Do injury resistant runners have distinct differences in clinical measures compared to recently injured runners?

Sarah Dillon [1, 2], Aoife Burke [1], Enda F. Whyte [1,3], Siobhán O'Connor [1,3], Shane Gore [1, 2] and Kieran A. Moran [1, 2,3].

[1] School of Health and Human Performance, Dublin City University, Dublin, Ireland.

[2] Insight SFI Research Centre for Data Analytics, Dublin City University, Dublin, Ireland.

[3] Centre for Injury Prevention and Performance, Athletic Therapy and Training, School of Health and Human Performance, Dublin City University, Dublin, Ireland

Corresponding Author: Sarah Dillon, School of Health and Human Performance, Lonsdale Building, Dublin City University, Collins Avenue, Glasnevin, Dublin 9, Ireland.

Email correspondence: sarah.dillon24@mail.dcu.ie

Telephone: +00353851680036

Abstract:

Introduction:

Although lower extremity muscle strength, joint motion and functional foot alignment are commonly used, time-efficient clinical measures that have been proposed as risk factors for running related injuries (RRIs), it is unclear if these factors can distinguish injury-resistance in runners.

Purpose:

This study compares clinical measures, with consideration of sex, between recently injured runners (3 months to 1 year prior), those with a high level of injury resistance who have been uninjured for at least 2 years, and never-injured runners.

Methods:

Averaged bilateral values and between-limb symmetry angles of lower limb isometric muscle strength, joint motion, navicular drop and Foot Posture Index (FPI) were assessed in a cohort of recreational runners and their injury history was recorded. Differences in clinical measures between injury groupings were examined, with consideration of sex.

Results:

Of the 223 runners tested, 116 had been recently injured, 61 had been injured >2 years ago and were deemed to have acquired re-injury resistance, and 46 were never injured. Plantar flexion was greater in both recently injured (*P* = .001) and acquired re-injury resistance runners (*P* = .001). compared to never-injured runners. Recently injured runners displayed higher hip abduction strength compared to never-injured runners (*P* = .019, η^2 = .038, small effect size). There were no statistically significant differences in the remaining measures between the injury groupings. With the exception of FPI, there was no interaction between sex and injury grouping for any of the measures.

Conclusion:

Commonly employed clinical measures of strength, joint motion and functional foot alignment were not superior in injury-resistant runners compared to recently injured runners, questioning their relevance in identifying future injury resistance of runners.

Key words: Running injuries, strength, pronation, joint motion.

Introduction:

Runners are subject to a high incidence of lower extremity injury of between approximately 20% to 80% (1). The pervasive biomechanical model of injury identifies excessive loading to tissues to be causative of injuries (2). Running is a cyclical movement that exposes the body to repetitive loads of up to 2.8 times body weight with each step (3). Clinical measures of muscle strength, functional foot alignment and joint motion have been suggested to be related to loading (4,5) and, although evidence is mixed, may be related to injury itself (6–8). Furthermore, studies involving asymmetry of these factors have demonstrated a similarly mixed relationship to injury (9–11). Imbalances in factors such as tissue strength and joint motion may be a precursor to injury. Additionally, at return to sport, asymmetry in factors such as tissue strength acquired as a result of injury-induced tissue damage may persist (9), potentially causing reinjury. These clinical measures are advantageous in being time-efficient, low cost and readily available to most clinicians, making their potential use in managing running related injuries (RRIs) particularly valuable.

