participants and Study Design

Testing took place in a biomechanics laboratory on three separate occasions: Baseline, Week 1 and Month 6 (Figure 3.3.1). Laboratory testing conditions (treadmill, treadmill speed, air temperature, footwear) were identical for each session (Baseline, Week 1 and Month 6). *An a-priori* statistical power analysis was performed to determine the required sample size to achieve a statistical power of 0.80 with an alpha level of 0.05 (Erdfelder, Faul and Buchner, 1996). $Peak_{accel}$ data from a study investigating the effects of exertion on impact acceleration were used (Derrick, Dereu and McLean, 2002), and it was determined that a sample size of at least 15 subjects would be required. Ethical Approval was granted from the Dublin City University Research Ethics Committee (DCUREC/2019/127). A convenience sample of 20 recreational runners who were injury-free at baseline were then recruited via email, allowing for drop-out and any injuries that may restrict participation within 6 months. Participants completed a Physical Activity Readiness Questionnaire (PAR-Q) and signed an informed consent form on their initial visit to the laboratory. Height (m) (Leicester Height Measure, SECA, UK), body mass (kg) (SECA, UK), and limb dominance were recorded. Limb dominance was determined as the leg that the participant would choose to kick a football (Brown, Zifchock and Hillstrom, 2014).

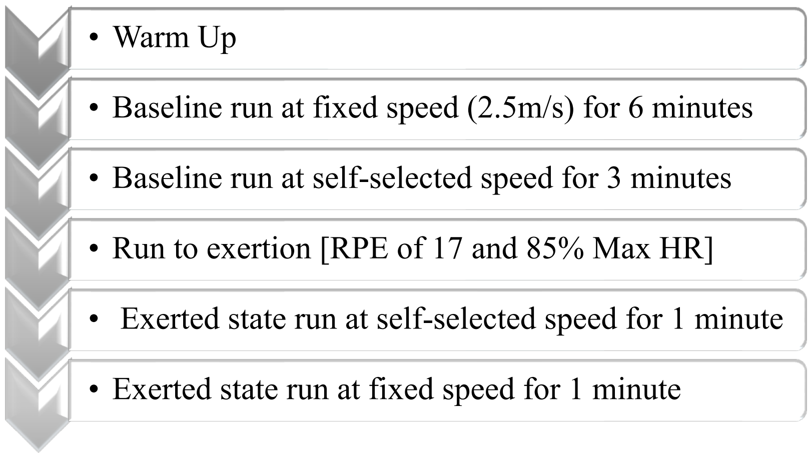

Figure 3.3.1 Repeatability study protocol flow-chart.

m/s: metres per second; RPE: rating of perceived exertion; Max: maximum; HR: heart rate.

Inertial sensors (Shimmer3 IMU, Shimmer, Ireland) containing accelerometers with a sampling rate of 512Hz and a measurement range of ±16g were used to capture the peak and rate of axial acceleration of the shanks bilaterally, as well as for the sacrum. Axial acceleration was examined as this has been the most frequently reported in previous literature (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008). Two inertial measurement units were attached bilaterally 5 cm proximal to the medial malleolus using double-sided sticky tape, with the y-axis of the sensor aligned with the long axis of the shank (Sheerin *et al.*, 2018). They were then tightly secured using Hypafix adhesive tape which wrapped and adhered directly to the skin. The sacrum sensor was held in place within a custom-made elastic belt, with the longitudinal axis aligned

to the vertical midline of the S2 spinous process (O Catháin, Richter and Moran, 2020). The belt was attached to the skin over the sacrum using double-sided sticky tape, and this was secured further by tape and an elastic waistband on top. Securing the inertial sensors with double-sided sticky tape and wrapping has been found to be more representative of tibial accelerations when compared to less secure methods such as the manufacturer provided straps (Johnson *et al.*, 2020). For consistency, the same researcher (SD) secured the shank and sacrum accelerometers for all participants at every testing session. Participants wore their normal running shoes. Running trials were conducted on a treadmill (Flow Fitness, Runner DTM3500i, The Netherlands) at two speeds: fixed speed (2.5m/s) and at a self-selected running speed. The fixed speed of 2.5m/s was chosen to allow for comparison of impact accelerations without the confounding factor of variations in speed affecting the participants' technique. This speed represented the average five-kilometre time of runners in the greater Dublin area, determined from the average speed reported on the Dublin Park Run database (www.parkrun.ie/events), and replicated the pace chosen in the [redacted for blind review] prospective injury study (NCT03671395 www.clinicaltrials.gov). Following the initial fixed speed run, participants ran at a self-selected speed. Participants were instructed to run at a speed that felt similar to their self-selected over-ground running speed for a normal 5km run. To ensure that participants selected a speed based on perception, the speed of the treadmill was only visible to the investigators. Participants were allowed to adjust the speed up or down until they felt that they had found a speed that was most reflective of their over-ground running speed (Kong, Candelaria and Tomaka, 2009).

During the baseline session, once sensors had been attached and secured, participants completed a 5 minute warm up consisting of dynamic stretches for the hamstrings, quadriceps, hip flexors, hip extensors and calf muscle groups (Yamaguchi, Takizawa and Shibata, 2015). Once the warm-up was complete, participants ran initially at a fixed speed of 2.5m/s for 6 minutes for familiarisation to treadmill running (Lavcanska, Taylor and Schache, 2005). Following this, participants ran at a self-selected speed for 3 minutes. Speed was then incrementally increased by 0.6m/s every three minutes (Steib *et al.*, 2013) for the run to an exerted state. At various points throughout the running protocol, heart rate was measured using a Polar Heart Rate Monitor (Polar Electro GmbH, Büttelborn, Germany) and Rate of Perceived Exertion (RPE) was assessed using the 13-point Borg Scale (Borg, 1970). These measures were monitored every three minutes, until an RPE of 15 was achieved, after which both measures were recorded every minute. Prior to beginning the run, participants were familiarised with the Borg Scale using the standard instructions provided by Borg (1970). Participants remained unaware of the stopping criteria and continued running at the incremental pace until they achieved both an RPE of 17 (very hard) and 85% of their heart rate maximum as determined by the Karvonen formula (Bazett-jones *et al.*, 2013). Following the completion of the exerted run, participants were recorded running at their self-selected speed for one minute and a further one minute at a fixed speed of 2.5m/s. Participants completed the same protocol exactly one week later, and subsequently six months later, provided they had not sustained a musculoskeletal injury in the time between these sessions. Participants were asked to wear the same shoes and training garments that they had worn to the initial session. These sessions took place at an identical time of day, room temperature testing and self-selected speeds as the baseline session, and the exact same Shimmer 3 IMU unit used for each segment on each participant across the three sessions.

3.3.2 Data Processing

Axial $Peak_{accel}$ and $Rate_{accel}$ of the shanks and sacrum were processed using a custom-built MATLAB script (Mathworks Inc., Natick, MA, USA). A fourth order, zero lag 60 Hz Butterworth filter was applied to the data, as documented in previous research (Sheerin *et al.*, 2018) and dropped packets were filled using a cubic spline. To ensure functionally equivalent values were extracted from the shank and sacrum sensors, the time series data were time-aligned via Shimmer software. $Peak_{accel}$ was taken as the maximal amplitude of the accelerometer's transient at initial contact and was expressed in units of standard gravity ($g = 9.8\ m/s^2$). A series of pilot studies were conducted to identify initial contact utilizing a pressure sensitive switch in combination with inertial sensors, identifying robust patterns within the data. Initial contact was identified using the tibial accelerometer as the local maxima preceding the $Peak_{accel}$. $Rate_{accel}$ (technically referred to as *jerk*) was calculated as the slope of the $Peak_{accel}$ (Figure 3.3.2). Ten consecutive foot-strikes for each of the following conditions were processed on both dominant and non-dominant limbs: non-exerted fixed speed of 2.5m/s (foot strikes taken within the last minute of the six minute trial), non-exerted self-selected speed, exerted self-selected speed, and exerted fixed speed of 2.5m/s.

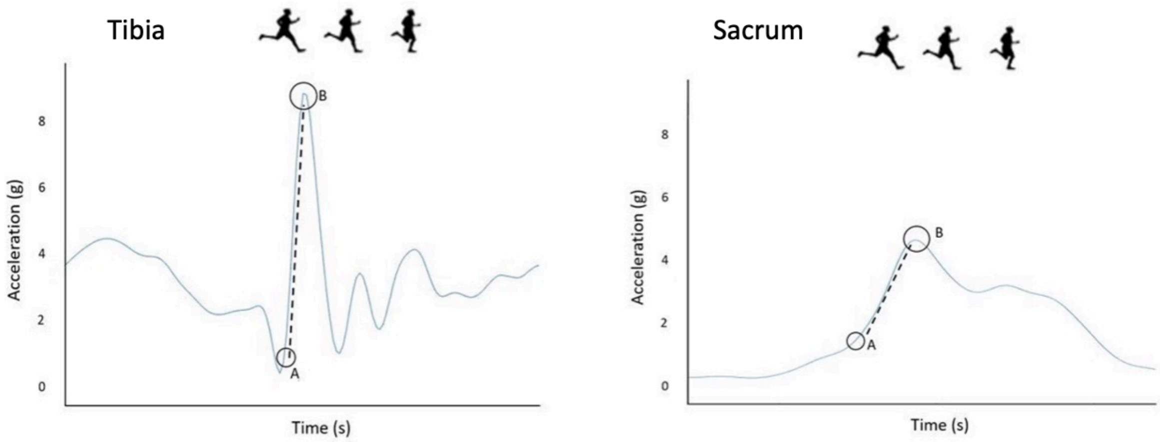

Figure 3.3.2 Trace of $Peak_{accel}$ and $Rate_{accel}$ for the shank (left) and sacrum (right).

(A): initial contact detected; dotted line - - - -: $Rate_{accel}$, which was calculated as the slope of the peak (B).

3.3.3 Statistics

Group means and standard deviations were calculated for the $Peak_{accel}$ and $Rate_{accel}$ of the sacrum and the two shanks. These values were analysed across all speeds and were compared between baseline, one week and six months. Data were screened for normality using boxplots and outliers were removed if values were >1.5 times the interquartile range from the median. A paired t-test was conducted to determine if any significant differences existed between dominant and non-dominant limbs, finding no significant differences existing between limbs. The reliability of individual limbs (i.e. dominant limb compared with dominant limb, and non-dominant limb compared with non-dominant limb) was assessed initially. The average (pooled mean) of the two limbs (dominant and non-dominant) was then assessed for reliability. Since no differences were found between individual limb versus pooled limb reliability, the results of this study will be presented for the pooled limb analysis only, in order to reduce the quantity of metrics and tables produced.

In order to determine a measurement of reliability, the test-retest relative reliability of impact accelerations, single measures of the intraclass correlation coefficient ($ICC_{2,1}$) were calculated using a two-way, mixed-effects model, with absolute agreement (Koo and Li, 2016). In accordance with de Vet *et al*., (2006), absolute agreement analysis formed the framework for test-retest absolute reliability, and was calculated using Cohen's d effect size (Cohen, 2013), standard error of measurement (SEM), (Weir, 2005) and minimal detectable change (MDC) (Wyrwich and Wolinsky, 2000). Calculations were as follows:

Relative Reliability

$ICC_{2,1}$: $(MS_R - MS_E)/(MS_R + ((k-1)*MS_E))$

MS_R: mean square for rows; MS_E: mean square for error; k: number of time points

Absolute Reliability/Absolute Agreement

Cohen's d Effect Size: $(\text{Mean}_1 - \text{Mean}_2)/SD_{Pooled}$

Pooled Standard Deviation (SD_{Pooled}): $\sqrt{((SD_1^2 + SD_2^2)/2)}$

Standard Error of Measurement (SEM): $SD_{Pooled} \times \sqrt{(1-ICC_{2,1})}$

SEM %: SEM/(Mean of Test and Retest values) x 100

Minimal Detectable Change (MDC): $1.96 \times \sqrt{2} \times SEM$

MDC %: MDC/Mean of Test and Retest values x 100

$ICC_{2,1}$ reliability was categorized as: poor (<0.5), moderate (0.5 ≤ 0.7), high (0.7 ≤ 0.9) and excellent (>0.9) (Munro, Visintainer and Page, 1986). Cohen's d effect size was interpreted as: trivial (0.0 - 0.19), small (0.2 - 0.59), moderate (0.6 – 1.19), large (1.2 – 1.99), or very large (≥2) (Batterham and Hopkins, 2006). Lower values of Cohen's d indicate greater absolute reliability, with trivial or small effect sizes indicative of acceptable absolute reliability (Sheerin *et al.*, 2018). With respect to SEM, the smaller the SEM the greater the absolute reliability. SEMs were expressed as a percentage of the mean, with SEM% <20% being regarded as acceptable (Santos *et al.*, 2008; Barbado, Moreside and Vera-Garcia, 2017). MDC assesses the minimal magnitude of change required to be 95% confident that the observed change between the sessions reflects true change, and not measurement error (Trouli *et al.*, 2008). Low MDC values indicate better absolute reliability, with a cut-off of <10% signifying acceptable change (Hughes *et al.*, 2019). In order to determine an overall rating of absolute reliability, the three measures of absolute reliability (effect sizes, SEM% and MDC%) were assessed for acceptability. If all three measures met acceptable cut-off ranges, the absolute reliability was classified as good. If two of the three measures met acceptable cut-off ranges, the absolute reliability was moderate, and if one or none of the three measures met acceptable cut-off ranges, absolute reliability was classified as being poor.

3.4 Results

Twenty male and female recreational runners volunteered to participate in this study. Two participants were excluded due to being injured between sessions (Male: n = 1; Female: n = 1). A total of 18 participants were included in the full analysis across the three time points. Demographics of the participants and details of the three running sessions can be viewed in Table 3.4.1. The mean self-selected running speed was 2.9 ± 0.2m/s (range: 2.6 – 3.3m/s).

Table 3.4.1 Demographics of participants

	All (n:18) Mean ± SD	**Male (n: 9)** Mean ± SD	**Female (n: 9)** Mean ± SD
Age (years)	23.5 ± 6.3	23.9 ± 8.1	23.3 ± 3.7
Height (cm)	171.4 ± 10.1	177.7 ± 8.2	165.1 ± 7.8
Weight (kg)	70.8 ± 13.7	82.0 ± 8.4	59.6 ± 6.7
Self Selected Speed (m/s)	2.9 ± 0.2	3.0 ± 0.2	2.8 ± 0.2
Duration of Run at Baseline (mm:ss)	18:55 ± 2:12	20:07 ± 2:22	18:23 ± 2:38
Duration Run at Week 1 (mm:ss)	19:07 ± 2:19	20:13 ± 2:24	18:26 ± 2:33
Duration of Run at Month 6 (mm:ss)	18:52 ± 2:21	19:53 ± 2:47	18:48 ± 03:23

n: number; SD: standard deviation; cm: centimetres; kg: kilograms; m/s: metres per second; mm:ss: minutes:seconds

Regarding non-exerted shank $Peak_{accel}$, relative reliability was high for both short-term (ST) and long-term (LT) time frames (Table 3.4.2). The trivial effect sizes, SEM% <20%, and MDC% >10% indicate an overall moderate level of absolute reliability across both fixed and self-selected speeds in the non-exerted state. When in an exerted state, $Peak_{accel}$ of the shank also demonstrated high relative reliability for both ST and LT time frames (Table 3.4.2). The trivial effect sizes, SEM% <20%, and MDC% >10% indicate an overall moderate level of absolute reliability for both fixed and self-selected speeds in the exerted state.

For non-exerted shank $Rate_{accel}$, relative reliability was excellent ST and high to excellent LT (Table 3.4.3). The trivial effect sizes, SEM% both <20% and >20%, combined with MDC% >10% indicate a poor to moderate level of absolute reliability, with LT speed shank $Rate_{accel}$ demonstrating the more unacceptable levels of absolute reliability. Exerted state $Rate_{accel}$ of the shank exhibited excellent ST and LT relative reliability through the post-exertion state (Table 2). The trivial effect sizes, SEM% <20% and MDC% >10% indicate a moderate level of absolute reliability across both fixed and self-selected speeds in the exerted state.

With respect to non-exerted sacrum $Peak_{accel}$, relative reliability was high ST and high to excellent LT (Table 3.4.4). The trivial to small effect sizes, SEM% <20%, and MDC% >10% indicate a moderate level of absolute reliability for both fixed and self-selected speeds in the non-exerted state. Exerted state $Peak_{accel}$ of the sacrum demonstrated high ST and LT relative reliability. The trivial to small effect sizes, SEM% <20%, and the MDC >10% indicate a moderate level of absolute reliability across both fixed and self-selected speeds in the exerted state.

Lastly, non-exerted sacrum $Rate_{accel}$ demonstrated high ST and LT relative reliability (Table 3.4.5). The trivial effect sizes, SEM% <20%, and the MDC% >10% indicate a moderate level of absolute reliability across both fixed and self-selected speeds in the non-exerted state. Exerted state $Rate_{accel}$ at the sacrum demonstrated high to excellent ST, and high LT relative reliability (Table 3.4.5). The trivial to small effect sizes, SEM% <20%, and the MDC% >10% indicate a moderate level of reliability across both fixed and self-selected speeds in the exerted state.

Despite the findings of high to excellent relative reliability across time points for both the shank and sacrum, it should be noted that $ICC_{95\%}$ confidence intervals had a wide range, as demonstrated in Tables 3.4.2 – 3.4.5.

Table 3.4.2 Results of test-retest reliability for shank Peak$_{accel}$.

	Non-exerted fixed speed	**Non-exerted SS**	**Exerted fixed speed**	**Exerted SS**
Baseline vs Week 1				
Baseline mean ± SD (g)	6.42 ± 2.15	7.21 ± 2.26	7.00 ± 2.28	8.02 ± 2.68
Week 1 mean ± SD (g)	6.70 ± 2.40	7.38 ± 2.38	7.03 ± 2.29	8.20 ± 2.88
Mean Difference (g)	0.28	0.17	0.03	0.18
ICC (95% CI)	0.80 (0.55 - 0.92)	0.81 (0.56 - 0.92)	0.82 (0.58 - 0.93)	0.81 (0.56 - 0.92)
Relative reliability rating	High	High	High	High
Effect size (Cohen's d)	0.13 [Trivial] - A	0.07 [Trivial] - A	0.01 [Trivial] - A	0.07 [Trivial] - A
Standard Error of Measurement; g (%)	1.0 (15.5%) - A	1.0 (13.9%) - A	1.0 (13.8%) - A	1.2 (14.9%) - A
Minimal Detectable Change; g (%)	2.8 (42.9%) - UA	2.8 (38.4%) - UA	2.7 (38.3%) - UA	3.4 (41.4%) - UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate
Baseline vs Month 6				
Baseline mean ± SD (g)	6.42 ± 2.15	7.21 ± 2.26	7.00 ± 2.28	8.02 ± 2.68
Month 6 mean ± SD (g)	6.90 ± 2.80	7.59 ± 2.48	7.10 ± 2.88	8.41 ± 3.12
Mean Difference (g)	0.48	0.38	0.10	0.39
ICC (95% CI)	0.79 (0.54 - 0.92)	0.86 (0.68 - 0.95)	0.84 (0.61 - 0.94)	0.90 (0.76 - 0.96)
Relative reliability rating	High	High	High	High
Effect size (Cohen's d)	0.19 [Trivial] - A	0.16 [Trivial] - A	0.04 [Trivial] - A	0.13 [Trivial] - A
Standard Error of Measurement; g (%)	1.1 (17.0%) - A	0.9 (11.9%) - A	1.0 (14.6%) - A	0.9 (11.2%) - A
Minimal Detectable Change; g (%)	3.1 (47.2%) - UA	2.4 (32.9%) - UA	2.9 (40.6%) - UA	2.5 (30.9%) - UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate

SS: self-selected speed; SD: standard deviation; g: g force; ICC: intraclass correlation coefficient; A: acceptable level of absolute reliability; UA: unacceptable level of absolute reliability.

Table 3.4.3 Results of test-retest reliability for shank Rate$_{accel}$.

	Non-exerted fixed speed	**Non-exerted SS**	**Exerted fixed speed**	**Exerted SS**
Baseline vs Week 1				
Baseline mean ± SD (g/s)	547.22 ± 231.03	654.40 ± 276.70	774.92 ± 299.48	890.35 ± 344.42
Week 1 mean ± SD (g/s)	560.76 ± 291.60	623.98 ± 250.68	762.74 ± 295.14	898.93 ± 344.05
Mean Difference (g/s)	13.54	30.42	12.18	8.58
ICC (95% CI)	0.94 (0.85 - 0.98)	0.92 (0.79 - 0.97)	0.92 (0.79 - 0.97)	0.94 (0.84 - 0.98)
Relative reliability rating	Excellent	Excellent	Excellent	Excellent
Effect size (Cohen's d)	0.05 [Trivial] - A	0.12 [Trivial] - A	0.04 [Trivial] - A	0.03 [Trivial] - A
Standard Error of Measurement; g/s (%)	64.0 (11.6%) - A	74.6 (11.7%) - A	84.1 (10.9%) - A	84.3 (9.4%) - A
Minimal Detectable Change; g/s (%)	177.4 (32.0%) - UA	206.7 (32.3%) - UA	233.1 (30.3%) - UA	233.7 (26.1%) - UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate
Baseline vs Month 6				
Baseline mean ± SD (g/s)	547.22 ± 231.03	654.40 ± 276.70	774.92 ± 299.48	890.35 ± 344.42
Month 6 mean ± SD (g/s)	592.60 ± 339.98	667.41 ± 281.02	786.76 ± 396.81	924.13 ± 414.93
Mean Difference (g/s)	45.38	13.01	11.84	33.78
ICC (95% CI)	0.83 (0.61 - 0.93)	0.92 (0.80 - 0.97)	0.91 (0.77 - 0.97)	0.94 (0.86 - 0.98)
Relative reliability rating	High	Excellent	Excellent	Excellent
Effect size (Cohen's d)	0.16 [Trivial] - A	0.05 [Trivial] - A	0.03 [Trivial] - A	0.09 [Trivial] - A
Standard Error of Measurement; g/s (%)	117.7 (20.7%) - UA	78.9 (11.9%) - A	104.4 (13.4%) - A	93.0 (10.3%) - A
Minimal Detectable Change; g/s (%)	326.3 (57.3%) - UA	218.6 (33.1%) - UA	289.5 (37.1%) - UA	257.8 (28.4%) - UA
Absolute reliability rating	Poor	Moderate	Moderate	Moderate

SS: self-selected speed; SD: standard deviation; g/s: g force units per second; ICC: intraclass correlation coefficient; A: acceptable level of absolute reliability; UA: unacceptable level of absolute reliability.

Table 3.4.4 Results of test-retest reliability for sacrum Peak$_{accel}$.

	Non-exerted fixed speed	**Non-exerted SS**	**Exerted fixed speed**	**Exerted SS**
<u>Baseline vs Week 1</u>				
Baseline mean ± SD (g)	3.59 ± 0.75	3.77 ± 0.81	3.79 ± 0.63	3.79 ± 0.82
Week 1 mean ± SD (g)	3.55 ± 0.65	3.81 ± 0.67	3.81 ± 0.67	3.81 ± 0.75
Mean Difference (g)	0.04	0.04	0.02	0.02
ICC (95% CI)	0.81 (0.55 - 0.93)	0.73 (0.38- 0.89)	0.85 (0.64 - 0.94)	0.85 (0.63 - 0.94)
Relative reliability rating	High	High	High	High
Effect size (Cohen's d)	0.06 [Trivial] - A	0.05 [Trivial] - A	0.03 [Trivial] - A	0.03 [Trivial] - A
Standard Error of Measurement; g (%)	0.3 (8.6%) - A	0.4 (10.2%) - A	0.3 (6.6%) - A	0.3 (8.0%) - A
Minimal Detectable Change; g (%)	0.9 (23.7%) - UA	1.1 (28.1%) - UA	0.7 (18.4%) - UA	0.8 (22.2%) - UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate
<u>Baseline vs Month 6</u>				
Baseline mean ± SD (g/s)	3.59 ± 0.75	3.77 ± 0.81	3.79 ± 0.63	3.79 ± 0.82
Month 6 mean ± SD (g/s)	3.65 ± 0.69	3.97 ± 0.80	3.83 ± 0.73	3.96 ± 0.77
Mean Difference (g/s)	0.06	0.20	0.05	0.17
ICC (95% CI)	0.94 (0.85 - 0.98)	0.87 (0.66 - 0.95)	0.87 (0.69 - 0.95)	0.86 (0.64 - 0.95)
Relative reliability rating	Excellent	High	High	High
Effect size (Cohen's d)	0.08 [Trivial] - A	0.25 [Small] - A	0.07 [Trivial] - A	0.22 [Small] - A
Standard Error of Measurement; g (%)	0.2 (4.9%) - A	0.3 (7.5%) - A	0.3 (6.4%) - A	0.3 (7.7%) - A
Minimal Detectable Change; g (%)	0.5 (13.5%) - UA	0.8 (20.8%) - UA	0.7 (17.8%) - UA	0.8 (21.3%) - UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate

SS: self-selected speed; SD: standard deviation; g: g force; ICC: intraclass correlation coefficient; A: acceptable level of absolute reliability; UA: unacceptable level of absolute reliability.

Table 3.4.5 Results of test-retest reliability for sacrum $Rate_{accel}$.

	Non-exerted fixed speed	Non-exerted SS	Exerted fixed speed	Exerted SS
Baseline vs Week 1				
Baseline mean ± SD (g/s)	237.71 ± 88.25	240.76 ± 72.51	264.62 ± 88.71	299.76 ± 50.91
Week 1 mean ± SD (g/s)	232.85 ± 85.03	250.25 ± 62.28	260.44 ± 93.73	319.48 ± 66.18
Mean Difference (g/s)	4.86	9.49	4.18	19.72
ICC (95% CI)	0.89 (0.73 - 0.96)	0.86 (0.65 - 0.94)	0.96 (0.90 - 0.99)	0.79 (0.47 - 0.92)
Relative reliability rating	High	High	Excellent	High
Effect size (Cohen's d)	0.06 [Trivial] A	0.14 [Trivial] A	0.05 [Trivial] A	0.33 [Small] A
Standard Error of Measurement; g/s (%)	28.7 (12.2%) A	25.2 (10.3%) A	12.9 (4.9%) A	26.8 (8.7%) A
Minimal Detectable Change; g/s (%)	79.7 (33.9%) UA	69.9 (28.5%) UA	35.8 (13.6%) UA	74.4 (24.0%) UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate
Baseline vs Month 6				
Baseline mean ± SD (g/s)	237.71 ± 88.25	240.76 ± 72.51	264.62 ± 88.71	299.76 ± 50.91
Month 6 mean ± SD (g/s)	228.85 ± 72.16	241.64 ± 58.68	258.44 ± 75.34	315.24 ± 58.58
Mean Difference (g/s)	8.86	0.88	6.18	15.48
ICC (95% CI)	0.88 (0.71 - 0.96)	0.81 (0.55 - 0.93)	0.84 (0.62 - 0.94)	0.86 (0.59 - 0.95)
Relative reliability rating	High	High	High	High
Effect size (Cohen's d)	0.11 [Trivial] A	0.01 [Trivial] A	0.08 [Trivial] A	0.28 [Small] A
Standard Error of Measurement; g/s (%)	27.8 (11.9%) A	28.6 (11.9%) A	32.8 (12.6%) A	20.5 (6.7%) A
Minimal Detectable Change; g/s (%)	77.0 (33.0%) UA	79.3 (32.9%) UA	90.9 (34.8%) UA	56.8 (18.5%) UA
Absolute reliability rating	Moderate	Moderate	Moderate	Moderate

SS: self-selected speed; SD: standard deviation; g/s: g force units per second; ICC: intraclass correlation coefficient; A: acceptable level of absolute reliability; UA: unacceptable level of absolute reliability.

3.5 Discussion

The purpose of this study was two-fold; firstly, to assess the test-retest relative and absolute reliability of axial $Peak_{accel}$ and $Rate_{accel}$ estimates of the shank and sacrum across both short- (1 week) and long-term (6 months) time periods, and secondly, to assess if these reliability measures remain consistent whilst in an exerted state.

With respect to the primary aim, this study demonstrated high to excellent short- and long-term relative reliability for shank and sacrum $Peak_{accel}$ and $Rate_{accel}$ across both fixed and self-selected speeds in the non-exerted state, with shank $Rate_{accel}$ demonstrating the greatest relative reliability of all components. These findings indicate that both shank and sacral $Peak_{accel}$ and $Rate_{accel}$ are reliable measures for retaining the rank ordering of a given population. Given the proposed relationship between impact accelerations and running-related injuries (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008), our findings suggest it is appropriate to use a single baseline assessment of shank and sacrum $Peak_{accel}$ and $Rate_{accel}$ for prospective studies, at least up to the six month mark in recreational runners. Studies should examine if this reliability extends beyond six months.

With regard to comparing these results to previous studies, the findings of high relative reliability for $Peak_{accel}$ at the shank were similar to Hughes *et al*., (2019), slightly higher than Van den Berghe *et al*., (2019), and lower than Sheerin *et al*., (2018). The higher reliability observed by Sheerin *et al*., (2018) may be due to them analysing experienced male runners who might have had greater consistency in their gait than the mixed sex population of recreational runners in this study; while lower reliability observed by Van den Berghe *et al*., (2019) might have been as a result of various methodological differences such as surface (over-ground) and/or the low number of trials analysed (3 foot-strikes versus 10 in our study). Only one previous study has assessed the relative reliability of $Peak_{accel}$ at the sacrum, with similar findings to the results of this study (Lindsay, Yaggie and McGregor, 2016). No previous studies have examined the reliability of $Rate_{accel}$. Studies investigating impact loading through vertical ground reaction force (vGRF) analysis have typically found greater reliability than those reported here and elsewhere for segmental impact accelerations (Karamanidis, Arampatzis and Brüggemann, 2004; Girard *et al.*, 2016). This may be a result of the large number of degrees of freedom at a segment (or joint) level (Bernstein, 1967), suggesting higher variability in movement at each segment level, subsequently converging to a more consistent whole-body outcome of the task (Turvey, Fitch and Tuller, 1982; Winter, 1984). However, it is important for research to examine segmental level loading rather than just whole-body loading, particularly at segments such as the shank and sacrum which become overloaded and injured regularly (Ellapen *et al.*, 2013; Malisoux *et al.*, 2015), because whole-body loading can potentially mask if impact loading is disproportionate and excessive at various segments.

With regards to absolute reliability, there was predominantly moderate reliability for $Peak_{accel}$ and $Rate_{accel}$ at the shank and sacrum in the non-exerted state at both fixed and self-selected speeds. Slightly superior absolute reliability was evident overall for the sacrum compared to the shank and for $Peak_{accel}$ than the $Rate_{accel}$. These findings imply shank and sacrum $Peak_{accel}$ and $Rate_{accel}$ to be appropriate and acceptable clinical measures where change at an individual participant level is of concern, such as with injury or in gait re-training or biofeedback interventions. When comparing absolute reliability to other studies, SEM is not always directly reported across similar research, but independent calculations based on published data demonstrated similar SEM to this study for shank $Peak_{accel.}$ (Hughes *et al.*, 2019; Van den Berghe *et al.*, 2019) Such comparisons could not be made with respect to shank $Rate_{accel}$, or indeed sacrum $Peak_{accel}$ and $Rate_{accel}$, as the necessary data was not available.

MDC appears to be more commonly reported within the literature as a measure of absolute reliability. Our study noted unacceptable MDC for pre-exertion $Peak_{accel}$ and $Rate_{accel}$ for the shank and sacrum at both speeds, as defined by MDC >10% (Hughes *et al.*, 2019). Previous studies have also observed similar unacceptable MDC values for shank $Peak_{accel}$ (1.1 – 3.0g) (Hughes *et al.*, 2019; Van den Berghe *et al.*, 2019). Akin to SEM, there is a paucity of MDC reporting for shank $Rate_{accel}$, and for sacrum $Peak_{accel}$ and $Rate_{accel}$. While overall absolute reliability was judged to be moderate, the MDC% was large suggesting that the use of peak and rate of sacrum and tibia impact accelerations may be limited to those intervention studies that elicit large changes in these measures. Thus, the level of acceptable MDC proposed by Hughes *et al*., (2019) (<10%) may seem somewhat arbitrary and unjustified, especially given the results of a biofeedback running re-training programme by Clansey *et al*., (2014), who reported a shank $Peak_{accel}$ change of 31% between pre and post-intervention measures. Perhaps future studies should endeavour to determine a more clinically relevant cut-off measure of MDC by observing the percentage differences in impact acceleration between healthy and injured runners.

With respect to the secondary aim of this study, which was to assess the reliability of impact accelerations in an exerted state, an almost identical pattern to non-exerted state findings was observed. High to excellent relative reliability was evident for $Peak_{accel}$ and $Rate_{accel}$ over short- and long-term periods in both the shank and sacrum, for both speeds. Regarding absolute reliability, combined effect sizes, SEM% and MDC% for the shank and sacrum indicated a moderate level of absolute reliability, which was a similar trend to that seen in the non-exerted state. The above suggests that overall, relative and absolute reliability are unaffected by exertion when compared to the non-exerted state, signifying that impact acceleration measures are acceptable and appropriate for prospective injury research, as well as gait re-training or biofeedback interventions following exertion in recreational runners. We are not aware of other studies which have examined the relative or absolute reliability of impact accelerations in an exerted state, highlighting the importance of our findings. As has been proposed in previous literature, running in an exerted state may result in significant, increases in peak shank acceleration (Mizrahi *et al.*, 2000; Derrick, Dereu and McLean, 2002). Although it is unclear if these increases in impact loading are a cause or effect of altered kinematics, these biomechanical changes have been found to relate to RRIs (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008), highlighting the necessity for post-exertion reliability assurance.

This study has some limitations. Testing was constrained to treadmill running which may differ from over-ground running (e.g. stride frequency, contact time, joint kinematics) (García-Pérez *et al.*, 2014), and thus potentially influence impact accelerations (Paul *et al.*, 1978). A second limitation was that participants wore the same shoes for the three sessions, meaning that the shoes were six months older on the third assessment day compared to the first assessment. There may have been substantially more wear on the shoes at this point, and subsequent reduced impact absorption may have been a factor during the six-month testing session. A third limitation may be the exertional protocol. This protocol may not directly reflect the fatiguing process that recreational runners typically endure during their regular training due to its graded nature and relatively short duration (~19 minutes). This protocol was chosen due to the time constraints. One other limitation may be the mounting of the inertial measurement units (IMU) that were used to estimate segmental acceleration.

Impact accelerations may change over time due to loosening of the mounting (e.g. sweating after a prolonged run), or due to session-to-session variability of IMU mounting tightness. This study did not do a controlled assessment of resonance frequency for the sensor mounting methods. Future research should also explore the effect of over-ground running and more ecologically valid exertion protocols on relative and absolute reliability. Additionally, further research is recommended in determining more precise cut-off values for clinically meaningful minimal detectable change and standard error of measurement, particularly given the recent rise in gait re-training and biofeedback intervention publications.

3.6 Conclusion

There is high to excellent relative reliability for $Peak_{accel}$ and $Rate_{accel}$ at both the shank and sacrum segments in the short- (1 week) and long-term (6 months), with little difference between fixed and self-selected speeds, and between non-exerted and exerted states. The findings suggest that these impact acceleration measures are appropriate in research and clinical practice where the rank ordering of runners within a group is of importance; for example, in the research of prospective running-related injuries. Regarding absolute reliability, the observation of predominantly moderate levels of reliability for both $Peak_{accel}$ and $Rate_{accel}$ at the shank and sacrum segments during fixed and self-selected speeds for non-exerted states signifies impact acceleration as an acceptable clinical measure of segmental loading, especially where interventions are being implemented, such as gait re-training or biofeedback. However, while overall absolute reliability was judged to be moderate, the MDC% was large implying that the use of sacrum and shank $Peak_{accel}$ and $Rate_{accel}$ may be limited to those intervention studies that elicit large changes in these measures.

Linking section from Chapter 3 to Chapter 4

From Chapter 3, it was concluded that impact accelerometers demonstrate high to excellent relative reliability of $Peak_{accel}$ and $Rate_{accel}$ at the shank and sacrum, and subsequently are appropriate and acceptable measures across short- and long-term time frames. The results suggest that these impact acceleration measures are suitable for research and clinical practice where the rank ordering of runners within a group is of interest, such as research in the area of injured and uninjured runners. Research of impact acceleration between injured and uninjured runners has been limited to date, with very few studies investigating sacral accelerations, and no studies investigating the rate of acceleration.

While Chapter 3 set a good precedent of reliability for impact accelerometer use, Chapter 4 aims to advance the research in the area of impact acceleration and injury. Although impact loading and has been found to relate to running-related injuries (RRIs), the research has focused largely on vertical ground reaction force (vGRF). Impact accelerometers offer a user-friendly and more ecologically valid measure of impact loading to vGRF, that may be helpful to clinicians who are working with injured and uninjured runners alike.

With a history of injury being one of the most consistently reported risk factors for injury, runners who have a previous injury are a very susceptible yet insightful group. Upon returning to participation following injury, runners may take one of two paths; (1) they will return to full activity levels and will not experience another injury, or (2) they will return to full activity and will become reinjured. Upon returning to participation, these two groups of runners may demonstrate biomechanics that are potentially injurious, or they may acquire an injury resistance. Little is known about the differences between these groups and whether impact acceleration can differentiate between these runners. In addition, runners who have no history of injury (i.e. never injured) provide a robust comparison group as they are effectively a control group which has been unaffected by previous injury.

Thus, the aims of Chapter 4 are to investigate if there are differences in tibia and sacrum $Peak_{accel}$ and $Rate_{accel}$ between recently injured runners, runners with an acquired injury resistance and never injured runners.

Chapter 4 Study 2 – Comparison of Impact Accelerations between Injury-resistant and Recently Injured Runners

Burke, A., Dillon, S., O'Connor, S., Whyte, E., Gore, G., Moran, K., 2022. Comparison of Impact Accelerations between Injury-resistant and Recently Injured Runers. *Plos One**.

**Submitted for publication to Plos One. The editor has asked for items raised by the reviewers to be addressed. These have been completed and resubmitted for review (26/05/2022) and the version here is the resubmitted version.*

4.1 Abstract

Introduction Previous injury has consistently been shown to be one of the greatest risk factors for running-related injuries (RRIs). Runners returning to participation following injury may still demonstrate injury-related mechanics (e.g. repetitive high impact loading), potentially exposing them to further injuries. The aim of this study was to determine if the magnitude ($Peak_{accel}$) and rate of loading ($Rate_{accel}$) at the tibia and sacrum differ between runners who have never been injured, those who have acquired injury resistance (runners who have not been injured in the past 2 years) and those who have been recently injured (RRI sustained 3-12 months ago).

Methods Runners completed an online survey capturing details of their RRI history over the previous 2 years. Never injured runners were matched by sex, quarterly annual mileage and typical training speed to runners who had acquired injury resistance and to runners who had been recently injured. Differences in $Peak_{accel}$ and $Rate_{accel}$ of the tibia and sacrum were assessed between the three groups during a treadmill run at a set speed, with consideration for sex.

Results A total of 147 runners made up the three injury status groups (n: 49 per group). There was a significant main effect of injury status for $Peak_{accel}$ and $Rate_{accel}$ at the sacrum, with recently injured runners demonstrating significantly greater $Rate_{accel}$ than never injured and acquired injury resistant runners. There was also a significant main effect for sex, with females demonstrating greater tibial $Peak_{accel}$, sacrum $Peak_{accel}$ and $Rate_{accel}$ than males.

Conclusion Rate$_{accel}$ at the sacrum distinguishes recently injured runners from never injured runners and runners who may have acquired injury resistance, potentially highlighting poor impact acceleration attenuation in recently injured runners.

4.2 Introduction

Recreational running is consistently reported as one of the most popular activities globally (Hulteen *et al.*, 2017). Running-related injuries (RRIs) are a prevalent issue however, with RRI prevalence rates of 66% reported in recreational runners (Messier *et al.*, 2018). Retrospective studies have made up a substantial proportion of the research exploring RRIs and their potential risk factors (Hreljac, Marshall and Hume, 2000; Milner *et al.*, 2006; Bramah *et al.*, 2018), likely due to the lower time and cost constraints associated with this type of research. One consistent risk factor which has been found to relate to subsequent injury has been a history of injury within the previous 12 months (Van Middelkoop *et al.*, 2008; Buist *et al.*, 2010; Mann *et al.*, 2015; Besomi *et al.*, 2019; Dallinga *et al.*, 2019). It is thought that these runners no longer exhibit the acute effects of the injury itself, but may still maintain some related factors of the injury during this time, potentially contributing to a reinjury (Saragiotto *et al.*, 2014). Analysis of these runners may provide an insight into the potential mechanisms of RRI occurrence. Another running group of note are runners who have fully recovered from injury, but have not suffered any subsequent injuries (e.g. > 2 years since their most previous injury). These runners appear to have acquired an injury resistance, and may be less likely to have maintained the related factors of their previous injury (Dillon *et al.*, 2021), or perhaps have adopted a more injury resistant running technique. Finally, a third group of interest would be those runners who have never been injured. With a high lifetime incidence of RRIs reported (> 90%) (Lun *et al.*, 2004), this minority, but perhaps very insightful group, appear to have a smaller risk for injury compared to the aforementioned groups (recently injured runners and injury resistant runners). Only one study has previously compared these three groups (Dillon *et al.*, 2021), but the focus of this study was in clinical measures of strength and mobility rather than impact acceleration.

From a biomechanical perspective, repetitive forces which overload musculoskeletal structures are responsible for the breakdown of tissue and resultant injury (Hreljac, 2004).

Studies investigating the nature of these repetitive forces and their potential role in causing RRIs have frequently analysed the magnitude and rate of vertical Ground Reaction Force (vGRF). However, there is little evidence to confirm that passive (impact) or active vGRF peaks have a relationship with RRIs (Hreljac, Marshall and Hume, 2000; Ferber *et al.*, 2002; Ribeiro *et al.*, 2015; Bigouette *et al.*, 2016), although there is some evidence to suggest that the rate of loading may have a relationship with specific RRIs, such as tibial stress fractures and plantar fasciitis (Ferber *et al.*, 2002; Pohl, Hamill and Davis, 2009; Ribeiro *et al.*, 2015). One potential limiting factor of these findings is the means by which impact loading has been assessed, with force plate analysis providing a summary measure of loading on the body as a whole, failing to account for the distribution of load at specific segmental levels (Van Der Worp, Vrielink and Bredeweg, 2016). A solution to this is the use of wearable accelerometer sensors, which provide a low cost, light weight, localised segmental analysis and user-friendly alternative to force plates and instrumented treadmills (Auvinet *et al.*, 2002; Laughton, McClay Davis and Hamill, 2003; Dufek, Mercer and Griffin, 2009). Tibial accelerations in particular have been the most popular focus of segmental load analysis when exploring the relationship between impact acceleration and RRIs (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008; Schütte *et al.*, 2018), with some evidence to suggest they are effective in discerning between injured and uninjured runners (Ferber *et al.*, 2002; Milner *et al.*, 2006). However, impact accelerations at the sacrum have rarely been assessed despite the prevalence of lower back and hip injuries experienced in runners (Ellapen *et al.*, 2013; Hespanhol Junior, Pena Costa and Lopes, 2013). As sacral accelerations have been found to be reflective of vGRF loading (LeBlanc *et al*., 2021), with accurate measures of vertical impact peak, loading rates and centre of mass displacement (Lee *et al*., 2010; Alcantra *et al*., 2021), inertial measurement devices worn at this location may therefore provide for a very useful transition towards an ecologically valid and clinically useful measure of loading. In addition, the focus of impact accelerometery studies has been on the magnitude of acceleration without consideration of the rate, even though the rate of vGRF has been shown to relate to RRIs (Ferber *et al.*, 2002; Pohl, Hamill and Davis, 2009; Ribeiro *et al.*, 2015).

There is a dearth of research in the area of impact acceleration and RRIs in male runners. There has been trends to suggest that female runners with a history of stress fracture tend to run with greater tibial peak impact acceleration than uninjured females (Ferber *et al.*, 2002; Milner *et al.*, 2006). Few studies have included males in their samples (Zifchock *et* *al.*, 2008; Schütte *et al.*, 2018), with the majority of studies exclusively looking at female runners (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006). Thus, it cannot be determined if the trends suggesting a link between peak acceleration and RRI in females are transferable to male running groups; research involving large cohorts of males is clearly required.

The aim of this study was to determine if the magnitude ($Peak_{accel}$) and rate ($Rate_{accel}$) of impact acceleration across two segments (tibia and sacrum) differs between runners who have never been injured, those who have acquired injury resistance (runners who have not been injured in the past 2 years) and those who have been recently injured (returned to running following an RRI sustained 3-12 months ago). Furthermore, given that sex has been shown to potentially be a non-modifiable risk factor for specific RRIs, a secondary aim was to determine if the difference in impact acceleration between the injury groups was different for male and female runners.

It is hypothesized that runners who have never been injured will demonstrate significantly lower impact acceleration ($Peak_{accel}$ and $Rate_{accel}$) compared to runners who have recently been injured, with injury resistant runners being intermediate of the two groups. It is also hypothesized that female runners will demonstrate significantly greater impact acceleration ($Peak_{accel}$ and $Rate_{accel}$) compared to males.

4.3 Methods

4.3.1. Study Design

This study was an early sub-study of a larger prospective longitudinal trial of recreational runners, examining the musculoskeletal, biomechanical and injury history risk factors of running-related injuries over an 12-month period (NCT03671395 www.clinicaltrials.gov). This study was approved by Dublin City University Research Ethics Committee, with written informed consent obtained from all participants prior to the study beginning (DCUREC/2017/186).

4.3.2. Participants

Male and female recreational runners, aged between 18 and 65 years, who typically ran a minimum of 10km per week for the past 6 months (Saragiotto *et al.*, 2014), were recruited from local running events, running clubs, social media recruitment drives and radio advertising between January and August 2018. Participants were excluded if they were currently injured or had sustained an injury within the 3 months prior to testing (Buist *et al.*, 2010), had a history of cardiovascular pathology, previous reconstructive joint surgery or joint replacement, or were pregnant. An online survey was given to eligible participants to gather information regarding their training history (weekly miles, quarterly annual miles, training speed and years running experience), and previous running injury history within the past two years. An RRI definition was adapted from a consensus statement, and was defined as "any running-related (training or competition) muscle, bone, tendon or ligament pain in the lower back/legs/knee/foot/ankle that caused a restriction or stoppage of running (distance, speed, duration or training) for at least 7 days or 3 consecutive scheduled training sessions, or that required the runner to consult a physician or other health professional" (Malisoux *et al.*, 2015; Yamato, Saragiotto and Lopes, 2015). *An a-priori* (alpha probability = 0.05, with a power of 1- ß = 0.80, effect size $f = 0.25$) statistical power analysis for a two-way ANOVA was performed using a G*Power program (G*Power 3.1.9.7) to determine the required sample size (Erdfelder, Faul and Buchner, 1996). A total of 128 participants would be the minimum number of participants necessary. Three participant groups were constructed using the injury history data: recreational runners who were never injured (group 1) were matched by sex, quarterly annual mileage and typical training speed with runners who had acquired injury resistance (group 2; runners who have not been injured in the past 2 years), and runners who had been returned to running following a recent RRI (group 3; RRI 3-12 months prior to testing). Where more than one recently injured or acquired injury resistant runner could be matched to the never injured runner, the runner was chosen at random by flipping a coin, so as to eliminate bias from the matching selection. Runners who had been injured 1-2 years pre-testing were excluded from selection in order to ensure a clear demarcation between the "injury resistant" and "recently injured" running groups (Dillon *et al.*, 2021).

4.3.3. Procedures

Participants signed an informed consent form on their initial visit to the laboratory. Prior to any physical testing, the primary researchers checked the survey responses for accuracy and completion, with all injury and training behaviour responses clarified with participants. Height (cm) (Leicester Height Measure, SECA, UK), body mass (kg) (SECA, UK), and limb dominance were recorded. Limb dominance was determined as the leg that the participant would choose to kick a football (Brown, Zifchock and Hillstrom, 2014). Inertial sensors (Shimmer3 IMU, Shimmer™, Ireland) containing accelerometers were used to capture (512Hz sampling rate) the magnitude ($Peak_{accel}$) and rate ($Rate_{accel}$) of impact acceleration of the tibia bilaterally, as well as for the sacrum. Two inertial measurement units were attached bilaterally 5 cm proximal to the medial malleolus using double-sided sticky tape, with the y-axis of the sensor aligned with the long axis of the shank. (Sheerin *et al.*, 2018) They were then tightly secured using Hypafix adhesive tape which wrapped and adhered directly to the skin. The sacrum sensor was held in place within a custom-made elastic belt, with the longitudinal axis aligned to the vertical midline of the S2 spinous process. (O Catháin, Richter and Moran, 2020) The belt was attached to the skin over the sacrum using double-sided sticky tape, and this was secured further by tape and an elastic waistband on top. Securing the inertial sensors with double-sided sticky tape and wrapping has been found to be more representative of tibial accelerations when compared to less secure methods such as the manufacturer provided straps (Johnson *et al.*, 2020). Running trials were conducted on a treadmill (Flow Fitness, Runner DTM3500i, The Netherlands) at a set speed of 9km/hr. The set speed of 9km/hr was chosen to allow for comparison of impact accelerations without the confounding factor of variations in speed affecting the participants' technique. This speed represented the average five-kilometre time of runners in the greater Dublin area, determined from the average speed reported on the Dublin Park Run database (www.parkrun.ie/events). During the testing session, once sensors had been attached and secured, participants completed a 5 minute warm up consisting of dynamic stretches for the hamstrings, quadriceps, hip flexors, hip extensors and calf muscle groups (Yamaguchi, Takizawa and Shibata, 2015). Participants then ran at 9km/hr for 6 minutes to ensure familiarisation to treadmill running (Lavcanska, Taylor and Schache, 2005).

4.3.4. Data Processing

Axial $Peak_{accel}$ and $Rate_{accel}$ of the shanks and sacrum were processed using a custom-built MATLAB script (Mathworks Inc., Natick, MA, USA). A fourth order, zero lag 60 Hz Butterworth filter was applied to the data, as documented in previous research (Sheerin *et al.*, 2018) and dropped packets were filled using a cubic spline. To ensure functionally equivalent values were extracted from the shank and sacrum sensors, the time series data were time-aligned using the custom-built MATLAB script. $Peak_{accel}$ was taken as the maximal amplitude of the accelerometer's local maxima at initial contact and was expressed in units of standard gravity ($g = 9.8\ m/s^2$). A series of pilot studies were conducted to identify initial contact utilizing a pressure sensitive switch in combination with inertial sensors, identifying robust patterns within the data. Rate$_{accel}$ was calculated as the slope of the Peak$_{accel}$ (Figure 4.3.1). Ten consecutive foot-strikes, taken immediately after the 6-minute familiarization, were processed on both dominant and non-dominant limbs.

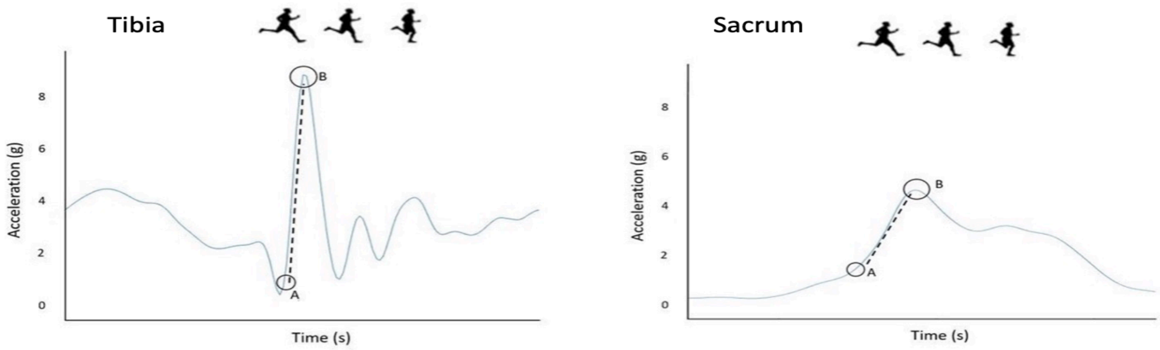

Figure 4.3.1 Trace of Peak$_{accel}$ and Rate$_{accel}$ for the shank (left) and sacrum (right).

(A): initial contact detected; dotted line - - - -: Rate$_{accel}$, which was calculated as the slope of the peak (B).

4.3.5. Statistical Analysis

Descriptive statistics were used to summarize demographics, anthropometrics, and training data. A two-way between groups ANOVA (3 x 2) (injury status group x sex) was used to screen for significant differences in age, anthropometrics (height, weight and BMI), quarterly annual mileage and average running speed. Years running experience was captured nominally (i.e. 1-2 years; 3-5 years; 6-10 years, 11-15 years; 15 years +), and a Pearson Chi Square test was used to determine if significant differences in the number of years running experience existed between injury status groups. Boxplots were used to identify outliers that were 1.5 times the interquartile range above the upper quartile and below the lower quartile, with data outside these thresholds removed from the analysis (Milner *et al.*, 2006). To determine if there was a significant difference in impact acceleration between the dominant and non-dominant limbs, paired sample t-tests were employed. If no differences between limbs existed, dominant and non-dominant limbs would be pooled as one measure.

A two-way between groups ANOVA (3 x 2) (injury status group x sex) was conducted to examine differences in impact accelerations (Peak$_{accel}$ and Rate$_{accel}$) at the tibia and sacrum. Homogeneity of variance was assessed by Levene's test for equality of variances. The three injury status groups were: never injured runners (runners with no history of injury), runners with an acquired injury resistance (runners who have not been injured in

the past 2 years), and recently injured runners (runners who had returned to running following an injury 3-12 months ago). Tukey HSD post-hoc tests were employed to identify differences between groups. The mean, standard deviation and effect size (partial eta squared) were reported using the classification proposed by Cohen (Cohen, 1988); [trivial effect size = 0.0 - 0.19; small effect size 0.2 – 0.59; moderate effect size = 0.6 – 1.19, large effect size = 1.2 – 1.99 and very large effect size = ≥ 2.0]. The alpha level for statistical significance was $p < .05$.

4.4 Results

One hundred and forty-seven (84 males, 63 females) recreational runners participating in a larger study (n = 310) were chosen in order to directly match participants across the three groups. A total of 49 recreational runners (28 male, 21 female) were identified as having never sustained an RRI. These 49 never injured runners were matched by sex, quarterly annual mileage, and typical training speed with 49 runners who had developed injury resistance, and with 49 runners who had recovered from a recent RRI 3-12 months before testing (Table 4.4.1). Participants ran on the treadmill for a mean time of 12 minutes and 32 seconds (± 5 minutes and 31 seconds). A breakdown of the RRIs sustained by the recently injured group can be viewed in Table 4.4.2. The knee was the most commonly injured region (23%), followed by the calf (20%) and foot (15%). Females had significantly lower weight, height, BMI and average training speeds than males ($p < .05$) (Table 4.4.1). No significant differences were found between the three injury groups for any of the demographic and training measures (age, weight, height, BMI, years running experience, quarterly annual mileage or average training speed) ($p > .05$) (Table 4.4.1). No significant differences were found for years running experience between the three injury status groups ($p = .78$).

Impact Acceleration

No significant differences were found between the dominant and non-dominant limbs for $Peak_{accel}$ or $Rate_{accel}$ of the tibia and sacrum ($p > 0.05$), and so the dominant and non-dominant limbs were pooled for subsequent analysis. The mean and standard deviation of impact acceleration results are presented in Table 4.4.3. No interaction effect was found between injury status and sex for any of the measures (tibia $Peak_{accel}$, tibia $Rate_{accel}$, sacrum $Peak_{accel}$ or sacrum $Rate_{accel}$) (Table 4.4.4). A significant main effect was found for injury status for sacrum $Peak_{accel}$ and sacrum $Rate_{accel}$ with trivial effect sizes (Table 4.4.4). Tukey post-hoc comparisons for sacrum $Peak_{accel}$ did not identify a significant difference between the three groups, however, the greater mean impact acceleration observed between the recently injured group compared to the acquired injury resistance group approached statistical significance ($p = .06$). Tukey post-hoc comparisons for sacrum $Rate_{accel}$ indicated that the mean impact acceleration for the recently injured group was significantly greater than both the never injured group and the acquired injury resistance group. A significant main effect for sex was found for tibia $Peak_{accel}$, tibia $Rate_{accel}$, and sacrum $Rate_{accel}$ with trivial effect sizes, with sacrum $Peak_{accel}$ approaching significance ($p = .07$) (Table 4.4.4). Females demonstrated significantly greater $Peak_{accel}$ and $Rate_{accel}$ at the tibia and significantly greater sacrum $Rate_{accel}$ than their male counterparts.

Table 4.4.1 Participant demographics (mean ± standard deviation).

Demographics	Never Injured (n = 49)		Injury Resistant (n = 49)		Recently Injured (n = 49)		Injury Status (P-value)	Sex (P-value)	Injury Status x Sex (P-value)
Sex	Male (n = 28)	Female (n = 21)	Male (n = 28)	Female (n = 21)	Male (n = 28)	Female (n = 21)	N/A	N/A	N/A
Age (years)	43.6 ± 11.7	40.2 ± 8.2	43.6 ± 8.0	42.7 ± 9.2	43.0 ± 6.3	45.4 ± 6.4	.435	.627	.244
Weight (kg)	81.8 ± 10.1§	59.9 ± 6.8§	82.1 ± 10.7§	61.5 ± 8.3§	80.6 ± 9.5§	61.5 ± 8.3§	.877	.000§	.753
Height (m)	1.8 ± 0.1§	1.6 ± 0.1§	1.8 ± 0.1§	1.7 ± 0.1§	1.8 ± 0.1§	1.6 ± 0.1§	.487	.000§	.395
BMI (kg/m^2)	26.0 ± 3.1§	22.3 ± 2.0§	25.7 ± 3.1§	22.6 ± 2.7§	25.2 ± 2.3§	23.5 ± 2.7§	.933	.000§	.189
Quarterly Annual Mileage (km)	386.7 ± 251.3	338.6 ± 330.7	359.4 ± 267.6	353.1 ± 262.6	374.2 ± 231.2	339.9 ± 236.9	.992	.503	.925
Average Training Speed (km/hr)	11.4 ± 2.1§	9.9 ± 2.7§	11.6 ± 1.7§	10.9 ± 1.5§	11.6 ± 1.6§	10.8 ± 1.5§	.273	.003§	.478

N: number of participants; kg: kilogram; m: metre; kg/m2: kilogram per metre squared; km: kilometre; km/hr: kilometres per hour; P-value: significance level of $p < .05$; § : significant difference between males and females ($p < .05$); N/A: not applicable.

Table 4.4.2 Breakdown of injury locations in the recently injured group.

	Male: n (%)	Female: n (%)	All: n (%)
Knee	8 (19.0%)	7 (30.4%)	15 (23.1%)
Calf/Achilles	9 (21.4%)	4 (17.4%)	13 (20.0%)
Foot	7 (16.7%)	3 (13.0%)	10 (15.4%)
Lower Back & SIJ	8 (19.0%)	1 (4.4%)	9 (13.9%)
Posterior Thigh	2 (4.8%)	3 (13.0%)	5 (7.7%)
Hip & Buttock	2 (4.8%)	2 (8.7%)	4 (6.2%)
Shin	3 (7.1%)	1 (4.4%)	4 (6.2%)
Ankle	1 (2.4%)	2 (8.7%)	3 (4.6%)
Groin	2 (4.8%)	0 (0.0%)	2 (3.1%)
Total	42 (100%)^	23 (100%)^	65 (100%)^

N: number of injuries; ^: 65 injuries between 49 runners – 36 runners sustained 1 RRI, 11 runners sustained 2 RRIs, 1 runner sustained 3 RRIs and 1 runner sustained 4 RRIs; SIJ: sacroiliac joint; All: males and females combined; ^Note: percentages may not add up to 100% as values were rounded up to 1 decimal place.

Table 4.4.3 Mean and standard deviation of $Peak_{accel}$ and $Rate_{accel}$ for the tibia and sacrum.

	Never Injured			Injury Resistant			Recently Injured		
Impact Acceleration	**All**	**Males**	**Females**	**All**	**Males**	**Females**	**All**	**Males**	**Females**
Tibia $Peak_{accel}$ (g)	5.84 ± 1.63	5.54 ± 1.16§	6.22 ± 2.06§	6.07 ± 1.47	5.53 ± 1.07§	6.84 ± 1.64§	5.92 ± 1.61	5.47 ± 1.10§	6.48 ± 1.97§
Range	3.8 – 10.3	3.8 – 8.1	3.8 – 10.3	3.8 – 10.2	3.8 – 8.3	3.8 – 10.2	3.6 – 10.2	3.8 – 8.3	3.6 – 10.2
Tibia $Rate_{accel}$ (g/s)	409.2± 179.9	382.1 ± 123.7§	445.4 ± 234.4§	470.3 ± 204.3	398.7 ± 239.5§	571.7 ± 239.5§	439.9 ± 195.0	397.4 ± 148.8§	494.6 ± 234.5§
Range	153.3 – 936.5	170.0 - 678.2	153.3 – 936.5	187.0 – 886.5	188.3 – 656.6	187.0 – 886.5	134.4 – 1118.5	134.4 – 710.9	138.5 – 1118.5
Sacrum $Peak_{accel}$ (g)	5.53 ± 1.60	5.29 ± 1.58	5.86 ± 1.59	5.34 ± 2.02	5.26 ± 1.83	5.45 ± 2.29	6.18 ± 1.76	5.82 ± 1.65	6.71 ± 1.83
Range	0.8 – 9.0	3.1 – 8.9	0.8 – 9.0	2.0 – 9.4	2.0 – 9.4	2.1 – 8.7	2.8 – 10.0	2.8 – 8.1	3.4 – 10.0
Sacrum $Rate_{accel}$ (g/s)	253.5 ± 140.5*	229.5 ± 131.2§	284.2 ± 149.2§	239.4 ± 139.1*	220.1 ± 128.4§	265.1 ± 151.6§	326.4 ± 170.9*	253.9 ± 111.0§	428.0 ± 190.1§
Range	34.0 – 739.5	74.1 – 596.0	34.0 – 739.5	37.1 – 587.3	37.1 – 587.3	72.9 – 494.1	105.0 – 660.3	105.0 – 482.1	118.8 – 660.3

$Peak_{accel}$: magnitude of acceleration; $Rate_{accel}$: rate of acceleration; g: g force; g/s: g force per second; All: Inclusive of both males and females; *: significant difference between injury status groups as identified in post-hoc analysis at p <.05; §:significant difference between males and females.

Table 4.4.4 Results of the two-way ANOVA investigating the differences between injury status and sex for impact acceleration.

	Injury Status		Sex		Injury Status x Sex interaction	
Impact Acceleration	P value	Effect Size	P value	Effect Size	P value	Effect Size
Tibia $Peak_{accel}$	.611	*.007*	.000*	.103 (Trivial)	.588	*.008*
Tibia $Rate_{accel}$	.190	*.024*	.001*	.084 (Trivial)	.361	*.015*
Sacrum $Peak_{accel}$	.043*	*.045 (Trivial)*	.072	.023	.643	*.006*
Sacrum $Rate_{accel}$	.002*	*.086 (Trivial)*	.000*	.095 (Trivial)	.053	*.041*

$Peak_{accel}$: magnitude of acceleration; $Rate_{accel}$: rate of acceleration; *: significant p value at p < .05.

4.5 Discussion

This study hypothesized that runners who have never been injured would demonstrate significantly lower impact acceleration ($Peak_{accel}$ and $Rate_{accel}$) compared to runners who had recently been injured, with injury resistant runners being intermediate of the two groups. It was also hypothesized that female runners would demonstrate significantly greater impact acceleration ($Peak_{accel}$ and $Rate_{accel}$) compared to males. The findings partly support the primary hypothesis, with results indicating that runners who have recently been injured demonstrating significantly greater $Rate_{accel}$ at the sacrum than runners who had never been injured. Although there was a significant main effect for injury status on sacrum $Peak_{accel}$, the post-hoc analysis did not reach significance ($p = .06$). There was no significant difference in tibia $Peak_{accel}$ or $Rate_{accel}$ between the three injury groups, and thus this aspect of the hypothesis was rejected. In addition, the acquired injury resistant group were not always found to be intermediate of the recently injured and never injured groups, a finding that was somewhat surprising in nature. The acquired injury resistant runners demonstrated greater tibia $Peak_{accel}$ and $Rate_{accel}$ than the never injured and recently injured runners. Although these differences were insignificant, the findings suggest that acquired injury resistant runners may have adapted a strategy for tolerating high loads at the tibia, and this strategy has assisted them in developing their injury resistance. However, it does appear that measures at the sacrum are more sensitive to injury status than the tibia, based on the significant findings between injury groups in this study. A previous study by Schütte *et al.*, (2018) observed a similar level of difference (10.0%) in sacrum $Peak_{accel}$ to our study (10.5%) between recently injured and uninjured runners, but no previous research has been conducted with respect to sacrum $Rate_{accel}$, and so comparison of these findings cannot be drawn.

Based upon the findings of our study, it appears that the never injured and acquired injury resistance runners use a technique that produces lower impact acceleration rates at the sacrum. Given that the never injured group demonstrated the lowest $Rate_{accel}$ at the sacrum, it seems that this low loading rate is protective against the likelihood of RRIs. For runners who have acquired injury resistance, this group may have adapted a strategy to reduce their $Rate_{accel}$ when returning to running after injury, ultimately aiming to alleviate excessive load on weakened or damaged structures, and to reduce their likelihood of sustaining subsequent RRIs. Perhaps the presence of high $Rate_{accel}$ in the recently injured group demonstrates a failure to adapt such a strategy and may indicate why this group has been injured most recently from the time of testing. Evidence of this has been demonstrated previously, where currently injured runners have demonstrated significantly greater vGRF loading rates compared to injury-free runners (Johnson *et al.*, 2020). As mentioned previously, sacral accelerations have been found to provide accurate reflections of vGRF impact peaks and loading rates, and thus the findings of differences in sacrum $\text{Rate}_{\text{accel}}$ between injured and uninjured runners is in support of the findings by Davis *et al*., (2016) and Ferber *et al*., (2002), whereby injured runners had significantly greater vertical impact peak and vertical average loading rates compared to uninjured runners. However, research to date has not captured impact loading across a continuous injury timeline (pre-injury, presence of injury and post-injury), and so this is only speculation of the potential injurious mechanisms and recovery strategies at play. It is important to consider that the recently injured group will inevitably develop into either a re-injury group or an injury-resistant group, and so future studies should track these individuals to see if there are ways to identify those who become re-injured and those who don't. A recent study has found hinderance from a previous injury to be highly associated with the occurrence of a subsequent RRI (Kemler and Huisstede, 2021), suggesting that runners may have returned to running without addressing the potential biomechanical factors that might have contributed to their initial injury. Considering the sensitivity of sacral impact accelerometers in distinguishing between injury groups in this study, there are prospects for runners to be more objectively guided in their return to running following RRIs.

In contrast to the findings at the sacrum, no significant main effects for injury status on $\text{Peak}_{\text{accel}}$ or $\text{Rate}_{\text{accel}}$ were evident at the tibia, which partially rejects the primary hypothesis. Although there are no previous studies that have investigated tibial $\text{Rate}_{\text{accel}}$ between injured and uninjured runners, there are mixed findings in the literature regarding differences between tibial $\text{Peak}_{\text{accel}}$ in injured and uninjured runners. The results of this study are in agreement with some studies that found no significant difference in tibia $\text{Peak}_{\text{accel}}$ between recently injured and uninjured runners (Zifchock, Davis and Hamill, 2006; Zifchock *et al.*, 2008; Schütte *et al.*, 2018). Conversely, our findings disagree with the results of Milner *et al.*, 2006 and Ferber *et al.*, (2002), who both found $\text{Peak}_{\text{accel}}$ at the tibia to be significantly greater in female runners with a history of lower limb stress fractures compared to uninjured runners. This contrast in findings may be due to two reasons. Firstly, the primary aim of our study was to compare impact acceleration in runners with a history of any overuse RRIs rather than focusing directly on specific RRIs such as lower limb stress fractures. Perhaps measures of $Peak_{accel}$ at the tibia are more sensitive in differentiating between runners who have a history of local injury to the tibia itself (Milner *et al.*, 2006), rather than differentiating between general overuse RRIs. Secondly, the secondary aim of this study was to determine the interaction effect of sex on injury status with respect to impact acceleration, necessitating the inclusion of male runners in our analysis.

A secondary hypothesis of this study was that female runners would demonstrate significantly greater impact acceleration ($Peak_{accel}$ and $Rate_{accel}$) at the tibia and sacrum compared to males. While there was no interaction effect between sex and injury status, sex was a main effect with significantly larger tibial $Peak_{accel}$ (11-19%), tibial $Rate_{accel}$ (14-30%) and sacrum $Rate_{accel}$ (17-41%) evident for females compared to males. In addition, differences between females and males for sacrum $Peak_{accel}$ (4-13%) approached significance ($p = .07$). Little research has been devoted to investigating the differences in impact acceleration between sexes during running, but the results of this study are similar to some previous findings where females have demonstrated greater $Peak_{accel}$ at the tibia (Hennig, 2001) and sacrum (Sinclair, 2016) compared to males. As stated previously, $Rate_{accel}$ has not been a focus of research to date, but differences in vGRF loading rates were similarly greater in females compared to males in previous studies (Ryu, 2005; Milner *et al.*, 2006; Park *et al.*, 2018). Differences in running kinematics (e.g. greater hip adduction) (Ferber, Davis and Williams, 2003), muscle contractions (e.g. delayed gluteus medius activation) (Willson *et al.*, 2011) and lower body alignment (e.g. greater tibia varum) (Matheson *et al.*, 1987) in females compared to males have been proposed as potential reasons for the higher impact accelerations in females (Mercer *et al.*, 2010; Sinclair, 2016). The factors mentioned above have been shown to relate to specific RRIs such as patellofemoral pain syndrome (Barton *et al.*, 2012), iliotibial band friction syndrome (Ferber *et al.*, 2010) and stress fractures (Milner, Hamill and Davis, 2010), potentially leading to an increased predisposition of specific injuries for female runners (Ferber, Davis and Williams, 2003). Given that the present study examined retrospective injuries, further prospective studies are required to investigate the impact acceleration differences between males and females, how this impact accelerations are affected by biomechanics, and if these factors relate to prospective injury occurrence.

Limitations

There are some limitations to this study, one of which is the retrospective nature of the analysis. Although this study provides a unique insight into novel injury groups (never injured and injury resistant runners), future research should examine the relations between segmental impact loading and RRI prospectively. Secondly, the injury history for this study was self-reported, and therefore may be subject to recall bias or inaccuracies. In efforts to minimize this, the side of injury and exact pathology of each RRI was not collated, and RRIs were grouped by general location.

4.6 Conclusion

This study found $Rate_{accel}$ at the sacrum to be significantly greater in recently injured runners compared to runners with acquired injury resistance and never injured runners. These findings suggest that $Rate_{accel}$ at the sacrum is an appropriate objective measure to distinguish recently injured runners, potentially informing rehabilitation goals for runners returning to running following RRIs. This study also found females to demonstrate significantly greater $Peak_{accel}$ and $Rate_{accel}$ at the tibia, and $Rate_{accel}$ at the sacrum than their male counterparts. As repetitive loading is thought to be an influential factor in RRI development, females with greater impact acceleration, or poor impact attenuation capacity may therefore be at increased susceptibility to overuse RRIs (e.g. stress fractures). This may indicate a clinical use for impact accelerometers in gait re-education for impact attenuation and potential injury prevention in female runners.

Linking Section from Chapter 4 to Chapter 5

From Chapter 4, impact acceleration was found to differ between recently injured runners and runners who had acquired injury resistance as well as those who had never been injured. The finding of a relationship between impact loading and injury aligns well with some previous research in the area of impact acceleration, and the study highlighted the value in investigating runners with a recent history of injury. However, risk factors for running-related injuries (RRIs) are thought to be multifactorial in nature, and it is important to consider other risk factors which may play a role.

Previous research has given significant consideration to the training practices of runners, as their behaviour in training likely influences the total cumulative load on the body (i.e. impact loading and training load). Similar to Chapter 4, Chapter 5 aims to investigate the differences between recently injured, acquired injury resistance and never injured runners, but this chapter will focus on how their training practices differ. Such practices will include training distance, speed, frequency, type of training (e.g. sprint work, hill runs, high intensity interval training), warm up and recovery strategies, frequency of shoe change and training surface. One additional practice which will be explored is the practice of running with persistent pain, also known as a “niggle”. Little to no research has investigated how many runners train while experiencing niggles, and how this practice may relate to injury.

Thus, the aims of Chapter 5 are to determine if recently injured runners have alternative training practices when compared to runners who have acquired injury resistance and runners who have never been injured.

Chapter 5 Study 3 - Training-related Factors that Differentiate between the Recently Injured, Injury-resistant and Never Injured Runner – A Retrospective Study

Burke, A., Dillon, S., O'Connor, S., Whyte, E., Gore, G., Moran, K., 2022. Training-related Factors that Differentiate between the Recently Injured, Injury-resistant and Never Injured Runner – A Retrospective Study. *Journal of Strength and Conditioning*.*

**Submitted for publication to Journal of Strength and Conditioning. Awaiting decision.*

5.1 Abstract

Introduction Several risk factors have been proposed to relate to the high prevalence rates of running-related injuries (RRIs), such as previous injury, and various training practices. One particular practice which appears to be common amongst runners is training with pain or a "niggle". However, little research has investigated the training practices of the never injured runner, and runners who may have acquired injury resistance.

Methods An online survey captured details of training practices and previous injury history from a population of 246 recreational male and female runners. Training practices were compared between three insightful groups, which were determined based on previous injury history; recently injured: RRI 3-12 months ago; acquired injury resistant: RRI 1-2 years ago; never injured: no RRI history.

Results Half of all participants (50%) reported to have sustained an RRI in the preceding 3-12 months, with the knee (22%) and calf (20%) most commonly affected. A greater percentage of recently injured runners reported to do hill runs, and change gradient on a frequent basis. Never injured runners reported to run lower mileage per week, with slower training speeds than recently injured runners. Twice as many recently injured runners reported to run with a niggle (43%) compared to never injured runners (21%).

Conclusion Recently injured runners appear to demonstrate some riskier training practices compared to acquired injury resistant and never injured runners, indicating the need for training modifications in RRI management and return to participation. Running with a

niggle seems to be a common practice amongst recently injured runners, but more research is required to determine the prospective contribution of niggles to RRIs.

5.2 Introduction

Running-related injuries (RRIs) are a prevalent issue, inspiring extensive research into the epidemiology and aetiology of these injuries. Retrospective studies have made up the majority of the research investigating RRIs and their potential risk factors, likely due to lower cost and time constraints related to this type of research. One predominant risk factor which has consistently been found to relate to subsequent (re-) injury has been a history of injury within the previous 12 months (Besomi *et al.*, 2019; Dallinga *et al.*, 2019). It is assumed that while these runners no longer exhibit the acute effects of the injury itself, they may be exposed to a potential reinjury due to maintaining some related factors that contributed to their previous injury during this time (Saragiotto *et al.*, 2014). Analysis of these runners may offer an insight into the potential mechanisms of RRI occurrence. Another running group of interest are runners who have recovered fully from injury, but have not sustained any subsequent injuries (e.g. > 2 years since their most previous injury). Given the high prevalence rate (66%) of RRIs (Messier *et al.*, 2018), these runners may have acquired injury resistance and may have adopted more injury resistant habits, or may have been less likely to have maintained the contributing factors of their previous injury (Dillon *et al.*, 2021). A third group we have identified of interest are runners who have never been injured. With such a high lifetime incidence of RRIs reported (> 90%) (Lun *et al.*, 2004), this minority, but perhaps very insightful group, appear to have a reduced risk for injury compared to the aforementioned groups (recently injured runners and injury resistant runners). Only one study has compared these three groups previously (Dillon *et al.*, 2021), focusing solely on differences in clinical measures of strength, mobility and foot posture.

Extensive research has sought to determine which intrinsic and extrinsic risk factors relate to RRIs. Sex, age, BMI and running experience have limited and conflicting findings in terms of intrinsic risk for RRIs (Theisen *et al.*, 2014; Malisoux *et al.*, 2015; Besomi *et al.*, 2019), with previous injury, as mentioned above, appearing to be one of the strongest intrinsic risk factors for RRIs. However, an additional potential intrinsic risk factor which has received very little attention in RRI research, is the presence of a persistent or nagging pain or complaint through training (Verhagen, Warsen and Silveira Bolling, 2021), sometimes referred to as a "niggle" (Neto *et al.*, 2021). Experiencing pain or a niggle while training may alter running biomechanics, subsequently creating an overload on already painful structures to the point that there is an even greater degree of structural damage than before (Wilke, Vleeming and Wearing, 2019). Alternatively, the runner may overload other tissues in efforts to reduce the load on the painful structure, and predispose these other tissues to unfamiliar demands and potential injury (Wilke, Vleeming and Wearing, 2019). It has recently been reported that up to 94% of runners continue to train, even though they are experiencing persistent pain during their training sessions (Linton and Valentin, 2018), and this appears to be a normal part of runners' practice (Verhagen, Warsen and Silveira Bolling, 2021). Research investigating the effects of a niggle on injury have found the risk of injury to be 3.6 times higher for football players when preceded by a niggle (Whalan, Lovell and Sampson, 2020), but no studies have examined the relationship between niggles and RRIs within a running population to date.

Extrinsic risk factors are factors external to the person, such as training related factors (e.g. training distance, frequency, speed, surface, footwear). Although it is conceivable that RRIs could be linked to training errors, studies exploring training variables as potential risk factors for RRIs have had mixed findings to date. Several authors have reported significantly higher daily (Jacobs and Berson, 1986), weekly (Di Caprio *et al.*, 2010), and seasonal distances (Knobloch, Yoon and Vogt, 2008), higher frequencies of training (Satterthwaite *et al.*, 1999; Knobloch, Yoon and Vogt, 2008; Di Caprio *et al.*, 2010), and faster training speeds (Jacobs and Berson, 1986; Hootman *et al.*, 2002; Hespanhol Junior, Pena Costa and Lopes, 2013) in injured runners compared to runners who did not sustain RRIs. In contrast, prospective research has found no relationship between training distance or speed and RRIs (Messier *et al.*, 2018).

The primary aim of this study is to determine the differences in intrinsic and extrinsic risk factors between three unique injury groups: runners who have never been injured, runners who have acquired injury resistance and runners who have recently been injured. A secondary aim is to investigate the prevalence of niggles amongst recreational runners, and how this may differ between the three injury groups.

5.3 Methods

5.3.1 Study Design

This retrospective cohort study was an early sub-study as part of a large scale prospective longitudinal trial of injury-free recreational runners, examining the musculoskeletal, biomechanical and injury history risk factors of RRIs over a 12-month period (NCT03671395 www.clinicaltrials.gov). This study was approved by Dublin City University Research Ethics Committee, with written informed consent obtained from all participants prior to the study beginning (DCUREC/2017/186).

5.3.2 Participants

Male and female recreational runners, aged between 18 and 65 years, who typically ran a minimum of 10km per week for the past 6 months (Saragiotto *et al.*, 2014), were recruited from local running events, running clubs, social media recruitment drives and radio advertising between January and August 2018. Participants were excluded if they were currently injured or had sustained an injury within the 3 months prior to testing, had a history of cardiovascular pathology, previous reconstructive joint surgery or joint replacement, or were pregnant. *An a-priori* (alpha error probability = 0.05, odds ratio of 2.0, a power of 1- ß = 0.80, effect size f = 0.25, X distribution = binomial) statistical power analysis for a two-way ANOVA was performed using a G*Power program (G*Power 3.1.9.7) to determine the required sample size. Due to the presence of multiple variables and difficulty choosing which variable to base the power analysis on, the effect size was determined using a standardized medium effect size value (0.25). Results indicated a minimum of 158 participants would be necessary.

5.3.3 Instrumentation

An online survey was developed based on pre-existing research that explored lifestyle and training factors relating to RRIs (Hespanhol Junior, Pena Costa and Lopes, 2013). Face validity of the survey was conducted by a group of 4 experts with epidemiological and aetiological research experience, and it was then piloted with a group of 30 physically active males and females.

The final survey (Appendix B) comprised of 3 sections with a total of 26 questions, presented as a mix of multiple choice and open ended responses. Satellite questions were automatically prompted to gather a more detailed response to index questions where relevant. Section A of the survey consisted of 3 questions capturing the unique ID, age and sex of the participants. Section B contained 21 questions comprising of training-related questions focussing on their history of training (years running experience, participation in non-running related exercise classes), the purpose of training (motivating factors, events) and their training habits (e.g. distance, speed, frequency of session, surface, footwear, presence of a niggle, experience of delayed onset of muscle soreness, execution of warm-ups, cool downs and recovery sessions). In order to document the presence of a niggle during running training, participants were asked to report and describe any "nagging pain or complaint in your lower back/lower limbs that did not restrict your training". The final section (Section C) was made up of 2 main questions acquiring information on their running-related injury history (number of RRIs, location, type, duration, medical advice sought, rehabilitation completion, exacerbation or recurrence of re-injuries). A running-related injury definition was adapted from a consensus statement, and was defined as "any running-related (training or competition) muscle, bone, tendon or ligament pain in the lower back/legs/knee/foot/ankle that caused a restriction or stoppage of running (distance, speed, duration or training) for at least 7 days or 3 consecutive scheduled training sessions, or that required the runner to consult a physician or other health professional" (Yamato, Saragiotto and Lopes, 2015). The severity of RRI was captured within five groupings according to the Athletics Consensus statement, and was based on the approximate number of days that running training was affected (0 days missed; 1-7 days missed; 8-28 days missed; 1-6 months missed; and greater than 6 months missed) (Timpka *et al.*, 2014). Due to the retrospective nature of the self-report injury recall, the authors of this study felt it may be easier for participants to select a window of time-loss rather than specifying the exact number of days affected by the injury.

5.3.4 Procedures

Participants signed an informed consent form on their initial visit to the laboratory and then completed the online survey (SurveyMonkey Inc, San Mateo, California, USA, www.surveymonkey.com). Height (cm) (Leicester Height Measure, SECA, UK) and body mass (kg) (SECA, UK) were recorded.

5.3.5 Statistical Analysis

Data from the survey were downloaded from SurveyMonkey into a Microsoft Excel file (Microsoft Windows 365, Version 16.0, Washington State). Data were screened in Excel for missing and/or erroneous responses. No missing data was observed for any of the participants. Following data screening, the survey was imported and analysed using SPSS (IBM Corp, IBM SPSS Statistics for Windows, Version 27.0, Armonk, NY). Descriptive statistics were used to present the demographics of the participants (sex, age, weight, height, BMI, self-reported training speed, quarterly annual mileage, number of running sessions per week and running experience). Three participant groups were constructed using the injury history data: runners who had never sustained a RRI were placed into the "never injured" group, runners who had been injured more than 2 years ago were placed in the "acquired injury-resistance" group, and runners who had been injured within the previous 3-12 months were placed in the "recently injured" group.

Chi-square (χ^2) analyses were performed to check for differences in nominal variables between the three injury groups. A two-way between groups ANOVA (3 x 2) (injury status group x sex) was conducted to investigate differences in age, anthropometrics (height, weight and BMI), quarterly annual mileage and average running speed between the three injury groups. A Tukey post-hoc test was used to identify the differences between the three injury groups. Effect sizes were reported using the classification proposed by Cohen (Cohen, 1988) [trivial effect size = 0.0 - 0.19; small effect size 0.2 – 0.59; moderate effect size = 0.6 – 1.19, large effect size = 1.2 – 1.99 and very large effect size = ≥ 2.0]. The alpha level for statistical significance was $p < .05$.

5.4 Results

A total of 310 runners volunteered to participate in the study. Two hundred and forty-six runners were eligible for inclusion in this retrospective analysis, based on them reporting to have never been injured, to have been injured > 2 years ago, or to have been injured within the previous 3-12 months. One hundred and forty six runners reported to have been injured 1-2 years prior to the session, and were excluded from the analysis at this point. This was done to ensure a clear distinction between those who we theorized to have "acquired injury resistance" (injured >2 years ago), and those who had been recently injured (injured 3-12 months ago). Demographics of the 246 runners who were included in the analysis (male n: 154, aged 43.9 ± 9.3 years; female n: 92, aged 42.4 ± 8.0 years) are presented in Table 5.4.1.

One hundred and twenty-four runners (50.4%) sustained a total of 158 RRIs in the previous 3-12 months. Male runners had a higher prevalence of RRI (66.1%) than females (33.9%). The knee (22.1%) and calf (19.6%) were the most commonly injured regions. The location, type and severity of all RRIs sustained in the previous 3-12 months can be viewed in Table 5.4.2. It is unknown how many injuries, or the location of injuries that the injury resistant group (RRI > 2 years ago) may have had previously. Details on these injuries were not requested as recall bias may have impacted upon the accuracy of this information.

The two-way between groups ANOVA revealed a statistically significant main effect for injury status on average training speed, with a post-hoc analysis identifying significantly greater speeds in recently injured runners (mean: 3.2m/s) compared to never injured runners (mean: 3.0m/s) (Table 5.4.3). In addition, there was a significant main effect for sex with males having significantly greater height, weight, BMI, number of runs per week, quarterly annual mileage, and average training speed (Table 5.4.3). No significant interaction effects were observed between sex and injury status.

A chi-square analysis revealed significant differences between injury groups for 12 variables (Table 5.4.4). A significantly greater percentage of recently injured runners reported that they: undertake foam rolling as part of their recovery, undertake foam rolling as part of their cool-down, rest as part of their recovery, do hill runs, and change gradient on a weekly basis compared to the never injured and acquired injury resistant group. Additionally, a significantly greater percentage of recently injured runners reported that they: wear insoles/ arch supports in their running shoes, undertake flexibility training at the gym, do static stretching as part a cool down, and stretch as part of their recovery compared to the acquired injury resistant group. Moreover, a significantly greater percentage of recently injured runners reported to continue training while experiencing a niggle compared to the never injured runners. Lastly, a significantly greater percentage of never injured runners reported to run an average of 10km per week (in comparison to distances greater than 10km per week), and to change their running shoes every 12 months (in comparison to changing shoes every 3, 6 or 9 months.

Table 5.4.1 Descriptive statistics of anthropometrics and training measures between groups.

	Never Injured			Acquired Injury Resistance			Recently Injured		
	All (n: 53) *Mean ± SD* *(95% CI)*	**Males (n: 30)** *Mean ± SD* *(95% CI)*	**Females (n: 23)** *Mean ± SD* *(95% CI)*	**All (n: 69)** *Mean ± SD* *(95% CI)*	**Males (n: 42)** *Mean ± SD* *(95% CI)*	**Females (n: 27)** *Mean ± SD* *(95% CI)*	**All (n: 124)** *Mean ± SD* *(95% CI)*	**Males (n: 82)** *Mean ± SD* *(95% CI)*	**Females (n: 42)** *Mean ± SD* *(95% CI)*
Age (years)	42.2 ± 10.0	43.5 ± 11.3	40.4 ± 7.9	44.4 ± 8.4	45.0 ± 8.1	43.4 ± 8.9	43.3 ± 8.5	43.5 ± 9.1	42.8 ± 7.4
	(39.5 – 44.9)	(39.5 – 47.5)	(37.2 – 43.6)	(42.4 – 46.4)	(42.6 – 47.5)	(40.0 – 46.8)	(41.8 – 44.8)	(41.5 – 45.5)	(40.6 – 45.0)
Weight (kg)	71.7 ± 13.9	80.9 ± 10.5	59.8 ± 6.7	73.5 ± 13.6	80.8 ± 11.3	62.3 ± 8.0	73.0 ± 11.9	78.7 ± 9.2	61.8 ± 7.8
	(68.0 – 75.4)	(77.1 – 84.7)	(57.1 – 62.5)	(70.3 – 76.7)	(77.4 – 84.2)	(59.3 – 65.3)	(70.9 – 75.1)	(76.7 – 80.7)	(59.4 – 64.2)
Height (m)	1.7 ± 0.1	1.8 ± 0.1	1.6 ± 0.7	1.7 ± 0.1	1.8 ± 0.1	1.7 ± 0.8	1.7 ± 0.1	1.8 ± 0.1	1.6 ± 0.1
	(1.7 – 1.7)	(1.8 – 1.8)	(1.3 – 1.9)	(1.7 – 1.7)	(1.8 – 1.8)	(1.4 – 2.0)	(1.7 – 1.7)	(1.8 – 1.8)	(1.6 – 1.6v
BMI (kg/m²)	24.2 ± 3.2	25.6 ± 3.2	22.3 ± 2.0	24.2 ± 3.2	25.1 ± 3.2	22.7 ± 2.6	24.2 ± 2.7	24.9 ± 2.5	22.9 ± 2.6
	(23.3 – 25.1)	(24.5 – 26.8)	(21.5 – 23.1)	(23.5 – 25.0)	(24.1 – 26.1)	(21.7 – 23.7)	(23.7 – 24.7)	(24.4 – 25.4)	(22.1 – 23.7)
Training Speed (m/s)	3.0 ± 0.7	3.1 ± 0.6	2.8 ± 0.7	3.1 ± 0.5	3.3 ± 0.5	2.9 ± 0.5	3.2 ± 0.4	3.3 ± 0.4	3.0 ± 0.4
	(2.8 – 3.2)	(2.9 – 3.4)	(2.4 – 3.1)	(3.0 – 3.3)	(3.1 – 3.4)	(2.8 – 3.1)	(3.1 – 3.3)	(3.2 – 3.4)	(2.9 – 3.1)
Quarterly annual mileage (km)	358.9 ± 276.5	383.5 ± 242.4	326.7 ± 318.3	437.7 ± 375.8	494.8 ± 433.6	348.7 ± 243.7	373.6 ± 253.6	403.0 ± 262.7	316.1 ± 226.7
	(284.5 – 433.3)	(296.8 – 470.2)	(196.6 – 456.8)	(349.0 – 526.4)	(363.7 – 625.9)	(256.8 – 440.6)	(329.0 – 418.2)	(346.1 – 459.9)	(247.5 – 384.7)
Runs per week	3.7 ± 1.4	3.9 ± 1.2	3.4 ± 1.6	4.0 ± 1.6	4.2 ± 1.7	3.5 ± 1.5	3.8 ± 1.3	3.9 ± 1.4	3.6 ± 1.0
	(3.3 – 4.1)	(3.5 – 4.3)	(2.8 – 4.1)	(6.3 – 4.4)	(3.7 – 4.7)	(2.9 – 4.1)	(3.6 – 4.0)	(3.6 – 4.2)	(3.3 – 3.9)
	All (n: 53) *n (%)* *(95% CI)*	**Males (n: 30)** *n (%)* *(95% CI)*	**Females (n: 23)** *n (%)* *(95% CI)*	**All (n: 69)** *n (%)* *(95% CI)*	**Males (n: 42)** *n (%)* *(95% CI)*	**Females (n: 27)** *n (%)* *(95% CI)*	**All (n: 124)** *n (%)* *(95% CI)*	**Males (n: 82)** *n (%)* *(95% CI)*	**Females (n: 42)** *n (%)* *(95% CI)*
Running Experience									
<1 year	6 (11.3%)	2 (6.6%)	4 (17.4%)	5 (7.2%)	2 (4.8%)	3 (11.1%)	8 (6.4%)	7 (8.5%)	1 (2.4%)
	(2.8 – 19.9)	(-2.3 – 15.6)	(1.9 – 32.9)	(1.1 – 13.4)	(-1.7 – 11.2)	(-0.7 – 23.0)	(2.1 – 10.8)	(2.5 – 14.6)	(-2.2 – 7.0)
1-2 years	8 (15.1%)	5 (16.7%)	3 (13.0%)	4 (5.8%)	2 (4.8%)	2 (7.4%)	14 (11.3%)	9 (11.0%)	5 (11.9%)
	(5.5 – 24.7)	(3.3 – 30.0)	(-0.7 – 26.8)	(0.3 – 11.3)	(-1.7 – 11.2)	(-2.5 – 17.3)	(5.7 – 16.9)	(4.2 – 17.7)	(2.1 – 21.7)
3-5 years	16 (30.2%)	10 (33.3%)	6 (26.1%)	25 (36.2%)	14 (33.3%)	11 (40.7%)	45 (36.3%)	24 (29.3%)	21 (50.0%)
	(17.8 – 42.6)	(16.5 – 50.2)	(8.1 – 44.0)	(24.9 – 47.6)	(19.1 – 47.6)	(22.2 – 59.3)	(27.8 – 44.8)	(19.4 – 39.1)	(34.9 – 65.1)
6-10 years	10 (18.9%)	5 (16.7%)	5 (21.7%)	22 (31.9%)	16 (39.1%)	6 (22.2%)	34 (27.4%)	23 (28.0%)	11 (26.2%)
	(8.3 – 29.4)	(3.3 – 30.0)	(4.9 – 38.6)	(20.9 – 42.9)	(23.4 – 52.8)	(6.5 – 37.9)	(19.6 – 35.3)	(18.3 – 37.8)	(2.9 – 39.5)
11-15 years	6 (11.3%)	4 (13.3%)	2 (8.7%)	5 (7.2%)	3 (7.1%)	2 (7.4%)	7 (5.6%)	7 (8.5%)	0 (0.0%)
	(2.8 – 19.9)	(1.2 – 25.5)	(-2.8 – 20.2)	(1.1 – 13.4)	(-0.7 – 14.9)	(-2.5 – 17.3)	(1.6 – 9.7)	(2.5 – 14.6)	(0.0 – 0.0)
> 15 years	7 (13.2%)	4 (13.3%)	3 (13.0%)	8 (11.6%)	5 (11.9%)	3 (11.1%)	16 (12.9%)	12 (14.6%)	4 (9.5%)
	(4.1 – 22.3)	(1.2 – 25.5)	(-0.7 – 26.8)	(4.0 – 19.1)	(2.1 – 21.7)	(-0.7 – 23.0)	(7.0 – 18.8)	(7.0 – 22.3)	(0.7 – 18.4)

SD: standard deviation; n: number; kg: kilogram; m: metre; kg/m²: kilogram per metre squared; km/hr: kilometres per hour; km: kilometre; 95% CI: upper and lower confidence interval percentages.

Table 5.4.2 Frequency of injury descriptives for recently injured runners.

	All (n: 124)		Male (n: 82)		Female (n: 42)	
	n	% (95% CI)	n	% (95% CI)	n	% (95% CI)
Location						
Knee	35	22.1 (15.7 – 28.6)	22	20.0 (12.5 – 27.5)	13	27.1 (14.5 – 39.7)
Calf	31	19.6 (13.4 – 25.8)	24	21.8 (14.1 – 29.5)	7	14.6 (4.6 – 24.6)
Foot	18	11.4 (6.4 – 16.3)	14	12.7 (6.5 – 19.0)	4	8.3 (0.5 – 16.2)
Posterior Thigh	18	11.4 (6.4 – 16.3)	14	12.7 (6.5 – 19.0)	4	8.3 (0.5 – 16.2)
Shin	13	8.2 (3.9 – 12.5)	8	7.3 (2.4 – 12.1)	5	10.4 (1.8 – 19.1)
Lower Back/SIJ	12	7.6 (3.5 – 11.7)	10	9.1 (3.7 – 14.5)	2	4.2 (-1.5 – 9.8)
Hip	9	5.7 (2.1 – 9.3)	5	4.5 (0.7 – 8.4)	4	8.3 (0.5 – 16.2)
Buttocks	8	5.1 (1.6 – 8.5)	4	3.6 (0.1 – 7.1)	4	8.3 (0.5 – 16.2)
Ankle	7	4.4 (1.2 – 7.6)	3	2.7 (-0.3 – 5.8)	4	8.3 (0.5 – 16.2)
Groin	4	2.5 (0.1 – 5.0)	4	3.6 (0.1 – 7.1)	0	0.0 (0.0 – 0.0)
Anterior Thigh	3	1.9 (-0.2 – 4.0)	2	1.8 (-0.7 – 4.3)	1	2.1 (-2.0 – 6.1)
Total	158	100.0	110	100.0	48	100.0
Type						
Muscle	54	34.2 (26.8 – 41.6)	39	35.5 (26.5 – 44.4)	15	31.3 (18.1 – 44.4)
Tendon	42	26.6 (19.7 – 33.5)	33	30.0 (21.4 – 38.6)	9	18.8 (7.7 – 29.8)
Bone	27	17.1 (11.2 – 23.0)	18	16.4 (9.5 – 23.3)	9	18.8 (7.7 – 29.8)
Nerve	7	4.4 (1.2 – 7.6)	5	4.5 (0.7 – 8.4)	2	4.2 (-1.5 – 9.8)
Ligament	6	3.8 (0.8 – 6.8)	4	3.6 (0.1 – 7.1)	2	4.2 (-1.5 – 9.8)
Meniscus	4	2.5 (0.1 – 5.0)	3	2.7 (-0.3 – 5.8)	1	2.1 (-2.0 – 6.1)
Unsure	18	11.4 (6.4 – 16.3)	8	7.3 (2.4 – 12.1)	10	20.8 (9.3 – 32.3)
Total	158	100.0	110	100.0	48	100.0
Severity						
0 days missed	13	8.2 (3.9 – 12.5)	11	10.0 (4.4 – 15.6)	2	4.2 (-1.5 – 9.8)
1-7 days missed	57	36.1 (28.6 – 43.6)	39	35.5 (26.5 – 44.4)	18	37.5 (23.8 – 51.2)
8-28 days missed	59	37.3 (29.8 – 44.9)	43	39.1 (30.0 – 48.2)	16	33.3 (20.0 – 46.7)
29 days - 6 months missed	25	15.8 (10.0 – 21.5)	14	12.7 (6.5 – 19.0)	11	22.9 (11.0 – 34.8)
6 months + missed	4	2.5 (0.1 – 5.0)	3	2.7 (-0.3 – 5.8)	1	2.1 (-2.0 – 6.1)
Total	158	100.0	110	100.0	48	100.0
Required medical advice						
Yes	147	93.0 (89.1 – 97.0)	104	94.5 (90.3 – 98.8)	43	89.6 (80.9 – 98.2)
No	11	7.0 (3.0 – 10.9)	6	5.5 (1.2 – 9.7)	5	10.4 (1.8 – 19.1)
Total	158	100.0	110	100.0	48	100.0
Received rehabilitation programme						
Yes	126	79.8 (73.5 – 86.0)	92	83.6 (76.7 – 90.5)	34	70.8 (58.0 – 83.7)
No	32	20.3 (14.0 – 26.5)	18	16.4 (9.5 – 23.3)	14	29.2 (16.3 – 42.0)
Total	158	100.0	110	100.0	48	100.0
Recovered fully						
Yes	91	57.6 (49.9 – 65.3)	66	60.0 (50.8 – 69.2)	25	52.1 (38.0 – 66.2)
No	36	22.8 (16.2 – 29.3)	22	20.0 (12.5 – 27.5)	14	29.2 (16.3 – 42.0)
Unsure	31	19.6 (13.4 – 25.8)	22	20.0 (12.5 – 27.5)	9	18.8 (7.7 – 29.8)
Total	158	100.0	110	100.0	48	100.0
Re-injury or Exacerbation						
Yes	83	52.5 (44.7 – 60.3)	60	54.5 (45.2 – 63.9)	23	47.9 (23.8 – 62.0)
No	52	32.9 (25.6 – 40.2)	36	32.7 (24.0 – 41.5)	16	33.3 (20.0 – 46.7)
Unsure	23	14.6 (9.1 – 20.1)	14	12.8 (6.5 – 19.0)	9	18.8 (7.7 – 29.8)
Total	158	100.0	110	100.0	48	100.0

CI: 95% confidence intervals; n: number; %: percentage; SIJ: sacroiliac joint.

Table 5.4.3 Results of two-way ANOVA assessing differences in anthropometrics and training measures between injury groups and sex.

Measure	P, Injury Status	Effect Size, Injury Status	P, Sex	Effect Size, Sex	P, Injury Status*Sex	Effect Size, Injury Status-Sex
Age	.39	.01	.14	.01	.71	.00
Weight	.67	.00	.00*	.47	.39	.01
Height	.29	.01	.00*	.46	.99	.00
BMI	.97	.00	.00*	.17	.23	.01
Training Speed	.05*	.03	.00*	.09	.84	.00
Quarterly Annual Mileage	.34	.01	.02*	.02	.70	.00
Runs per week	.61	.00	.01*	.03	.65	.00

*Significant difference between groups at p < .05; BMI: body mass index; trivial effect size = 0.0 - 0.19; small effect size 0.2 – 0.59; moderate effect size = 0.6 – 1.19, large effect size = 1.2 – 1.99 and very large effect size = ≥ 2.0 .

Table 5.4.4 Significant findings from chi-square analyses between injury groups.

		Injury Status						χ^2 (*df*)	P	Phi
		Never Injured		*Acquired Injury Resistance*		*Recently Injured*				
	Sig. Group Differences	**n**	**%**	**n**	**%**	**n**	**%**			
Foam rolling recovery	(NI, AIR) < RI	15	28.3%	14	20.3%	57	46.0%	14.17 (2)	.00	.24
Foam rolling cool down	(NI, AIR) < RI	9	17.0%	12	17.4%	43	34.7%	9.75 (2)	.01	.20
Rest recovery	(NI, AIR) < RI	14	26.4%	23	33.3%	61	49.2%	9.73 (2)	.01	.20
Hill runs	(NI, AIR) < RI	29	54.7%	41	59.4%	93	75.0%	8.84 (2)	.01	.19
Change gradient on a weekly basis	(NI, AIR) < RI	8	15.1%	12	17.4%	39	31.5%	7.74 (2)	.02	.18
Wearing insoles/arch supports	AIR < RI	9	17.0%	9	13.0%	37	29.8%	8.33 (2)	.02	.18
Flexibility training at the gym	AIR < RI	6	11.3%	6	8.7%	29	23.4%	8.28 (2)	.02	.18
Static stretch cool down	AIR < RI	28	52.8%	35	50.7%	85	68.5%	7.39 (2)	.03	.17
Stretching recovery	AIR < RI	13	24.5%	15	21.7%	48	38.7%	7.26 (2)	.03	.17
Presence of a niggle	NI < RI	11	20.8%	28	40.6%	53	42.7%	13.40 (4)	.01	.23
12 months between shoe change	NI > (AIR, RI)	26	49.1%	20	29.0%	35	28.2%	7.97 (2)	.02	.18
10km distance per week	NI > RI	9	17.0%	9	13.0%	6	4.8%	7.40 (2)	.03	.17

χ^2: chi-square; *df*: degrees of freedom; n: number of cases; %: percentage of group; NI: never injured group; AIR: acquired injury resistance group; RI: recently injured group; <: significantly less than; >: significantly greater than; (,): both groups within brackets statistically different to group outside of bracket; p: alpha level.

5.5 Discussion

This study investigated the differences in intrinsic and extrinsic factors between three distinct injury groups: runners who have never been injured, runners proposed to have acquired injury resistance and runners who have recently been injured. Fifty per cent of runners included in this study reported to have sustained an RRI within the previous 12 months, with the injury profile of these recently injured runners similar to other RRI epidemiological studies (Hespanhol Junior, Pena Costa and Lopes, 2013; Malisoux *et al.*, 2015; Dallinga *et al.*, 2019) with knee, calf, muscle and tendon injuries most frequent. Just 58% of the recently injured runners felt that they had recovered fully from their most recent injury, with 53% of recently injured runners reporting a re-injury or exacerbation of their most recent injury. This finding supports the view that previous injury is one of the strongest and most consistent risk factors for subsequent injuries in runners (van der Worp *et al.*, 2015). In theory, RRIs that have healed completely (i.e. injured tissues that have returned to full, pre-injury strength, range of motion and proprioception) should not increase the risk of a subsequent RRI (Hootman *et al.*, 2002; van der Worp *et al.*, 2015). However, if RRIs have caused permanent structural or biomechanical dysfunction, or if pre-injury risk factors have not been identified and addressed, the runner may be placed at a greater likelihood of future injuries (Meeuwisse *et al.*, 2007). Therefore, ensuring the injured tissue has fully recovered and susceptibility to known risk factors is addressed, is critical prior to runners returning to participation (Meeuwisse *et al.*, 2007).

Recently injured runners (43%) were twice as likely to continue training despite the presence of a niggle, compared to the never injured group (21%). This is a novel finding, with limited studies investigating the relationship between a niggle and injury within the literature. Previous RRI research has reported up to 86% of runners continuing to train and race despite having a current running-related pain (Linton and Valentin, 2018), with a recent qualitative study reporting this to be a common practice of runners (Verhagen, Warsen and Silveira Bolling, 2021). However, these studies did not compare the prevalence of niggles or complaints between injured and uninjured runners. It has been speculated that continuing to run through acute pain may lead to a greater degree of structural damage to the painful tissue (Wilke, Vleeming and Wearing, 2019). In efforts to offload this, runners may modify their running biomechanics and potentially overload other tissues that would be less familiar with the demands, subsequently exposing other tissues to potential injury (Wilke, Vleeming and Wearing, 2019). This may help to explain why over half of the runners in this study reported to have sustained a re-injury or exacerbation of their most previous injury, upon return to training. A recent study in footballers found the risk of injury was 3.6 times higher when preceded by a niggle complaint (Whalan, Lovell and Sampson, 2020), highlighting the potential importance of assessing for and documenting niggles going forward.

Other factors which were more prevalently reported by the recently injured runners were changing gradient on a weekly basis, doing hill runs and having higher training speeds. Hill running and increased speed have both been found to cause greater loading on posterior chain structures, such as the Achilles tendon, which may be injurious if the load capacity of these structures are compromised (Napier and Willy, 2021). Although hill running and changes of gradient are valued components of running regimes (Sallade and Koch, 1992), excessive time spent doing hill work or abrupt increases in hill running have been proposed as injury risks (Sallade and Koch, 1992). Increased speed has also been found to relate to RRIs, and similar to the findings of this study, higher percentages of injured runners reported faster speeds than uninjured runners (Jacobs and Berson, 1986; Hootman *et al.*, 2002). Therefore, changing gradient on a weekly basis, undertaking hill runs and having higher training speeds could be proposed as causative factors as they are less likely to be an effect of the injury, due to the fact that healthcare providers do not typically prescribe such strenuous tasks following a recent injury. In contrast, one potential protective factor for injury may be a short(er) distance. This study found a significantly greater percentage of never injured runners ran an average of 10km per week compared to recently injured runners, who reported to run more than 10km per week. There is conflicting findings within the literature with respect to distance as a risk factor, with some studies reporting increased risk with increased distance (Satterthwaite *et al.*, 1999; Di Caprio *et al.*, 2010), and others reporting increased risk with lower distances (Hootman *et al.*, 2002). There appears to be a fine balance between overuse and under-conditioning in runners (Satterthwaite *et al.*, 1999), with more research needed in this area. Nevertheless, it seems that recently injured runners continue to demonstrate riskier training practices (running with a niggle, higher training speeds, etc.). Therefore, training practice modifications should be considered in the management of RRIs.

Extrinsically, several factors have been proposed to relate to injury within the literature, especially those associated with training habits, such as warm up, cool down and recovery strategies (Jacobs and Berson, 1986). Contrary to what one might expect, factors such as flexibility training, static stretching, foam rolling and actively resting were more commonly reported amongst recently injured runners in this study. As with any retrospective research, it is difficult to determine whether these factors were a cause or an effect of the injury. A recent study by Linton (2020) found stretching to be a popular component of cool down strategies amongst running coaches and running group leaders, with over 80% of coaches implementing this regularly. In this study, only half of the never injured and acquired injury resistance runners reported to stretch during cool downs, with even less undertaking flexibility or stretching as part of their recovery. It is plausible that recently injured runners either self-determined or were advised by a health professional to undertake flexibility and stretching interventions in response to their recent injury, with the intention of increasing muscle length and joint range of motion, or to assist in collagen fiber alignment in healing tissues. The majority of recently injured runners in this study (80%) reported to have received a rehabilitation programme, and perhaps these runners were maintaining some facets of their rehabilitation prescription in an effort to avoid re-injury. However, this study did not acquire specific details of rehabilitation programmes or compliance with programmes, and so this is only speculation. With respect to foam rolling, these devices are often used for the self-treatment of myofascial pain in both preventative and rehabilitative settings (Freiwald *et al.*, 2016), and may also be used with the purpose of enhancing recovery after significant endurance efforts (Freiwald *et al.*, 2016). As was noted earlier, a greater percentage of recently injured runners reported to have niggles, and foam rolling may have been a direct response to try and self-treat these pains.

Another finding which may be counterintuitive in trying to identify potential causative factors to examine in future prospective studies is that the significantly greater percentage of recently injured runners who reported wearing insoles or arch support devices in their running footwear, compared to the other injury groups. Insoles may often be advised for both injury prevention and injury treatment as a means of enhancing shock absorption, restricting excessive pronation and to correct lower limb malalignment (Urabe *et al.*, 2014). The retrospective nature of this study however, does not allow us to determine if the recently injured runners used insole or arch support devices before their most recent injury, or if they began to use them in response to their most recent injury. In keeping with footwear factors, the results of this study also revealed a lengthy duration (12 months) between running shoe change in never injured runners compared to acquired injury resistance and recently injured runners. Previous research has found injured runners to have lower miles per shoe compared to uninjured runners (Duffey *et al.*, 2000), with authors speculating that the injured runners changed their footwear more frequently due to the reduced shock attenuation capacity of older or worn shoes (Duffey *et al.*, 2000). Perhaps never injured runners have a greater ability to attenuate shock, or they may not experience the same magnitude of impact that injured runners experience, and so they are less reliant on this feature of their running shoes. Impact loading and shock attenuation was not a focus of this study however, and the explanation behind this finding remains unknown. Perhaps the never injured runners were simply less concerned with changing footwear, as they had no previous injury issues to try and alleviate. Finally, the lack of any differences in sex, age, weight, height, BMI and years of running experience between the three injury groups, are consistent with previous research examining intrinsic factors relating to RRIs (Theisen *et al.*, 2014; Malisoux *et al.*, 2015; Besomi *et al.*, 2019).

Limitations

The retrospective nature of this study limits our ability to definitively ascertain whether differences between the three injury groups (never injured, acquired injury resistance and recently injured) were present as a result of the injury, or if the differences may have been causative or protective in nature. In addition, the self-report nature of RRI reporting in this study is subject to recall bias. As the survey was adapted from previous RRI research surveys (Junior *et al*., 2013), this study did not conduct a formal psychometric testing in the development of the survey questions, and as a result the internal validity of the survey is unknown. Future studies should endeavour to determine the validity of survey contents before conducting large-scale research.

The current study also captured a snapshot of various training metrics from their previous 3 months of training (e.g. current weekly distance, annual quarterly distance, average training speed, number of sessions per week), which may be subject to change if the runner alters their training through the year to prepare for various running events. Future studies should endeavour to track RRIs and other running-related factors prospectively.

5.6 Conclusion

This study found 1 in 2 runners to have sustained an RRI within the previous 12 months, with the knee and calf most commonly affected. In terms of intrinsic risk, twice as many recently injured runners continued to train despite the presence of a niggle compared to never injured runners. This may be a substantial contributing factor to future injury, and should be monitored closely rather than being overlooked by both runners and clinicians alike. Future studies examining runners' attitudes and behaviours to train while experiencing niggles would be a beneficial addition to understanding the aetiology of RRIs. Future prospective studies should perhaps focus on potential causative factors for RRIs include changing gradient frequently, doing hill runs and having higher training speeds. While an overload in training is necessary for improved performance and musculoskeletal adaptation, runners should exercise caution when compounding training load with demanding tasks such as gradients and speed. More research is warranted in the area of training load, and how injury prevention strategies may be guided by appropriate overload.

Linking Section from Chapter 5 to Chapter 6

From Chapter 5, it was found that recently injured runners demonstrated riskier training practices compared to injury resistant and never injured runners. These practices included training with a niggle, training at faster speeds and changing gradient on a frequent basis, potentially indicating the need for training modifications in RRI management and return to participation for recently injured runners. However, one limitation of this research is its retrospective nature, meaning there is uncertainty whether the runners had been implementing these risky training practices before they became injured, or if the practices are newly developed since their return to running.

To address this limitation, Chapter 6 aims to improve the quality of research in this area by investigating the risk factors for injury in a large-scale prospective study. This study will compare impact acceleration, running kinematics (motion analysis at the foot, ankle, knee, hip, pelvis and trunk), and training practices between runners who sustained prospective injuries and those who remined injury free. Prospective research in this area has been relatively limited by small sample sizes, short surveillance periods and univariate analyses. Thus, this study will aim to determine the aetiological risk factors for prospective RRIs in a large cohort (n = 258) over a lengthy duration (12 months), with multivariate analyses of kinetic, kinematic and training-related variables.

Chapter 6 Study 4 – Aetiological Factors of Running-related Injuries: A 12 Month Prospective "Running Injury Surveillance Centre" (RISC) Study

Burke, A., Dillon, S., O'Connor, S., Whyte, E., Gore, G., Moran, K., 2022. Aetiological Factors of Running-related Injuries – A 12 Month Prospective "Running Injury Surveillance Centre" (RISC) Study – A Prospective Study. *Medicine and Science in Sport and Exercise Science.**

**Submitted for publication to Medicine and Science in Sport and Exercise Science. Awaiting decision.*

6.1 Abstract

Introduction Running-related injuries (RRIs) are a prevalent issue for runners, with several risk factors proposed to be causative. The majority of studies in the area are limited by retrospective study design, small sample sizes and seem to focus on individual risk factors in isolation.

Purpose This study aims to investigate the multifactorial contribution of risk factors to prospective RRIs, with consideration of impact acceleration, running kinematics and training-related factors in a large sample of recreational runners.

Study Design Prospective cohort study.

Methods Two hundred and fifty-eight recreational runners participated in the prospective study, where data pertaining to their injury history and training practices (survey), impact acceleration (accelerometers), and running kinematics (foot, ankle, knee, hip, pelvis and trunk) were gathered at a baseline testing session. Runners were tracked for injuries for one year. A Cox regression, with days to RRI as the event, was performed for each variable independently, before being adjusted for sex, age and mileage. A multivariate Cox regression model was subsequently performed.

Results A total of 51% of runners sustained a prospective injury, with the calf being the most commonly affected region. Univariate analysis found previous history of injury <

1 year ago, training for a marathon, frequent changing of shoes (every 0-3 months), and running technique (non-rearfoot strike pattern, less knee valgus, greater knee rotation) to be significantly associated with injury. The multivariate analysis revealed previous injury, training for a marathon, less knee valgus, and greater thorax drop to the contralateral side to be risk factors for injury.

Conclusion This study found several factors to be associated with injury. With the omission of previous injury history, the risk factors (footwear, marathon training and running kinematics) identified in this study may be easily modifiable, and therefore could inform injury prevention strategies. This is the first study to find foot strike pattern and trunk kinematics to relate to prospective injury, indicating the need for further research in these areas, particularly with adequately powered sample sizes.

6.2 Introduction

The proposed benefits of running are vast, with millions of runners worldwide improving their cardiovascular, musculoskeletal and psychological health with participation (Lopes *et al.*, 2012). However, the activity of running has proven to be costly for nearly 2 out of every 3 runners, with consistently high running-related injury (RRI) prevalence rates reported (Messier *et al.*, 2018; Kakouris, Yener and Fong, 2021). Overuse injuries to the knee (e.g. patellofemoral pain syndrome), shin (e.g. medial tibial stress syndrome), calf (e.g. Achilles tendinopathy) and foot (e.g. plantar fasciitis) appear to be the most common RRIs (Kakouris, Yener and Fong, 2021), typically resulting from cumulative loads that exceed the structural capacity of various tissues (Bertelsen *et al.*, 2017). RRIs have been found to cause an average time-loss of 4 weeks (Hespanhol Junior *et al.*, 2016), with this restriction often associated with a financial cost to the runner, in addition to a deterioration of cardiovascular and emotional health (Hespanhol Junior *et al.*, 2016). For this reason, several studies have sought to determine the aetiological factors of RRIs.

Several risk factors have been proposed to relate to RRIs, with sex (Messier *et al.*, 2018), age (Satterthwaite *et al.*, 1999), impact loading (Davis, Bowser and Mullineaux, 2016), running technique (Dudley *et al.*, 2017), training behaviour (Hespanhol Junior, Pena Costa and Lopes, 2013) and previous history of injury (Van Middelkoop *et al.*, 2008) all thought to be influential. Thus, it is critical to examine all factors and how their combined interaction may impact the occurrence of prospective RRIs.

There are perhaps five limiting factors to the current research. Firstly, it is predominantly retrospective in nature, with few studies examining the effects of trunk (n = 1) (Shen *et al.*, 2019), pelvis (n = 1) (Shen *et al.*, 2019), hip (n = 2) (Noehren, Davis and Hamill, 2007; Dudley *et al.*, 2017), knee (n = 4) (Noehren, Davis and Hamill, 2007; Hein *et al.*, 2014; Dudley *et al.*, 2017; Messier *et al.*, 2018), and foot (n = 3) (Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Messier *et al.*, 2018) kinematics prospectively. Only one prospective study has investigated the effects of impact acceleration on RRIs (Winter *et al.*, 2020). Secondly, some of the prospective studies are underpowered by virtue of small sample size (Noehren, Davis and Hamill, 2007; Kuhman *et al.*, 2016a; Dudley *et al.*, 2017; Becker, Nakajima and Wu, 2018; Winter *et al.*, 2020), which may limit their ability to detect statistically significant differences. Thirdly, while it is well recognised that aetiological factors appear to be multifactorial in nature (Bertelsen *et al.*, 2017; Napier and Willy, 2021), studies have focused on specific risk factors in isolation (e.g. impact loading only) (Bredeweg *et al.*, 2013; Davis, Bowser and Mullineaux, 2016), or have concentrated on limited segments of the kinematic chain (Messier *et al.*, 2018), which may overlook the interdependent contributions of various segments such as the pelvis or trunk to prospective injury. Fourthly, the results of prospective research to date have largely involved force plate data collection which limits analysis to 3-10 strides. A recent study has identified that at least 20 consecutive strides should be utilized for stable kinematic motion capture and spatiotemporal analysis (Riazati, Caplan and Hayes, 2019). Although the precision of impact loading and kinematic motion analysis is strongest within a laboratory, the recent implementation of inertial measurement units for impact loading analysis should facilitate the examination of more representative strides, while also allowing a more insightful examination of segmental loading with simultaneous kinematic analysis. Lastly, the conflicting definitions of injury amongst the prospective RRI research has made comparisons between studies challenging, with none of the aforementioned prospective studies utilizing a consensus based definition of RRI to date (Bredeweg *et al.*, 2013; Davis, Bowser and Mullineaux, 2016; Messier *et al.*, 2018).

Thus, the aim of this study was to investigate the multifactorial contribution and interaction of impact loading, kinematic (foot, ankle, knee, hip, pelvis and trunk) and training-related factors that contribute towards prospectively injured recreational runners during a 12 month period.

6.3 Methods

6.3.1 Study Design

The Running Injury Surveillance Centre (RISC) Study was a 12 month prospective longitudinal trial of 310 recreational runners based in the greater Dublin area of Ireland (NCT03671395 www.clinicaltrials.gov). The study was approved by the Dublin City University Research Ethics Committee (DCUREC/2017/186), and informed consent was obtained from all participants prior to participation.

6.3.2 Participants

Male and female recreational runners aged over 18 years, who ran a minimum of 10km per week for the preceding 6 months (Saragiotto, Yamato and Lopes, 2014), were recruited from local running clubs, running events, radio advertising and social media recruitment drives between January and August 2018. Participants were excluded if they were currently injured or had sustained an injury within the 3 months prior to testing (Buist *et al.*, 2010), had a history of cardiovascular illness, previous reconstructive joint surgery or joint replacements, or were pregnant. Study researchers (AB and SD) gave eligible participants an overview of the study, and collected baseline demographic, anthropometric, training behaviour, injury history and biomechanical data during a baseline testing session. A running-related injury definition was adapted from a consensus statement, and was defined as "any running-related (training or competition) muscle, bone, tendon or ligament pain in the lower back/legs/knee/foot/ankle that caused a restriction or stoppage of running (distance, speed, duration or training) for at least 7 days or 3 consecutive scheduled training sessions, or that required the runner to consult a physician or other health professional" (Malisoux *et al.*, 2015; Yamato, Saragiotto and Lopes, 2015).

Participants were asked to contact researchers if they had sustained an injury. Participants were also contacted via email or phone every fortnight for a period of 12 months from the date of their baseline session, to ensure they were still training regularly, and to determine the occurrence of any running-related injuries (RRIs) that may not have been reported immediately. If participants became injured, their injury was assessed by a Certified

Athletic Therapist (AB) or a Chartered Physiotherapist (SD) to establish a diagnosis. If participants were unable to attend an injury assessment, they were encouraged to retrieve a diagnosis from a registered healthcare professional. Injured runners were tracked until their return to activity, and were subsequently tracked for further injuries until the 12 month surveillance period had ended. Participants who had an acceptable response rate (>80%, (Webster *et al.*, 2019)) through the 12 month surveillance period were included in the final analysis.

6.3.3 Instruments

6.3.3.1 Survey

Participants completed an online survey prior to baseline testing. The online survey was developed based on pre-existing research that explored lifestyle and training factors relating to RRIs (Hespanhol Junior, Pena Costa and Lopes, 2013). Face validity of the survey was conducted by a group of four experts with epidemiological and aetiological research experience, and it was then piloted with a group of 30 physically active males and females. The final survey (Appendix B) comprised of 3 sections with a total of 26 questions, presented as a mix of multiple choice and open ended responses. Satellite questions were automatically prompted to gather a more detailed response to index questions where relevant. Section A of the survey consisted of 3 questions capturing the unique ID, age and sex of the participants. Section B contained 21 questions comprising of training-related questions focussing on their history of training (years running experience, participation in non-running related exercise classes), the purpose of training (motivating factors, events) and their typical training parameters (e.g. distance, speed, frequency of session, surface, footwear, presence of a niggle, experience of delayed onset of muscle soreness, execution of warm-ups, cool downs and recovery sessions). In order to document the presence of a niggle during running training, participants were asked to report and describe any "nagging pain or complaint in your lower back/lower limbs that did not restrict your training". The final section (Section C) was made up of two main questions acquiring information on their running-related injury history (number of RRIs, location, type, duration, medical advice sought, rehabilitation completion, exacerbation or recurrence of re-injuries).

6.3.3.2 Anthropometrics

Height (cm) (Leicester Height Measure, SECA, UK) and body mass (kg) (SECA, UK) were recorded. Leg length was then measured, which was the length (cm) between the

Anterior Superior Iliac Spine and the Medial Malleolus (Carlos *et al.*, 2016). Ankle width and knee width were measured using a callipers, and data were subsequently entered into Vicon Nexus to fulfil modelling requirements.

6.3.3.3 Biomechanical Analysis

Three-dimensional kinematic analysis was used to assess running technique. A 17-camera vantage motion capture system (Vicon Motion Systems, Oxford, UK) set to sample at 200Hz. Two high speed video cameras, sampling at 100Hz were placed 4m behind of and perpendicular to the treadmill for visual interpretation of their running technique, if required (Belli et al., 1998). Thirty-two reflective markers, 14 mm in diameter, were placed on bony landmarks of the trunk, pelvis and lower limbs according to a custom Plug in Gait model (Vicon Motion Systems, Oxford, UK) as follows: C7, T10, sternum, clavicle, acromioclavicular joint, anterior superior iliac spine, posterior superior iliac spine, pelvic crest, proximal thigh, distal thigh, lateral thigh, proximal tibia, distal tibia, lateral fibula, lateral malleolus, heel and metatarsal head (Marshall et al., 2014). Rigid body segments of the trunk, pelvis, thigh, shank and foot, and the joint angles between these segments were defined by the Vicon Plug in Gait modelling routine (Dynamic Plug in Gait). Stance phase data were extracted at specific time points (Table 6.3.1). The stance phase was chosen as this is a time during gait where up to 4 times the body weight of the runner is acting on the body, and as a result, it has been found to be the most injurious phase of running gait (Lieberman *et al*., 2010). Previous studies have focused their attention on distal segments (e.g. foot and knee) with less attention given to the whole kinematic chain. As the trunk and pelvis play influential roles in how the hips, knees and feet act, this study assessed kinematics across the sagittal, frontal and transverse planes for all segments, in order to capture a full and comprehensive analysis of the stance phase during running gait. Foot strike pattern was determined by the foot contact angle at initial contact. Foot contact angles >8.0° were classified as rearfoot strike (RFS) pattern, < -1.6° a forefoot strike (FFS) pattern, and -1.6° to 8.0° represented a midfoot strike (MFS) pattern (Altman and Davis, 2012). As numbers in the MFS and FFS groups were lower, these groups were combined to form a non-rearfoot strike pattern group (Paquette, Milner and Melcher, 2017).

Inertial measurement units (Shimmer3 IMU, Shimmer™, Ireland) containing accelerometers were used to capture the peak ($Peak_{accel}$) and rate ($Rate_{accel}$) of impact acceleration of the tibia bilaterally, as well as for the sacrum, at a sampling rate of 512Hz.

Two inertial measurement units were attached to the tibia bilaterally, 5 cm proximal to the medial malleolus using Hypafix® tape adhered directly to the skin, with the y-axis aligned with the long axis of the tibia (Sheerin *et al.*, 2018). The sacrum sensor was held in place within a custom-made elastic belt, with the longitudinal axis aligned to the vertical midline of the S2 spinous process (O Catháin, Richter and Moran, 2020). This was secured further by an elastic waistband and tape. Applying tape and supportive wrapping to sensors has previously been found to capture more accurate impact acceleration data (Johnson *et al.*, 2020). Participants wore their normal running shoes.

Table 6.3.1 Time points for extracted stance phase variables

Stance phase variable	**Definition**
Initial contact	Angle when the foot makes contact with the ground
Maximum/Peak angle	Maximum angle achieved during stance
Minimum angle	Minimum angle achieved during stance
Toe off	Angle when the foot leaves the ground
Excursion	Maximum – minimum angle during stance
Angle at peak knee flexion	Angle when the knee reaches peak knee flexion

6.3.4 Procedure

Once all reflective markers and IMUs had been attached to the body, participants completed a 5 minute warm-up consisting of dynamic stretches for the hamstrings, quadriceps, hip flexors, hip extensors and calf muscle groups (Yamaguchi, Takizawa and Shibata, 2015). Running trials were conducted on a treadmill (Flow Fitness, Runner DTM3500i, The Netherlands) at a fixed speed of 9km/hr. The fixed speed of 9km/hr was chosen to allow for comparison of kinematics and impact acceleration without the confounding factor of variations in speed affecting the participants' technique. This speed represented the average five-kilometre time of runners in the greater Dublin area, determined from the average speed reported on the Dublin Park Run database (www.parkrun.ie/events). Participants ran at 9km/hr for 6 minutes to ensure familiarisation to treadmill running (Lavcanska, Taylor and Schache, 2005).

6.3.5 Data Processing

Motion capture data was filtered using a 4th order zero lag 15Hz Butterworth filter with a cut-off frequency of 15Hz. Data were visually screened for entropy and amplitude using a custom-built MATLAB script (Mathworks Inc., Natick, MA, USA). Data were then synthesized using MATLAB to calculate the biomechanical variables of interest. Data in the three planes of movement were obtained for each segment of both limbs (foot, ankle, knee, hip, pelvis and trunk) during the gait cycle at initial contact, time of peak knee flexion and toe-off. Maximum, minimum and excursion values per stride of each segment were also recorded.

$Peak_{accel}$ and $Rate_{accel}$ of the tibia and sacrum were processed using a custom-built MATLAB script (Mathworks Inc., Natick, MA, USA). A 4th order, zero lag 60 Hz Butterworth filter was applied to the data and dropped packets were filled using a cubic spline. $Peak_{accel}$ was taken as the maximal amplitude of the accelerometer's transient at initial contact and was expressed in units of standard gravity ($g = 9.8\ m/s^2$). $Rate_{accel}$ was calculated as the $Peak_{accel}$ divided by the time to $Peak_{accel}$ (Crowell and Davis, 2011) (Figure 1). Consecutive foot-strikes, taken immediately after the 6-minute familiarization, were processed on both limbs.

An average of 90 strides for each limb were examined. Consistent with previous research, multiple imputation was utilized to generate multiple plausible datasets at random for dropped data packets (Kiernan *et al.*, 2018). These datasets were analysed separately and pooled at the end. In this procedure, 20 imputed datasets were generated using SPSS and pooled using Rubin's rules (Rubin, 2004). In order to validate the imputation accuracy, a second imputation trial was completed where known data were deleted from two participants (Kiernan *et al.*, 2018). A subsequent independent t-test revealed no statistical difference between original data and imputed data ($p > 0.05$).

6.3.6. Statistical Analysis

All statistical analyses were performed using SPSS (IBM Corp, IBM SPSS Statistics for Windows, Version 27.0, Armonk, NY). Descriptive statistics were calculated for baseline demographics, with frequencies assessed for categorical variables, and means and standard deviations for continuous variables. Boxplots were utilized to identify outliers in the kinematic and kinetic datasets. Outliers were defined as values >1.5 times the interquartile range away from the median (Milner *et al.*, 2006), and these were removed from the data prior to statistical analysis of differences between the groups. For runners who sustained an RRI, the limb that was injured was used in the analysis. If a runner had sustained multiple RRIs, the limb that sustained the first RRI was used. Where runners had not sustained an

RRI, a random selection of their uninjured limbs was chosen. This selection was conducted at the end of the 12-month surveillance, where a percentage of injured group dominant and non-dominant limbs were matched at random the same percentage of uninjured group dominant and non-dominant limbs. Differences in demographic characteristics between injured and uninjured runners were initially assessed with an independent t-test for continuous measures, and a chi-squared test for categorical variables.

To evaluate the contribution of possible risk factors for RRI, Cox regression was implemented with the event defined as the participant's first RRI, or no RRI if the participant remained uninjured during the 12 month surveillance. The event time was defined as the number of days until their first RRI (injured), or until the end of the surveillance period (uninjured). Potential RRI risk factors were first entered into a univariate Cox regression to determine the independent relationship with injury. Correlations between all potential risk factors were assessed using Spearman's rho test. If a correlation between two factors was greater than 0.8, only one of the risk factors was chosen for the multivariate analysis. Risk factors which were found to demonstrate an independent relationship with RRI in the univariate analysis ($p \leq 0.25$) were then entered into a multivariate Cox regression prediction model, using the backward likelihood ratio approach, with $p \leq 0.10$ applied as a cut-off level for acceptance. Hazard ratios (HR) and the corresponding 95% confidence intervals (CI) were evaluated for the risk factors associated with RRI, with statistical significance was set at $p < 0.05$.

6.4 Results

A total of 310 recreational runners volunteered to participate in this study. Fifty-two participants were removed from the final analyses for the following reasons: sustained a non-running-related injury (e.g. work based or road traffic accident injury) (n = 14), had impact acceleration or kinematic data that were considered as outliers (n = 11), developed a long-term illness (n = 10), had poor response rates through the surveillance period (n = 10), became pregnant (n = 3), participated in other team-based sports (n = 3), or had stopped running (n = 1). Therefore, a total of 258 runners (163 males and 95 females) were considered for the final analyses.

6.4.1 Baseline characteristics

Demographic and anthropometric characteristics for these participants can be viewed in Table 6.4.1. There were significantly more runners with a history of previous injury in the injured group (48%) compared to the uninjured group (33%) ($p = 0.01$). No other differences existed between the groups for demographic characteristics.

6.4.2 RRI Prevalence

One hundred and thirty-two runners (51%) sustained a total of 166 RRIs during the 12-month surveillance period. Eighty-five males (52%) and forty-seven females (50%) sustained at least one prospective RRI, with no statistical difference between sexes. A breakdown of the RRIs by pathology can be seen in Figure 6.4.1. Achilles tendinopathy (14%), calf strains (9%) and lower back pain (8%) were the three most common pathologies experienced by all runners. The mean time-loss from injury was 50.3 ± 68.8 days (Range: 4 – 365 days).

Table 6.4.1 Demographic and anthropometric characteristics.

	All (n = 258) Mean ± SD	**Injured (n = 132) Mean ± SD**	**Uninjured (n = 126) Mean ± SD**	**P value**
Age (years)	43.3 ± 8.9	43.5 ± 8.3	43.1 ± 9.5	0.74
Height (m)	1.7 ± 1.0	1.7 ± 0.1	1.7 ± 0.1	0.72
Weight (kg)	72.9 ± 13.1	72.2 ± 12.8	73.5 ± 13.4	0.41
BMI (kg/m^2)	24.1 ± 3.0	24.0 ± 2.9	24.3 ± 3.1	0.39
Average training speed (km/hr)	11.4 ± 1.7	11.6 ± 1.7	11.3 ± 1.8	0.24
Annual quarterly mileage (km)	421.3 ± 283.9	420.6 ± 279.6	422.1 ± 289.3	0.97
Previous injury in past 12 months (yes)	n = 106 (41%)	n = 64 (48%)	n = 42 (33%)	0.01*

n: sample size; SD: standard deviation; m: metres; kg: kilograms; BMI: body mass index; kg/m^2: kilogram per metres squared; km/hr: kilometres per hour; km: kilometres; *: significant p-value at $p < 0.05$.

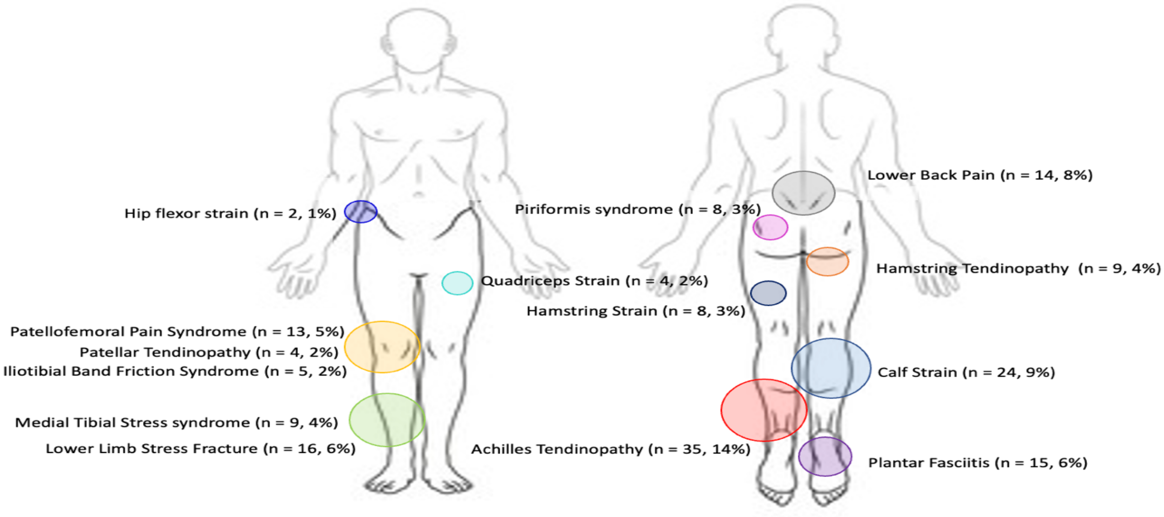

Figure 6.4.1 Running-related injury pathologies.

Calf strain (14%) and Achilles tendinopathy (14%) were the most common injuries suffered by males, while Achilles tendinopathy (13%), lower limb stress fracture (5%) and hamstring tendinopathy (5%) were the most common injuries sustained by females (Table 6.4.2). Males were significantly more likely to have sustained a calf strain compared to females (p = 0.01), but no other differences were found between sexes.

Table 6.4.2 Running-related injury pathology by sex.

	All (n = 258: 100%)	**Males (n = 163: 63%)**	**Females (n = 95: 37%)**	**P value**
Achilles Tendinopathy	n = 35 (21%)	n = 23 (14%)	n = 12 (13%)	0.70
Calf Strain	n = 24 (15%)	n = 22 (14%)	n = 2 (2%)	0.01*
Lower Limb Stress Fracture	n = 16 (10%)	n = 11 (7%)	n = 5 (5%)	0.67
Plantar Fasciitis	n = 15 (9%)	n = 11 (7%)	n = 4 (4%)	0.55
Lower Back Pain	n = 14 (8%)	n = 11 (7%)	n = 3 (3%)	0.48
Patellofemoral Pain Syndrome	n = 13 (8%)	n = 11 (7%)	n = 2 (2%)	0.22
Hamstring Tendinopathy	n = 9 (5%)	n = 4 (3%)	n = 5 (5%)	0.29
Medial Tibial Stress Syndrome	n = 9 (5%)	n = 5 (3%)	n = 4 (4%)	0.58
Hamstring Strain	n = 8 (5%)	n = 7 (4%)	n = 1 (1%)	0.28
Piriformis Syndrome	n = 8 (5%)	n = 5 (3%)	n = 3 (3%)	0.69
Iliotibial Band Friction Syndrome	n = 5 (3%)	n = 3 (2%)	n = 2 (2%)	0.68
Quadriceps Strain	n = 4 (2%)	n = 3 (2%)	n = 1 (1%)	0.62
Patellar Tendinopathy	n = 4 (2%)	n = 1 (1%)	n = 3 (3%)	0.17
Hip Flexor Strain	n = 2 (1%)	n = 1 (1%)	n = 1 (1%)	0.69

n: sample size; *: significant Chi-square p-value between males and females at p< 0.05.

6.4.3 Risk Factors for RRI

Means and standard deviation of demographic, impact acceleration and kinematic variables for injured and uninjured runners, in addition to differences between injury groups, can be viewed in Supplemental Table C1 (Appendix C).

The univariate Cox regression analysis showed that having a previous history of injury < 1 year ago, training for a marathon, frequent changing of shoes (every 0-3 months) (Table 6.4.4), and running technique (non-rearfoot strike pattern, lower knee valgus at initial contact, lower knee valgus at toe off, lower peak knee valgus angle, greater knee internal rotation at peak knee flexion, and greater knee internal-external rotation excursion) to be significantly associated with prospective injury ($p < 0.05$). After adjusting for sex, age and mileage, all factors remained significant with the exception of foot strike pattern. Upon post-hoc examination, it was determined that the addition of mileage as a covariate resulted in non-rearfoot strike becoming insignificant ($p = 0.11$). In addition, greater peak thorax drop to the contralateral side became a significant univariate factor after adjusting for sex, age and mileage ($p < 0.05$). A full outline of univariate analysis findings can be seen in Supplemental Table C2 (Appendix C).

With respect to the multivariate Cox regression analysis, only four variables remained in the final model (Table 6.4.5), with two of these being statistically significant ($p < 0.05$). A lower knee valgus at toe off (HR: 1.09; 95% CI: 1.03 to 1.16, $p = 0.01$) and training for a marathon (HR: 1.47; 95% CI: 1.01 to 2.24, $p = 0.04$) were both found to be significant risk factors for prospective injury. Thorax drop to contralateral side and previous history of injury < 1 year ago were significant contributors to the final multivariate model, but were not significantly different between injured and uninjured runners ($p > 0.05$).

Table 6.4.3 Univariate Cox regression findings for demographic and training-related factors.

Variable	Injured (n = 132) Mean ± SD	Uninjured (n = 126) Mean ± SD	Unadjusted HR	95% CI Lower to Upper	P value	Adjusted HR	95% CI Lower to Upper	P value
Female sex (Male is reference)	47 females (50%)	48 females (50%)	0.93	0.65 to 1.33	0.71			
Age (years)	43.5 ± 8.3	43.1 ± 9.5	1.00	0.98 to 1.02	0.98			
Weight (kg)	72.2 ± 12.8	73.5 ± 13.4	0.99	0.98 to 1.01	0.38	0.99	0.97 to 1.00	0.11
Height (m)	1.7 ± 0.1	1.7 ± 0.1	0.69	0.11 to 4.19	0.68	0.25	0.18 to 3.44	0.30
BMI (kg/m^2)	24.0 ± 2.9	24.3 ± 3.1	0.97	0.92 to 1.03	0.36	0.96	0.90 to 1.03	0.24
Annual quarterly mileage (km)	420.6 ± 279.6	422.1 ± 289.3	1.00	1.00 to 1.00	0.77			
Training Speed (km/hr)	11.6 ± 1.7	11.3 ± 1.8	1.06	0.96 to 1.16	0.27	1.06	0.96 to 1.17	0.28

kg: kilogram; m: metre; kg/m2: kilogram per metre squared; km: kilometre; km/hr: kilometres per hour;; n: sample size; SD: standard deviation; HR: hazard ratio; CI: confidence interval; *: p value significant at $p < 0.05$. The adjusted results are statistically controlled for sex, age and mileage

Table 6.4.4 Significant univariate Cox regression findings.

Variable	Injured (n = 132) Mean ± SD	Uninjured (n = 126) Mean ± SD	Unadjusted HR	95% CI Lower to Upper	P value	Adjusted HR	95% CI Lower to Upper	P value
FSP – RFS (Reference)	71 RFS (54%)	79 RFS (70%)	1.00			1.00		
FSP – NRFS	61 NRFS (46%)	35 NRFS (30%)	1.14	1.00 to 2.06	0.05*	1.37	0.93 to 2.01	0.11
Knee Valgus at Initial Contact (°)	-1.6 ± 2.9	-2.6 ± 2.8	1.09	1.03 to 1.16	0.00*	1.10	1.03 to 1.17	0.00*
Knee Valgus at Toe Off (°)	-2.7 ± 3.0	-3.8 ± 3.1	1.09	1.03 to 1.15	0.00*	1.10	1.04 to 1.17	0.00*
Peak Knee Valgus (°)	-1.0 ± 3.0	-1.9 ± 3.0	1.07	1.01 to 1.13	0.02*	1.08	1.02 to 1.15	0.01*
Knee Int Rot at Peak Knee Flexion (°)	21.3 ± 7.5	19.5 ± 8.0	1.03	1.00 to 1.05	0.03*	1.03	1.00 to 1.05	0.04*
Knee Rotation Excursion (°)	20.3 ± 5.2	19.3 ± 4.1	1.04	1.00 to 1.08	0.03*	1.05	1.01 to 1.09	0.02*
Peak Thorax Drop to Contralateral Side (°)	1.2 ± 2.3	0.8 ± 2.2	1.06	0.98 to 1.15	0.13	1.09	1.00 to 1.18	0.05*
No previous injury (Reference)	68 (52%)	84 (67%)	1.00			1.00		
Previous Injury	64 (48%)	42 (33%)	1.57	1.12 to 2.21	0.01*	1.57	1.10 to 2.23	0.01*

Not training for a marathon (Reference)	48 (46%)	70 (54%)	1.00			1.00		
Training for a marathon	84 (64%)	56 (46%)	1.75	1.22 to 2.50	0.00*	1.76	1.22 to 2.54	0.00*
Change shoes 0-3 months (Reference)	14 (11%)	13 (10%)	1.00			1.00		
Change shoes 4-6 months	40 (30%)	37 (29%)	0.50	0.23 to 1.07	0.07	0.49	0.23 to 1.06	0.07
Change shoes 7-12 months	42 (32%)	33 (26%)	0.46	0.22 to 0.98	0.05*	0.45	0.20 to 0.99	0.05*
Change shoes 12 months +	36 (27%)	43 (34%)	0.40	0.19 to 0.86	0.02*	0.38	0.17 to 0.85	0.02*

FSP: foot strike pattern; RFS: rear-foot strike; NRFS: non-rear-foot strike; Int Rot: internal rotation; n: sample size; SD: standard deviation; HR: hazard ratio; CI: confidence interval; *: p value significant at $p < 0.05$. The adjusted results are statistically controlled for sex, age and mileage.

Table 6.4.5 Results of the multivariate Cox regression.

Variable	Injured (n = 132) Mean ± SD	Uninjured (n = 126) Mean ± SD	HR	95% CI Lower to Upper	P value
Knee Valgus at Toe Off (°)	-2.7 ± 3.0	-3.8 ± 3.1	1.09	1.03 to 1.16	0.006*
Thorax Drop to Contralateral Side (°)	1.2 ± 2.3	0.8 ± 2.2	1.08	1.00 to 1.17	0.063
No previous injury (Reference)	68 (52%)	84 (67%)	1.00		
Previous Injury	64 (48%)	42 (33%)	1.57	1.41 to 2.04	0.069
Not training for a marathon (Reference)	48 (46%)	70 (54%)	1.00		
Training for a marathon	84 (64%)	56 (46%)	1.47	1.01 to 2.14	0.043*

n: sample size; SD: standard deviation; HR: hazard ratio; CI: confidence interval; *: p value significant at $p < 0.05$.

6.5 Discussion

This discussion primarily compares and contrasts the findings of this study with prospective research, where possible. The prioritising of prospective comparisons over retrospective comparisons is because of the unclear cause and effect differentiation that retrospective research presents. It is feasible that where a smaller value for a variable is evident in the injured group of a retrospective study, it is a compensatory response for a larger value in the injured group causing the injury (as would be evident in a prospective study), and vice versa.

6.5.1 Injury Prevalence

The one year injury prevalence of 51% is similar to previous studies (Winter *et al.*, 2020; Desai *et al.*, 2021). The calf was the most commonly injured region, supporting a trend which has been observed previously (Mann *et al.*, 2015; Franke, Backx and Huisstede, 2019; Winter *et al.*, 2020). The knee has often been found to be the most commonly injured region within running epidemiology research (Messier *et al.*, 2018; Napier *et al.*, 2018; Dallinga *et al.*, 2019), but was the second most popular location in this study. Authors are uncertain why this may be, but propose that the greater prevalence of non-rearfoot strike runners (46%) observed in the injured group of this study may indicate greater posterior lower leg complex loading (Kulmala *et al.*, 2013), compared to the patellofemoral joint load that is observed in rearfoot strike runners (Goss, 2012; Kulmala *et al.*, 2013). Limited studies in the past have reported the pathology of injury, making comparisons limited. The most common injuries in this study were Achilles tendinopathy, calf strain, lower limb stress fracture and plantar fasciitis, findings which extend the credence of previous research (McKean, Manson and Stanish, 2006; Knobloch, Yoon and Vogt, 2008; Di Caprio *et al.*, 2010; Dudley *et al.*, 2017).

6.5.2 Potential Risk Factors for RRI

6.5.2.1 Demographic Characteristics

Intrinsic risk factors such as sex, age and anthropometry have been well researched in RRIs. Although the present study found males to suffer significantly more calf injuries than females, there was no significant effect for sex on overall injury in the Cox regression model. This is in support of Satterwaite *et al.*, (1999), who also noted males to be at greater risk of calf injuries. The evidence for sex as a risk factor for RRI is conflicting however, with some studies suggesting males to be at greater risk of injury (Satterthwaite *et al.*, 1999; Buist *et al.*, 2010), some proposing that females are at greater risk (Messier *et al.*, 2018), and some finding no risk associated with either sex (Reinking *et al.*, 2007; Ghani Zadeh Hesar *et al.*, 2009; Hirschmüller *et al.*, 2012; Nielsen, Buist, *et al.*, 2013). It has been speculated that injury risk may differ between sexes due to the differences in anatomical (femoral inclination and femoral anteversion) (Eckhoff *et al.*, 1994; Heiderscheit, Hamill and Caldwell, 2000; Powers, 2003a), physiological (heart and lung size and capacity) (Boles and Ferguson, 2010) and biomechanical (joint kinematics and landing strategies) (Souza and Powers, 2009; Baggaley *et al.*, 2015; Gaitonde, Ericksen and Robbins, 2019) characteristics of males and females, however the basis for such differences is largely theoretical to date.

Regarding increasing age, some studies have found deficits to flexibility, strength, bone density, and proprioception (McKean, Manson and Stanish, 2006). These physiological changes along with a reduced capacity for healing and recovery could suggest an increase in susceptibility to prospective injuries for an older athlete (Marti *et al.*, 1988; McKean, Manson and Stanish, 2006). The present study however did not find age to relate to injury, which adds further support to previous findings (Reinking *et al.*, 2007; Nielsen, Buist, *et al.*, 2013; Messier *et al.*, 2018).

With respect to anthropometrics, body mass index (BMI) is one of the most popular measures utilised within research, as it is considerate of both height and weight. It has been proposed that a greater BMI would result in excessive loading or forces on the lower extremities (Manek *et al.*, 2003). The present study fortifies the findings of several others having found no association between BMI and RRIs (Messier *et al.*, 2018; Besomi *et al.*, 2019; Dallinga *et al.*, 2019).

6.5.2.2. Previous history of injury and training-related factors

The present study found that having an injury within the previous year increased the odds of sustaining a prospective injury by 1.57 times, a finding that adds further validation to systematic reviews in the area (Saragiotto *et al.*, 2014; van der Worp *et al.*, 2015). When returning from previous injury, there may be incomplete healing of the original injury (van der Worp *et al.*, 2015), which may cause permanent and long-lasting structural or biomechanical mal-adaptations, increasing the chances of subsequent re-injuries (Van Der Worp *et al.*, 2012). To compound this, if rehabilitation was insufficient in terms of addressing predisposing intrinsic (strength, mobility, flexibility, impact loading) and extrinsic (load, speed, footwear) risk factors for the injury, the return to full participation may be at a compromised level resulting in potentially dysfunctional movement and coordination strategies (Drew, Cook and Finch, 2016; Toohey *et al.*, 2017). This may overload previously vulnerable or weak structures and again, tissue failure may result (Saragiotto *et al.*, 2014).

With regards to training-related factors, the present study found that training for a marathon was significantly associated with a 1.76 greater risk of injury. This reinforces the findings of Macera *et al.*, (1991) who too found a greater risk of RRI in runners training for a marathon. Marathon runners generally prepare for the event with generally periodical increments in training mileage, but to date there are inconsistent findings regarding mileage, with some authors noting significantly lower training volumes in marathon runners compared to those who had high training volumes (van Poppel *et al.*, 2018; Mohseni *et al.*, 2021), and other studies reporting significantly higher training volumes in marathon runners compared to those who had low training volume (Van Middelkoop *et al.*, 2008; Nielsen *et al.*, 2012). The present study found no effect of mileage on RRIs, a finding that bolsters the majority of research in this area (Nielsen *et al.*, 2014; Theisen *et al.*, 2014; Messier *et al.*, 2018; Besomi *et al.*, 2019; Dallinga *et al.*, 2019). A potential reason for the lack of clarity may be that most studies capture absolute mileage at a point in time, and subsequently relate this to injury. While this method is logistically and financially advantageous for researchers, it does not consider the change in mileage over time and therefore may not identify sharp increases or changes in training volume. Recent systematic reviews have advocated for the implementation of the exponentially weighted moving average model, a variant of the acute: chronic workload ratio, which considers training volume on an ongoing basis, and is more likely to inform of deleterious training loads that may cause injury in non-contact sports (Griffin *et al.*, 2020; Maupin *et al.*, 2020).

With regards to footwear, the present study found that infrequent changing of running shoes is protective of injury, suggesting that those who change shoes less frequently (> 3 months) to be at lesser risk of injury. This finding lends further support to Taunton *et al.*, (2003), who too reported a significantly lower risk for injury in males who had infrequent shoe changes (4-6 months) compared to a change every 1-3 months. A frequent change of shoes may be associated with injury particularly if the shoes are of a different brand, model or cushioning. These changes may alter the foot position (e.g. foot strike pattern) thereby changing the distribution of loading within the lower extremity (Willy and Davis, 2014), and runners may be unfamiliar with the associated overload as a result (Hreljac, 2005; Bertelsen *et al.*, 2017).

Regarding training speed, the present study did not find speed to relate to injury, a finding that is akin to previous prospective research (Theisen *et al.*, 2014; L Malisoux *et al.*, 2015; Messier *et al.*, 2018). Although greater speeds increase the loading on the body (Grabowski and Kram, 2008; Kluitenberg *et al.*, 2012; Orendurff *et al.*, 2018), it is possible that the increase in general running speed is slow enough over time (due to the slow rate of physiological anaerobic adaptations) that the body has time to adapt to the associated increase in loading.

6.5.2.3 Impact Acceleration

The present study did not find any association between injury and either the $Peak_{accel}$ or $Rate_{accel}$. Only one study to date has investigated the association between impact acceleration and prospective injury, and similar to our findings, observed no significant differences in sacrum peak acceleration between injured and uninjured runners (Winter *et al.*, 2020). Although retrospective research has found a potential relationship between higher tibial acceleration and tibial stress fractures in female runners (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006), it is unclear whether the high loading was a cause or an effect of the lower limb stress fractures in these studies. In addition, these retrospective studies may have found a link due to the investigation of specific RRI injuries local to the segment that they examined (Ferber *et al.*, 2002; Milner *et al.*, 2006; Zifchock, Davis and Hamill, 2006), as opposed to general overuse RRIs collectively. Although this injury specific approach is insightful in some regards, it does not inform injury prevention practices for the majority of runners who generally will not know what specific injury they need to protect against. Thus, determining the risk factors for all overuse RRIs collectively will serve the greater running community more effectively than determining the risk factors for specific individual RRIs.

6.5.2.4 Running kinematics

Regarding running kinematics, there were significant associations found between injury and both knee and thorax kinematics. Less knee valgus was associated with injury in the present study. This is important as only one study appears to have previously examined this, and although less peak knee valgus angles were observed in injured runners, their finding was not significant (Dudley *et al.*, 2017). This lack of significance however, may have been due to an underpowering of their statistical analysis associated with the low number of injured participants (n = 12). Evidently, there is a lack of research in the area of knee kinematics and prospective injury in runners, but the proposed theory relating knee motion to injury hypothesises that extreme or excessive varus and valgus knee positions increase the load bearing on the medial and lateral knee (Bruns, Volkmer and Luessenhop, 1993; Sharma *et al.*, 2001). This may lead to high patellofemoral stress, overloading of the articular cartilage and subchondral bone (Farrokhi, Keyak and Powers, 2011), in addition to increased strain on the iliotibial band (Noehren *et al.*, 2014).

The present study also found greater knee internal rotation at peak knee flexion and greater knee rotation excursion to relate to injury. This provides new evidence for knee kinematics and RRIs, with no prospective studies previously investigating knee internal rotation at peak knee flexion. Furthermore, only one prospective study has assessed knee rotation excursion, reporting no difference between injured and uninjured runners (Hein *et al.*, 2014). This may have been due to an underpowered sample size of injured runners (n = 10), or due to methodological differences, whereby Hein *et al.*, (2014) examined Achilles tendon injuries only. It has been hypothesized that greater knee internal rotation and greater knee rotation excursion may cause an increase in pressure and load at the patellofemoral joint (Lee, Morris and Csintalan, 2003b; Powers, 2003b), and that a lack of control of these motions is thought to play an important role in the development of patellofemoral pain syndrome (Schwane, 2011).

Regarding trunk kinematics, greater peak thorax drop to the contralateral side was found to relate to injury. Again, the present study adds new evidence to this area with only one study previously examining thorax kinematics and prospective RRIs (Shen *et al.*, 2019). Shen *et al*. (2019) found no differences in peak trunk flexion and peak trunk ipsilateral flexion between injured and uninjured runners, although their sample size was likely underpowered (n = 15). The thorax and upper body account for approximately 60% of a person's total body mass (Ford *et al.*, 2013), and therefore trunk motion likely influences loading (Simic *et al.*, 2011). Thorax drop to the contralateral side has been found to be a normal aspect of gait in healthy subjects (Preece, Mason and Bramah, 2016), and the motion is due to the activity of the oblique abdominal muscles (Saunders *et al.*, 2005). This intricate interplay of thorax and pelvic kinematics and musculature allows runners to minimize centre of mass displacement (Preece, Mason and Bramah, 2016). However, the inability to control excessive thorax drop and other trunk motion may lead to excessive stress on the pelvis (Franklyn-Miller *et al.*, 2017) and lower limb such as the calf muscle complex (Teng and Powers, 2014), and as a result may overload susceptible tissues leading to injury.

An additional finding of interest (although not significant in the adjusted analysis) was that non-rearfoot strike runners were more likely to have sustained a prospective injury than rearfoot strike runners, a finding that is similar to the results of Hollander *et al.*, (2020) and Dingenen *et al.*, (2019). A non-rearfoot strike pattern is thought to invoke greater loading on the plantarflexor muscles and Achilles tendon (Goss, 2012; Kulmala *et al.*, 2013; Hamill and Gruber, 2017), which aligns well with the calf and Achilles tendon being the most commonly injured sites in the present study. This is the first prospective study to examine foot strike technique in its categorical form, with previous studies assessing continuous measures of foot contact angle (Dudley *et al.*, 2017) and strike index (Kuhman *et al.*, 2016b; Messier *et al.*, 2018) only. As eluded to in a recent systematic review, perhaps the investigation of foot strike technique via continuous measures is not sensitive enough to differentiate the loading differences that exist between rearfoot and non-rearfoot strike runners (Burke *et al.*, 2021), and that examining discrete foot strike patterns (non-rearfoot versus rearfoot strikes) is more relevant.

Although several kinematic risk factors for general overuse RRIs have been identified in this univariate analysis, this approach may have some limitations. By investigating the risk factors of all RRIs collectively, there is the potential to miss some distinctive risk factors for lower limb stress fractures or overuse knee injuries specifically. These injuries are common amongst runners and studies in the past have found individual risk factors such as loading rates, and kinematics at the knee, hip, pelvis and trunk to overload specific structures local to the site of these injuries. It is conceivable that there may be an under-lying relationship between biomechanical variables, whereby RRIs in general come from some form of abnormal whole-body biomechanics or pathological gait. However, it seems likely that the mechanisms for each specific injury are distinctly unique, in which case, the biomechanics need to be studied separately. An example of this has been observed by Bramah *et al*., (2018) where a pathological gait was determined for runners who had recurrent calf strain injuries.

6.5.2.5 Multivariate Analysis

Four variables contributed to the final model, with two of these being significant. Multivariate analyses typically suggest factors that interact with each other to explain injury (Wakkee, Hollestein and Nijsten, 2014). Thus, it may be important to consider these variables in combination rather than in isolation. Less knee valgus at toe off and training for a marathon were both found to be significant risk factors for prospective injury. In practice, it may be pertinent to consider load management when training for a marathon. While knee kinematics may require effort to adjust, training load is a more modifiable mediator in this instance and as a result, may be a useful consideration for injury prevention strategies. Although thorax drop to the contralateral side and previous history of injury < 1 year ago were not significant in the final multivariate model, they too are important factors to consider within the greater picture, given their presence in the final model. Having a previous history of injury is not modifiable, but it can help to identify runners who may be more susceptible upon returning to participation. Therefore, runners who have a history of injury within the past year should take measures to ensure effective rehabilitation.

6.5.3 Clinical Implications

A number of factors were identified that increased the risk of prospective injury in this study. Consistent with previous research, having a history of injury appears to be one of the greatest risk factors for future injury. Clinically, healthcare professionals and biomechanists should strive to prescribe appropriate and effective rehabilitation, to ensure the runners can regain tissue strength and capacity to tolerate training loads again. The present study also found training for a marathon to be a risk for injury, and perhaps runners should be made aware of this when considering their commitment to the event. It has been advised that runners should build a solid foundation of running fitness, followed by gradual increases in running volume incorporating various speeds and distances (Hamstra-Wright *et al.*, 2013).

Running kinematics were also found to relate to injury, factors which may be effectively altered with running retraining programmes (Dunn *et al.*, 2018). Several studies have reported significant reductions in pain (Noehren, Scholz and Davis, 2011; Breen *et al.*, 2015; Roper *et al.*, 2016) and injury occurrence (Chan *et al.*, 2018) with running retraining, with some demonstrating long-term efficacy in maintaining kinematic (Teran-Yengle, Cole and Yack, 2016) and impact acceleration changes (Bowser *et al.*, 2018) over 8 to 12 months respectively.

6.5.4 Study Limitations

This study has four main limitations. Firstly, data pertaining to impact acceleration, kinematics and training were obtained at one point in time prior to injury occurrence, and it is therefore unknown how consistent these factors would have been throughout the 1 year surveillance period. For greater accuracy and application, future studies should perhaps consider more frequent assessment, or even run-by-run assessment. Secondly, the kinetic and kinematic data was collected during treadmill running, which may not be reflective of the training surface that the participants typically train on (Riley *et al.*, 2008; Milner, Hawkins and Aubol, 2020). Thirdly, runners ran at a fixed speed of 9km/hr, which may have been slower or faster than their typical training pace, and as a result may have influenced their natural gait. However, running speed has been shown to affect both impact acceleration and kinematics (Brughelli, Cronin and Chaouachi, 2011), and the aim for a fixed speed in the present study was to control for this effect amongst a large cohort of runners (Bredeweg *et al.*, 2013; Davis, Bowser and Mullineaux, 2016). Lastly, injuries in the present were investigated collectively as general overuse RRIs. This was conducted with a view to inform injury prevention strategies going forward, as determining the risk factors for RRIs collectively will attend to the greater running community more effectively than establishing the risk factors for specific RRIs individually.

6.6 Conclusion

This prospective study provided further clarity to the body of evidence suggesting that RRIs are multifactorial in nature. Training-related risk factors that proved significant included training for a marathon and frequent changing of footwear (every 0-3 months), factors that are easily managed from an injury avoidance perspective. In terms of running technique, this is the first study to find evidence for a relationship between non-rearfoot strike pattern and prospective injury risk, highlighting the importance of categorical foot strike analysis. Other kinematics which indicated heightened injury risk included lesser knee valgus, greater knee rotation and greater thorax drop to the contralateral side, all significant factors which have not been well investigated with respect to prospective injury previously. Lastly, the present study further supported the significance that having a history of injury increased future injury risk; clearly indicating the need for careful return to participation practices.

Further large scale prospective research should seek to consider more frequent or on-going (e.g. run-by-run) analyses of impact acceleration, kinematics and training load through the prospective trial period.

Funding

This study was supported by a grant from Science Foundation Ireland (grant number SFI/12/RC/2289), co-funded by the European Regional Development Fund.

Chapter 7 Overall Discussion and Future Recommendations

7.1 Overall Discussion of Thesis

This thesis exhibits a pioneering edge in the research of risk factors for running-related injuries (RRIs). As noted from the review of literature in Chapter 2, RRIs are a prevalent issue with 1 in every 2 runners becoming injured (Winter *et al.*, 2020; Desai *et al.*, 2021), a finding that is reiterated both retrospectively (Chapter 4 and 5) and prospectively in this thesis (Chapter 6). The dual approach of retrospective and prospective risk factor investigation is a unique facet of this thesis, allowing a more refined interpretation of factors which may be a cause or effect of injury, which is not otherwise possible by conducting retrospective research in isolation. Although retrospective research has its limitations, it does provide an ability to identify differences in runners who have recently been injured. This determinant provided scaffolding for a unique aspect of this thesis whereby recently injured runners were compared with never injured and acquired injury resistance runners, groups which have received little attention within the research to date. The comparison between these three groups warrants scientific merit, especially considering the high re-injury rate for RRIs (Desai *et al.*, 2021), as it sheds a new light on the differences between those who are susceptible to RRIs, those who have developed a resistance to RRIs, and those who have never experienced an RRI. A brief synopsis of thesis results will be outlined below, before comparisons are made between retrospective and prospective findings.

Chapter 3 found high to excellent relative reliability for magnitude ($Peak_{accel}$) and rate ($Rate_{accel}$) at both the tibia and sacrum segments in the short- (1 week) and long-term (6 months), findings which support the use of impact acceleration measures in research and clinical practice where the rank ordering of runners within a group is of importance (e.g. in injury surveillance studies such as those conducted in this thesis). Chapter 4 of this thesis found $Rate_{accel}$ at the sacrum to be significantly greater in recently injured runners compared to runners with acquired injury resistance and never injured runners. This is important, especially given that sacrum accelerations have been found to reflect vGRF loading, and thus this finding is in support of those that found associations between the magnitude and rate of impact loading to relate to injuries. Chapter 5 noted twice as many recently injured runners to continue to train despite the presence of a niggle compared to never injured runners. An additional finding of this chapter was the reporting of potentially risky training practices amongst recently injured runners, whereby they incorporated faster training speeds, hill running and changes of gradient on a weekly basis as part of their training, practices which were significantly different to the never injured and acquired injury resistant groups. Both speed and gradient running have been found to increase load on the body, and it is therefore not surprising that the recently injured runners who had exhibited high loading in Chapter 4, were found to have these practices in their training. Although retrospevctive in nature, these factors were sensitive enough to differentiate between those at greater risk of RRIs, and combined with prospective findings may inform injury prevention strategies. Lastly, Chapter 6 provided a platform to comprehensively investigate the biomechanical and training-related risk factors of RRIs. This was the first study to find evidence for an increased risk between non-rearfoot strike pattern and prospective injury risk, highlighting the importance of categorical foot strike analysis. Other kinematic factors which indicated heightened injury risk included lesser knee valgus, greater knee rotation and greater thorax drop to the contralateral side. These factors are all readily modifiable, with previous research demonstrating effective running-retraining for reductions in pain (Noehren, Scholz and Davis, 2011; Breen *et al.*, 2015; Roper *et al.*, 2016) and injury occurrence (Chan *et al.*, 2018). Training-related factors that were found to increase the risk of injury included training for a marathon and frequent changing of footwear (every 0-3 months). Finally, Chapter 6 further supported the significance of having a history of injury in terms of increasing future injury risk, a factor that clearly indicates the need for careful return to participation practices.

A comparison of retrospective and prospective findings

Interestingly, there was little crossover between the factors which were found to relate to injury retrospectively (Chapters 4 and 5) and those that were found to be a risk prospectively (Chapter 6). Regarding internal load, differences between retrospective and prospective research were evident. This thesis is one of only two studies which has assessed impact acceleration and prospective RRIs (Winter *et al.*, 2020), and is the first to investigate the rate of impact acceleration. Chapter 4 of this thesis found $Rate_{accel}$ at the sacrum to be significantly greater in recently injured runners compared to runners with acquired injury resistance and never injured runners. However, impact acceleration at the sacrum nor at the tibia were found to relate to prospective RRIs (Chapter 6). This likely indicates that the meausres of impact acceleration taken in this study are not sensitive enough to be considered as a risk factor for prospective injury. However, these measures did distinguish between those who had a recent injury, and so may inform injur rehabilitation or return to participation practices. It appears that recently injured runners exhibit greater rate of impact loading in the year following injury, but this seems to reduce as time elapses. Thus impact acceleration, and $Rate_{accel}$ at the sacrum in particular, may be an important consideration for rehabilitation programmes, where impact acceleration or factors that lead to high impact acceleration (e.g. knee flexion angle) could be easily targeted. Although once-off measures of impact acceleration in this study were not predictive of prospective injuries, evidence from the retrospective analysis demonstrates a use for these measures clinically, especially following recent injury. However, the challenge is to determine when sacrum acceleration measures begin to elevate following injury, and how long these changes may persist for. A way of determining this may be through more frequent analysis of sacrum loading through the return to participation period, rather than once-off assessments. Regular tracking of acceleration would provide an insightful perspective on how the body adapts following injury, to the point where the runner acquires injury resistance, or where they may become reinjured. Given the accessibility and user friendly nature of impact accelerometers, measures of sacrum acceleration therefore provide a useful and ecologically valid tool for runners, coaches and clinicians.

In terms of intrinsic risk, disparities between retrospective and prospective findings were evident. Twice as many recently injured runners reported to train despite the presence of a niggle compared to never injured runners in the retrospective analysis (Chapter 5), but this was not echoed in the prospective analysis (Chapter 6). This finding adds new evidence to the area, as the effects of niggles on RRIs have not been investigated within running populations previously. This may be a substantial contributing factor to re-injury, as it may be a sign of incomplete healing or overload, as supported by the 3 fold increase in injury risk for football players who complained of niggles 7 days prior to their injury (Whalan, Lovell and Sampson, 2020). Although this is a novel area in RRIs, the findings of this chapter warrant a close and frequent monitoring of niggles by both runners and healthcare professionals. Elsewhere in the results, frequent changing of footwear (every 0-3 months) was found to increase the likelihood of RRI, a finding that was mirrored prospectively (Chapter 6). The trend of infrequent footwear between never injured (Chapter 5) and uninjured runners (Chapter 6) seems somewhat protective of injury, and perhaps suggests a familiarity or comfort with the shoes by these runners. Thus, if runners are seeking to change footwear on a frequent basis, this may be an indication of heightened injury risk, and as a result, it is a factor that should be monitored closely. Other potentially risky training practices were observed amongst recently injured runners in the retrospective analysis (Chapter 5), whereby they incorporated hill running and changes of gradient on a weekly basis as part of their training, practices which were significantly different to the never injured and acquired injury resistant groups. While an overload in training is necessary for improved performance and musculoskeletal adaptation, runners should exercise caution when compounding training load with demanding tasks such as gradients and speed, especially when returning from injury. These differences in risky practices were not evident in the prospective investigation (Chapter 6), potentially indicating that these practices may have been implemented as part of rehabilitation plans following injury for those who were recently injured retrospectively. It could be proposed that runners undertook gradient and hill training in efforts to build strength and endurance in posterior chain structures such as the calf, an area of injury which had high prevalence rates (20%) in the retrospective study (Chapter 5). These runners may also have been looking to retrun to their pre-injury level of fitness quickly, and so they may have undertook more strenuous exercise to achieve this. Overall, the training load metrics assessed in this study (once-off measure of distance, volume, speed, frequency) did not relate to prospective injury, although this is likely due to the limitations in the methods of assessment. Training parameters regularaly change from day to day and from week to week, depending on the purpose of training for the runner. Therefore, a more frequent tracking of training load would be superior in the study of its relationship to injury. Given the intricate relationship between training, recovery and sleep (Soligard *et al*., 2016), a device that is capable of a more holistic and frequent assessment of these factors would provide for a greater understanding of RRI development. Wearable technology such as smart watches have the capacity to capture ongoing measures of training load, recovery and sleep provide a strong and minimally invasive platform for studies to assess these as risk factors going forward.

To summarise, this thesis furthers existing knowledge and adds new evidence for risk factors of RRIs. In accordance with the TRIPP injury prevention model (Finch, 2006), this thesis has added considerably to the first two steps (injury surveillance and establishment of aetiology of injury). Therefore, the findings of this study could inform injury prevention strategies for recreational runners. These strategies could subsequently be assessed for efficacy by comparing RRI prevalence rates pre- and post-intervention, a practice which is lacking in running but has successfully been applied in other sports (Schlingermann *et al.*, 2018; Nuhu *et al.*, 2021). In the context of retrospective findings, factors distinguishing recently injured runners from acquired injury resistant and never injured runners may inform rehabilitation or return to participation practices.

7.2 Future Directions

This thesis inspires further research across several domains. Firstly, while the present study identified a number of factors prospectively related to RRIs, it clearly does not capture the ongoing variance of internal and external load that runners experience week to week. A possible limitation to the current work is the assumption that a one-off baseline assessment of loading and technique might remain unchanged over 12 months. While the reliability study showed high to excellent reliability over short- and long-term time frames, it is likely that loading and technique change over time due to runners having: differing levels of fatigue, low severity of injury (e.g. niggles) and increased familiarization and adaptation to training demands. As wearable technology advances, a solution to this challenge would be to assess loading and technique in the runners on a frequent basis (e.g. run by run), which would provide both internal (impact acceleration) and external (distance, speed, duration, incline) loading on a more continuous basis. This would also facilitate the investigation of changing training loads (e.g. sharp increases or decreases in load) on RRIs.

Secondly, previous injury was found to be a significant risk factor for prospective injury (Chapter 6), suggesting that factors may change following injury and will therefore govern re-injury (Meeuwisse *et al.*, 2007). Thus, risk factors should be explored across a continuum (e.g. pre-injury, during recovery, return to participation, and medium- to long-term post-injury). This would provide a greater understanding of how these factors may change as a result of injury both in the short- and long-term, and help to identify why some runners are more resistant to re-injury than others. This would likely be more achievable with the use of wearable technology as described above.

The findings of this thesis may inform the basis of an injury prevention programme for runners. With the exception of previous injury history, many of the risk factors identified in Chapter 6 may be easily modifiable. Previous studies have demonstrated effective protocols for reducing pain (Noehren, Scholz and Davis, 2011; Breen *et al.*, 2015; Roper *et al.*, 2016) and injury occurrence (Chan *et al.*, 2018) via running re-training, with long-term retention of the kinematic changes (Teran-Yengle, Cole and Yack, 2016). However, these injury prevention models should be developed in consultation with runners, healthcare professionals and experts within the area, in order to ensure relevance, efficacy, and validity (Finch, 2006).

It is apparent from Chapters 4, 5 and 6 that some variables associated with injury were not investigated in this thesis, including but not limited to sleep, stress and personality traits, some of which have been found to relate to RRIs previously (Mousavi *et al.*, 2021). Furthermore, it is well documented that RRIs may not only be influenced by excessive loading, but also by tissue strength (Hreljac, 2004). Future studies should therefore strive to accurately assess muscle and or tendon strength, to help determine the contribution of tissue strength to injury (e.g. quantitative ultrasound (Franchi *et al.*, 2018; Sahr, Sturnick and Nwawka, 2018) and quantitative CT scans (Donnelly, 2011)).

This thesis investigated discrete data points in loading (i.e. peak impact acceleration) and technique (i.e. peak angle, angle at initial contact, etc.). However, it is plausible that an examination of all the data points over the continuous gait cyle may provide greater insight into RRIs, for example the use of functional data analysis techniques and analysis of continuous phases (Richter *et al.*, 2014). In addition, a direct comparison of discrete and continuous data analysis methods would provide much needed insight into how advantageous continuous data analysis methods are (if any), given that they are far more challenging to undertake and do not appear to be a part of traditional statistical training within universities. Furthermore, clusters of movement patterns may give a unique insight into potentially injurious techniques, as has been demonstrated with chronic groin injuries (Franklyn-Miller *et al.*, 2017). This could be further advanced with the continuous use of wearable technology to generate large amounts of data, whereby machine learning could allow for alternative data analytical approaches (Xu *et al.*, 2022).

Lastly, it may be fruitful to further explore the current dataset of this thesis to address some outstanding research questions such as:

i) What technique distinguishes high to low impact accelerations, which could be explored by comparing the technique of the top and bottom 25 percentile groups for impact acceleration,

ii) What technique distinguishes rearfoot striker and non-rearfoot strike runners,

iii) How many strides are required to produce consistent kinematics and impact accelerations when treadmill running?,

iv) Can clinicians of various experience visually identify extremes in running technique (e.g. contralateral thorax drop) using 2D video recordings?

v) What are the effects of differing injury definitions on injury prevalence rates?

Bibliography

Alcantara, R.S. *et al*. (2021). Sacral acceleration can predict whole-body kinetics and stride kinematics across running speeds. *PeerJ*, *9*, p.e11199.

Altman, A. R. and Davis, I. S. (2012) ‘A kinematic method for footstrike pattern detection in barefoot and shod runners’, *Gait and Posture*, 35(2), pp. 298–300. doi: 10.1016/j.gaitpost.2011.09.104.

Altman, A. R. and Davis, I. S. (2016) ‘Prospective comparison of running injuries between shod and barefoot runners’, *British Journal of Sports Medicine*, 50(8), pp. 476–480. doi: 10.1136/bjsports-2014-094482.

Arendse, R. E. *et al.* (2004) ‘Reduced eccentric loading of the knee with the pose running method.’, *Medicine And Science In Sports And Exercise*, 36(2), pp. 272–277.

Armstrong, R. B., Warren, G. L. and Warren, J. A. (1991) ‘Mechanisms of Exercise-Induced Muscle Fibre Injury’, *Sports Medicine*, 12(3), pp. 184–207. doi: 10.2165/00007256-199112030-00004.

Atkinson, G. and Nevill, A. M. (1998) ‘Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine’, *Sports Medicine*, 26(4), pp. 217–238. doi: 10.2165/00007256-199826040-00002.

Auvinet, B. *et al.* (2002) ‘Runner’s stride analysis: comparison of kinematic and kinetic analyses under field conditions’, *Science & Sports*, 17(2), pp. 92–94. doi: 10.1016/S0765-1597(02)00122-3.

Azevedo, L. *et al.* (2009) ‘Biomechanical variables associated with Achilles tendinopathy in runners’, *British Journal of Sports Medicine*, 43(4), pp. 288–292. doi: 10.1136/BJSM.2008.053421.

Baggaley, M. *et al.* (2015) ‘Frontal plane kinematics of the hip during running: Are they related to hip anatomy and strength?’, *Gait and Posture*, 42(4), pp. 505–510. doi: 10.1016/j.gaitpost.2015.07.064.

Baker, R. L. *et al.* (2018) ‘Differences in Knee and Hip Adduction and Hip Muscle Activation in Runners With and Without Iliotibial Band Syndrome’, *PM&R*, 10(10), pp. 1032–1039. doi: 10.1016/J.PMRJ.2018.04.004.

Barbado, D., Moreside, J. and Vera-Garcia, F. J. (2017) ‘Reliability and Repetition Effect of the Center of Pressure and Kinematics Parameters That Characterize Trunk Postural

Control During Unstable Sitting Test', in *PM and R*. Elsevier Inc., pp. 219–230. doi: 10.1016/j.pmrj.2016.08.029.

Barton, C. J. *et al.* (2012) 'The relationship between rearfoot, tibial and hip kinematics in individuals with patellofemoral pain syndrome', *Clinical Biomechanics*, 27(7), pp. 702–705. doi: 10.1016/J.CLINBIOMECH.2012.02.007.

Batterham, A. M. and Hopkins, W. G. (2006) 'Making meaningful inferences about magnitudes.', *International journal of sports physiology and performance*, 1(1), pp. 50–57. doi: 10.1123/ijspp.1.1.50.

Bazett-jones, D. M. *et al.* (2013) 'Effect of Patellofemoral Pain on Strength and Mechanics after an Exhaustive Run', *Med. Sci. Sports Exerc*, 45(7). doi: 10.1249/MSS.0b013e3182880019.

Beck, B.R. and Osternig, L.R., (1994). Medial tibial stress syndrome. The location of muscles in the leg in relation to symptoms. *JBJS*, *76*(7), pp.1057-1061.

Becker, J., Nakajima, M. and Wu, W. F. W. (2018) 'Factors Contributing to Medial Tibial Stress Syndrome in Runners: A Prospective Study.', *Medicine and science in sports and exercise*, 50(10), pp. 2092–2100. doi: 10.1249/MSS.0000000000001674.

Bennett, J. E., Reinking, M. F. and Rauh, M. J. (2012) 'The relationship between isotonic plantar flexor endurance, navicular drop, and exercise-related leg pain in a cohort of collegiate cross-country runners.', *International journal of sports physical therapy*, 7(3), pp. 267–78.

Van den Berghe, P. *et al.* (2019) 'Validity and reliability of peak tibial accelerations as real-time measure of impact loading during over-ground rearfoot running at different speeds', *Journal of Biomechanics*, 86, pp. 238–242. doi: 10.1016/j.jbiomech.2019.01.039.

Bernstein, N. (1967) 'The Co-ordination and Regulation of Movements'.

Bertelsen, M. L. *et al.* (2017) 'A framework for the etiology of running-related injuries', *Scandinavian Journal of Medicine and Science in Sports*. Blackwell Munksgaard, pp. 1170–1180. doi: 10.1111/sms.12883.

Besier, T.F. *et al*. (2008). The influence of femoral internal and external rotation on cartilage stresses within the patellofemoral joint. *Journal of Orthopaedic Research*, *26*(12), pp.1627-1635.

Besomi, M. *et al.* (2019) 'Training volume and previous injury as associated factors for running-related injuries by race distance: A cross-sectional study', *Journal of Human Sport and Exercise*, 14(3), pp. 549–559. doi: 10.14198/jhse.2019.143.06.

Bigouette, J. *et al.* (2016) 'Altered vertical ground reaction forces in participants with chronic ankle instability while running', *Journal of Athletic Training*, 51(9), pp. 682–687. doi: 10.4085/1062-6050-51.11.11.

Blair, S. N., Kohl, H. W. and Goodyear, N. N. (1987) 'Rates and Risks for Running and Exercise Injuries: Studies in Three Populations', *Research Quarterly for Exercise and Sport*, 58(3), pp. 221–228. doi: 10.1080/02701367.1987.10605453.

Blanch, P. and Gabbett, T. J. (2016) 'Has the athlete trained enough to return to play safely? The acute:chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury', *British Journal of Sports Medicine*, 50(8), pp. 471–475. doi: 10.1136/bjsports-2015-095445.

Boles, C. and Ferguson, C. (2010) 'The Female Athlete', *Radiologic Clinics*, 48(6), pp. 1249–1266. doi: 10.1016/j.csm.2017.07.014.

Borg, G. (1970) 'Perceived exertion as an indicator of somatic stress.', *Scandinavian Journal of Rehabilitation Medicine*, 2(2), pp. 92–98.

Bovens, A. M. P. *et al.* (1989) 'Occurrence of running injuries in adults following a supervised training program', *International Journal of Sports Medicine*, 10(SUPPL. 3), pp. S186–S190. doi: 10.1055/s-2007-1024970.

Bowser, B., Hamill, J. and Davis, I. (2010) 'A prospective study of loading variables in female runners who develop plantar fasciitis', in *American Society of Biomechanics*.

Bowser, B. J. *et al.* (2018) 'Reducing impact loading in runners: A one-year follow-up', *Medicine and Science in Sports and Exercise*, 50(12), pp. 2500–2506. doi: 10.1249/MSS.0000000000001710.

Bramah, C. *et al.* (2018) 'Is There a Pathological Gait Associated With Common Soft Tissue Running Injuries?', *American Journal of Sports Medicine*, 46(12), pp. 3023–3031. doi: 10.1177/0363546518793657.

Bramah, C. *et al.* (2021) 'Kinematic characteristics of male runners with a history of recurrent calf muscle strain injury', *International Journal of Sports Physical Therapy*, 16(3), pp. 732–740. doi: 10.26603/001c.22971.

Bredahl, D. N. *et al.* (2013) 'Increased running pace increases net joint moment at the ankle more than at the knee in recreational runners', *International journal of Human Kinetics and Sporting Science*, 1(2), pp. 12–17.

Bredeweg, S. W. *et al.* (2013) 'Differences in kinetic variables between injured and noninjured novice runners: A prospective cohort study', *Journal of Science and Medicine in Sport*, 16(3), pp. 205–210. doi: 10.1016/j.jsams.2012.08.002.

Breen, D. T. *et al.* (2015) 'Gait re-training to alleviate the symptoms of anterior exertional lower leg pain: a case series.', *International Journal Of Sports Physical Therapy*, 10(1), pp. 85–94.

Brooks, G., Fahey, T. and Baldwin, K. (2004) *Exercise physiology: Human bioenergetics and its application*. 4th edn, *McGraw-Hill*. 4th edn. New York. doi: 10.1080/00336297.1985.10483837.

Brown, A. M. *et al.* (2016) 'The effects of fatigue on lower extremity kinematics, kinetics and joint coupling in symptomatic female runners with iliotibial band syndrome', *Clinical Biomechanics*, 39, pp. 84–90. doi: 10.1016/J.CLINBIOMECH.2016.09.012.

Brown, A. M., Zifchock, R. A. and Hillstrom, H. J. (2014) 'The effects of limb dominance and fatigue on running biomechanics', *Gait and Posture*, 39(3), pp. 915–919. doi: 10.1016/j.gaitpost.2013.12.007.

Brughelli, M., Cronin, J. and Chaouachi, A. (2011) 'Effects of running velocity on running kinetics and kinematics', *Journal of Strength and Conditioning Research*, 25(4), pp. 933–939. doi: 10.1519/JSC.0b013e3181c64308.

Bruns, J., Volkmer, M. and Luessenhop, S. (1993) 'Pressure distribution at the knee joint - Influence of varus and valgus deviation without and with ligament dissection', *Archives of Orthopaedic and Trauma Surgery*, 113(1), pp. 12–19. doi: 10.1007/BF00440588.

Buchheit, M. and Laursen, P. B. (2013) 'High-intensity interval training, solutions to the programming puzzle: Part II: Anaerobic energy, neuromuscular load and practical applications', *Sports Medicine*. Springer, pp. 927–954. doi: 10.1007/s40279-013-0066-5.

Buczek, F. and Cavanagh, P. (1990) 'Stance phase knee and ankle kinematics and kinetics during level and downhill running', *Medicine and Science in Sports and Exercise*, 22(5), pp. 669–677.

Buist, I *et al.* (2010) 'Incidence and risk factors of running-related injuries during preparation for a 4-mile recreational running event', *British Journal of Sports Medicine*, 44(8), pp. 598–604. doi: 10.1136/BJSM.2007.044677.

Buist, I *et al.* (2010) 'Predictors of running-related injuries in novice runners enrolled in a systematic training program: A prospective cohort study', *American Journal of Sports Medicine*, 38(2), pp. 273–280. doi: 10.1177/0363546509347985.

Burke, A. *et al.* (2021) 'Risk Factors for Injuries in Runners: A Systematic Review of Foot Strike Technique and Its Classification at Impact', *Orthopaedic Journal of Sports Medicine*. SAGE Publications Ltd. doi: 10.1177/23259671211020283.

Di Caprio, F. *et al.* (2010) 'Foot and lower limb diseases in runners: assessment of risk factors.', *Journal of sports science & medicine*, 9(4), pp. 587–96. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24149785.

Carlos, L. *et al.* (2016) 'Lower limb alignment characteristics are not associated with running injuries in runners : Prospective cohort study', 1391(June). doi: 10.1080/17461391.2016.1195878.

Chan, Z. Y. *et al.* (2018) 'Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial', *American Journal of Sports Medicine*, 46(2), pp. 388–395. doi: 10.1177/0363546517736277.

Chang, W. L., Shih, Y. F. and Chen, W. Y. (2012) 'Running injuries and associated factors in participants of ING Taipei Marathon', *Physical Therapy in Sport*, 13(3), pp. 170–174. doi: 10.1016/j.ptsp.2011.08.001.

Cheung, R. T. H. and Davis, I. S. (2011) 'Landing pattern modification to improve patellofemoral pain in runners: a case series.', *The Journal Of Orthopaedic And Sports Physical Therapy*, 41(12), pp. 914–919. doi: 10.2519/jospt.2011.3771.

Cohen, J. (1988) *Statistical Power Analysis for the Behavioural Sciences*. Second Edi. New Jersey: Lawrence Erlbaum Associates, Inc.

Cohen, J. (2013) *Statistical Power Analysis for the Behavioral Sciences*, *Statistical Power Analysis for the Behavioral Sciences*. doi: 10.4324/9780203771587.

Crowell, H. P. and Davis, I. S. (2011) 'Gait retraining to reduce lower extremity loading in runners', *Clinical Biomechanics*, 26(1), pp. 78–83. doi: 10.1016/j.clinbiomech.2010.09.003.

Dallinga, J. *et al.* (2019) 'Injury incidence and risk factors: A cohort study of 706 8-km or 16-km recreational runners', *BMJ Open Sport and Exercise Medicine*, 5(1), p. 489. doi:

10.1136/bmjsem-2018-000489.

Damsted, C. *et al.* (2018) ‘Is there evidnce for an association between changes in training load and running-related injuries? A systematic review’, *International Journal of Sports Physical Therapy*, 13(6), pp. 931–942. doi: 10.26603/ijspt20180931.

Daoud, A. I. *et al.* (2012) ‘Foot strike and injury rates in endurance runners: A retrospective study’, *Medicine and Science in Sports and Exercise*, 44(7), pp. 1325–1334. doi: 10.1249/MSS.0b013e3182465115.

de David, A. C., Carpes, F. P. and Stefanyshyn, D. (2015) ‘Effects of changing speed on knee and ankle joint load during walking and running’, *Journal of Sports Sciences*, 33(4), pp. 391–397. doi: 10.1080/02640414.2014.946074.

Davis, I., Bowser, B. and Mullineaux, D. (2016) ‘Greater vertical impact loading in female runners with medically diagnosed injuries: a prospective investigation’, *British Journal of Sports Medicine*, 50(4), pp. 887–892.

Davis, I. S., Bowser, B. and Mullineaux, D. (2010) ‘Do impacts cause running injuries? A prospective investigation’, in *American Society of Biomechanics*.

Delgado, T. L. *et al.* (2013) ‘Effects of foot strike on low back posture, shock attenuation, and comfort in running’, *Medicine and Science in Sports and Exercise*, 45(3), pp. 490–496. doi: 10.1249/MSS.0b013e3182781b2c.

Derrick, T. R. (2004) ‘The effects of knee contact angle on impact forces and accelerations.’, *Medicine and science in sports and exercise*, 36(5), pp. 832–7. doi: 10.1249/01.MSS.0000126779.65353.CB.

Derrick, T. R., Dereu, D. and McLean, S. P. (2002) ‘Impacts and kinematic adjustments during an exhaustive run.’, *Medicine And Science In Sports And Exercise*, 34(6), pp. 998–1002.

Desai, P. *et al.* (2021) ‘Recreational Runners With a History of Injury Are Twice as Likely to Sustain a Running-Related Injury as Runners With No History of Injury: A 1-Year Prospective Cohort Study’, *The Journal of orthopaedic and sports physical therapy*, 51(3), pp. 144–150. doi: 10.2519/jospt.2021.9673.

Dierks, T. A. *et al.* (2011) ‘Lower extremity kinematics in runners with patellofemoral pain during a prolonged run.’, *Medicine and science in sports and exercise*, 43(4), pp. 693–700. doi: 10.1249/MSS.0b013e3181f744f5.

Dijkhuis, T. B. *et al.* (2020) 'Increase in the Acute:Chronic Workload Ratio relates to Injury Risk in Competitive Runners', *International Journal of Sports Medicine*. doi: 10.1055/a-1171-2331.

Dillon, S. *et al.* (2021) 'Do Injury-Resistant Runners Have Distinct Differences in Clinical Measures Compared with Recently Injured Runners?', *Medicine & Science in Sports & Exercise*, 53(9), pp. 1807–1817. doi: 10.1249/mss.0000000000002649.

Dingenen, B. *et al.* (2019) 'Two-dimensional video analysis can discriminate differences in running kinematics between recreational runners with and without running-related knee injury', *Physical Therapy in Sport*, 38, pp. 184–191. doi: 10.1016/j.ptsp.2019.05.008.

Dixon, S. J., Collop, A. C. and Batt, M. E. (2000) 'Surface effects on ground reaction forces and lower extremity kinematics in running', *Medicine and Science in Sports and Exercise*, 32(11), pp. 1919–1926. doi: 10.1097/00005768-200011000-00016.

Donnelly, E. (2011) 'Methods for assessing bone quality: A review', in *Clinical Orthopaedics and Related Research*. Springer New York LLC, pp. 2128–2138. doi: 10.1007/s11999-010-1702-0.

Donoghue, O. A. *et al.* (2008) 'Lower limb kinematics of subjects with chronic achilles tendon injury during running.', *Research In Sports Medicine (Print)*, 16(1), pp. 23–38. doi: 10.1080/15438620701693231.

Drew, M. K., Cook, J. and Finch, C. F. (2016) 'Sports-related workload and injury risk: Simply knowing the risks will not prevent injuries: Narrative review', *British Journal of Sports Medicine*, pp. 1306–1308. doi: 10.1136/bjsports-2015-095871.

Drew, M. K. and Finch, C. F. (2016) 'The Relationship Between Training Load and Injury, Illness and Soreness: A Systematic and Literature Review', *Sports Medicine*. Springer International Publishing, pp. 861–883. doi: 10.1007/s40279-015-0459-8.

Dubois, B. *et al.* (2015) 'Effects of minimalist and traditional running shoes on injury rates: a pilot randomised controlled trial', *Footwear Science*, 7(3), pp. 159–164. doi: 10.1080/19424280.2015.1049300.

Dudley, R. I. *et al.* (2017) 'A prospective comparison of lower extremity kinematics and kinetics between injured and non-injured collegiate cross country runners', *Human Movement Science*, 52, pp. 197–202. doi: 10.1016/j.humov.2017.02.007.

Dufek, J. S., Mercer, J. A. and Griffin, J. R. (2009) *The Effects of Speed and Surface*

Compliance on Shock Attenuation Characteristics for Male and Female Runners, *Journal of Applied Biomechanics*.

Duffey, M. J. *et al.* (2000) 'Etiologic factors associated with anterior knee pain in distance runners.', *Medicine And Science In Sports And Exercise*, 32(11), pp. 1825–1832.

Dugan, S. A. and Bhat, K. P. (2005) 'Biomechanics and Analysis of Running Gait', *Physical Medicine and Rehabilitation Clinics of North America*, 16(3), pp. 603–621. doi: 10.1016/j.pmr.2005.02.007.

Dunn, M. D. *et al.* (2018) 'Effects of running retraining on biomechanical factors associated with lower limb injury', *Human Movement Science*, 58, pp. 21–31. doi: 10.1016/J.HUMOV.2018.01.001.

Eckhoff, D. G. *et al.* (1994) 'Femoral morphometry and anterior knee pain', in *Clinical Orthopaedics and Related Research*, pp. 64–68. doi: 10.1097/00003086-199405000-00012.

Ellapen, T. *et al.* (2013) 'Common running musculoskeletal injuries among recreational half-marathon runners in KwaZulu-Natal', *South African Journal of Sports Medicine*, 25(2), p. 39. doi: 10.17159/2413-3108/2013/v25i2a372.

Erdfelder, E., Faul, F. and Buchner, A. (1996) 'GPOWER: A general power analysis program', *Behavior Research Methods, Instruments, and Computers*, 28(1), pp. 1–11. doi: 10.3758/BF03203630.

Esculier, J.-F., Bouyer, L. J. and Roy, J.-S. (2015) 'The Effects of a Multimodal Rehabilitation Program on Symptoms and Ground-Reaction Forces in Runners with Patellofemoral Pain Syndrome', *Journal of Sport Rehabilitation*, 25(1), pp. 23–30. doi: 10.1123/jsr.2014-0245.

Esculier, J.-F., Roy, J.-S. and Bouyer, L. J. (2015) 'Lower limb control and strength in runners with and without patellofemoral pain syndrome', *Gait & Posture*, 41(3), pp. 813–819. doi: 10.1016/J.GAITPOST.2015.02.020.

Farrokhi, S., Keyak, J. H. and Powers, C. M. (2011) 'Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: A finite element analysis study', *Osteoarthritis and Cartilage*, 19(3), pp. 287–294. doi: 10.1016/j.joca.2010.12.001.

Feehery, R. V. (1986) 'The biomechanics of running on different surfaces.', *Clinics in podiatric medicine and surgery*, 3(4), pp. 649–659. Available at:

https://europepmc.org/article/med/2946394.

Ferber, R. *et al.* (2002) 'Kinetic Variables in Subjects With Previous Lower Extremity Stress Fractures', *Medicine & Science in Sports & Exercise*, 34(5), p. S5. doi: 10.1097/00005768-200205001-00025.

Ferber, R. *et al.* (2010) 'Competitive Female Runners With a History of Iliotibial Band Syndrome Demonstrate Atypical Hip and Knee Kinematics', *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), pp. 52–58. doi: 10.2519/jospt.2010.3028.

Ferber, R., Davis, I. M. C. and Williams, D. S. (2003) 'Gender differences in lower extremity mechanics during running', *Clinical Biomechanics*, 18(4), pp. 350–357. doi: 10.1016/S0268-0033(03)00025-1.

Ferreira, A. C. *et al.* (2012) 'Prevalence and associated risks of injury in amateur street runners from Belo Horizonte, MG', *Revista Brasileira de Medicina do Esporte*, 18(4), pp. 252–255. doi: 10.1590/S1517-86922012000400007.

Finch, C. (2006) 'A new framework for research leading to sports injury prevention', *Journal of Science and Medicine in Sport*, p. 10. doi: 10.1016/j.jsams.2006.02.007.

Foch, E. *et al.* (2015) 'Associations between iliotibial band injury status and running biomechanics in women', *Gait & Posture*, 41(2), pp. 706–710. doi: 10.1016/J.GAITPOST.2015.01.031.

Foch, E. and Milner, C. E. (2014) 'Frontal Plane Running Biomechanics in Female Runners with Previous Iliotibial Band Syndrome', *Journal of Applied Biomechanics*, 30(1), pp. 58–65. doi: 10.1123/jab.2013-0051.

Fonseca, M. *et al.* (2015) 'Association of different factors with the prevalence of injuries in runners of Rio de Janeiro's Half Marathon', *Journal of Exercise Physiology Online*, 18(2), pp. 58–65.

Ford, K. R. *et al.* (2013) 'Relationship between hip strength and trunk motion in college cross-country runners', *Medicine and Science in Sports and Exercise*, 45(6), pp. 1125–1130. doi: 10.1249/MSS.0b013e3182825aca.

Franchi, M. V. *et al.* (2018) 'Muscle Architecture Assessment: Strengths, Shortcomings and New Frontiers of in Vivo Imaging Techniques', *Ultrasound in Medicine and Biology*, pp. 2492–2504. doi: 10.1016/j.ultrasmedbio.2018.07.010.

Franke, T. P. C., Backx, F. J. G. and Huisstede, B. M. A. (2019) 'Running themselves into the ground? Incidence, prevalence, and impact of injury and illness in runners preparing for a half or full marathon', *Journal of Orthopaedic and Sports Physical Therapy*, 49(7), pp. 518–528. doi: 10.2519/jospt.2019.8473.

Franklyn-Miller, A. *et al.* (2017) 'Athletic groin pain (part 2): A prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns', *British Journal of Sports Medicine*, 51(5), pp. 460–468. doi: 10.1136/bjsports-2016-096050.

Franz, J. *et al.* (2009) 'Changes in the coordination of hip and pelvis kinematics with mode of locomotion', *Gait & Posture*, 29(3), pp. 494–498.

Finni, T *et al*., (2018). Non-uniform displacement and strain between the soleus and gastrocnemius subtendons of rat Achilles tendon. *Scandinavian Journal of Medicine & Science in Sports*, 28(3), pp.1009- 17.

Freiwald, J. *et al.* (2016) 'Foam-Rolling in sport and therapy – Potential benefits and risks: Part 2 – Positive and adverse effects on athletic performance', *Sports Orthopaedics and Traumatology*, 32(3), pp. 267–275. doi: 10.1016/j.orthtr.2016.07.002.

Fries, J.F., Singh, G., Morfeld, D., O'Driscoll, P. and Hubert, H., 1996. Relationship of running to musculoskeletal pain with age. A six-year longitudinal study. *Arthritis & Rheumatism: Official Journal of the American College of Rheumatology*, *39*(1), pp.64-72.

Fukusawa, L., Stoddard, R. and Lopes, A. D. (2020) 'There is no difference in footstrike pattern distribution in recreational runners with or without anterior knee pain', *Gait and Posture*, 79, pp. 16–20. doi: 10.1016/j.gaitpost.2020.03.020.

Fuller, J. T. *et al.* (2017) 'Body Mass and Weekly Training Distance Influence the Pain and Injuries Experienced by Runners Using Minimalist Shoes: A Randomized Controlled Trial.', *The American Journal Of Sports Medicine*, 45(5), pp. 1162–1170. doi: 10.1177/0363546516682497.

Gabbett, T. J. (2016) 'The training-injury prevention paradox: Should athletes be training smarter and harder?', *British Journal of Sports Medicine*, 50(5), pp. 273–280. doi: 10.1136/bjsports-2015-095788.

Gaitonde, D. Y., Ericksen, A. and Robbins, R. C. (2019) 'Patellofemoral pain syndrome', *American Family Physician*, 99(2), pp. 88–94. doi: 10.5505/bsbd.2014.76588.

García-Pérez, J. A. *et al.* (2014) 'Effects of treadmill running and fatigue on impact acceleration in distance running', *Sports Biomechanics*, 13(3), pp. 259–266. doi:

10.1080/14763141.2014.909527.

Van Gent, R. N. *et al.* (2007) ‘Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review.’, *British journal of sports medicine*, 41(8), pp. 469–80; discussion 480. doi: 10.1136/bjsm.2006.033548.

Gerlach, K. E. *et al.* (2005) ‘Kinetic changes with fatigue and relationship to injury in female runners’, *Medicine and Science in Sports and Exercise*, 37(4), pp. 657–663. doi: 10.1249/01.MSS.0000158994.29358.71.

Ghani Zadeh Hesar, N. *et al.* (2009) ‘A prospective study on gait-related intrinsic risk factors for lower leg overuse injuries.’, British Journal of Sports Medicine, 43(13), pp. 1057–1061. doi: 10.1136/bjsm.2008.055723.

Girard, O. *et al.* (2016) ‘Intrasession and intersession reliability of running mechanics during treadmill sprints’, *International Journal of Sports Physiology and Performance*, 11(4), pp. 432–439. doi: 10.1123/ijspp.2015-0145.

Goss, D. L. and Gross, M. T. (2012) ‘Relationships among self-reported shoe type, footstrike pattern, and injury incidence.’, *U.S. Army Medical Department Journal*, pp. 25–30.

Goss, D. L. and Gross, M. T. (2013) ‘A Comparison of Negative Joint Work and Vertical Ground Reaction Force Loading Rates in Chi Runners and Rearfoot-Striking Runners’, Journal of Orthopaedic & Sports Physical Therapy, 43(10), pp. 685–692. doi: 10.2519/jospt.2013.4542.

Goss, L. T. C. D. L. (2012) ‘A Review of Mechanics and Injury Trends Among Various Running Styles’, *US Army Medcal Department Journal*, July-Sep, pp. 62–71.

Grabowski, A. M. and Kram, R. (2008) ‘Effects of Velocity and Weight Support on Ground Reaction Forces and Metabolic Power during Running’, *Journal of Applied Biomechanics*, 24(3), pp. 288–297. doi: 10.1123/jab.24.3.288.

Grau, S. *et al.* (2011) ‘Kinematic classification of iliotibial band syndrome in runners’, *Scandinavian Journal of Medicine & Science in Sports*, 21(2), pp. 184–189. doi: 10.1111/j.1600-0838.2009.01045.x.

Griffin, A. *et al.* (2020) ‘The Association Between the Acute:Chronic Workload Ratio and Injury and its Application in Team Sports: A Systematic Review’, *Sports Medicine*. Springer, pp. 561–580. doi: 10.1007/s40279-019-01218-2.

Grimston, S. K. *et al.* (1991) ‘Bone Mass, External Loads, and Stress Fracture in Female Runners’, *International Journal of Sport Biomechanics*, 7(3), pp. 293–302. doi: 10.1123/ijsb.7.3.293.

Gruber, A. H. *et al.* (2015) ‘Ground Reaction Forces In Rearfoot And Forefoot Running Assessed By A Continuous Wavelet Transform’, *Medicine & Science in Sports & Exercise*, 47, p. 710. doi: 10.1249/01.mss.0000478661.95317.63.

Haghighat, F. *et al.* (2021) ‘Trunk, pelvis, and knee kinematics during running in females with and without patellofemoral pain’, *Gait and Posture*, 89, pp. 80–85. doi: 10.1016/j.gaitpost.2021.06.023.

Haglund-Åkerlind, Y. and Eriksson, E. (1993) ‘Range of motion, muscle torque and training habits in runners with and without Achilles tendon problems’, *Knee Surgery, Sports Traumatology, Arthroscopy*, 1(3–4), pp. 195–199. doi: 10.1007/BF01560205.

Hamill, J. and Gruber, A. A. H. (2017) ‘Is changing footstrike pattern beneficial to runners?’, *Journal of sport and health science*, 6(2), pp. 146–153. doi: 10.1016/j.jshs.2017.02.004.

Hamstra-Wright, K. L. *et al.* (2013) ‘The influence of training and mental skills preparation on injury incidence and performance in marathon runners’, *Journal of Strength and Conditioning Research*, 27(10), pp. 2828–2835. doi: 10.1519/JSC.0b013e31828a4733.

Handsfield, G.G., Inouye, J.M., Slane, L.C., Thelen, D.G., Miller, G.W. and Blemker, S.S., (2017). A 3D model of the Achilles tendon to determine the mechanisms underlying nonuniform tendon displacements. *Journal of biomechanics*, *51*, pp.17-25.

Hasegawa, H., Yamauchi, T. and Kraemer, W. (2007) ‘Foot strike patterns of runners at the 15-km point during an elite-level half marathon’, *Journal of Strength and Conditioning Research*, 21(3), p. 888.

Hashizume, S. and Yanagiya, T. (2017) ‘A Forefoot Strike Requires the Highest Forces Applied to the Foot Among Foot Strike Patterns.’, *Sports Medicine International Open*, 1(2), pp. E37–E42. doi: 10.1055/s-0042-122017.

Heiderscheit, B. C., Hamill, J. and Caldwell, G. E. (2000) ‘Influence of Q-angle on lower-extremity running kinematics.’, *The Journal Of Orthopaedic And Sports Physical Therapy*, 30(5), pp. 271–278.

Hein, T. *et al.* (2014) ‘Prospective analysis of intrinsic and extrinsic risk factors on the development of Achilles tendon pain in runners', *Scandinavian Journal of Medicine & Science in Sports*, 24(3), pp. e201–e212. doi: 10.1111/sms.12137.

Hennig, E. M. (2001) Gender difference for running in athletic footwear. Zuerich, Switzerland.

Hébert-Losier, K. *et al*. (2012). Influence of knee flexion angle and age on triceps surae muscle activity during heel raises. *The Journal of Strength & Conditioning Research*, *26*(11), pp.3124-3133.

Hespanhol Junior, L. C. *et al.* (2015) 'Meta-Analyses of the Effects of Habitual Running on Indices of Health in Physically Inactive Adults', *Sports Medicine*, 45(10), pp. 1455–1468. doi: 10.1007/s40279-015-0359-y.

Hespanhol Junior, L. C. *et al.* (2016) 'Health and economic burden of running-related injuries in runners training for an event: A prospective cohort study', *Scandinavian journal of medicine & science in sports*, 26(9), pp. 1091–1099. doi: 10.1111/sms.12541.

Hespanhol Junior, L. C., Pena Costa, L. O. and Lopes, A. D. (2013) 'Previous injuries and some training characteristics predict running-related injuries in recreational runners: A prospective cohort study', *Journal of Physiotherapy*, 59(4), pp. 263–269. doi: 10.1016/S1836-9553(13)70203-0.

Hiller, C. E., Kilbreath, S. L. and Refshauge, K. M. (2011) 'Chronic Ankle Instability: Evolution of the Model', *Journal of Athletic Training*, 46(2), pp. 133–141. doi: 10.4085/1062-6050-46.2.133.

Hirschmüller, A. *et al.* (2012) 'Prognostic value of achilles tendon doppler sonography in asymptomatic runners', *Medicine and Science in Sports and Exercise*, 44(2), pp. 199–205. doi: 10.1249/MSS.0b013e31822b7318.

Hollander, K. *et al.* (2020) 'Multifactorial Determinants of Running Injury Locations in 550 Injured Recreational Runners', *Medicine & Science in Sports & Exercise*, Publish Ah. doi: 10.1249/mss.0000000000002455.

Van Hooren, B. *et al.* (2020) 'Is Motorized Treadmill Running Biomechanically Comparable to Overground Running? A Systematic Review and Meta-Analysis of Cross-Over Studies', *Sports Medicine*. Springer, pp. 785–813. doi: 10.1007/s40279-019-01237-z.

Hootman, J. M. *et al.* (2002) 'Predictors of lower extremity injury among recreationally active adults', *Clinical Journal of Sport Medicine*, 12(2), pp. 99–106. doi:

10.1097/00042752-200203000-00006.

Hreljac, A. (2004) ‘Impact and overuse injuries in runners’, *Medicine and Science in Sports and Exercise*, 36(5), pp. 845–849.

Hreljac, A. (2005) ‘Etiology, prevention, and early intervention of overuse injuries in runners: A biomechanical perspective’, *Physical Medicine and Rehabilitation Clinics of North America*, pp. 651–667. doi: 10.1016/j.pmr.2005.02.002.

Hreljac, A., Marshall, R. N. and Hume, P. A. (2000) ‘Evaluation of lower extremity overuse injury potential in runners.’, *Medicine and science in sports and exercise*, 32(9), pp. 1635–41. doi: 10.1097/00005768-200009000-00018.

Hughes, T. *et al.* (2019) ‘The value of tibial mounted inertial measurement units to quantify running kinetics in elite football (soccer) players. A reliability and agreement study using a research orientated and a clinically orientated system’, *Journal of Electromyography and Kinesiology*, 44, pp. 156–164. doi: 10.1016/j.jelekin.2019.01.001.

Hulin, B. T. *et al.* (2016) ‘The acute: Chronic workload ratio predicts injury: High chronic workload may decrease injury risk in elite rugby league players’, *British Journal of Sports Medicine*, pp. 231–236. doi: 10.1136/bjsports-2015-094817.

Hulteen, R. *et al.* (2017) ‘Global participation in sport and leisure-time physical activities: A systematic review and meta-analysis’, *Preventive Medicine*, 95, pp. 14–25.

Ireland, M. L. *et al.* (2003) ‘Hip Strength in Females With and Without Patellofemoral Pain’, *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), pp. 671–676. doi: 10.2519/jospt.2003.33.11.671.

Izquierdo-Renau, M. *et al.* (2020) ‘Impact Acceleration During Prolonged Running While Wearing Conventional Versus Minimalist Shoes’, *Research Quarterly for Exercise and Sport*, pp. 1–7. doi: 10.1080/02701367.2020.1726271.

Jacobs, S. J. and Berson, B. L. (1986) ‘Injuries to runners: A study of entrants to a 10,000 meter race’, *The American Journal of Sports Medicine*, 14(2), pp. 151–155. doi: 10.1177/036354658601400211.

Jakobsen, B. W. *et al.* (1994) ‘Prevention of injuries in long-distance runners’, *Knee Surgery, Sports Traumatology, Arthroscopy*, 2(4), pp. 245–249. doi: 10.1007/BF01845597.

Johnson, C. *et al.* (2020) ‘A comparison of attachment methods of skin mounted inertial measurement units on tibial accelerations’, *Journal of Biomechanics*, 113, p. 110118. doi:

10.1016/j.jbiomech.2020.110118.

Johnson, C. D. *et al.* (2020) 'Impact-Related Ground Reaction Forces Are More Strongly Associated With Some Running Injuries Than Others', *American Journal of Sports Medicine*, 48(12), pp. 3072–3080. doi: 10.1177/0363546520950731.

Junge, A. and Dvorak, J. (2000) 'Influence of Definition and Data Collection on the Incidence of Injuries in Football', *The American Journal of Sports Medicine*, 28(5_suppl), pp. 40–46. doi: 10.1177/28.suppl_5.s-40.

Kakouris, N., Yener, N. and Fong, D. T. P. (2021) 'A systematic review of running-related musculoskeletal injuries in runners', *Journal of Sport and Health Science*, pp. 513–522. doi: 10.1016/j.jshs.2021.04.001.

Karamanidis, K., Arampatzis, A. and Brüggemann, G. P. (2004) 'Reproducibility of electromyography and ground reaction force during various running techniques', *Gait and Posture*, 19(2), pp. 115–123. doi: 10.1016/S0966-6362(03)00040-7.

Kelly, S. T. and Lodge, C. A. (2018) 'Effects of the GAA15 in reducing lower extremity injury rates in adolescent males participating in hurling', *Physiotherapy Practice and Research*, 39(2), pp. 99–105. doi: 10.3233/PPR-180112.

Kelsey, J. L. *et al.* (2007) 'Risk factors for stress fracture among young female cross-country runners', *Medicine and Science in Sports and Exercise*, 39(9), pp. 1457–1463. doi: 10.1249/mss.0b013e318074e54b.

Kemler, E. and Huisstede, B. (2021) 'Performance goals of runners are associated with the occurrence of running-related injuries', *Physical Therapy in Sport*, 50, pp. 153–158.

Kiernan, D. *et al.* (2018) 'Accelerometer-based prediction of running injury in National Collegiate Athletic Association track athletes', *Journal of Biomechanics*, 73, pp. 201–209. doi: 10.1016/J.JBIOMECH.2018.04.001.

Kluitenberg, B. *et al.* (2012) 'Comparison of vertical ground reaction forces during overground and treadmill running . A validation study'. *BMC Musculoskeletal Disorders*, 13(1), pp. 1-8.

Knapik, J. J. (2015) 'The Importance of Physical Fitness for Injury Prevention: Part 2', *Journal of special operations medicine : a peer reviewed journal for SOF medical professionals*, 15(2), pp. 112–115.

Knobloch, K., Yoon, U. and Vogt, P. M. (2008) 'Acute and overuse injuries correlated to hours of training in master running athletes', *Foot and Ankle International*, 29(7), pp. 671–676. doi: 10.3113/FAI.2008.0671.

Knowles, S. B. *et al.* (2007) 'Cost of injuries from a prospective cohort study of North Carolina high school athletes', *Injury Prevention*, 13(6), pp. 416–421. doi: 10.1136/ip.2006.014720.

Knowles, S. B., Marshall, S. W. and Guskiewicz, K. M. (2006) 'Issues in estimating risks and rates in sports injury research.', *Journal of athletic training*, 41(2), pp. 207–15.

Kong, P. W., Candelaria, N. G. and Tomaka, J. (2009) 'Perception of self-selected running speed is influenced by the treadmill but not footwear', *Sports Biomechanics*, 8(1), pp. 52–59. doi: 10.1080/14763140802629990.

Koo, T. K. and Li, M. Y. (2016) 'A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research', *Journal of Chiropractic Medicine*, 15(2), pp. 155–163. doi: 10.1016/j.jcm.2016.02.012.

Kuhman, D. *et al.* (2016a) 'Comparison of ankle kinematics and ground reaction forces between prospectively injured and uninjured collegiate cross country runners.', *Human Movement Science*, 47, pp. 9–15. doi: 10.1016/j.humov.2016.01.013.

Kuhman, D., Melcher, D. and Paquette, M. R. (2016) 'Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners', *European Journal of Sport Science*, 16(4), pp. 433–440. doi: 10.1080/17461391.2015.1086818.

Kulmala, J. *et al.* (2013) 'Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers', *Medicine and Sciene in Sport and Exercise*, 45(12), pp. 2306–2313.

Lafortune, M. A., Hennig, E. M. and Lake, M. J. (1996) 'Dominant role of interface over knee angle for cushioning impact loading and regulating initial leg stiffness', *Journal of Biomechanics*, 29(12), pp. 1523–1529. doi: 10.1016/S0021-9290(96)80003-0.

Larson, P. *et al.* (2011) 'Foot strike patterns of recreational and sub-elite runners in a long-distance road race', *Journal of Sports Sciences*, 29(15), pp. 1665–1673. doi: 10.1080/02640414.2011.610347.

Laughton, C. A., McClay Davis, I. and Hamill, J. (2003) 'Effect of strike pattern and orthotic intervention on tibial shock during running', *Journal of Applied Biomechanics*, 19(2), pp. 153–168. doi: 10.1123/jab.19.2.153.

Lavcanska, V., Taylor, N. F. and Schache, A. G. (2005) 'Familiarization to treadmill running in young unimpaired adults', *Human Movement Science*, 24(4), pp. 544–557. doi: 10.1016/j.humov.2005.08.001.

LeBlanc, B. *et al*. (2021). Continuous estimation of ground reaction force during long distance running within a fatigue monitoring framework: A Kalman filter-based model-data fusion approach. *Journal of Biomechanics*, *115*, p.110130.

Lee, J.B. *et al*. (2010). Identifying symmetry in running gait using a single inertial sensor. *Journal of Science and Medicine in Sport*, *13*(5), pp.559-563.

Lee, T. Q., Morris, G. and Csintalan, R. P. (2003) 'The Influence of Tibial and Femoral Rotation on Patellofemoral Contact Area and Pressure', *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), pp. 686–693. doi: 10.2519/jospt.2003.33.11.686.

Lieberman, D. E. *et al.* (2010) 'Foot strike patterns and collision forces in habitually barefoot versus shod runners', *Nature*, 463, pp. 531–535. doi: 10.1038/nature08723.

Lieberman, D. E. (2012) 'What can we learn about running from barefoot running: an evolutionary medical perspective', *Exercise and Sport Sciences Reviews*, 40(2), pp. 63–72.

Lindsay, T. R., Yaggie, J. A. and McGregor, S. J. (2016) 'A wireless accelerometer node for reliable and valid measurement of lumbar accelerations during treadmill running', *Sports Biomechanics*, 15(1), pp. 11–22. doi: 10.1080/14763141.2015.1123760.

Linton, L. and Valentin, S. (2018) 'Running with injury: A study of UK novice and recreational runners and factors associated with running related injury', *Journal of Science and Medicine in Sport*, 21(12), pp. 1221–1225. doi: 10.1016/j.jsams.2018.05.021.

Liu, H. *et al.* (2012) 'Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: A review of the literature', *Journal of Sport and Health Science*, 1(2), pp. 92–101.

Liu, K., Uygur, M. and Kaminski, T. W. (2012) 'Effect of Ankle Instability on Gait Parameters: A Systematic Review', *Athletic Training & Sports Health Care*, 4(6), pp. 275–281. doi: 10.3928/19425864-20120523-01.

Lohman, E. B. *et al.* (2011) 'A comparison of the spatiotemporal parameters, kinematics, and biomechanics between shod, unshod, and minimally supported running as compared to walking.', *Physical Therapy In Sport: Official Journal Of The Association Of Chartered Physiotherapists In Sports Medicine*, 12(4), pp. 151–163. doi: 10.1016/j.ptsp.2011.09.004.

Lopes, A. D. *et al.* (2011) 'Musculoskeletal pain is prevalent among recreational runners who are about to compete : an observational study of 1049 runners', *Journal of*

Physiotherapy, 57(3).

Lopes, A. D. *et al.* (2012) ‘What are the Main Running-Related Musculoskeletal Injuries ? A Systematic Review’, 42(10), pp. 891–905.

Loudon, J. K. and Reiman, M. P. (2012) ‘Lower extremity kinematics in running athletes with and without a history of medial shin pain.’, *International journal of sports physical therapy*, 7(4), pp. 356–64.

Loudon, J., Manske, R. and Reiman, M. (2013) *Clinical mechanics and kinesiology*.

Louw, Q. and Grimmer, K. (2006) ‘Biomechanical factors associated with the risk of knee injury when landing from a jump’, *South African Journal of Sports Medicine*, 18(1), p. 18. doi: 10.17159/2078-516x/2006/v18i1a248.

Luginick, B. S. *et al.* (2018) ‘Kinematics of recreational runners with iliotibial band injury’, *Journal of Human Sport and Exercise*, 13(3), pp. 698–709. doi: 10.14198/jhse.2018.133.19.

Lun, V. *et al.* (2004) ‘Relation between running injury and static lower limb alignment in recreational runners’, *British Journal of Sports Medicine*, 38(5), pp. 576–580. doi: 10.1136/bjsm.2003.005488.

Luz, B. C. *et al.* (2018) ‘Relationship between rearfoot, tibia and femur kinematics in runners with and without patellofemoral pain.’, *Gait & Posture*, 61, pp. 416–422. doi: 10.1016/j.gaitpost.2018.02.008.

Lysholm, J. and Wiklander, J. (1987) ‘Injuries in runners’, *The American Journal of Sports Medicine*, 15(2), pp. 168–171. doi: 10.1177/036354658701500213.

Macera, C. A. *et al.* (1991) ‘Postrace morbidity among runners’, *American Journal of Preventive Medicine*, 7(4), pp. 194–198. doi: 10.1016/s0749-3797(18)30912-7.

Malisoux, Laurent *et al.* (2015) ‘A step towards understanding the mechanisms of running-related injuries’, *Journal of Science and Medicine in Sport*, 18(5), pp. 523–528. doi: 10.1016/j.jsams.2014.07.014.

Malisoux, L *et al.* (2015) ‘Can parallel use of different running shoes decrease running-related injury risk?’, *Scandinavian Journal of Medicine and Science in Sports*, 25(1), pp. 110–115. doi: 10.1111/sms.12154.

Malisoux, L., Chambon, N., Urhausen, A., *et al.* (2016) ‘Influence of the Heel-to-Toe Drop of Standard Cushioned Running Shoes on Injury Risk in Leisure-Time Runners A

Randomized Controlled Trial With 6-Month Follow-up', *American Journal of Sports Medicine*, 44(11), pp. 2933–2940. doi: 10.1177/0363546516654690.

Malisoux, L., Chambon, N., Delattre, N., *et al.* (2016) 'Injury risk in runners using standard or motion control shoes: A randomised controlled trial with participant and assessor blinding', *British Journal of Sports Medicine*, 50(8), pp. 481–487. doi: 10.1136/bjsports-2015-095031.

Manek, N. J. *et al.* (2003) 'The association of body mass index and osteoarthritis of the knee joint: An examination of genetic and environmental influences', *Arthritis and Rheumatism*, 48(4), pp. 1024–1029. doi: 10.1002/art.10884.

Mann, R. *et al.* (2015) 'Association of previous injury and speed with running style and stride-to-stride fluctuations', *Scandinavian Journal of Medicine and Science in Sports*, 25(6), pp. e638–e645. doi: 10.1111/sms.12397.

Marti, B. *et al.* (1988) 'On the epidemiology of running injuries. The 1984 Bern Grand-Prix study', *American Journal of Sports Medicine*, 16(3), pp. 285–294. doi: 10.1177/036354658801600316.

Matheson, G. O. *et al.* (1987) 'Stress fractures in athletes A study of 320 cases', *The American Journal of Sports Medicine*, 15(1), pp. 46–58.

Maupin, D. *et al.* (2020) 'The Relationship Between Acute: Chronic Workload Ratios and Injury Risk in Sports: A Systematic Review', *Open Access Journal of Sports Medicine*, Volume 11, pp. 51–75. doi: 10.2147/oajsm.s231405.

McCrory, J. *et al.* (1999) 'Etiologic factors associated with Achilles tendinitis in runners.', *Medicine And Science In Sports And Exercise*, 31(10), pp. 1374–1381.

McCrory, J. L. *et al.* (1999) 'Etiologic factors associated with Achilles tendinitis in runners', *Medicine and Science in Sports and Exercise*, 31(10), pp. 1374–1381.

McGowan, C. J. *et al.* (2015) 'Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications', *Sports Medicine*. Springer International Publishing, pp. 1523–1546. doi: 10.1007/s40279-015-0376-x.

McHugh, M. and Nesse, M. (2008) 'Effect of stretching on strength loss and pain after eccentric exercise', *Medicine and science in sports and exercise*, 40(3), p. 566. doi: 10.1249/00005768-200605001-01583.

McHugh, M. P. and Cosgrave, C. H. (2010) 'To stretch or not to stretch: The role of stretching in injury prevention and performance', *Scandinavian Journal of Medicine and Science in Sports*. John Wiley & Sons, Ltd, pp. 169–181. doi: 10.1111/j.1600-0838.2009.01058.x.

McKean, K. A., Manson, N. A. and Stanish, W. D. (2006) 'Musculoskeletal injury in the masters runners.', *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*, 16(2), pp. 149–54.

McQuade, K. J. (1986) 'A case-control study of running injuries: Comparison of patterns of runners with and without running injuries', *Journal of Orthopaedic and Sports Physical Therapy*, 8(2), pp. 81–84. doi: 10.2519/jospt.1986.8.2.81.

van Mechelen, W. (1992) 'Running Injuries: A Review of the Epidemiological Literature', *Sports Medicine: An International Journal of Applied Medicine and Science in Sport and Exercise*. Springer International Publishing, pp. 320–335. doi: 10.2165/00007256-199214050-00004.

Van Mechelen, W. *et al.* (1993) 'Prevention of running injuries by warm-up, cool-down, and stretching exercises', *The American Journal of Sports Medicine*, 21(5), pp. 711–719. doi: 10.1177/036354659302100513.

Meeuwisse, W. *et al.* (2007) 'A dynamic model of etiology in sport injury: the recursive nature of risk and causation.', *Clinical Journal of Sport Medicine*, 17(3), pp. 215–219.

Mercer, J. A. *et al.* (2010) 'A Description of Shock Attenuation for Children Running', *Journal of Athletic Training*, 45(3), pp. 259–264.

Mercer, J. A. and Horsch, S. (2015) 'Heel-toe running: A new look at the influence of foot strike pattern on impact force.', *Journal Of Exercise Science And Fitness*, 13(1), pp. 29–34. doi: 10.1016/j.jesf.2014.12.001.

Messier, S. P. *et al.* (1991) 'Etiologic factors associated with patellofemoral pain in runners.', *Medicine and science in sports and exercise*, 23(9), pp. 1008–15. Available at: http://www.ncbi.nlm.nih.gov/pubmed/1943620 (Accessed: 30 April 2019).

Messier, S. P. *et al.* (1995) 'Etiology of iliotibial band friction syndrome in distance runners.', *Medicine And Science In Sports And Exercise*, 27(7), pp. 951–960. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=7564981&site=ehost-live.

Messier, S. P. *et al.* (2018) 'A 2-Year Prospective Cohort Study of Overuse Running

Injuries: The Runners and Injury Longitudinal Study (TRAILS).', *The American Journal Of Sports Medicine*, 46(9), pp. 2211–2221. doi: 10.1177/0363546518773755.

Van Middelkoop, M. *et al.* (2008) 'Risk factors for lower extremity injuries among male marathon runners', *Scandinavian Journal of Medicine and Science in Sports*, 18(6), pp. 691–697. doi: 10.1111/j.1600-0838.2007.00768.x.

Miller, R. H. *et al.* (2007) 'Lower extremity mechanics of iliotibial band syndrome during an exhaustive run', *Gait & Posture*, 26(3), pp. 407–413. doi: 10.1016/J.GAITPOST.2006.10.007.

Milner, C. E. *et al.* (2006) 'Biomechanical factors associated with tibial stress fracture in female runners', *Medicine and Science in Sports and Exercise*, 38(2), pp. 323–328. doi: 10.1249/01.mss.0000183477.75808.92.

Milner, C. E., Hamill, J. and Davis, I. (2007) 'Are knee mechanics during early stance related to tibial stress fracture in runners?', *Clinical Biomechanics*, 22(6), pp. 697–703. doi: 10.1016/J.CLINBIOMECH.2007.03.003.

Milner, C. E., Hamill, J. and Davis, I. S. (2010) 'Distinct Hip and Rearfoot Kinematics in Female Runners With a History of Tibial Stress Fracture', *Journal of Orthopaedic & Sports Physical Therapy*, 40(2), pp. 59–66. doi: 10.2519/jospt.2010.3024.

Milner, C. E., Hawkins, J. L. and Aubol, K. G. (2020) 'Tibial acceleration during running is higher in field testing than indoor testing', *Medicine and Science in Sports and Exercise*, 52(6), pp. 1361–1366. doi: 10.1249/MSS.0000000000002261.

Mizrahi, J. *et al.* (2000) 'Effect of fatigue on leg kinematics and impact acceleration in long distance running', *Human Movement Science*, 19(2), pp. 139–151. doi: 10.1016/S0167-9457(00)00013-0.

Mohseni, M. M. *et al.* (2021) 'Factors Associated With Half- and Full-Marathon Race-Related Injuries: A 3-Year Review', *Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine*, 31(5), pp. e277–e286. doi: 10.1097/JSM.0000000000000775.

Moore, I. S. (2016) 'Is There an Economical Running Technique? A Review of Modifiable Biomechanical Factors Affecting Running Economy', *Sports Medicine*. Springer International Publishing, pp. 793–807. doi: 10.1007/s40279-016-0474-4.

Mousavi, S. H. *et al.* (2021) 'Factors associated with lower limb injuries in recreational runners: A cross-sectional survey including mental aspects and sleep quality', *Journal of Sports Science and Medicine*, 20(2), pp. 204–215. doi: 10.52082/jssm.2021.204.

Munro, B., Visintainer, M. and Page, E. (1986) *Statistical methods for health care research*. Philadelphia: J.B. Lippincott.

Nakagawa, T. H., Maciel, C. D. and Serrão, F. V. (2015) 'Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain', *Manual Therapy*, 20(1), pp. 189–193. doi: 10.1016/J.MATH.2014.08.013.

Nakaoka, G. *et al.* (2021) 'The Association Between the Acute:Chronic Workload Ratio and Running-Related Injuries in Dutch Runners: A Prospective Cohort Study', *Sports Medicine*, 51(11), pp. 2437–2447. doi: 10.1007/s40279-021-01483-0.

Napier, C. *et al.* (2018) 'Kinetic risk factors of running-related injuries in female recreational runners', *Scandinavian Journal of Medicine and Science in Sports*, 28(10), pp. 2164–2172. doi: 10.1111/sms.13228.

Napier, C. and Willy, R. W. (2021) 'The Prevention and Treatment of Running Injuries: A State of the Art', *International Journal of Sports Physical Therapy*, 16(4), p. 968. doi: 10.26603/001c.25754.

Neto, F. *et al.* (2021) 'The training characteristics of recreational-level triathletes: Influence on fatigue and health', 9(7). doi: 10.3390/sports9070094.

Ng, G.Y.F., Zhang, A.Q. and Li, C.K., (2008). Biofeedback exercise improved the EMG activity ratio of the medial and lateral vasti muscles in subjects with patellofemoral pain syndrome. *Journal of electromyography and kinesiology*, *18*(1), pp.128-133.

Nielsen, R. O. *et al.* (2012) 'Training errors and running related injuries: a systematic review.', *International journal of sports physical therapy*, 7(1), pp. 58–75.

Nielsen, R. O., Nohr, E. A., *et al.* (2013) 'Classifying running-related injuries based upon etiology, with emphasis on volume and pace.', *International Journal Of Sports Physical Therapy*, 8(2), pp. 172–179.

Nielsen, R. O., Buist, I., *et al.* (2013) 'Predictors of running-related injuries among 930 novice runners: A 1-year prospective follow-up study', *Orthopaedic Journal of Sports Medicine*, 1(1), pp. 1–7. doi: 10.1177/2325967113487316.

Nielsen, R. Ø. *et al.* (2014) 'Excessive Progression in Weekly Running Distance and Risk of Running-Related Injuries: An Association Which Varies According to Type of Injury', *Journal of Orthopaedic & Sports Physical Therapy*, 44(10), pp. 739–747. doi: 10.2519/jospt.2014.5164.

Nigg, B. M. and Yeadon, M. R. (1987) 'Biomechanical aspects of playing surfaces', *Journal of Sports Sciences*, 5(2), pp. 117–145. doi: 10.1080/02640418708729771.

Nilsson, J. and Thorstensson, A. (1989) 'Ground reaction forces at different speeds of human walking and running', *Acta Physiologica Scandinavica*, 136(2), pp. 217–227. doi: 10.1111/j.1748-1716.1989.tb08655.x.

Noehren, B., Pohl, M. B., *et al.* (2012) 'Proximal and distal kinematics in female runners with patellofemoral pain', *CLINICAL BIOMECHANICS*, 27(4), pp. 366–371. doi: 10.1016/j.clinbiomech.2011.10.005.

Noehren, B., Sanchez, Z., *et al.* (2012) 'The effect of pain on hip and knee kinematics during running in females with chronic patellofemoral pain', *Gait & Posture*, 36(3), pp. 596–599. doi: 10.1016/J.GAITPOST.2012.05.023.

Noehren, B. *et al.* (2014) 'Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome', *Journal of Orthopaedic and Sports Physical Therapy*, 44(3), pp. 217–222. doi: 10.2519/jospt.2014.4991.

Noehren, B., Davis, I. and Hamill, J. (2007) 'ASB Clinical Biomechanics Award Winner 2006: Prospective study of the biomechanical factors associated with iliotibial band syndrome.', *Clinical Biomechanics*, 22(9), pp. 951–956. doi: 10.1016/j.clinbiomech.2007.07.001.

Noehren, B., Scholz, J. and Davis, I. (2011) 'The effect of real-time gait retraining on hip kinematics, pain and function in subjects with patellofemoral pain syndrome', *British Journal of Sports Medicine*, 45(9), pp. 691–696. doi: 10.1136/bjsm.2009.069112.

Norris, M., Kenny, I. C. and Anderson, R. (2016) 'Comparison of accelerometry stride time calculation methods', *Journal of Biomechanics*, 49(13), pp. 3031–3034. doi: 10.1016/j.jbiomech.2016.05.029.

Novacheck, T. (1998) 'The biomechanics of running', *Gait & Posture*, 7(1), pp. 77–95.

Nuhu, A. *et al.* (2021) 'Effect of the FIFA 11+ soccer specific warm up programme on the incidence of injuries: A cluster-randomised controlled trial', *PLoS ONE*, 16(5 May). doi: 10.1371/journal.pone.0251839.

Nunns, M. *et al.* (2013) 'Biomechanical characteristics of barefoot footstrike modalities.', *Journal Of Biomechanics*, 46(15), pp. 2603–2610. doi: 10.1016/j.jbiomech.2013.08.009.

O Catháin, C., Richter, C. and Moran, K. (2020) 'Can Directed Compliant Running Reduce the Magnitude of Variables associated with the Development of Running Injuries?', *Journal of Strength and Conditioning Research*.

Orendurff, M. S. *et al.* (2018) 'A little bit faster: Lower extremity joint kinematics and kinetics as recreational runners achieve faster speeds', *Journal of Biomechanics*, 71, pp. 167–175. doi: 10.1016/j.jbiomech.2018.02.010.

Paquette, M., Milner, C. and Melcher, D. (2017) 'Foot contact angle variability during a prolonged run with relation to injury history and habitual foot strike pattern', *Scandinavian Journal of Medicine and Science in Sports*, 27(2), pp. 217–222. doi: 10.1111/sms.12647.

Park, S.-K. *et al.* (2018) 'Gender Differences in Ground Reaction Force Components', *Korean Journal of Sport Biomechanics*, 28(2), pp. 101–108.

Paul, I. L. *et al.* (1978) 'Musculo-skeletal shock absorption: Relative contribution of bone and soft tissues at various frequencies', *Journal of Biomechanics*, 11(5), pp. 237–239. doi: 10.1016/0021-9290(78)90049-0.

Pescatello, L., Riebe, D. and Thompson, P. (2014) *ACSM's guidelines for exercise testing and prescription*. Edited by L. W. & Wilkins.

Petersen, J. *et al.* (2014) 'Comparisons of increases in knee and ankle joint moments following an increase in running speed from 8 to 12 to 16 km·h- 1', *Clinical Biomechanics*, 29(9), pp. 959–964. doi: 10.1016/j.clinbiomech.2014.09.003.

Pink, M. *et al.* (1994) 'Lower Extremity Range of Motion in the Recreational Sport Runner', *The American Journal of Sports Medicine*, 22(4), pp. 541–549. doi: 10.1177/036354659402200418.

Pohl, M. B. *et al.* (2008) 'Biomechanical predictors of retrospective tibial stress fractures in runners', *Journal of Biomechanics*, 41(6), pp. 1160–1165. doi: 10.1016/j.jbiomech.2008.02.001.

Pohl, M. B., Davis, I. S. and Hamill, J. (2007) 'Prospective Study of Kinetic Factors Associated with Tibial Stress Fractures in Runners', in *American Society of Biomechanics*.

Pohl, M. B., Hamill, J. and Davis, I. S. (2009) 'Biomechanical factors associated with tibial stress fracture in female', *Clinical Journal of Sport Medicine*, 19(5), pp. 372–376. doi: 10.1097/JSM.0b013e3181b8c270.

van Poppel, D. *et al.* (2018) 'Risk models for lower extremity injuries among short- and long distance runners: A prospective cohort study', *Musculoskeletal Science and Practice*, 36, pp. 48–53. doi: 10.1016/j.msksp.2018.04.007.

Portefaix, H. and Simon, A. (2016) 'Les chaussures minimalistes, un traitement dans la tendinopathie achilléenne?', *Kinesitherapie*, 16(172), pp. 21–29. doi: 10.1038/nature08723.

Potthast, W. *et al.* (2010) 'The Influences of Impact Interface , Muscle Activity , and Knee Angle on Impact Forces and Tibial and Femoral Accelerations Occurring After External Impacts', pp. 1–9.

Powers, C. M. (2000) 'Patellar Kinematics, Part II: The Influence of the Depth of the Trochlear Groove in Subjects With and Without Patellofemoral Pain', *Physical Therapy*, 80(10), pp. 965–973. doi: 10.1093/ptj/80.10.965.

Powers, C. M. (2003a) 'The Influence of Altered Lower-Extremity Kinematics on Patellofemoral Joint Dysfunction: A Theoretical Perspective', *Journal of Orthopaedic & Sports Physical Therapy*, 33(11), pp. 639–646. doi: 10.2519/jospt.2003.33.11.639.

Preece, S. J., Mason, D. and Bramah, C. (2016) 'The coordinated movement of the spine and pelvis during running', *Human Movement Science*, 45, pp. 110–118. doi: 10.1016/j.humov.2015.11.014.

Ramskov, D. *et al.* (2013) 'No association between q-angle and foot posture with running-related injuries: a 10 week prospective follow-up study.', *International journal of sports physical therapy*, 8(4), pp. 407–15.

Rasmussen, C. H. *et al.* (2013) 'Weekly running volume and risk of running-related injuries among marathon runners.', *International journal of sports physical therapy*, 8(2), pp. 111–20.

Reenalda, J. *et al.* (2019) 'Kinematics and shock attenuation during a prolonged run on the athletic track as measured with inertial magnetic measurement units', *Gait and Posture*, 68, pp. 155–160. doi: 10.1016/j.gaitpost.2018.11.020.

Reinking, M. *et al.* (2007) 'Exercise-related leg pain in collegiate cross-country athletes: extrinsic and intrinsic risk factors', *jospt.org*, 37(11), pp. 670–678. doi: 10.2519/jospt.2007.2534.

Riazati, S., Caplan, N. and Hayes, P. R. (2019) 'The number of strides required for treadmill running gait analysis is unaffected by either speed or run duration', *Journal of Biomechanics*, 97. doi: 10.1016/j.jbiomech.2019.109366.

Ribeiro, A. P. *et al.* (2015) 'Dynamic Patterns of Forces and Loading Rate in Runners with Unilateral Plantar Fasciitis: A Cross-Sectional Study.', *Plos One*, 10(9), pp. e0136971–e0136971. doi: 10.1371/journal.pone.0136971.

Richter, C. *et al.* (2014) 'Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping', *Journal of Biomechanics*, 47(12), pp. 3012–3017. doi: 10.1016/j.jbiomech.2014.07.001.

Riley, P. O. *et al.* (2008) 'A kinematics and kinetic comparison of overground and treadmill running', *Medicine and Science in Sports and Exercise*, 40(6), pp. 1093–1100. doi: 10.1249/MSS.0b013e3181677530.

Roper, J. L. *et al.* (2016) 'The effects of gait retraining in runners with patellofemoral pain: A randomized trial', *Clinical Biomechanics*, 35, pp. 14–22. doi: 10.1016/j.clinbiomech.2016.03.010.

Rubin, D. B. (2004) *Multiple Imputation for Nonresponse in Surveys*, *John Wiley & Sons*. doi: 10.2307/3172772.

Ruder, M. *et al.* (2017) 'Relationship of Footstrike Pattern and Landing Impacts During a Marathon Race', *Medicine & Science in Sports & Exercise*, 49(5S), p. 136.

Ryan, M. *et al.* (2014) 'Examining injury risk and pain perception in runners using minimalist footwear', *British Journal of Sports Medicine*, 48(16), pp. 1257–1262. doi: 10.1136/bjsports-2012-092061.

Ryu, J. (2005) 'Gender differences in the impact magnitude and its attenuation during running', *Korean Journal of Sport Biomechanics*, 15(1), pp. 91–109. doi: 10.5103/kjsb.2005.15.1.091.

Sadigursky, D. *et al.* (2017) 'The FIFA 11+ injury prevention program for soccer players: A systematic review', *BMC Sports Science, Medicine and Rehabilitation*, 9(1), pp. 1–8. doi: 10.1186/s13102-017-0083-z.

Sahr, M., Sturnick, D. R. and Nwawka, O. K. (2018) 'Quantitative Ultrasound Assessment of the Achilles Tendon Under Varied Loads', *Journal of ultrasound in medicine : official journal of the American Institute of Ultrasound in Medicine*, 37(10), pp. 2413–2418. doi: 10.1002/jum.14589.

Sallade, J. R. and Koch, S. (1992) 'Training errors in long distance running.', *Journal of athletic training*, 27(1), pp. 50–3.

Santos, B. R. *et al.* (2008) 'Reliability of centre of pressure summary measures of postural steadiness in healthy young adults', *Gait and Posture*, 27(3), pp. 408–415. doi: 10.1016/j.gaitpost.2007.05.008.

Saragiotto, B. T. *et al.* (2014) 'What are the main risk factors for running-related injuries?', *Sports Medicine*, pp. 1153–1163. doi: 10.1007/s40279-014-0194-6.

Saragiotto, B. T., Yamato, T. P. and Lopes, A. D. (2014) 'What do recreational runners think about risk factors for running injuries? A descriptive study of their beliefs and opinions', *Journal of Orthopaedic and Sports Physical Therapy*, 44(10), pp. 733–738. doi: 10.2519/jospt.2014.5710.

Satterthwaite, P. *et al.* (1999) 'Risk factors for injuries and other health problems sustained in a marathon', *British Journal of Sports Medicine*, 33(1), pp. 22–26. doi: 10.1136/bjsm.33.1.22.

Saunders, S. W. *et al.* (2005) 'Changes in three dimensional lumbo-pelvic kinematics and trunk muscle activity with speed and mode of locomotion', *Clinical Biomechanics*, 20(8), pp. 784–793. doi: 10.1016/j.clinbiomech.2005.04.004.

Saxena, A., O'Brien, T. and Bunce, D., (1990). Anatomic dissection of the tibialis posterior muscle and its correlation to medial tibial stress syndrome. *The Journal of foot surgery*, *29*(2), pp.105-108.

Schache, A. *et al.* (1999) 'The coordinated movement of the lumbo–pelvic–hip complex during running: a literature review', *Gait & Posture*, 10(1), pp. 30–47.

Schache, A. G., Blanch, P. D. and Murphy, A. T. (2000) 'Relation of anterior pelvic tilt during running to clinical and kinematic measures of hip extension.', *British journal of sports medicine*, 34(4), pp. 279–83. doi: 10.1136/bjsm.34.4.279.

Schlingermann, B. E. *et al.* (2018) 'Effects of the gaelic athletic association 15 on lower extremity injury incidence and neuromuscular functional outcomes in collegiate gaelic games', *Journal of Strength and Conditioning Research*, 32(7), pp. 1993–2001. doi: 10.1519/JSC.0000000000002108.

Schütte, K. H. *et al.* (2018) 'Influence of outdoor running fatigue and medial tibial stress syndrome on accelerometer-based loading and stability', *Gait & Posture*, 59, pp. 222–228.

doi: 10.1016/J.GAITPOST.2017.10.021.

Schwane, B. G. (2011) *Trunk and Lower Extremity Kinematics in Individuals With and Without Patellofemoral Pain Syndrome*. The University of North Carolina at Chapel Hill.

Schwellnus, M. *et al.* (2016) ‘How much is too much? (Part 2) International Olympic Committee consensus statement on load in sport and risk of illness’, *British Journal of Sports Medicine*, 50(17), pp. 1043–1052. doi: 10.1136/bjsports-2016-096572.

Sharma, L. *et al.* (2001) ‘The role of knee alignment in disease progression and functional decline in knee osteoarthritis’, *Journal of the American Medical Association*, 286(2), pp. 188–195. doi: 10.1001/jama.286.2.188.

Sheerin, K. *et al.* (2016) The reliability and variability of three-dimensional tibial acceleration during running. ISBS-conference proceedings archive.

Sheerin, K. R. *et al.* (2018) ‘The one-week and six-month reliability and variability of three-dimensional tibial acceleration in runners*’, *Sports Biomechanics*, 17(4), pp. 531–540. doi: 10.1080/14763141.2017.1371214.

Sheerin, K. R., Reid, D. and Besier, T. F. (2019) ‘The measurement of tibial acceleration in runners—A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use’, *Gait & Posture*, 67, pp. 12–24. doi: 10.1016/J.GAITPOST.2018.09.017.

Shen, P. *et al.* (2019) ‘Effects of running biomechanics on the occurrence of iliotibial band syndrome in male runners during an eight-week running programme—a prospective study’, *Sports Biomechanics*, pp. 1–11. doi: 10.1080/14763141.2019.1584235.

Shih, Y., Lin, K. L. and Shiang, T. Y. (2013) ‘Is the foot striking pattern more important than barefoot or shod conditions in running?’, *Gait and Posture*, 38(3), pp. 490–494. doi: 10.1016/j.gaitpost.2013.01.030.

Shorten, M. and Mientjes, M. I. V. (2011) ‘The “heel impact” force peak during running is neither “heel” nor “impact” and does not quantify shoe cushioning effects’, *Footwear Science*, 3(1), pp. 41–58. doi: 10.1080/19424280.2010.542186.

Simic, M. *et al.* (2011) ‘Gait modification strategies for altering medial knee joint load: A systematic review’, *Arthritis Care and Research*, pp. 405–426. doi: 10.1002/acr.20380.

Sinclair, J. (2016) ‘Sex differences in shock attenuation during running’, *Central European Journal of Sport Sciences and Medicine* |, 15(3), pp. 37–42. doi: 10.18276/cej.2016.3-04.

Sinclair, J. and Selfe, J. (2015) ‘Sex differences in knee loading in recreational runners’, *Journal of Biomechanics*, 48(10), pp. 2171–2175. doi: 10.1016/j.jbiomech.2015.05.016.

Smits, D. *et al.* (2016) ‘Short-Term Absenteeism and Health Care Utilization Due to Lower Extremity Injuries among Novice Runners: A Prospective Cohort Study’, *Clinical Journal of Sport Medicine*, 26(6), pp. 502–509. doi: 10.1097/JSM.0000000000000287.

Soligard, T. *et al.* (2016) ‘How much is too much? (Part 1) International Olympic Committee consensus statement on load in sport and risk of injury’, *British Journal of Sports Medicine*, 50(17), pp. 1030–1041. doi: 10.1136/bjsports-2016-096581.

Souza, R. B. (2016) ‘An Evidence-Based Videotaped Running Biomechanics Analysis.’, *Physical medicine and rehabilitation clinics of North America*, 27(1), pp. 217–36. doi: 10.1016/j.pmr.2015.08.006.

Souza, R. B. and Powers, C. M. (2009) ‘Differences in Hip Kinematics, Muscle Strength, and Muscle Activation Between Subjects With and Without Patellofemoral Pain’, *Journal of Orthopaedic & Sports Physical Therapy*, 39(1), pp. 12–19. doi: 10.2519/jospt.2009.2885.

Souza, R., R.B. and Powers, C. M. (2009) ‘Predictors of hip internal rotation during running: an evaluation of hip strength and femoral structure in women with and without patellofemoral pain’, *The American Journal of Sports Medicine.* 37 (3), pp. 579-587. doi: 10.1177/0363546508326711.

Steib, S. *et al.* (2013) ‘Effects of fatiguing treadmill running on sensorimotor control in athletes with and without functional ankle instability’, *Clinical Biomechanics*, 28(7), pp. 790–795. doi: 10.1016/j.clinbiomech.2013.07.009.

Sugimoto, D. *et al.* (2019) ‘Running Propensities of Athletes with Hamstring Injuries’, *Sports*, 7(9), p. 210. doi: 10.3390/sports7090210.

Sun, X. *et al.* (2018) ‘Do Strike Patterns or Shoe Conditions have a Predominant Influence on Foot Loading?’, *Journal Of Human Kinetics*, 64, pp. 13–23. doi: 10.1515/hukin-2017-0205.

Taunton, J. E. *et al.* (2002) ‘A retrospective case-control analysis of 2002 running injuries.’, *British journal of sports medicine*, 36(2), pp. 95–101. doi: 10.1136/bjsm.36.2.95.

Taunton, J. E. *et al.* (2003) ‘A prospective study of running injuries: The Vancouver Sun Run “In Training” clinics’, *British Journal of Sports Medicine*, 37(3), pp. 239–244. doi:

10.1136/bjsm.37.3.239.

Teng, H. L. and Powers, C. M. (2014) 'Sagittal plane trunk posture influences patellofemoral joint stress during running', *Journal of Orthopaedic and Sports Physical Therapy*, 44(10), pp. 785–792. doi: 10.2519/jospt.2014.5249.

Teran-Yengle, P., Cole, K. J. and Yack, H. J. (2016) 'Short and long-term effects of gait retraining using real-time biofeedback to reduce knee hyperextension pattern in young women', *Gait and Posture*, 50, pp. 185–189. doi: 10.1016/j.gaitpost.2016.08.019.

Theisen, D. *et al.* (2014) 'Influence of midsole hardness of standard cushioned shoes on running-related injury risk', *British Journal of Sports Medicine*, 48(5), pp. 371–376. doi: 10.1136/bjsports-2013-092613.

Theisen, D., Malisoux, L. and Gette, P. (2016) 'Footwear and running-related injuries–Running on faith?', *Sports Orthopaedics and Traumatology*, 32(2), pp. 169–176.

Thompson, M. A. *et al.* (2015) 'Kinematic and kinetic comparison of barefoot and shod running in mid/forefoot and rearfoot strike runners', *Gait and Posture*, 41(4), pp. 957–959. doi: 10.1016/j.gaitpost.2015.03.002.

Tiberio, D. (1987) 'The Effect of Excessive Subtalar Joint Pronation on Patellofemoral Mechanics: A Theoretical Model', *Journal of Orthopaedic & Sports Physical Therapy*, 9(4), pp. 160–165. doi: 10.2519/jospt.1987.9.4.160.

Timpka, T. *et al.* (2014) 'Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics (track and field): consensus statement', *bjsm.bmj.com*. doi: 10.1136/bjsports-2013-093241.

Toft, E. *et al.* (1989) 'Passive tension of the ankle before and after stretching', *The American Journal of Sports Medicine*, 17(4), pp. 489–494. doi: 10.1177/036354658901700407.

Toohey, L. A. *et al.* (2017) 'Is subsequent lower limb injury associated with previous injury? A systematic review and meta-analysis', *British Journal of Sports Medicine*, pp. 1670–1678. doi: 10.1136/bjsports-2017-097500.

Trouli, M. N. *et al.* (2008) 'Translation of the Neck Disability Index and validation of the Greek version in a sample of neck pain patients', *BMC Musculoskeletal Disorders*, 9(1), pp. 1–8. doi: 10.1186/1471-2474-9-106.

Turner, D. *et al.* (2010) 'The minimal detectable change cannot reliably replace the minimal important difference', *Journal of Clinical Epidemiology*, 63(1), pp. 28–36. doi: 10.1016/j.jclinepi.2009.01.024.

Turvey, M., Fitch, H. and Tuller, B. (1982) *The Bernstein Perspective: I. The Problems of Degrees of Freedom and Context-Conditioned Variability. Human Motor Behavior*. Lawrence Erlbaum Associates.

Urabe, Y. *et al.* (2014) 'Effect of shoe insole for prevention and treatment of lower extremity injuries', *The Journal of Physical Fitness and Sports Medicine*, 3(4), pp. 385–398. doi: 10.7600/jpfsm.3.385.

Valenzuela, K. A. *et al.* (2015) 'Effect of Acute Alterations in Foot Strike Patterns during Running on Sagittal Plane Lower Limb Kinematics and Kinetics', (December 2014), pp. 225–232.

Vannatta, C. N. and Kernozek, T. W. (2015) 'Patellofemoral Joint Stress during Running with Alterations in Foot Strike Pattern', *Medicine and Science in Sports and Exercise*, 47(5), pp. 1001–1008. doi: 10.1249/MSS.0000000000000503.

Verhagen, E., Warsen, M. and Silveira Bolling, C. (2021) 'I just want to run: How recreational runners perceive and deal with injuries', *BMJ Open Sport and Exercise Medicine*, 7(3). doi: 10.1136/bmjsem-2021-001117.

de Vet, H.C. *et al*. (2006). When to use agreement versus reliability measures. *Journal of clinical epidemiology*, *59*(10), pp.1033-1039.

Vieira, T.M. *et al*. (2013). How much does the human medial gastrocnemius muscle contribute to ankle torques outside the sagittal plane?. *Human movement science*, *32*(4), pp.753-767.

Viru, A. and Viru, M. (2000) 'Nature of training effects', *Exerc Sport Sci*, 6(7), pp. 67–95. Available at: https://www.researchgate.net/publication/299838539 (Accessed: 20 May 2020).

Wakkee, M., Hollestein, L. M. and Nijsten, T. (2014) 'Multivariable analysis', *Journal of Investigative Dermatology*, 134(5), p. e20. doi: 10.1038/jid.2014.132.

Walter, S. D. *et al.* (1989) 'The Ontario cohort study of running-related injuries', *Archives of Internal Medicine*, 149(11), pp. 2561–2564. doi: 10.1001/archinte.1989.00390110113025.

Warr, B. *et al.* (2015) 'Characterization of foot-strike patterns: lack of an association with injuries or performance in soldiers', *Military Medicine*, 180(7), pp. 830–834.

Webster, K. E. *et al.* (2019) 'Factors Associated With a Return to Preinjury Level of Sport Performance After Anterior Cruciate Ligament Reconstruction Surgery', *American Journal of Sports Medicine*, 47(11), pp. 2557–2562. doi: 10.1177/0363546519865537.

Weir, J. P. (2005) 'Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM', *Journal of Strength and Conditioning Research*, pp. 231–240. doi: 10.1519/15184.1.

Wen, D. Y., Puffer, J. C. and Schmalzried, T. P. (1997) 'Lower extremity alignment and risk of overuse injuries in runners', *Medicine and Science in Sports and Exercise*, 29(10), pp. 1291–1298. doi: 10.1097/00005768-199710000-00003.

Wen, D. Y., Puffer, J. C. and Schmalzried, T. P. (1998) 'Injuries in runners: A prospective study of alignment', *Clinical Journal of Sport Medicine*, 8(3), pp. 187–194. doi: 10.1097/00042752-199807000-00005.

Whalan, M., Lovell, R. and Sampson, J. A. (2020) 'Do Niggles Matter? - Increased injury risk following physical complaints in football (soccer)', *Science and Medicine in Football*, 4(3), pp. 216–224. doi: 10.1080/24733938.2019.1705996.

Wilke, J., Vleeming, A. and Wearing, S. (2019) 'Overuse injury: The result of pathologically altered myofascial force transmission?', *Exercise and Sport Sciences Reviews*, 47(4), pp. 230–236. doi: 10.1249/JES.0000000000000205.

Wille, C. M. *et al.* (2014) 'Ability of Sagittal Kinematic Variables to Estimate Ground Reaction Forces and Joint Kinetics in Running', *Journal of Orthopaedic & Sports Physical Therapy*, 44(10), pp. 825–830. doi: 10.2519/jospt.2014.5367.

Willson, J. *et al.* (2012) 'Male and female gluteal muscle activity and lower extremity kinematics during running', *Clinical Biomechanics*, 27(10), pp. 1052–1057.

Willson, J. D. *et al.* (2011) 'Gluteal muscle activation during running in females with and without patellofemoral pain syndrome', *Clinical Biomechanics*, 26(7), pp. 735–740. doi: 10.1016/j.clinbiomech.2011.02.012.

Willy, R. W. *et al.* (2012) 'Are mechanics different between male and female runners with patellofemoral pain?', *Medicine and science in sports and exercise*, 44(11), p. 2165. doi: 10.1249/MSS.0B013E3182629215.

Willy, R. W. and Davis, I. S. (2014) 'Kinematic and kinetic comparison of running in standard and minimalist shoes', *Medicine and Science in Sports and Exercise*, 46(2), pp. 318–323. doi: 10.1249/MSS.0b013e3182a595d2.

Wilson, J. F., Rochelle, R. D. and Bischoff, J. E. (1997) 'Identification and correlation of human footfall load parameters using multivariate analysis', *Journal of Biomechanical Engineering*, 119(1), pp. 115–123. doi: 10.1115/1.2796053.

Wilson, T. (2007) 'The Measurement of Patellar Alignment in Patellofemoral Pain Syndrome: Are We Confusing Assumptions With Evidence?', *Journal of Orthopaedic & Sports Physical Therapy*, 37(6), pp. 330–341. doi: 10.2519/jospt.2007.2281.

Winter, D. A. (1984) 'Kinematic and kinetic patterns in human gait: Variability and compensating effects', *Human Movement Science*, 3(1–2), pp. 51–76. doi: 10.1016/0167-9457(84)90005-8.

Winter, S. C. *et al.* (2020) 'A Multifactorial Approach to Overuse Running Injuries: A 1-Year Prospective Study', *Sports Health*, 12(3), pp. 296–303. doi: 10.1177/1941738119888504.

Wirtz, A. D. *et al.* (2012) 'Patellofemoral joint stress during running in females with and without patellofemoral pain', *The Knee*, 19(5), pp. 703–708. doi: 10.1016/J.KNEE.2011.09.006.

De Wit, B. and De Clercq, D. (1997) 'Differences in sagittal plane kinematics between barefoot and shod running', in *Proceedings of the Second Annual Congress of the European College of Sport Sciences*.

Witvrouw, E. *et al.* (2004) 'Stretching and injury prevention: An obscure relationship', *Sports Medicine*. Springer, pp. 443–449. doi: 10.2165/00007256-200434070-00003.

van der Worp, H., Vrielink, J. W. and Bredeweg, S. W. (2016) 'Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis', *British Journal of Sports Medicine*, pp. 450–457. doi: 10.1136/bjsports-2015-094924.

van der Worp, M. P. *et al.* (2015) 'Injuries in Runners; A Systematic Review on Risk Factors and Sex Differences', *PLOS ONE*. Edited by A. A. Zadpoor, 10(2), p. e0114937. doi: 10.1371/journal.pone.0114937.

van der Worp, M. P. *et al.* (2012) 'Iliotibial band syndrome in runners: A systematic review', *Sports Medicine*, pp. 969–992. doi: 10.2165/11635400-000000000-00000.

Wyrwich, K. W. and Wolinsky, F. D. (2000) ‘Identifying meaningful intra-individual change standards for health- related quality of life measures’, *Journal of Evaluation in Clinical Practice*, 6(1), pp. 39–49. doi: 10.1046/j.1365-2753.2000.00238.x.

Xu, D. *et al.* (2022) ‘Explaining the differences of gait patterns between high and low-mileage runners with machine learning’, *Scientific Reports*, 12(1). doi: 10.1038/s41598-022-07054-1.

Yamaguchi, T., Takizawa, K. and Shibata, K. (2015) ‘Acute effect of dynamic stretching on endurance running performance in well-trained male runners’, *Journal of Strength and Conditioning Research*, 29(11), pp. 3045–3052. doi: 10.1519/JSC.0000000000000969.

Yamato, T. *et al.* (2015) ‘Definitions Used To Define A Running-Related Musculoskeletal Injury: A Systematic Review’, *Journal of Orthopaedic & Sports Physical Therapy*, 45(5), pp. 375–380.

Yamato, T. P., Saragiotto, B. T. and Lopes, A. D. (2015) ‘A consensus definition of running-related injury in recreational runners: A modified Delphi approach’, *Journal of Orthopaedic and Sports Physical Therapy*, 45(5), pp. 375–380. doi: 10.2519/jospt.2015.5741.

Yeung, S. S., Yeung, E. W. and Gillespie, L. D. (2011) ‘Interventions for preventing lower limb soft-tissue running injuries’, *Cochrane Database of Systematic Reviews*. doi: 10.1002/14651858.cd001256.pub2.

Yong, J. *et al.* (2018) ‘Acute changes in foot strike pattern and cadence affect running parameters associated with tibial stress fractures.’, *Journal Of Biomechanics*, 76, pp. 1–7. doi: 10.1016/j.jbiomech.2018.05.017.

Zifchock, R. *et al.* (2008) ‘Side-to-side differences in overuse running injury susceptibility: A retrospective study’, *Human Movement Science*, 27(6), pp. 888–902. doi: 10.1016/J.HUMOV.2008.03.007.

Zifchock, R. A., Davis, I. and Hamill, J. (2006) ‘Kinetic asymmetry in female runners with and without retrospective tibial stress fractures’, *Journal of Biomechanics*, 39(15), pp. 2792–2797. doi: 10.1016/J.JBIOMECH.2005.10.003.

Appendices

Appendix A

Risk Factors for Injuries in Runners: A systematic Review of Foot Strike Technique and Its Classification at Impact

Burke, A., Dillon, S., O'Connor, S., Whyte, E., Gore, G., Moran, K., 2021. Risk Factors for Injuries in Runners: A systematic Review of Foot Strike Technique and Its Classification at Impact. *Orthopaedic Journal of Sports Medicine*. *https://doi.org/10.1177/23259671211020283*

Abstract

Background It has been suggested that foot strike technique (FST) at initial contact is related to running-related injuries (RRIs).

Purpose To explore the relationship between FST and RRIs.

Study Design Systematic review; Level of evidence, 3.

Methods A systematic electronic search was performed using MEDLINE, PubMed, Sports Discus, Scopus, and Web of Science databases. Included were studies published in the English language that explored the relationship between FST and RRIs from January 1960 to August 2019. Results were extracted and collated. The GRADE (Grading of Recommendations, Assessment, Development and Evaluation) approach was applied to synthesize the quality of evidence.

Results We reviewed 13 studies exploring the relationship between FST and RRIs. Of these, 6 studies reported FST categorically (foot strike pattern [FSP]), and 7 reported continuous measures (foot contact angle [FCA], ankle flexion angle [AFA], and strike index [SI]). Three of the 6 studies looking at categorical FSP found rearfoot strikers (RFS) to have a significantly greater retrospective injury rate than non-RFS strikers, with 1 other study noting a greater risk associated with midfoot and forefoot strike. Regarding the continuous measures of FST, only 1 of the 7 studies reported a significant relationship with RRIs.

Conclusion There was low evidence to suggest a relationship between FST (or its subcategories of categorical FSP and continuous measures) and RRIs. While two-thirds of the categorical studies found a relationship between FSP and RRIs, the quality of these studies was very low with limitations such as retrospective study design, low subject numbers and poor FSP assessment methods. More large-scale prospective studies are required.

Introduction

Running is an extremely popular sport and physical activity (Deelen *et al.*, 2019) with proven health benefits, such as cardiovascular, respiratory and psychological improvements (Smits *et al.*, 2016). However, running prevalence rates of running-related injuries (RRIs) are as high as 79% in recreational runners (Van Mechelen *et al.*, 1993; Lun *et al.*, 2004) and 85% in novice runners (Bovens *et al.*, 1989; Kluitenberg *et al.*, 2015). Taking a biomechanical model approach to injury, RRIs are caused by high loading relative to tissue strength (Hreljac, Marshall and Hume, 2000). Given that the foot is the first point of ground impact, and has the potential to mediate the subsequent force applied to the body (Goss and Gross, 2012; Kulmala *et al.*, 2013), the relationship between foot strike technique (FST) and injury has received significant attention within the scientific (Daoud *et al.*, 2012; Goss and Gross, 2012; Warr *et al.*, 2015; Paquette, Milner and Melcher, 2017) and general running communities (McDougall, 2009).

It has been speculated that for the majority of human evolutionary history, runners would have ran barefoot, or would have ran in minimalist footwear with little or no cushioning (e.g. sandals) (Lieberman *et al.*, 2010). It is thought that this style of running would encourage a running technique where the forefoot strikes the ground first, or alternatively the runner might land with a flat foot, in order to manage the impact load (Lieberman *et al.*, 2010). However, with the introduction of modern running shoes and increased cushioning properties within these shoes, shod runners are thought to be more facilitated to strike the ground with their heels (rearfoot strike) (Lieberman *et al.*, 2010). It is unknown how or why runners arise with a specific foot strike technique (i.e. some runners land on their toes first, whilst others land on their heels), but it appears that evolution of both humans and running shoe properties may have played a role in the predominance of rearfoot strike pattern prevalence that we see amongst the modern day running community (Larson *et al.*, 2011b; Daoud *et al.*, 2012).

Thus far, FST has been defined in two ways: through nominal means via foot strike pattern (FSP) classification, and through continuous measures. Nominally, FSP classification has been categorised into various sub-groups based on which part of the foot contacts the ground first: rearfoot strike (RFS), midfoot strike (MFS) and forefoot strike (FFS) (Cavanagh and Lafortune, 1980). RFS describes initial contact with the heel or posterior aspect of the foot; FFS involves contact with anterior aspects of the foot; while MFS involves simultaneous contact of both the posterior and anterior parts (Almeida, 2015). Some studies have also combined MFS and FFS patterns, grouping them together as non-RFS (Warr *et al.*, 2015; Ruder *et al.*, 2019). Studies which have reported FSP classifications use either visual analysis of a sagittal plane video camera (Daoud *et al.*, 2012; Warr *et al.*, 2015; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020), categorization of continuous measures (foot and ankle contact angles and strike index) (Donoghue *et al.*, 2008; Mann *et al.*, 2015; Dudley *et al.*, 2017; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019), or with self-reporting methods (Goss and Gross, 2012).

Continuous measures of FST have been derived from three assessment techniques: (1) measuring the foot contact angle (FCA), (2) measuring the ankle flexion angle (AFA) at contact; and (3) calculating the centre of pressure during impact relative to foot length (strike index (SI)). Foot contact angle has been determined through 3D motion analysis (Dudley *et al.*, 2017; Paquette, Milner and Melcher, 2017; Dingenen *et al.*, 2019). Ankle flexion angle has also been determined through 3D motion analysis, and describes whether the ankle is in a dorsi-flexed or plantar-flexed position at initial contact (Donoghue *et al.*, 2008). Lastly, strike index has been examined using force plates (Kuhman *et al.*, 2016b; Messier *et al.*, 2018) and pressure sensitive insoles (Mann *et al.*, 2015), and has been defined as the position of the centre of pressure during landing relative to foot length (Cavanagh and Lafortune, 1980). Whilst FST measures may have been captured as a continuous measure (e.g. FCA, AFA or SI), some authors have subsequently categorized these into nominal FSPs. With respect to FCA, there has been variations in the values suggested to represent each FSP. (Altman and Davis (2012) suggest FCAs of greater than 8.0° represent RFS, less than -1.6° represent FFS, and -1.6° to 8.0° a MFS, following a comparative analysis between FCA and SI measures. Other authors suggest that: RFS is any positive FCA, FFS any negative FCA, and MFS being 0° (Lieberman *et al.*, 2010). The challenge with this classification is how infrequent a landing of exactly 0° may be, and this guideline may therefore be too stringent. With respect to AFA, it has been proposed that landing in: dorsi-flexion represents a RFS, planter-flexion represents a FFS, and a neutral angle reflects a MFS (Donoghue *et al.*, 2008). Lastly, according to Cavanagh and Lafortune (1980) a SI of less than 33% represents a RFS, 34%-66% represents a MFS, and greater than 67% represents a FFS.

Interest in the relationship between FST and injury has, at least in part, been guided by research examining the relationship between FSP and loading. Some research has found RFSs result in higher magnitudes (Kulmala *et al.*, 2013; Mercer and Horsch, 2015; Thompson *et al.*, 2015) and rates (Kulmala *et al.*, 2013; Shih, Lin and Shiang, 2013; Yong *et al.*, 2018b) of whole-body loading (via vertical ground-reaction forces), and higher knee loading (Goss and Gross, 2012; Kulmala *et al.*, 2013), in comparison to a FFS (or non-RFS). While loading forms a necessary component of training, resulting in homeostatic positive responses and adaptations (Viru and Viru, 2000; Brooks, Fahey and Baldwin, 2004), excessive cumulative load and a poor work-recovery ratio may result in maladaptation to training and an increased risk of injury (Drew and Finch, 2016; Schwellnus *et al.*, 2016). Based on the excessive load that some foot strike patterns may produce, and the potential for this cumulative load to become injurious over time (Hreljac, Marshall and Hume, 2000; Bredeweg *et al.*, 2013; Davis, Bowser and Mullineaux, 2016), many researchers have suggested that FST, especially a RFS pattern, may be causative of RRIs (Daoud *et al.*, 2012; Goss and Gross, 2012). While this may be intuitive, a direct relationship needs to be established.

To the best of our knowledge, only 1 systematic review (Anderson *et al.*, 2019) has explored the relationship between FST and injury, and this was done as part of a much broader systematic review. That review (Anderson *et al.*, 2019) however, only identified 1 study, which was in the area of FSP and injury. The authors of that review neglected to include "injury" in their search terms, and subsequently may have missed relevant studies. Our systematic review therefore collated all of the existing research on FST (FSP, FCA, AFA and SI) and RRI, which may be valuable for clinicians, coaches and athletes in the prevention and management of RRIs. The aim of this review was to investigate if FST (both categorical and continuous measures) relates to RRIs.

Methods

Protocol and Registration

This systematic review was registered with Prospero (Centre for Reviews and Dissemination), on 17/07/2019 (CRD42020142747). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement provided structural guidelines for writing this review.[51]

Identification and Selection of Studies

A systematic review was undertaken by two authors (AB, SD) from November 2-9, 2020. MEDLINE, PubMed, Sports Discus, Scopus and Web of Science databases were searched to identify studies investigating FST and RRIs from January 1960 to November 2020. The search was restricted to clinical trials, case-comparison and cohort studies that were in English using human subjects. Reviews, commentaries, opinion articles, case-studies and conference proceedings were excluded. The search terms used are available in Supplemental Table A1, and were combined using Boolean terms.

Three authors (AB, SD and KM) determined the inclusion and exclusion criteria before the search commenced (Supplemental Table A2). All studies investigating FST and RRIs were included. Running-related injuries were identified with guidance from a consensus definition, and was defined as any pain attributed to running, involving muscles, joints, tendons, ligaments and/or bones of the lower extremities (hip, groin, thigh, knee, lower leg, ankle, foot, and toe) that caused a restriction or stoppage of running (distance, speed, duration of training), or that required the runner to consult a physician or other healthcare professional (Yamato, Saragiotto and Lopes, 2015). Specific definitions of injury per reviewed articles can be viewed in Supplemental Table A5. Titles and abstracts were reviewed independently (AB, SD) using predetermined selection criteria. A full manuscript review was performed if selection was unclear. Disagreements were resolved by discussion or third party mediation (KM).

Risk-of-Bias Assessment

Each study's methodological quality was assessed independently (AB, SD) using a modified Downs and Black Quality Index (Downs and Black, 1998). Index items that did not pertain to the nature of the selected studies were excluded from the assessment

(Supplemental Table A3). The modified index comprised of 19 items within four categories: information reporting, external validity, internal validity, and selection bias. Items representing a high and low risk of bias were scored 0 and 1, respectively. Total scores of 0-5 were classified as high risk, 6-12 as moderate risk, and 13-19 as low risk. The index has good test-retest reliability (r =0.88), inter-rater reliability (r =0.75), and high internal consistency (α =0.89) (Downs and Black, 1998).

Data Extraction

Data extraction of the selected articles was performed by one author (AB). The study design, population, sample size, participant characteristics (age, sex, BMI), FSP prevalence, definition of injury, testing characteristics (testing surface, testing speed, FST classification), and other outcome variables were recorded. To evaluate the association between FST and RRIs, p-values, hazard ratios (HRs), odds ratios (ORs), and relative risks (RRs) (mean and 95% CIs) were extracted where possible. Study authors were contacted via email to request full datasets where missing or incomplete.

Assessment of Evidence

Due to the wide heterogeneity of methods and outcome measures, a meta-analysis was not possible. The quality of the body of evidence was therefore determined by the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) approach which analyses the following areas: study design, study limitations (risk of bias), inconsistency of results, indirectness of studies, imprecision of study results, and publication bias (Guyatt *et al.*, 2011). The quality of evidence for each outcome measure was presented on a four-scale rating system (high, moderate, low and very low) (Guyatt *et al.*, 2011). Details of the GRADE approach and scoring criteria are in the Supplemental Appendix.

Results

Overview of findings

A total of 2270 articles were identified. After duplicate articles were removed, 675 titles and abstracts were reviewed. Eighteen articles were shortlisted, of which five were excluded [full text was not in English (n=2), rearfoot motion was the only kinematic variable assessed (n=2), and foot strike pattern was a means of matching injured runners with controls (n=1)]. The remaining thirteen papers were included for review. Reviewing their bibliographies did not reveal any additional includable studies. A PRISMA flow diagram of study selection is in Figure A1.

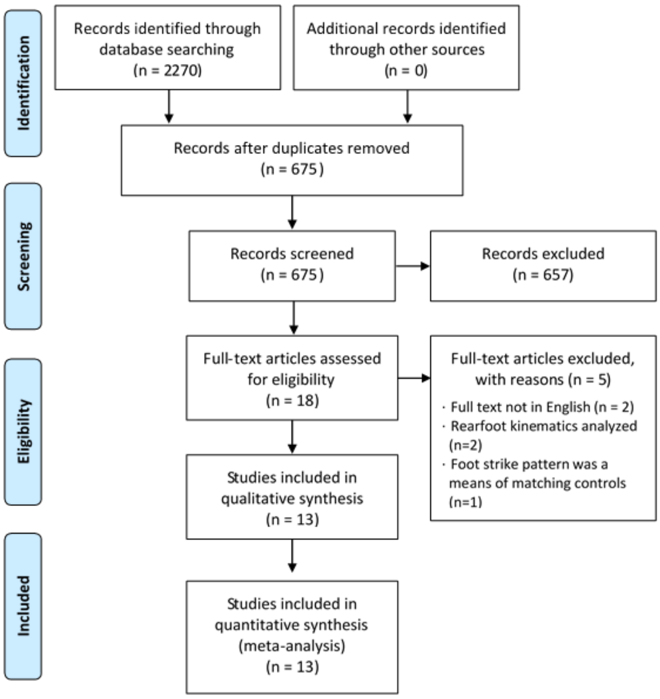

Figure A7.2.1 PRISMA flow diagram.

Risk of Bias

Scoring of the quality assessment is detailed in Supplemental Table A4. The mean score for the 19 item risk of bias assessment was 11.1 (range, 11-17). Two studies had a moderate risk of bias (Donoghue *et al.*, 2008; Goss and Gross, 2012), and eleven studies had a low risk (Daoud *et al.*, 2012; Warr *et al.*, 2015; Mann *et al.*, 2015; Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020). The most common risk items were: participants not being representative of the population, no blinding of the examiners to the outcome, and a lack of power calculations.

Synthesis of Study Characteristics

A summary of the thirteen studies' designs, inclusive of participant, injury and testing characteristics, can be viewed in Supplemental Table A5. Three of the thirteen studies included were prospective (Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Messier *et al.*, 2018) and ten were retrospective cohort studies (Donoghue *et al.*, 2008; Daoud *et al.*, 2012; Goss and Gross, 2012; Mann *et al.*, 2015; Warr *et al.*, 2015; Paquette, Milner and Melcher, 2017; Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020). Analysis of participant characteristics revealed a total of 2,564 participants, with a range of study sample sizes from 19 participants to 881 participants [(median: 70 participants (interquartile range: 36–320 participants)], with recreational (n=6), military (n=1), collegiate cross country running (n=3), and mixed (recreational, collegiate and military, n=1; recreational and competitive, n=1) groups being investigated. One study did not report the population of runners that was studied (Sugimoto *et al.*, 2019). Twelve studies had a mixed sex population, with one study looking exclusively at male runners (Warr *et al.*, 2015). Body mass index (BMI) did not differ greatly between studies that reported them (20.5-24.9 kg/m^2 reported across nine studies) (Daoud *et al.*, 2012; Mann *et al.*, 2015; Kuhman *et al.*, 2016b; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020). The proportion of participants analysed ranged from 79-100%. Reasons given for the analysis being below 100% included: barefoot runners being excluded due to small sample size (Goss and Gross, 2012), runners sustaining non-RRIs (Kuhman *et al.*, 2016b), poor image quality (Dingenen *et al.*, 2019), and injuries to the non-dominant limb, where only the dominant limb had been tested (Dudley *et al.*, 2017).

With respect to injury characteristics, the timeframe for injury surveillance ranged between 4 months and 7 years [(median: 18 months (interquartile range: 12-60 months)]. However, one study did complete an additional analysis of injuries sustained within a lifetime (Warr *et al.*, 2015), which has not been included in the former interquartile range calculation. The definition of injury varied across many studies, with only seven authors demonstrating a similar time-loss definition ranging between one session (Dudley *et al.*, 2017), one week (Goss and Gross, 2012; Mann *et al.*, 2015; Warr *et al.*, 2015; Dingenen *et al.*, 2019), two weeks (Messier *et al.*, 2018), and three months of interrupted training (Fukusawa, Stoddard and Lopes, 2020). One study neglected to define injury (Paquette, Milner and Melcher, 2017).

With regard to FSP classification and testing, six studies classified FSP into distinct foot strike patterns [RFS, MFS, FFS and non-RFS (midfoot or forefoot strike pattern combined)] through visual analysis of sagittal plane video recordings of foot contact angles (Daoud *et al.*, 2012; Warr *et al.*, 2015; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and

Lopes, 2020; Hollander *et al.*, 2020), or self-reporting (Goss and Gross, 2012). In contrast, seven studies examined FST on two continuous scales: (1) initial ground contact angles (FCA, AFA) through 3D motion analysis (Donoghue *et al.*, 2008; Dudley *et al.*, 2017; Dingenen *et al.*, 2019), and (2) location of initial point of contact relative to foot length [strike index (SI)] using pressure sensitive insoles (Mann *et al.*, 2015) and force plate analysis (Kuhman *et al.*, 2016b; Messier *et al.*, 2018). There were also differences in testing conditions with three studies analysing running on an over-ground surface within a laboratory (Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Messier *et al.*, 2018), six on a treadmill (Donoghue *et al.*, 2008; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2017; Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019; Hollander *et al.*, 2020), and two on an outdoor runway (Warr *et al.*, 2015; Fukusawa, Stoddard and Lopes, 2020). One study analysed running on both an outdoor track and a treadmill (Daoud *et al.*, 2012), reporting identical FSP categorization across surfaces. One study asked participants to self-report their FSP through an online survey (Goss and Gross, 2012).

There was also variation in the number of foot strikes analysed [median: 5 (interquartile range: 3–7); full range 2-161)]. With regards to running speed, nine studies directed participants to run at a self-selected pace that was reflective of their typical training (Donoghue *et al.*, 2008; Mann *et al.*, 2015; Dudley *et al.*, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020) or running event pace (Warr *et al.*, 2015; Paquette, Milner and Melcher, 2017). Kuhman *et al.*, (2016) and Sugimoto *et al.*, (2019) tested participants at a predetermined speed (4.0-4.5 m/s and 1.8-2.3 m/s, respectively), while Daoud *et al.*, (2012) examined running at self-selected and predetermined speeds of 3.0m/s-5.0m/s. For the nine of the fifty-two runners who changed their FSP with increasing speed (Daoud *et al.*, 2012), the FSP for which the subject ran the majority of their miles at was used in the FSP classification of that runner. Of the eight studies analysing self-selected speeds, six studies (Donoghue *et al.*, 2008; Mann *et al.*, 2015; Dudley *et al.*, 2017; Dingenen *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020) reported the actual test speed, which ranged between 2.1 and 3.0 m/s.

Regarding the evidence of a relationship between FST and RRIs, there is very low evidence to confidently say that a relationship exists (Table A2). Less than 40% (5/13) of studies found a significant relationship between FST and RRI, which included 1,595 of the total 2,564 participants (Daoud *et al.*, 2012; Goss and Gross, 2012; Dingenen *et al.*, 2019;

Sugimoto *et al.*, 2019; Hollander *et al.*, 2020). When FST was analysed through FSP classification, 66% (4/6) of the studies, which included 1,553 of 2,016 participants, reported RRI prevalence (Goss and Gross, 2012; Sugimoto *et al.*, 2019; Hollander *et al.*, 2020) and rate (Daoud *et al.*, 2012) to be related to FSP. Two of these studies found general overuse RRI rates (Daoud *et al.*, 2012; Goss and Gross, 2012) and one study found hamstring injury rates (Sugimoto *et al.*, 2019) to be greater in RFS runners compared to MFS or FFS runners, with one of these studies having a moderate risk of bias (Goss and Gross, 2012) and the other two having a low risk of bias (Daoud *et al.*, 2012; Sugimoto *et al.*, 2019) (Table A3). In contrast, Hollander *et al.*, (2020) found Achilles tendon injuries to be significantly greater in MFS runners compared to both RFS and FFS runners, and posterior shank injuries to be significantly greater in FFS runners compared to both RFS and MFS runners. It should be noted that all of the studies examining the relationship between categorical measures of FST and RRI were retrospective cohort studies.

Table A2. Scoring of studies through the GRADE approach

Outcome (Number of Studies)	Initial Rating of Study Design	Study Limitations	Inconsistency	Indirectness	Imprecision	Publication Bias	Grading Up	GRADE Quality of Evidence
Nominal Measures								
Foot Strike Pattern (n = 6) [2,016 participants]	Low ⊕⊕⊖⊖	-1	N/A	0	-1	0	0	Very Low ⊕⊖⊖⊖
Continuous Measures								
Foot Contact Angle (n = 3) [117 participants]	Low ⊕⊕⊖⊖	0	N/A	-1	-1	-1	0	Very Low ⊕⊖⊖⊖
Ankle Flexion Angle (n = 1) [22 participants]	Low ⊕⊕⊖⊖	-1	N/A	-1	-1	-1	0	Very Low ⊕⊖⊖⊖
Strike Index (n = 3) [409 participants]	Low ⊕⊕⊖⊖	0	N/A	-1	-1	0	0	Very Low ⊕⊖⊖⊖

Level of evidence: ⊕⊕⊕⊕: high , ⊕⊕⊕⊖: moderate , ⊕⊕⊖⊖: low, ⊕⊖⊖⊖: very low; N/A: not applicable, (n:): number of studies.

Table A3. Results of studies exploring categorical measures of foot strike technique and running-related injuries

Study	Injury measure	RFS	MFS	FFS	NRFS	Significance	Outcome
Retrospective							
Daoud *et al.*, n = 52	Injury rates per 10,000 miles (mean ± SEM)	**Mild repetitive RRIs: 3.19 ± 0.55*** **Moderate repetitive RRIs: 4.96 ± 0.84*** Severe repetitive RRIs: 3.70 ± 0.64 **Moderate and severe repetitive RRIs: 8.66 ± 1.02***	N/A	**Mild repetitive RRIs: 1.25 ± 0.67*** **Moderate repetitive RRIs: 2.03 ± 0.66*** Severe repetitive RRIs: 2.97 ± 1.01 **Moderate and severe repetitive RRIs: 5.00 ± 1.43***	N/A	**P = 0.025*** **P = 0.006*** P = 0.54 **P = 0.037***	**Mild and moderate repetitive stress injury rates are ~2.5 times higher in RFS vs FFS***
		Mild traumatic RRIs: 2.61 ± 0.81 Moderate traumatic RRIs: 1.18 ± 0.58 Severe traumatic RRIs: 0.59 ± 0.21 Moderate & severe traumatic RRIs: 1.77 ± 0.58	N/A	Mild traumatic RRIs: 0.78 ± 0.56 Moderate traumatic RRIs: 1.25 ± 0.35 Severe traumatic RRIs: 0.31 ± 0.18 Moderate & severe traumatic RRIs: 1.56 ± 0.42	N/A	P = 0.06 P = 0.91 P = 0.32 P = 0.78	-
		Mild Rearfoot strike RRIs: 1.93 ± 0.44* **Moderate Rearfoot strike RRIs: 3.36 ± 0.68*** Severe Rearfoot strike RRIs: 2.44 ± 0.53 **Moderate & severe Rearfoot strike RRIs: 5.80 ± 0.84***	N/A	**Mild Rearfoot strike RRIs: 0.47 ± 0.39*** **Moderate Rearfoot strike RRIs: 0.78 ± 0.43*** Severe Rearfoot strike RRIs: 1.41 ± 0.75 **Moderate & severe Rearfoot strike RRIs: 2.19 ± 1.00***	N/A	**P = 0.012*** **P = 0.001*** P = 0.26 **P = 0.006***	**Injury rates x2.7 times higher for RFS vs FFS***
		Mild Forefoot strike RRIs: 0.42 ± 0.15 Moderate Forefoot strike RRIs: 0.67 ± 0.26 Severe Forefoot strike RRIs: 0.76 ± 0.32 Moderate & severe Forefoot strike RRIs: 1.43 ± 0.41	N/A	Mild Forefoot strike RRIs: 0.47 ± 0.22 Moderate Forefoot strike RRIs: 0.94 ± 0.39 Severe Forefoot strike RRIs: 0.94 ± 0.44 Moderate & severe Forefoot strike RRIs: 1.88 ± 0.65	N/A	P = 0.86 P = 0.57 P = 0.74 P = 0.56	-
Goss and Gross n = 881	Injury prevalence rate per year (% injured)	**52.4%**	34.7%	22.8%	N/A	**P < 0.001***	**Injury rates greater (18-30%) in RFS vs MFS and FFS*.**
Warr *et al.*, n = 341	Injury prevalence (% injured)	Acute RRI ≤ 5 years: 14% Overuse RRI ≤ 5 years: 32% RRI in a lifetime: 50%	N/A	N/A	Acute RRI ≤ 5 years: 7% Overuse RRI ≤ 5 years: 31% RRI in a lifetime: 56%	P = 0.51	-

Hollander *et al.*, n = 550	Injury prevalence (% injured)	**Location** Lower Back: ~73% Hip/Groin: ~71% Thigh: ~75% Knee: ~73% Achilles Tendon: ~60% Ankle: ~65% Foot/Toes: ~68%	**Location** Lower Back: ~10% Hip/Groin: ~10% Thigh: ~6% Knee: ~8% **Achilles Tendon: ~20%*** Ankle: ~4% Foot/Toes: ~12%	**Location** Lower Back: ~17% Hip/Groin: ~19% Thigh: ~19% Knee: ~19% Achilles Tendon: ~20% Ankle: ~31% Foot/Toes: ~20%	N/A	P > 0.05 P > 0.05 P > 0.05 P > 0.05 **P = 0.04*** P > 0.05 P > 0.05	Runners with a MFS pattern were at 2.27 times greater odds of sustaining an Achilles tendon injury.
		Sub-location Posterior Thigh: ~75% Anterior Knee: ~76% Lateral Knee: ~70% Anterior Shank: ~77% Posterior Shank: ~66%	**Sub-location** Posterior Thigh: ~10% Anterior Knee: ~8% Lateral Knee: ~9% Anterior Shank: ~6% Posterior Shank: ~16%	**Sub-location** Posterior Thigh: ~15% Anterior Knee: ~16% Lateral Knee: ~21% Anterior Shank: ~17% **Posterior Shank: ~18%***	N/A	P > 0.05 P > 0.05 P > 0.05 P > 0.05 **P = 0.004***	Runners with a FFS pattern were at 2.6 times greater odds of sustaining a posterior shank injury.
Fukusawa *et al.*, n = 122	Injury prevalence (% injured)	Anterior Knee Pain : 97% Uninjured: 93%	N/A	N/A	Anterior Knee Pain: 3% Uninjured: 7%	P > 0.05	-
Sugimoto *et al.*, n = 70	Injury prevalence (% injured)	**Hamstring injury: 74%*** Uninjured: 43%	Hamstring injuries: 20% Uninjured: 20%	Hamstring injuries: 6% Uninjured: 37%	N/A	**P = 0.004***	74% of runners with hamstring injuries demonstrated a RFS pattern, vs 43% RFS in healthy controls.

RFS: Rear-foot strike; MFS: mid-foot strike; FFS: fore-foot strike; NRFS: non-rear-foot strike; SEM: Standard error of mean; RRI: running-related injury; n: number of participants; ≤: less than or equal to; N/A: not applicable; <: less than; *: significant p value at p< 0.05; Rearfoot strike based RRIs: running-related injuries predicted by the authors to be more common in rearfoot strike runners; Forefoot strike based RRIs: running-related injuries predicted by the authors to be more common in forefoot strike runners; vs: versus; -: no significant differences; **Bold highlighted text in table body**: significant findings.

When FST was analysed through continuous measures (FCA, AFA and SI), only one of the seven studies reported a significant relationship between FST and RRI, with Dingenen *et al.*, (2019) (n=506 participants) reporting a significantly lower FCA (injured: 6.8° vs uninjured 9.7°) in runners who had current running-related knee injuries compared to uninjured controls (Table A4).

Table A4. Results of studies exploring continuous measures of foot strike technique and running-related injuries

Study	Foot Strike Technique Assessment	Injured (Mean ± SD)	Uninjured (Mean ± SD)	Mean Difference (Uninjured limb – Injured limb)	Significance
Prospective					
Dudley *et al.*, n = 31	Foot Contact Angle	11.2°	11°	-0.2°	P = 0.94
Retrospective					
Paquette *et al.*, n = 44	Foot Contact Angle	5.0 ± 5.9°	4.7 ± 6.5°	-0.3°	P = 0.88
Dingenen *et al.*, n = 42	Foot Contact Angle	6.8 ± 5.1°	9.7 ± 6.0°	+2.9°	**P = 0.03***
Donoghue *et al.*, n = 22	Ankle Flexion Angle	3.3 ± 5.5°	2.9 ± 4.9°	-0.4°	P > 0.05
Prospective					
Kuhman *et al.*, n = 19	Strike $Index_1$	44.8 ± 50.0%	55.8 ± 48.7%	10.0%	P = 0.64
Messier *et al.*, n = 300	Strike $Index_2$	12.0 ± 18.0%	14.0 ± 0.0%	2.0%	P = 0.44
Retrospective					
Mann *et al.*, n = 90	Strike $Index_3$	25.1 ± 9.4%	23.7 ± 10.3%	-1.4%	P = 0.58

SD: Standard deviation; n: number of participants; °: degrees; >: greater than; Strike $Index_1$: Ratio of COP location at foot-strike relative to modified foot length (%) measured through 3D motion analysis; Strike $Index_2$: % distance from the heel measured through 3D motion analysis; SI_3: % of total sole length of pressure-sensitive insole.

Discussion

The overall finding is that there is very low evidence to suggest a relationship between foot strike technique (FST) and running-related injury (RRI). While two-thirds of categorical studies found a relationship between FSP and RRI, the quality of these studies was very low. This became particularly evident in the GRADE assessment, with moderate risk of biases and imprecision of study methodologies featuring in the down grading of FSP as an outcome measure.

One potential reason for the majority of categorical studies finding a relationship between FSP and RRI, but no such trends being noted for continuous measures, may be due to the dichotomisation or trichotomization of data in FSP studies. Categorising FST data into RFS, MFS, FFS or non-RFS (MFS and FFS combined) allows the identification of defined groups that may produce distinct loading patterns. The lack of findings for continuous measures of FST suggests that as foot contact angle changes from RFS (with maximum dorsi-flexion) to FFS (with maximum plantar-flexion), there is not a continuous linear change in the associated loading on the body, e.g. peak or rate of vGRF (Stiffler-Joachim *et al.*, 2019). While both FFS and RFS involve impact with the ground, the RFS pattern appears to demonstrate a higher magnitude and earlier timing of the vertical impact peak compared to FFS running (Lieberman *et al.*, 2010), which has been proposed to relate to overuse RRIs (Milner *et al.*, 2006; Van Gent, Siem, Middelkoop, *et al.*, 2007; Pohl, Hamill and Davis, 2009a). Although there may be a vertical impact with FFS, it might not be evident as a peak in the time domain (Shorten and Mientjes, 2011; Boyer, Rooney and Derrick, 2014). Additionally, loading at the knee (greater patellofemoral joint reaction forces (Willson *et al.*, 2015), tibiofemoral average loading rate (Bowersock *et al.*, 2017) and knee extensor moments (Kulmala *et al.*, 2013)) can be greater in RFS patterns compared to FFS patterns. It should be acknowledged however, that loading of the Achilles (Achilles tendon peak force (Hashizume and Yanagiya, 2017) and ankle plantar-flexor moments (Kulmala *et al.*, 2013; Hashizume and Yanagiya, 2017)) is greater with a non-RFS pattern compared to a RFS pattern. Because of this potential influence of high loading on overuse RRIs (Ferber *et al.*, 2002; Pohl, Hamill and Davis, 2009a), and the demonstration of greater loading with various FSPs, several authors have speculated that there may be a relationship between FSP and RRI (Goss and Gross, 2013; Kulmala *et al.*, 2013; Shih, Lin and Shiang, 2013; Kuhman, Melcher and Paquette, 2016; Yong *et al.*, 2018b).

This speculation has been further encouraged through the findings of Daoud *et al.*, (2012), Goss and Gross, (2012), and Sugimoto *et al.*, (2019) as reported in this review, whereby injury rates were significantly greater in RFS running compared to non-RFS running. Daoud *et al.*, (2012) noted repetitive injury rates to be significantly greater in RFS compared to FFS runners. In agreement with Daoud *et al.*, (2012), Goss and Gross, (2012) and Sugimoto *et al.*, (2019) also found retrospective overuse injury and hamstring injury rates, respectively, to be significantly greater in RFS runners in comparison to FFS runners. Interestingly, a recent study by Hollander *et al.*, (2020) reported there to be no relationship between RFS and RRI, but they did find strong associations between non-RFS patterns and injury, with MFS runners more than twice as likely to have sustained an Achilles tendon injury (OR: 2.3), and FFS runners more than twice as likely to have sustained a posterior lower leg injury (OR: 2.6) in comparison to RFS runners (Hollander *et al.*, 2020). In contrast to the findings of the studies above (Daoud *et al.*, 2012; Goss and Gross, 2012; Sugimoto *et al.*, 2019; Hollander *et al.*, 2020), both Warr *et al.*, (2015) and Fukusawa, Stoddard and Lopes, (2020) did not find a relationship between FSP and RRI. Warr *et al.*, (2015) solely examined military personnel, whose injuries may be attributable to high training volume, additional load carriage, and obstacle course and land navigations (Majumdar, Pal and Majumdar, 2010; Knapik *et al.*, 2013), suggesting that this group may not be ideal for examination and generalisation of the possible relationship between FST and RRIs. While Goss and Gross, (2012) included military personnel, their prevalence (recreational, military and collegiate cross-country) was not described and so it is unclear if their inclusion was large enough to affect the results. Although Fukusawa, Stoddard and Lopes, (2020) examined the relationship between FSP and running-related knee injuries in recreational runners, the injured runners in this study had been training with knee pain for an average of 12 months.

Despite the FSP prevalence being similar between injured (RFS: 97%; non-RFS: 3%) and uninjured groups (RFS: 93%; non-RFS: 7%), it would appear that the uninjured group may have been more habituated to the loading associated with a RFS pattern. Perhaps the runners with knee pain sustained injury due to their inability to withstand this loading, and a subsequent inability to adapt their mechanics to dissipate these loads appropriately. In addition, it appears that only one (Roper *et al.*, 2016) of two intervention studies found a beneficial effect of FST modification (changing from RFS to non-RFS) in RRI reduction,(Roper *et al.*, 2016; Morris *et al.*, 2019) and both of these studies have poor study design, very low level of evidence (as measured using the GRADE assessment approach) and low subject numbers, further supporting the main findings of this systematic review.

For continuous measures of FST, it does not appear that FCA, AFA or SI relate to RRIs in recreational (Donoghue *et al.*, 2008; Mann *et al.*, 2015; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019) and collegiate cross country runners (Kuhman *et al.*, 2016b; Dudley *et al.*, 2017). Only one of six studies found a relationship between FCA and RRI, with lower FCA observed in recreational runners who had a current knee injury compared to healthy controls (Dingenen *et al.*, 2019). A lower FCA (6.8°) would be suggestive of a MFS landing pattern (Bade, Aaron and McPoil, 2016). Authors of the study speculated that the lower FCA values observed in the injured group were indicative of a potential compensatory pattern adapted by the runners in efforts to reduce knee loading (Dingenen *et al.*, 2019). Due to the retrospective case-control nature of this study, it is difficult to know how accurate this speculation may be.

Differences between study methodologies may be somewhat responsible for the lack of consistency between results, some of which included differences in FST assessment, testing conditions and definition of injury. Regarding continuous measurements of FST assessment, FCA, AFA and SI have been analysed through force plate and 3D motion analysis (Donoghue *et al.*, 2008; Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Dingenen *et al.*, 2019) and pressure sensitive insoles (Mann *et al.*, 2015). Meanwhile categorically, FSP was determined through sagittal plane video camera recordings (Daoud *et al.*, 2012; Warr *et al.*, 2015; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020), and through self-reported FSP methods via an online survey (Goss and Gross, 2012). However, accuracy of self-reporting is limited, with only 44%-69% of runners able to accurately report their FSP (Goss *et al.*, 2015; Bade, Aaron and McPoil, 2016), which may explain differences in prevalence between Goss and Gross, (2012) (RFS: 31%; MFS: 43%; FFS: 20%) and other studies (RFS: 69-97%; MFS: 3-24%; FFS: 2-31%) (Hasegawa, Yamauchi and Kraemer, 2007; Larson *et al.*, 2011b; Daoud *et al.*, 2012; Mann *et al.*, 2015; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020). In consequence, the findings of Goss and Gross, (2012) may be somewhat erroneous. In contrast to self-reporting methods, there is high correlation between all other measures of FST assessment with R values of 0.92-0.94 (Altman and Davis, 2012; Mann *et al.*, 2014) and an ICC value of 0.97 between SI (as determined through pressure sensitive insoles (Mann *et al.*, 2014) and force plate analysis (Altman and Davis, 2012)) and FCA (as determined through 3D motion analysis (Altman and Davis, 2012; Mann *et al.*, 2014)). Moreover, it has been demonstrated that sagittal plane video recording, which is the most inexpensive method, has excellent accuracy (91% accuracy) in determining FSP when compared with both 3D motion analysis and pressure sensitive insoles (Meyer *et al.*, 2018).

Regarding testing conditions, most studies analysed ≤ 5 foot strikes (Donoghue *et al.*, 2008; Daoud *et al.*, 2012; Warr *et al.*, 2015; Kuhman *et al.*, 2016b; Dudley *et al.*, 2017; Paquette, Milner and Melcher, 2017; Messier *et al.*, 2018; Fukusawa, Stoddard and Lopes, 2020). Given that within-subject FCA variation can be up to 21º throughout a run, and 56% of runners may demonstrate a combination of RFS, MFS and FFS patterns during the same run (Lieberman *et al.*, 2015), analysing ≤ 5 foot strikes may result in atypical FSTs being selected as representative.

Other testing conditions which varied across studies included surface and running speed. It has been reported that surface stiffness can affect FST, with harder surfaces encouraging a non-RFS technique (Lieberman *et al.*, 2015). Additionally, speed may influence FST, with RFS more commonly associated with slower speeds (Forrester and Townend, 2015; Mann *et al.*, 2015). With some studies using self-selected speeds and others using predetermined speeds, comparison of results across studies is challenging. While there are too few studies to discuss whether surface conditions and running speed have an effect on examining the relationship between FST and RRI, there is clearly a need for consensus on FST analysis. This is especially pertinent for determining the best methods for assessing: (i) FST, (ii) the minimum number of foot strikes needed to best reflect the runners' most representative FST, and (iii) whether the reporting of FST should be categorical (i.e. FSP) or in its absolute continuous form (i.e. FCA, AFA and SI). Unfortunately, no studies have directly compared the aforementioned approaches on the same data set.

Another methodological difference between studies was the definition of injury. Whilst some RRIs were reflective of a restriction in performance for one full session (Dudley *et al.*, 2017), other RRIs required this restriction in performance to last at least one week (Goss and Gross, 2012; Mann *et al.*, 2015; Warr *et al.*, 2015; Dingenen *et al.*, 2019). This variance in injury definition poses a challenge when cross-comparing or pooling study results. In addition, given the evidence that loading on specific tissues and structures varies with FSP (i.e. RFS: greater tibiofemoral load and patellofemoral compression force (Willson *et al.*, 2015; Bowersock *et al.*, 2017); FFS: greater load on plantar-flexor muscles and Achilles tendon (Goss, 2012; Kulmala *et al.*, 2013; Hamill and Gruber, 2017)), it may not be optimal to investigate RRIs collectively, but rather investigations should be based on pathology. Comparison of FST with a general binominal overuse injury outcome (i.e. injured or uninjured) does not account for the implications of injury severity of specific pathologies. Whilst the analysis of specific injury sites (e.g. knee, calf, shin) assists in our understanding of where the body was overloaded, consideration of the exact pathology may be more insightful in determining the clinical relevance of a potential relationship between FST and RRI. For example, common pathologies affecting runners at the shin might include medial tibial stress syndrome (MTSS) or a tibial stress fracture (Gallo, Plakke and Silvis, 2012). Both of these pathologies have resulted due to excessive load at the site of the tibia, but would have significantly different severities in terms of time-loss and healthcare provisions (Gallo, Plakke and Silvis, 2012). Although some recent research has demonstrated analysis of FST and specific sites of injury (Dingenen *et al.*, 2019; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020), only one study in this review explored how FST may relate to specific pathologies (Daoud *et al.*, 2012), but may not have had sufficient power to find significant relationships.

These findings are in agreement with the conclusions of a non-systematic narrative review regarding the concepts, classifications and implications for FST and RRIs by Hoenig, Rolvien and Hollander, (2020) who suggested that relationships between FST and RRIs are mostly unclear at present and thus should be considered critically. Although the review by Hoenig, Rolvien and Hollander, (2020) is descriptive as opposed to the systematic approach taken in this review, the authors identify similar limitations from scoping the literature such as the lack of standardized methodologies and definitions relating to FST. Despite taking a more narrative approach, the authors note that foot strike pattern may increase the risk of some RRIs (RFS runners might experience more knee injuries, while MFS/FFS runners might experience ankle and foot injuries) (Hoenig, Rolvien and Hollander, 2020), but the basis of this evidence is indirect as it stems from studies comparing the kinetics and kinematics of various FSPs, rather than directly comparing injuries between RFS, MFS and FFS runners. Similar to the conclusion of our review, this highlights the need for more research looking at the relationship between FST and specific injury pathologies.

Limitations of the Studies

Limitations of the reviewed studies, which were initially identified in the risk of bias assessment, include: examiners not being blinded to the outcome, a lack of power calculation in determining the required sample size for a clinical effect, and poor reporting and/or control of potential confounding factors (e.g. years running experience, workload ratios, other physical training stress experienced in military groups) for RRIs (Supplemental Table 4). The majority of studies also had low sample sizes and may not have been sufficiently powered for detection of significance. In addition, studies did not always explore interaction effects between FST and other potential injury causing factors. Given that RRIs are multifactorial in nature (Dudley *et al.*, 2017; Messier *et al.*, 2018), and these aetiological factors can be inter-dependent, exploration of all potential confounding factors should be undertaken, especially in groups such as military and collegiate runners who may have significant inter-dependent RRI risk factors (e.g. training volume, training frequency, training load/additional weight carriage). Another limitation of the studies is the diversity of methodologies and outcome measures utilised, impeding cross-comparison of studies and synthesis of findings, particularly with respect to the definition of injury and FST analysis. Additionally, there appears to be a lack of analysis on specific RRIs and their relationship with FST, potentially limiting our understanding of how FST and specific injury pathologies relate. Imprecision of study results and indirectness of study methodologies featured as common pitfalls in the GRADE assessment, highlighting the need for more rigorous and sophisticated methods, with better standards of analysis required (e.g. reporting confidence intervals and relative effects). With respect to FST assessment, whilst 3D motion and force plate analysis, sagittal plane video recordings and pressure sensitive insoles all demonstrate valid and reliable FST assessments, direct comparison of categorical and continuous measures of FST is impossible. Additionally, the number of foot strikes assessed was quite low.

Finally, one very significant limitation was the predominance of retrospective case-control study designs. It cannot be determined whether or not the retrospective findings relating FST to RRI are actually a cause or an effect of the injury. In particular, it is worth noting that none of the foot strike pattern studies (Daoud *et al.*, 2012; Goss and Gross, 2012; Warr *et al.*, 2015; Sugimoto *et al.*, 2019; Fukusawa, Stoddard and Lopes, 2020; Hollander *et al.*, 2020) were prospective, thus the necessity for more large-scale prospective analysis on FST and its relationship with RRIs is warranted.

Limitations of this review

This study was limited to a narrative analysis given the wide heterogeneity of study methodologies and outcome measures reported. Whilst all included studies investigated a form of FST and RRIs, this exploration may not have been the intended aim of all studies, and thus there were difficulties with extracting and synthesising the results, preventing the completion of a meta-analysis.

Conclusion

There is a very low level of evidence to suggest a relationship between FST and RRIs. While two thirds of categorical studies did find a relationship between FSP and RRI, these studies are limited by very low quality such as retrospective case-control study design low sample sizes and the use of potentially inaccurate self-reporting methodologies.

Therefore, more large-scale prospective studies with sufficient power are required. Studies looking at the relationship between FST and RRIs should consider other known confounding factors that relate to injury (e.g. training load, years' experience, previous injury history), and conduct adequate statistical analysis allowing for multi-factorial analyses where necessary. Standardization of FST is required and both categorical and continuous measures should be reported where possible, along with determining the number of foot strikes necessary to represent the FST of a runner. Moreover, additional statistical analysis should be undertaken to investigate the effect of FST and specific RRI pathologies (e.g. patellofemoral pain syndrome, tibial stress fractures, Achilles tendinopathy) rather than solely exploring RRIs collectively.

Supplementary material for publication

Supplemental Table A1. Search Terms Used

Population	"running" OR "runners"
	AND
Outcome	"injury" OR "injuries" OR "injured"
	AND
Variables	"rearfoot" OR "rear-foot" OR "midfoot" OR "mid-foot" OR "forefoot" OR "fore-foot" OR "foot contact angle" OR "foot angle" OR "foot strike pattern" OR "foot strike angle" OR "foot impact angle" OR "strike index"

Supplemental Table A2. Inclusion and Exclusion Criteria

Inclusion
Studies which have researched running populations (novice, recreational, military and collegiate levels).
Studies which have looked at foot strike pattern at initial contact, foot contact angles or strike index at impact during running trials.
Studies which have explored running-related injuries and how the kinematics of the foot affect this.
Studies which compared injured participants to controls.
Studies written in the English language.
Studies which are fully published papers/journal articles.
Exclusion
Studies which have researched cohorts that are not exclusively runners.
Studies which examined upper limb musculoskeletal running injuries.
Studies that are not written in the English language.
Studies that have been published as conference proceedings or abstracts.
Studies that are opinion articles.

Supplemental Table A3. Risk-of-Bias Assessment*

Risk of Bias Assessment (Almeida, 2015)

Criteria	Description
1. Aim clearly described	The aim/hypothesis/objective is clearly described
2. Outcomes described	The main outcomes to be measured are clearly described in the introduction or methods section
3. Subjects clearly described	The characteristics of the subjects included in the trial are clearly described. If running experience was deemed insufficiently described, this was answered no
4. Interventions clearly described	Each intervention to be completed is clearly described
5. Distribution of confounders described	Confounding factors are clearly described. Confounders to be considered include subject's sex, age, weight, running experience, running speed, and foot strike
6. Main findings clearly described	Simple outcome data are reported for all major findings so the reader can check the major analysis and conclusions
7. Estimates of random variability in data	In non-normally distributed data, the interquartile range of results should be reported. In normally distributed data, standard deviations or confidence intervals should be reported
8. All important adverse events reported	The study demonstrates a comprehensive attempt to record all adverse events. This could include discomfort associated with any running condition or delayed onset of muscle soreness
9. Actual probability values reported	Actual probability values (e.g., not $p<0.05$) have been reported for the main outcomes, except where the probability value is less than .001
10. Subjects asked are representative of the population	The source population for subjects and how they were selected are described. Subjects would be representative if they comprised the entire population, an unselected sample of consecutive subjects, or a random sample. Where the study does not report the proportion of the source population from which the subjects are derived, the answer is no
11. Subjects representative of population	The subjects prepared to participate are representative of the entire population from which they were recruited. Validation that the sample was representative would include demonstrating that the distribution of confounding factors was the same in the study sample and the source population
12. Examiners blinded	There was an attempt to blind those measuring the main outcomes
13. Data dredging	Any analysis that had not been planned at the outset of the study is clearly described. If no retrospective unplanned subgroup analysis is reported, the answer is yes
14. Appropriate statistical tests	The statistical tests used to assess the main outcomes are appropriate
15. Valid and reliable main outcome measures	For studies where the outcome measures are clearly described, the answer is yes. For studies that refer to other work or that demonstrate the outcome measures are accurate, the answer is yes

16. Subjects recruited from same population	The subjects in different intervention groups were recruited from the same population. If the subjects acted as their own control, this was answered yes
17. Subjects recruited over same time period	The subjects in different intervention groups were recruited over the same time period. If the subjects acted as their own control, this was answered yes
18. Intervention order randomised	The order of the intervention tested was randomized
19. Adequate adjustment for confounding	There was adequate adjustment for confounding in the analysis from which the main findings were drawn. If the effect of the main confounders was not investigated or confounding was demonstrated but no adjustment was made in the final analysis, this was answered no
20. Sufficient power	If the study reported a power calculation, this was answered yes

Questions 1-17, 19 and 20 were used to assess risk of bias in the primary review (Relationship between foot strike technique and RRI). Questions 1-20 were used to assess risk of bias in the secondary review (Effect of foot strike technique intervention on risk of RRI).

Supplemental Table A4. Quality assessment of studies included in the primary review (Foot strike technique and running-related injuries)

Question	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***Total***
Retrospective Studies																				
Donoghue et al[12]	1	1	1	1	0	1	1	1	1	0	0	0	1	1	1	0	0	0	0	11
Goss and Gross[19]	1	1	1	1	1	0	1	1	1	0	0	0	1	1	0	1	1	0	0	12
Daoud et al[10]	1	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	0	15
Mann et al[37]	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	17
Warr et al[55]	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	0	0	15
Paquette et al[47]	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	0	0	1	13
Prospective Studies																				
Kuhman et al[29]	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	16
Dudley et al[14]	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	17
Messier et al[42]	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	17

Modified Risk of Bias Assessment Questions: 1:Aim clearly described; 2: Outcomes described; 3: Subjects clearly described; 4: Interventions clearly described; 5: Distribution of confounders clearly described; 6: Main findings clearly described; 7: Estimates of random variability in data; 8: All important adverse events reported; 9: Actual probability values reported; 10: Subjects asked are representative of population; 11: Subjects representative of population; 12: Examiners blinded; 13: Data dredging; 14: Appropriate statistical tests; 15: Valid and reliable main outcome measures; 16: Subjects recruited from same population 17: Subjects recruited over same time period; 18: Adequate adjustment for confounding; 19: Sufficient power.

Supplemental Table A5. Summary of Study Characteristics

Study Characteristics			Participant Characteristics							Testing Characteristics		
Author and year of publication	**Sample size and duration of injury surveillance**	**Definition of injury**	**Running group**	**Age (yrs)**	**Sex (%)**	**BMI (kg/m^2)**	**FSP Prevalence**	**No. included/ analysed (% included)**	**No. injured : No. uninjured**	**Surface**	**Speed**	**Foot strike classification**
Prospective												
Dudley *et al.*[18]	n = 31. 1 collegiate cross-country season	"Any musculoskeletal complaint of the lower extremities or back causing the restriction of participation in one full practice session".	Collegiate cross-country	20	M: 48% F: 52%	N/R	N/A	32/31 (97%)	12 : 19	Overground in lab	SSS (Mean test speed: 3.9m/s)	FCA: 3D motion capture analysis (5 foot strikes) Not categorized into FSP
Kuhman *et al.*[36]	n = 19. 1 collegiate cross-country season	N/R	Collegiate cross-country	20 ± 2	M: 58% F: 42%	20.3 ± 1.2	N/A	19/24 (79%)	10 : 9	Overground in lab	4.0-4.5m/s	SI: Force plate (5 foot strikes) Not categorized into FSP
Messier *et al.*[48]	n = 300. 2 years	"Grade 1: maintaining full activity in spite of symptoms; Grade 2: reducing weekly mileage and; Grade 3: interrupting all training for at least 2 weeks".	Recreational	41 ± 10	M: 57% F: 43%	24.2 ± 3.4	N/A	300/300 (100%)	199 :101	Overground in lab	SSS (Mean test speed: N/R)	SI: Force plate (3 foot strikes) Not categorized into FSP
Retrospective												
Daoud *et al.*[11] 2012	n = 52. 5 collegiate cross-country seasons	"Full: athlete continues running without restrictions; >50%: athlete runs at a reduced intensity or distance, greater than half of normal training; <50%: athlete runs at a reduced intensity or distance, less than half of normal training; Cross-training: athlete is not running, but is cross-training; Off: athlete is either running nor cross-training".	Collegiate cross-country	19 ± 1	M: 56% F: 44%	20.5 ± 1.5	RFS: 69% MFS: 0% FFS: 31%	52/52 (100%)	N/R	Treadmill and Outdoor track	Treadmill: 3-5m/s, Outdoor: SSS	FSP: Video camera (3 foot strikes) FSP Categorization: Visual^

Goss and Gross[23] 2012	n = 881. 1 year	"Something that caused you to modify your training schedule for at least 1 week due to pain or discomfort (with or without medical care)".	Recreational, collegiate and military	38 ± 9	M: 50% F: 50%	N/R	RFS: 31% MFS: 43% FFS: 20% Unsure: 6%	904/881 (97%)	881 : 0	N/A	N/A	FSP: Self-reported (foot strikes N/R) FSP Categorization: N/R
Warr *et al.*[67] 2015	n = 341. 5 years and over a lifetime	"Any injury over the course of the participants life that caused them to modify their training schedule for at least 1 week due to pain or discomfort (with or without formal medical care)".	Military	25 ± 5	M: 100% F: 0%	N/R	RFS: 87% MFS: 9% FFS: 4%	341/341 (100%)	138 : 203	Outdoor runway	Pace of a 2 mile run event (Mean test speed: 3.6m/s)	FSP: video camera (2 foot strikes) FSP Categorization: Visual^
Hollander *et al.*,[32] 2021	n = 550. 7 years	"Any musculoskeletal pain (i.e. muscles, bones, tendons, ligaments) to the lower body that required medical attention". Lower back injuries were also included.	Recreational and Competitive	37 ± 13	M: 50% F: 50%	23.3 ± 3.0	RFS: 71% MFS: 10% FFS: 19%	550/550 (100%)	550 : 0	Treadmill	SSS (Mean test speed: 2.1m/s)	FSP: video camera (10 foot strikes) FSP Categorization: Visual^
Fukusawa *et al.*,[21] 2020	n = 122. N/R	"Presence of diffuse and intermittent pain on the anterior part of the knee for at least 3 months."	Recreational	37 ± 10	M: 70% F:30%	24.6 ± 2.6	RFS: 95% Non-RFS: 5%	122/124 (98%)	60 : 62	Outdoor runway	SSS (Mean test speed: 2.6m/s)	FSP: video camera (5 foot strikes) FSP Categorization: Visual Categories not defined in manuscript text
Sugimoto *et al.*,[62] 2019	n = 70. 5 years	Diagnosis of a hamstring strain which occurred during running, diagnosed by physical examination and MRI.	N/R	29 ± 13	M: 34% F: 66%	21.8 ± 2.6	RFS: 59% MFS: 20% FFS: 51%	71/70 (100%)	35 : 35	Treadmill	PDS between 1.8 – 2.3m/s	FSP: video camera (10 – 60 seconds) FSP Categorization: Visual^
Donoghue *et al.*[15] 2008	n = 22. 1 year	Presence of chronic Achilles tendon injury	Recreational	42 ± 8	M: 91% F: 9%	N/R	N/R	22/22 (100%)	11 : 11	Treadmill	SSS (Mean test speed: 2.7m/s)	AFA: 3D motion capture analysis (5 foot strikes) FSP Categorization: N/R

Paquette *et al*.[53] 2017	n = 44. 1 year	N/R	Recreational	29 ± 8	M: 55% F: 45%	22.4 ± 2.4	RFS: 36% Non-RFS: 64%	44/44 (100%)	23 : 21	Treadmill	75% of their 10km PB pace (Mean test speed: RFS 3.4m/s, Non-RFS 2.8m/s)*	FCA: 3D motion capture analysis (5 foot strikes) FSP Categorization: N/R
Dingenen *et al*.,[14] 2019	n = 42 2 years	"Presence of a current running-related knee injury, which caused a restriction of or cessation of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, and that required the runner to consult a physician or other health professional."	Recreational	31 ± 8	M: 29% F: 71%	22.4 ± 2.2	N/R	42/42 (100%)	18 : 24	Treadmill	SSS (Mean test speed: 2.8m/s)	FCA: video camera (7 foot strikes) Not categorized into FSP
Mann *et al*.[45] 2015	n = 90. 1 year	"A physical pain or complaint altering or interrupting running activity for at least 1 week, affecting the lower extremities and progressive in nature".	Recreational	41 ± 9	M: 73% F: 27%	22.9 ± 2.3	RFS: 93% Non-RFS: 7%	90/90 (100%)	44 : 46	Treadmill	SSS (Mean test speed: 3.0m/s)	SI: Pressure sensitive insoles (161 ± 12 foot strikes) FSP Categorization: N/R

*Values are presented as mean ± standard deviation unless otherwise specified; yrs: years; SSS: self-selected speed; PDS: pre-determined speed; n: number of participants; kg/m^2: kilogram per metre squared; FSP: foot strike pattern; m/s: metres per second; N/R: not reported; 3D: 3 dimensional; AFA: ankle flexion angle; FCA: foot contact angle; SI: strike index; RFS: rear-foot strike; MFS: mid-foot strike; FFS: fore-foot strike; Non-RFS: Non-rear-foot strike; km: kilometre; PB: personal best; *Testing speeds significantly different between RFS and Non-RFS runners: N/A: not applicable; Visual^: foot strike pattern categorized visually based on the following descriptions – rearfoot strike was when the rear part of the foot (or heel) made contact with the ground or treadmill first, midfoot strike was when there was simultaneous contact of the heel and toes together, forefoot strike was when the toes contacted the ground or treadmill first, and non-rearfoot strike was when there was simultaneous landing of the heel and toes together, or if the toes contacted the ground or treadmill first.*

Appendix B

RISC Study Survey utilized in thesis

Section A - Demographics
Q.1. What is your unique ID number?
Open-ended response.

Q.2. What age are you?
Open-ended response [Numerical].

Q.3. Please select your gender.
- *Male*
- *Female*
- *Prefer not to say*

Section B - Training
Q.4. Do you attend any exercise classes? Please tick all that apply.
- *Yoga*
- *Pilates*
- *Aerobics*
- *Dance/Zumba*
- *Spinning*
- *Altitude Chamber*
- *Boxercise*
- *HIIT (High Intensity Interval Training)*
- *S&C (Strength & Conditioning)*
- *TRX*
- *CrossFit*
- *Swimming*
- *MMA*
- *Other (Please specify)*
- *No I don't attend exercise classes*

Q.4. (a) How many times per week do you attend exercise classes?
- *1 time per week*
- *2 times per week*
- *3 times per week*
- *4 times per week*
- *5 times per week*
- *6 times per week*
- *7 times per week*
- *7+ times per week*

Q.5. Do you regularly go to the gym? Please tick no if you go to the gym for the purpose of group exercise classes.
- *Yes, 1-2 times per week*

- ☐ *Yes, 3-4 times per week*
- ☐ *Yes, 5-7 times per week*
- ☐ *No, I don't go to the gym*

Q.5. (a) What does a typical gym session consist of for you? Please tick all that apply.

- ☐ *Cardiovascular (e.g. Rowing, Cross Trainer, Swimming, Bike)*
- ☐ *Strength (e.g. Free Weights, Weight Machines)*
- ☐ *Flexibility (e.g. Stretching)*
- ☐ *Plyometrics (e.g. Hops, Jumps, Box Jumps)*
- ☐ *Other (Please specify)*

Q.6. Since you first started running training, what is the total amount of years that you have trained? (Please do not include years when you did not train regularly e.g. taking a year out).

- ☐ *6-12 months*
- ☐ *1-2 years*
- ☐ *3-5 years*
- ☐ *6-10 years*
- ☐ *11-15 years*
- ☐ *15+ years*

Q.7. Do you run throughout the year or on a seasonal basis?

- ☐ *Throughout the year*
- ☐ *Seasonal basis*

Q.7. (a) If you ticked "seasonal basis", how many months of the year do you run?

- ☐ *1 month*
- ☐ *2 months*
- ☐ *3 months*
- ☐ *4 months*
- ☐ *5 months*
- ☐ *6 months*
- ☐ *7 months*
- ☐ *8 months*
- ☐ *9 months*
- ☐ *10 months*
- ☐ *11 months*

Q.8. What is the purpose of running for you? Please tick all that apply.

- ☐ *Fitness*
- ☐ *Physique*
- ☐ *Enjoyment*
- ☐ *Mental health*
- ☐ *Train for competition*
- ☐ *To accomplish a personal goal*
- ☐ *Social interaction*
- ☐ *Convenience*

- ☐ *Other (Please specify)*

Q.8. (a) Please rank in order of importance the purpose of running for you. e.g. 1= primary purpose.
Select number from drop-down menu beside each respective motivation.
Q.9. Do you have any running related events that you are currently training for or that you plan to train for within the next year? Please tick all that apply.

- ☐ *5km*
- ☐ *10km*
- ☐ *Mini-marathon*
- ☐ *10 mile*
- ☐ *Half-marathon*
- ☐ *¾ marathon*
- ☐ *Marathon*
- ☐ *Ultra-marathon*
- ☐ *Ironman*
- ☐ *Duathlon*
- ☐ *Triathlon*
- ☐ *Cross-country*
- ☐ *Adventure race*
- ☐ *Trail/Mountain race*
- ☐ *Organised track and field event*
- ☐ *Other (Please specify)*
- ☐ *I am not training for a running related event*

Q.10. On average, how many times per week do you run?

- ☐ *1 time per week*
- ☐ *2 times per week*
- ☐ *3 times per week*
- ☐ *4 times per week*
- ☐ *5 times per week*
- ☐ *6 times per week*
- ☐ *7 times per week*
- ☐ *7+ times per week*

Q.11. At present, what distance (kilometres) per week do you run?
Open-ended response [Numerical].
Q.12. How many kilometres collectively have you ran over the course of the last three months?
Open-ended response [Numerical].
Q.13. What is your average running pace? (km/hr) If you are unsure, please refer to pace graph provided.
Open-ended response [Numerical].
Q.14. Do you regularly increase the intensity of running training week to week?

- ☐ *Yes*
- ☐ *No*
- ☐ *I am unsure*

Q.14. (a) How do you increase the intensity of running training from week to week? Please tick all that apply.

- *Increase distance*
- *Increase pace*
- *Increase the number of running sessions*
- *Change gradient*
- *Do tempo runs*
- *Other (Please specify)*

Q.15. Do you include any of the following sessions as part of your running training? Please tick all that apply.

- *Interval training*
- *Speed work*
- *Hill running*
- *Fartlek*
- *Other (Please specify)*

Q.16. What surface do you run on most often? If you run on multiple surfaces for an equal number of sessions, please tick those that apply.

- *Road*
- *Grass*
- *Footpath*
- *Track*
- *Sand*
- *Treadmill*
- *Astroturf*
- *Other (Please specify)*

Q.17. How often do you change running shoes?

- *Every 0-3 months*
- *Every 4-6 months*
- *Every 7-12 months*
- *Every 12+ months*

Q.18. Do you wear insoles or insole devices in your running shoes? (Arch support, heel lift, etc.)

- *Yes, they were prescribed to me*
- *Yes, I bought them in a shop*
- *Yes, my shoes are manufactured with a specific arch support/shock absorption feature*
- *No, I don't wear insoles or insole devices*
- *I am unsure*

Q.19. Do you apply any strapping/taping/braces/supports before going for a run? (Please do not include orthotic devices/insoles).

- *Yes, always*
- *Yes, sometimes*
- *No, I don't apply strapping/taping/braces/supports*

- I am unsure

Q.19. (a) What location of the body do you apply strapping/taping/support/brace to? Please tick all that apply.

- *Lower back*
- *Sacroiliac joint*
- *Hip*
- *Inner thigh*
- *Buttock*
- *Front of thigh*
- *Back of thigh*
- *Outer thigh*
- *Knee*
- *Shin*
- *Calf*
- *Ankle*
- *Foot*
- *Heel*
- *Toes*

Q.20. Do you currently have any persistent or nagging pain or complaint in your lower back/lower limbs that you experience while running but does not restrict your training?

- *Yes*
- *No*
- *I am unsure*

Q.20. (a) Please give details of this persistent pain (e.g. you may describe the location, type, severity, duration, etc.).
Open-ended response [Text].
Q.21. Delayed Onset of Muscle Soreness (DOMS) is a muscular pain/ache following a session of increased intensity or unfamiliar activity. The soreness typically lasts 24-72 hours. Do you experience DOMS?

- *Yes, typically once a week*
- *Yes, typically once a fortnight*
- *Yes, typically once a month*
- *Yes, typically multiple times per year*
- *No, I do not experience DOMS*
- *I am unsure*

Q.22. Do you usually warm up before a running session?

- *Yes, always*
- *Yes, sometimes*
- *No, I do not usually warm-up*
- *I am unsure*

Q.22. (a) What does your warm up consist of? Please tick all that apply.

- *Static stretch*
- *Dynamic stretch*

- Cardiovascular
- Foam rolling
- Plyometrics
- Joint mobility
- Other (Please specify)

Q.23. Do you usually warm down/cool down after a running session?

- *Yes, always*
- *Yes, sometimes*
- *No, I do not usually warm-up*
- *I am unsure*

Q.23. (a) What does your warm down/cool down normally consist of? Please tick all that apply.

- *Static stretch*
- *Dynamic stretch*
- *Cardiovascular*
- *Foam rolling*
- *Massage*
- *Swimming*
- *Other (Please specify)*

Q.24. Do you include any recovery sessions as part of your training? A recovery session is a planned session where the objective is to re-establish an optimal state for training (e.g. rest, massage, light cardio, baths).

- *Yes, always*
- *Yes, sometimes*
- *No, I do not usually warm-up*
- *I am unsure*

Q.24. (a) Which of the following are included in your recovery session? Please tick all that apply.

- *Rest*
- *Foam rolling*
- *Stretching*
- *Light run*
- *Cycle*
- *Swim*
- *Cryotherapy*
- *Hot baths*
- *Massage*
- *Light resistance training*
- *Other (Please specify)*

Section C – Running-related Injury

Q.25. Have you ever experienced a running- related injury? (A running related injury is any muscle, bone tendon or ligament pain that caused you to stop running/restricted your running (either your speed, distance or duration) and lasted 7 days or three consecutive training sessions/ required you to seek a physician or health care practitioner.)

- *Yes*
- *No*
- *I am unsure*

Q.26. Have you had any previous running related injuries in the past 2 years? A running-related injury is any muscle, bone, tendon or ligament pain in the lower back/legs/knee/foot/ankle that caused you to stop running/ restricted your running (either your distance, speed, duration or training)

AND

i. lasted at least 7 days or 3 consecutive scheduled training sessions

OR

ii. required you to consult a physician or other health care professional.

- *Yes, I had a lower back/lower limb running-related injury that lasted at least 7 days or 3 scheduled training sessions (i).*
- *Yes, I had a lower back/lower limb running-related injury that required me to consult a physician or other healthcare professional (ii).*
- *Yes, I had a lower back/lower limb running-related injury that lasted at least 7 days or 3 scheduled training sessions (i)* ***AND*** *that required me to consult a physician or other healthcare professional (ii).*
- *No, I have not has any lower back/lower limb running-related injury in the past 2 years.*
- *I am unsure.*

Q.26. (a) How many lower back/lower limb running-related injuries have you had in the past 2 years?

- *1 running-related injury*
- *2 running-related injuries*
- *3 running-related injuries*
- *4 running-related injuries*
- *5 running-related injuries*
- *5+ running-related injuries*

Q.26. (a)(i) Thinking of one of these back/lower limb running-related injuries in the past 2 years please select the location of the body that you had this injury.

- *Lower back*
- *Sacroiliac joint*
- *Hip*
- *Inner thigh*
- *Buttock*
- *Front of thigh*
- *Back of thigh*
- *Outer thigh*
- *Knee*
- *Shin*

- *Calf*
- *Ankle*
- *Foot*
- *Heel*
- *Toes*

Q.26. (a)(ii) What month did this injury occur?
Select month from drop-down menu.
Q.26. (a)(iii) What year did this injury occur?
Select year from drop-down menu.
Q.26. (a)(iv) Still thinking of this injury, what type of injury was it?

- *Cut/Graze*
- *Contusion/Bruise*
- *Ligament tear/Sprain (e.g. twisted ankle)*
- *Subluxation/Dislocation*
- *Broken bone/Fracture (****NOT** a stress fracture)*
- *Cartilage/Meniscus/Labrum injury*
- *Stress fracture*
- *Muscle strain/tear/rupture*
- *Tendon injury*
- *Nerve injury*
- *Shin splints type pain (****NOT** a stress fracture)*
- *Bursitis*
- *Fat pad aggravation*
- *Blisters*
- *Other (Please specify)*

Q.26. (a)(v) Still thinking of this injury, did you miss any training because of it?

- *No, I did not miss training*
- *Yes, I missed less than 7 days*
- *Yes, I missed between 7 and 28 days*
- *Yes, I missed between 1 and 6 months*
- *Yes, I missed more than 6 months*
- *I am unsure*
- *Other (Please specify)*

Q.26. (a)(vi) Still thinking of this injury, did you require any medical advice? Please tick all that apply.

- *No, I did not require any medical advice*
- *Yes, I got medical advice from an internet resource*
- *Yes, I received medical advice from my coach*
- *Yes, I received medical advice from my GP/doctor*
- *Yes, I received medical advice from a medical professional (Chartered Physiotherapist, Certified Athletic Therapist, Physical Therapist, Chiropractor, Osteopath)*
- *I had to go to A&E*

- *I received medical advice from a family member or fried who is not a medical professional*

Q.26. (a)(vii) Still thinking of this injury, did you complete a rehabilitation programme after the injury? A rehabilitation programme usually involves completing a set of exercises that have been specifically tailored to your injury.

- Yes, I was given once by a medical professional *(Doctor, Chartered Physiotherapist, Certified Athletic Therapist, Physical Therapist, Chiropractor, Osteopath)*
- *Yes, I rehabilitated the injury myself*
- *No, I did not need a rehabilitation programme*
- *I am unsure*
- *Other (Please specify)*

Q.26. (a)(viii) Still thinking of this injury, do you feel you have recovered fully from this injury?

- *Yes*
- *No*
- *I am unsure*

Q.26. (a)(ix) Still thinking of this injury, has there been any exacerbation or re-injury of this in the past 2 years? Exacerbation refers to the worsening of your initial injury before it was fully recovered. Re-injury refers to a recurring injury after your initial injury had recovered.

- *Yes, I had a re-injury at the same location and of the same type*
- *Yes, I have had an exacerbation at the same location and of the same type*
- *Yes, I had a re-injury at the same location and of a different type*
- *Yes, I have had an exacerbation at the same location and of a different type*
- *I am unsure*
- *No, I have not had any exacerbations or re-injuries*

Q.26. (a)(ix)(1) How soon after the initial injury did the exacerbation occur?

- *Within 2 months*
- *Between 2 and 12 months*
- *Between 12 and 24 months*
- *I am unsure*

Q.26. (a)(ix)(2) How soon after the initial injury did the re-injury occur?

- *Within 2 months*
- *Between 2 and 12 months*
- *Between 12 and 24 months*
- *I am unsure*

Appendix C

Supplementary information for Aetiological factors of running-related injuries: A 12 month prospective "Running Injury Surveillance Centre" (RISC) Study

Supplemental Table C1. Kinetic and Kinematic Variable Means and Standard Deviation, with Independent T-Test and Univariate Cox Regression Findings.

	Injured Mean ± SD	Uninjured Mean ± SD	Injured v Uninjured P value	Unadjusted HR	95% CI Lower to Upper	P value	Adjusted HR	95% CI Lower to Upper	P value
Demographics									
Age (years)	43.5 ± 8.3	43.1 ± 9.5	0.74	1.00	0.98 to 1.02	0.98			
Weight (m)	72.2 ± 12.8	73.5 ± 13.4	0.41	0.99	0.98 to 1.01	0.38	0.99	0.97 to 1.00	0.11
Height (kg)	1.7 ± 0.1	1.7 ± 0.1	0.72	0.69	0.11 to 4.19	0.68	0.25	0.18 to 3.44	0.30
BMI (kg/m^2)	24.0 ± 2.9	24.3 ± 3.1	0.39	0.97	0.92 to 1.03	0.36	0.96	0.90 to 1.03	0.24
Average training speed (km/hr)	11.6 ± 1.6	11.3 ± 1.8	0.24	1.06	0.96 to 1.16	0.27	1.06	0.96 to 1.17	0.28
Annual quarterly mileage (km)	420.6 ± 279.6	422.1 ± 289.3	0.97	1.00	1.00 to 1.00	0.77			
Impact Acceleration									
Tibia $Peak_{accel}$ (g)	5.9 ± 2.5	5.7 ± 2.3	0.46	1.03	0.96 to 1.10	0.43	1.03	0.96 to 1.11	0.44
Tibia $Rate_{accel}$ (g/s)	317.4 ± 233.7	301.4 ± 231.3	0.59	1.00	1.00 to 1.00	0.56	1.00	1.00 to 1.00	0.55
Sacrum $Peak_{accel}$ (g)	5.1 ± 2.6	4.8 ± 2.4	0.41	1.04	0.97 to 1.11	0.30	1.03	0.96 to 1.11	0.44
Sacrum $Rate_{accel}$ (g/s)	494.6 ± 321.2	487.7 ± 288.7	0.86	1.00	1.00 to 1.00	0.84	1.00	1.00 to 1.00	0.79
Kinematics									
Initial Contact (°)									
Foot Dorsiflexion	10.4 ± 6.2	11.2 ± 6.4	0.28	0.99	0.96 to 1.01	0.31	0.99	0.96 to 1.02	0.43
Ankle Eversion	1.8 ± 2.3	1.7 ± 1.9	0.65	1.04	0.95 to 1.13	0.42	1.04	0.94 to 1.14	0.47

Ankle Dorsiflexion	9.0 ± 5.1	8.9 ± 5.2	0.85	1.00	0.97 to 1.04	0.89	1.01	0.97 to 1.05	0.72
Ankle External Rotation	-7.0 ± 9.2	-6.5 ± 7.6	0.65	0.99	0.97 to 1.01	0.46	0.99	0.97 to 1.02	0.58
Knee Valgus	-1.6 ± 2.9	-2.6 ± 2.8	0.01*	1.09	1.03 to 1.16	0.00*	1.10	1.03 to 1.17	0.00*
Knee Flexion	18.0 ± 4.4	17.0 ± 4.3	0.11	1.03	0.99 to 1.07	0.19	1.02	0.98 to 1.07	0.34
Knee Internal Rotation	5.1 ± 6.5	4.2 ± 7.1	0.30	1.02	0.99 to 1.04	0.23	1.02	0.99 to 1.04	0.29
Hip Adduction	8.8 ± 3.4	9.7 ± 4.0	0.06	0.96	0.91 to 1.00	0.06	0.95	0.90 to 1.00	0.03*
Hip Flexion	34.6 ± 6.2	34.7 ± 6.1	0.82	1.00	0.97 to 1.03	0.79	0.99	0.97 to 1.02	0.71
Hip Rotation (+ Internal Rotation; - External Rotation)	-0.9 ± 6.5	-1.2 ± 7.0	0.68	1.01	0.98 to 1.03	0.64	1.01	0.98 to 1.04	0.53
Pelvic Drop to Contralateral Side	1.7 ± 2.2	2.1 ± 2.7	0.19	0.96	0.89 to 1.03	0.25	0.95	0.89 to 1.03	0.19
Anterior Pelvic Tilt	14.3 ± 5.0	14.5 ± 5.6	0.69	0.99	0.96 to 1.03	0.72	0.99	0.96 to 1.03	0.74
Pelvis Rotation to Ipsilateral Side	-3.4 ± 4.0	-3.6 ± 3.5	0.71	1.02	0.97 to 1.07	0.57	1.01	0.96 to 1.07	0.70
Thorax Drop to Ipsilateral Side	-2.6 ± 2.4	-2.7 ± 2.4	0.80	1.02	0.95 to 1.10	0.52	1.04	0.96 to 1.12	0.37
Thorax Anterior Tilt	8.0 ± 4.6	7.3 ± 4.6	0.20	1.02	0.98 to 1.06	0.25	1.03	0.99 to 1.07	0.18
Thorax Rotation to Ipsilateral Side	-12.2 ± 4.3	-12.4 ± 5.0	0.86	1.00	0.96 to 1.04	0.97	1.00	0.96 to 1.05	0.90
Peak Knee Flexion (°)									
Foot Plantarflexion	-2.5 ± 1.1	-2.6 ± 1.7	0.57	1.04	0.92 to 1.17	0.57	1.04	0.92 to 1.18	0.57
Ankle Eversion	5.6 ± 2.5	5.6 ± 2.4	0.96	1.02	0.95 to 1.10	0.63	1.02	0.94 to 1.10	0.66
Ankle Dorsiflexion	24.3 ± 3.4	23.7 ± 3.6	0.17	1.01	0.99 to 1.05	0.34	1.02	0.99 to 1.05	0.25
Ankle External Rotation	-21.6 ± 8.3	-21.1 ± 7.6	0.65	0.99	0.97 to 1.01	0.43	0.99	0.97 to 1.02	0.57
Knee Valgus	-4.0 ± 3.6	-4.6 v 3.4	0.22	1.03	0.98 to 1.09	0.21	1.04	0.98 to 1.10	0.18
Knee Flexion	42.6 ± 4.9	42.2 ± 3.9	0.42	1.02	0.98 to 1.07	0.29	1.02	0.98 to 1.07	0.34
Knee Internal Rotation	21.3 ± 7.5	19.5 ± 8.0	0.07	1.03	1.00 to 1.05	0.03*	1.03	1.00 to 1.05	0.04*
Hip Adduction	11.9 ± 4.2	12.6 ± 4.6	0.23	0.98	0.94 to 1.02	0.24	0.97	0.93 to 1.02	0.22
Hip Flexion	27.9 ± 6.5	28.0 ± 7.0	0.95	1.00	0.98 to 1.03	0.98	1.00	0.98 to 1.03	0.91
Hip External Rotation	-5.4 ± 6.3	-5.2 ± 7.1	0.83	1.00	0.97 to 1.02	0.82	1.00	0.97 to 1.03	0.86
Pelvic Drop to Contralateral Side	3.5 ± 2.7	3.7 ± 2.8	0.61	0.98	0.92 to 1.05	0.61	0.99	0.92 to 1.05	0.66
Anterior Pelvic Tilt	11.8 ± 5.0	11.8 ± 6.1	0.95	1.00	0.97 to 1.03	0.97	1.00	0.97 to 1.03	0.92
Pelvis Rotation to Ipsilateral Side	-4.6 ± 4.0	-4.5 ± 3.6	0.88	0.99	0.95 to 1.04	0.81	0.99	0.94 to 1.04	0.57

Thorax Drop to Ipsilateral Side	-3.9 ± 2.0	-4.0 ± 3.6	0.62	1.03	0.95 to 1.12	0.49	1.04	0.96 to 1.13	0.33
Thorax Anterior Tilt	9.9 ± 4.8	9.3 ± 4.6	0.31	1.02	0.98 to 1.06	0.33	1.02	0.98 to 1.07	0.24
Thorax Rotation to Ipsilateral Side	-4.8 ± 3.9	-5.1 ± 4.4	0.58	1.00	0.96 to 1.05	0.84	1.01	0.96 to 1.05	0.79
Toe Off (°)									
Foot Plantarflexion	-49.5 ± 7.0	-51.3 ± 7.2	0.06	1.02	1.00 to 1.05	0.06	1.03	1.00 to 1.05	0.07
Ankle Abduction (+ Eversion; - Inversion)	0.3 ± 2.1	0.2 ± 2.0	0.87	1.01	0.93 to 1.10	0.77	1.01	0.92 to 1.11	0.81
Ankle Plantarflexion	-12.3 ± 5.9	-13.2 ± 6.1	0.28	1.01	0.99 to 1.05	0.34	1.02	0.99 to 1.05	0.25
Ankle Rotation (+ Internal Rotation; - External Rotation)	-1.0 ± 8.4	-0.9 ± 8.2	0.91	1.00	0.98 to 1.02	0.81	1.00	0.98 to 1.02	0.88
Knee Valgus	-2.7 ± 3.0	-3.8 ± 3.1	0.01*	1.09	1.03 to 1.15	0.00*	1.10	1.04 to 1.17	0.00*
Knee Flexion	17.0 ± 6.6	17.9 ± 6.7	0.32	0.98	0.96 to 1.01	0.19	0.98	0.95 to 1.01	0.16
Knee Internal Rotation	4.6 ± 6.1	4.4 ± 7.2	0.86	1.00	0.98 to 1.03	0.75	1.00	0.98 to 1.03	0.75
Hip Adduction	1.0 ± 3.3	1.5 ± 3.3	0.21	0.96	0.91 to 1.01	0.15	0.95	0.90 to 1.01	0.10
Hip Extension	-3.0 ± 5.6	-3.2 ± 6.3	0.82	1.00	0.97 to 1.03	0.96	1.00	0.97 to 1.03	0.96
Hip External Rotation	-8.1 ± 6.5	-8.0 ± 7.1	0.91	1.00	0.97 to 1.02	0.90	1.00	0.97 to 1.03	0.99
Pelvic Drop to Ipsilateral Side	-3.8 ± 2.5	-3.7 ± 2.4	0.73	0.98	0.91 to 1.05	0.59	0.99	0.91 to 1.07	0.76
Anterior Pelvic Tilt	16.8 ± 4.7	16.6 ± 5.7	0.80	1.01	0.97 to 1.04	0.73	1.01	0.97 to 1.04	0.73
Pelvis Rotation to Contralateral Side	2.6 ± 4.1	2.4 ± 3.5	0.76	1.02	0.97 to 1.07	0.53	1.01	0.96 to 1.05	0.74
Thorax Drop to Contralateral Side	1.0 ± 2.5	0.7 ± 2.2	0.30	1.05	0.97 to 1.14	0.20	1.07	0.99 to 1.16	0.10
Thorax Anterior Tilt	7.9 ± 4.9	7.6 ± 4.6	0.69	1.01	0.97 to 1.04	0.76	1.01	0.97 to 1.05	0.64
Thorax Rotation to Contralateral Side	13.1 ± 4.6	13.2 ± 4.3	0.95	1.00	0.96 to 1.04	0.95	1.00	0.96 to 1.05	0.98
Excursion/ ROM (°)									
Foot Flexion	59.9 ± 9.9	62.5 ± 10.4	0.05*	0.98	0.97 to 1.00	0.06	0.99	0.97 to 1.00	0.08
Ankle Eversion	6.0 ± 1.7	6.2 ± 1.8	0.43	0.99	0.89 to 1.09	0.77	0.99	0.89 to 1.10	0.87
Ankle Flexion	38.9 ± 5.9	39.3 ± 5.7	0.54	1.00	0.97 to 1.03	0.86	1.00	0.96 to 1.03	0.80
Ankle Rotation	22.9 ± 5.3	23.0 ± 4.8	0.85	1.00	0.97 to 1.04	0.85	1.00	0.97 to 1.04	0.89
Knee Abduction	3.6 ± 1.5	3.5 ± 1.4	0.58	1.04	0.92 to 1.17	0.53	1.06	0.94 to 1.21	0.35
Knee Flexion	28.8 ± 5.6	28.5 ± 5.3	0.66	1.02	0.98 to 1.05	0.36	1.02	0.98 to 1.05	0.30
Knee Rotation	20.3 ± 5.2	19.3 ± 4.1	0.11	1.04	1.00 to 1.08	0.03*	1.05	1.01 to 1.09	0.02*

Hip Adduction	11.9 ± 3.8	12.2 ± 3.9	0.56	0.99	0.94 to 1.04	0.67	0.99	0.94 to 1.04	0.74
Hip Flexion	38.0 ± 5.2	38.5 ± 4.8	0.42	0.99	0.96 to 1.02	0.54	0.99	0.95 to 1.03	0.49
Hip Rotation	10.5 ± 3.8	10.1 ± 3.3	0.31	1.03	0.98 to 1.08	0.26	1.04	0.98 to 1.09	0.20
Pelvic Abduction	8.2 ± 2.9	8.6 ± 3.1	0.30	0.97	0.92 to 1.04	0.40	0.96	0.90 to 1.03	0.28
Pelvis Tilt	7.3 ± 1.9	7.4 ± 2.0	0.91	1.01	0.92 to 1.11	0.81	1.01	0.92 to 1.11	0.89
Pelvis Rotation	8.5 ± 3.5	8.1 ± 3.5	0.48	1.02	0.97 to 1.08	0.36	1.03	0.97 to 1.10	0.29
Thorax Abduction	5.4 ± 2.3	5.2 ± 1.6	0.38	1.05	0.96 to 1.15	0.34	1.06	0.96 to 1.17	0.23
Thorax Tilt	3.5 ± 1.3	3.5 ± 1.3	0.92	1.02	0.89 to 1.17	0.78	1.03	0.89 to 1.20	0.71
Thorax Rotation	25.5 ± 6.8	25.6 ± 6.4	0.85	1.00	0.97 to 1.03	0.92	1.00	0.96 to 1.03	0.89
Maximum/Peak Angle (°)									
Foot Dorsiflexion	10.4 ± 6.2	11.3 ± 6.3	0.27	0.99	0.96 to 1.01	0.31	0.99	0.96 to 1.02	0.42
Ankle Eversion	6.1 ± 2.6	6.2 ± 2.4	0.78	1.01	0.94 to 1.08	0.87	1.01	0.93 to 1.89	0.84
Ankle Dorsiflexion	26.6 ± 3.8	26.2 ± 3.6	0.39	1.04	0.99 to 1.09	0.17	1.04	0.99 to 1.09	0.14
Ankle Rotation (+ Internal Rotation; - External Rotation)	-0.1 ± 8.4	0.3 ± 7.9	0.78	1.00	0.97 to 1.02	0.69	1.00	0.97 to 1.02	0.77
Knee Valgus	-1.0 ± 3.0	-1.9 ± 3.0	0.02*	1.07	1.01 to 1.13	0.02*	1.08	1.02 to 1.15	0.01*
Knee Flexion	42.7 ± 4.9	42.2 ± 3.9	0.42	1.02	0.98 to 1.07	0.29	1.02	0.98 to 1.07	0.34
Knee Internal Rotation	23.0 ± 7.6	21.5 v 7.7	0.14	1.02	1.00 to 1.05	0.06	1.03	1.00 to 1.05	0.05*
Hip Adduction	12.7 ± 3.9	13.5 ± 4.4	0.14	0.97	0.93 to 1.01	0.14	0.97	0.92 to 1.01	0.12
Hip Flexion	34.7 ± 6.2	35.0 ± 6.0	0.77	1.00	0.97 to 1.03	0.78	0.99	0.97 to 1.02	0.71
Hip Internal Rotation	1.1 ± 6.2	0.9 ± 6.8	0.80	1.00	0.98 to 1.03	0.76	1.01	0.98 to 1.04	0.65
Pelvic Drop to Contralateral Side	4.1 ± 2.6	4.6 ± 2.7	0.20	0.96	0.90 to 1.03	0.23	0.96	0.89 to 1.03	0.22
Anterior Pelvic Tilt	17.1 ± 4.7	17.0 ± 5.6	0.96	1.00	0.97 to 1.04	0.87	1.00	0.97 to 1.04	0.85
Pelvis Rotation to Contralateral Side	2.9 ± 3.9	2.6 ± 3.4	0.55	1.02	0.97 to 1.08	0.37	1.02	0.96 to 1.07	0.55
Thorax Drop to Contralateral Side	1.2 ± 2.3	0.8 ± 2.2	0.21	1.06	0.98 to 1.15	0.13	1.09	1.00 to 1.18	0.05
Thorax Anterior Tilt	10.6 ± 4.8	10.1 ± 4.6	0.43	1.02	0.98 to 1.05	0.44	1.02	0.98 to 1.06	0.34
Thorax Rotation to Contralateral Side	13.2 ± 4.6	13.2 ± 4.2	0.93	1.00	0.96 to 1.04	0.92	1.00	0.95 to 1.05	0.98
Minimum (°)									
Foot Plantarflexion	-49.5 ± 7.0	-51.3 ± 7.2	0.06	1.02	1.00 to 1.05	0.07	1.03	1.00 to 1.05	0.07

Ankle Abduction (+ Eversion; - Inversion)	0.1 ± 2.1	-0.1 ± 2.0	0.73	1.02	0.94 to 1.12	0.64	1.02	0.93 to 1.12	0.70
Ankle Plantarflexion	-12.3 ± 5.9	-13.2 ± 6.1	0.28	1.01	0.99 to 1.05	0.35	1.02	0.99 to 1.05	0.25
Ankle External Rotation	-23.0 ± 8.2	-22.8 ± 7.3	0.86	0.99	0.97 to 1.02	0.58	1.00	0.97 to 1.02	0.69
Knee Valgus	-4.6 ± 3.5	-5.4 ± 3.2	0.07	1.05	1.00 to 1.11	0.06	1.06	1.00 to 1.12	0.05
Knee Flexion	13.9 ± 4.9	13.7 ±4.6	0.81	1.00	0.96 to 1.04	0.92	1.00	0.96 to 1.03	0.78
Knee Internal Rotation	2.7 ± 5.8	2.2 ± 6.9	0.56	1.01	0.93 to 1.04	0.46	1.01	0.98 to 1.04	0.50
Hip Adduction	0.8 ± 3.2	1.3 ± 3.2	0.22	0.96	0.91 to 1.02	0.16	0.95	0.90 to 1.01	0.11
Hip Extension	-3.2 ± 5.6	-3.5 ± 6.1	0.70	1.00	0.97 to 1.03	0.82	1.00	0.97 to 1.04	0.88
Hip External Rotation	-9.4 ± 6.0	-9.2 ± 6.9	0.76	1.00	0.97 to 1.02	0.77	1.00	0.97 to 1.03	0.83
Pelvic Drop to Ipsilateral Side	-4.0 ± 2.4	-4.0 ± 2.2	0.92	0.99	0.92 to 1.07	0.78	1.00	0.91 to 1.09	0.93
Anterior Pelvic Tilt	9.7 ± 4.8	9.7 ± 5.8	0.93	1.00	0.97 to 1.03	0.94	1.00	0.97 to 1.04	0.89
Pelvis Rotation to Ipsilateral Side	-5.5 ± 3.9	-5.5 ± 3.5	0.94	1.00	0.95 to 1.05	0.99	0.99	0.94 to 1.05	0.77
Thorax Drop to Ipsilateral Side	-4.2 ± 2.1	-4.3 ± 2.2	0.62	1.03	0.95 to 1.12	0.48	1.04	0.96 to 1.13	0.35
Thorax Anterior Tilt	7.1 ± 4.7	6.6 ± 4.5	0.40	1.01	0.98 to 1.05	0.47	1.02	0.98 to 1.06	0.38
Thorax Rotation to Ipsilateral Side	-12.3 ± 4.3	-12.4 ± 5.0	0.85	1.00	0.96 to 1.04	0.96	1.00	0.96 to 1.05	0.88

g: g force; g/s: g force per second; °: degrees; ROM: range of motion; CI: confidence interval; *: significant p value at < 0.05.

Supplemental Table C2. Univariate Cox regression findings for categorical variables

Variable	Unadjusted HR	95% CI Lower to Upper	P value	Adjusted HR	95% CI Lower to Upper	P value
RFS (Reference)	1.00					
NRFS	1.14	1.00 to 2.06	0.05*	1.37	0.93 to 2.01	0.11
No previous injury (References)	1.00					
Previous Injury	1.57	1.12 to 2.21	0.01*	1.57	1.10 to 2.23	0.01*
Not training for 5km (Reference)	1.00					
5km	0.77	0.53 to 1.11	0.16	0.77	0.53 to 1.12	0.17
Not training for 10km (Reference)	1.00					
10km	0.92	065 to 1.30	0.63	0.91	0.64 to 1.30	0.60
Not training for half-marathon (Reference)	1.00					
Half Marathon	0.91	0.64 to 1.29	0.58	0.91	0.64 to 1.28	0.58
Not training for marathon (Reference)	1.00					
Marathon	1.75	1.22 to 2.50	0.00*	1.76	1.22 to 2.54	0.00*
Doesn’t do speed work (Reference)	1.00					
Speed Work	1.20	0.84 to 1.71	0.32	1.23	0.85 to 1.76	0.27
Doesn’t do hill runs (Reference)	1.00					
Hill Runs	1.20	0.82 to 1.75	0.35	1.20	0.82 to 1.77	0.36
Change shoes every 0-3 months (Reference)	1.00					
Change shoes 4-6 months	0.50	0.23 to 1.07	0.07	0.49	0.23 to 1.06	0.07
Change shoes 7-12 months	0.46	0.22 to 0.98	0.05*	0.45	0.20 to 0.99	0.05*
Change shoes 12 months +	0.40	0.19 to 0.86	0.02*	0.38	0.17 to 0.85	0.02*
Doesn’t wear insoles (Reference)	1.00					
Wear Insoles	0.96	0.63 to 1.46	0.83	0.97	0.64 to 1.48	0.89
Doesn’t experience a niggle (Reference)	1.00					
Niggle	1.16	0.81 to 1.66	0.42	1.16	0.81 to 1.67	0.42

Niggle Unsure	0.75	0.36 to 1.57	0.45	0.76	0.37 to 1.60	0.47
Never does a warm up	1.00					
Warm up always	1.30	0.80 to 2.11	0.30	1.33	0.81 to 2.16	0.26
Warm up sometimes	1.31	0.80 to 2.12	0.28	1.31	0.81 to 2.14	0.27

RFS: rearfoot strike pattern; NRFS: non-rearfoot strike pattern; km: kilometre; HR: hazard ratio; CI: confidence interval; *: significant at p value < 0.05.

Appendix D

STROBE Statement for Aetiological factors of running-related injuries: A 12 month prospective "Running Injury Surveillance Centre" (RISC) Study

	Item No.	Recommendation	Page No.	Relevant text from manuscript
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract		Lines 1: Aetiological factors of running-related injuries: A 12 month prospective "Running Injury Surveillance Centre" (RISC) Study
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found		Lines 17-31: Methods and results of abstract.
Introduction				
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported		Lines 41-93 : Introduction
Objectives	3	State specific objectives, including any prespecified hypotheses		Lines 90-93 : "Thus, the aim of this study was to investigate the multifactorial contribution and interaction of impact loading, kinematic (foot, ankle, knee, hip, pelvis and trunk) and training-related factors that contribute towards prospectively injured recreational runners during a 12 month period."
Methods				
Study design	4	Present key elements of study design early in the paper		Lines 96-99 : Methodology
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection		Lines 104-131: Lines 133-226 : Methodology

Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	Lines 103-110 : "Male and female recreational runners aged over 18 years, who ran a minimum of 10km per week for the preceding 6 months (Saragiotto, Yamato and Lopes, 2014), were recruited from local running clubs, running events, radio advertising and social media recruitment drives between January and August 2018. Participants were excluded if they were currently injured or had sustained an injury within the 3 months prior to testing (Buist *et al.*, 2010), had a history of cardiovascular illness, previous reconstructive joint surgery or joint replacements, or were pregnant."
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	Lines 261-266 : "For runners who sustained an RRI, the limb that was injured was used in the analysis. If a runner had sustained multiple RRIs, the limb that sustained the first RRI was used. Where runners had not sustained an RRI, a random selection of their uninjured limbs was chosen. This selection was conducted at the end of the 12-month surveillance, where a percentage of injured group dominant and non-dominant limbs were matched at random the same percentage of uninjured group dominant and non-dominant limbs."
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	Lines 122-129 "If participants became injured, their injury was diagnosed by the researchers (a Certified Athletic Therapist (AB) or a Chartered Physiotherapist (SD)). If participants were unable to attend an injury assessment, a diagnosis was confirmed by phone call."
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	Table 6.3.1 Lines 134-226
Bias	9	Describe any efforts to address potential sources of bias	The trial methodology was registered before data collection. Reporting bias: Positive and negative findings were clearly reported.

			Recall bias: Participants were contacted about injuries every 2 weeks to minimise recall bias.
Study size	10	Explain how the study size was arrived at	Lines 107-109 : "A recent prospective study with a sample size of 300 recreational runners (Messier *et al.*, 2018) provided a target sample size, to ensure adequate power for statistical analyses"

Continued on next page

Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	Lines 228-252
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	Lines 254-283
		(*b*) Describe any methods used to examine subgroups and interactions	Lines 276-279 "An adjusted univariate Cox regression was then complete with sex, age and mileage as covariates"
		(*c*) Explain how missing data were addressed	Lines 245-252 : "Consistent with previous research, multiple imputation was utilized to generate multiple plausible datasets at random for dropped data packets (Kiernan *et al.*, 2018). These datasets were analysed separately and pooled at the end. In this procedure, 20 imputed datasets were generated using SPSS and pooled using Rubin's rules (Rubin, 2004). In order to validate the imputation accuracy, a second imputation trial was completed where known data were deleted from two participants (Kiernan *et al.*, 2018). A subsequent independent t-test revealed no statistical difference between original data and imputed data ($p > 0.05$)"
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	Lines 130-132 : "Participants who had an acceptable response rate (>80%, (Webster *et al.*, 2019)) through the 12 month surveillance period were included in the final analysis."
		(*e*) Describe any sensitivity analyses	This study examined analysed data with and without adjustment for age, sex and mileage.
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	Lines 288-295 : "A total of 310 recreational runners volunteered to participate in this study. Fifty-two participants were removed from the final analyses for the following reasons: sustained a non-running-related injury (e.g. work based or road traffic accident injury) (n = 14), had

			impact acceleration or kinematic data that were considered as outliers (n = 11), developed a long-term illness (n = 10), had poor response rates through the surveillance period (n = 10), became pregnant (n = 3), participated in other team-based sports (n = 3), or had stopped running (n = 1). Therefore, a total of 258 runners (163 males and 95 females) were considered for the final analyses."
		(b) Give reasons for non-participation at each stage	Lines 288-295
		(c) Consider use of a flow diagram	Not reported
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	Lines 297-301 Table 6.4.1
		(b) Indicate number of participants with missing data for each variable of interest	N/A
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	Lines 261-266
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	Lines 310-312 : "One hundred and thirty-two runners (51%) sustained a total of 166 RRIs during the 12-month surveillance period. Eighty-five males (52%) and forty-seven females (50%) sustained at least one prospective RRI, with no statistical difference between sexes."
		Cross-sectional study—Report numbers of outcome events or summary measures	
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	Tables 6.4.3, 6.4.4, 6.4.5 Supplemental Table 2.
		(*b*) Report category boundaries when continuous variables were categorized	Tables 6.4.3, 6.4.4, 6.4.5 Supplemental Table 2.
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	N/A

Continued on next page

Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	Tables 6.4.3, 6.4.4, 6.4.5 Supplemental Tables 1 and 2.
Discussion			
Key results	18	Summarise key results with reference to study objectives	Lines 616-631 : Conclusion
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	Lines 597-614 Study Limitations
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	Lines 616-631 : Conclusion
Generalisability	21	Discuss the generalisability (external validity) of the study results	Lines 578-595 Clinical Implications
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Lines 633-635 : Funding

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.