Due to cost and time constraints, retrospective studies are the predominant methodology in examining factors associated with running related injuries. One group of runners frequently studied are those who have relatively recently recovered from injury and returned to play (e.g. less than 12 months post injury). This group is of interest because they are thought to no longer retain the acute effects of injury itself, but may still maintain factors related to injury given the high risk of re-injury during this period (12). A second group of runners worth studying are those who have recovered from injury but have not experienced a reinjury (e.g. > 2 years since injury). This acquired re-injury resistance group may logically be less likely to retain the risk factors associated with injury/re-injury, or at least have a reduced weighting. A third and final group worth examining, and perhaps the most interesting, would be those who have never been injured. Given the high lifetime incidence of RRIs (~92 %) (13) this group would potentially have no or significantly reduced levels of risk factors. A comparison of these three groups may provide novel and important insight into the three clinical-based factors possibly related to RRIs: muscle strength, functional foot alignment and joint motion. To the authors' knowledge, no previous study has undertaken such a three-way comparison for any factors related to RRIs. Zifchock and colleagues (2008) (10) examined differences in hip motion and arch height between never-injured (n=20) and previously injured recreational runners (n=20), reporting both to be greater in the previously injured group. However, results of the study should be interpreted with caution as this was a small study and it did not take into account the possibly confounding effect of sex, a potentially important factor given that males are reported to be at an increased risk of RRIs (14) and sex-specific differences in injury risk profiles have been suggested to exist (15). In addition, Zifchock *et al.*, (2008) (10) did not examine muscle strength as a primary factor, which may be important because of its relationship to both tissue loading (through movement technique) and tissue integrity, whose balance is central to the occurrence of musculoskeletal injuries (2). The examination of clinical measures may provide greater insight into the potentially distinct characteristics of runners who have either acquired re-injury resistance or have never been injured in comparison to those who have been recently injured, and the results may inform injury prevention and rehabilitation strategies.

This study therefore aims to examine the effect of injury status and sex on values of strength, functional foot alignment and joint motion using three distinct injury status groups: those who have recently returned from injury (injured 3 months - 1 year previously), those who have acquired re-injury resistance (remained uninjured for >2 years), and those who have never been injured (never injured). It was hypothesised that those with a high level of injury resistance (ie. never-injured runners and those who had not been injured for over two years) may have advantageous clinical measures of strength, functional foot alignment and joint motion compared with a recently injured group. A secondary aim was to investigate whether asymmetry values would be distinctive among groups, with injury resistant runners hypothesised to have less asymmetry. It was also hypothesised that sex-specific differences may exist between groups.

Methods

Participants

As part of a more extensive study, male and female recreational runners from Dublin and its surrounding areas were recruited between the period of January to August 2018. Recreational runners between 18-65 years with no injury within the last three months were included in this study (14). Three participant groups were later constructed: those injured 3-12 months prior ('recently injured'), those whose most recent injury was over two years ago ('acquired re-injury resistance'), and those who had never been injured ('never injured'). A history of injury in the preceding year is cited as a main risk factor for future injury (12). Therefore, it was hypothesised that participants with a longer duration since injury would be less likely to retain the effects of injury and may demonstrate clinical factors that can contribute to their 'injury resistance'. The exclusion of participants injured 1-2 years previously was done to ensure clear demarcation between 'recently injured' and 'acquired re-injury resistance' groups. To limit the effects of injuries related to non-running activities, participants were excluded if they participated in team, contact or high impact sports. A recreational runner was defined as a person who runs a minimum of 10km per week, for at least six months prior to their inclusion in the study (12).

Sample Size

Sample size was determined *a priori (*alpha probability = 0.05, with a power of $1 - \beta = 0.80$, effect size (f) = 0.25) for a Two Way Analysis of Variance (ANOVA) using a power analysis program, G*Power 3.1.9.7 (16). Due to the presence of multiple variables and difficulty ascertaining which variable to base the power analysis on, the effect size was determined using a standardised medium effect size value (small = 0.1, medium = 0.25, large = 0.40) (16). A total sample size of 158 was reached.

Ethical Approval

Ethical approval was sought from and granted by the Dublin City University Ethics Committee (DCUREC/2017/186).

Procedures:

Eligible participants completed an informed consent form to partake in this study and then completed an online survey regarding their injury and training history. Participants then attended a single baseline testing session in which isometric strength, joint motion, navicular drop and foot posture index (FPI) were assessed following the completion of the Par-Q questionnaire. Their survey information was verbally reviewed for accuracy and completeness. Height (m) and body mass (kg) were recorded using a portable stadiometer and electronic weighing scales, respectively (Seca, UK). A Certified Athletic Therapist (AB) and a Chartered Physiotherapist with experience in musculoskeletal therapy (SD) completed all testing components. Both testers practiced all aspects of the protocol prior to testing under the instruction and supervision of a senior researcher and clinician. Due to the presence of multiple and bilateral injuries and potential recall bias in remembering the side of injury, the average value of the sum of both sides were used for each measure.

Isometric muscle strength

Isometric hip abduction, hip extension, knee flexion, knee extension and ankle plantar flexion strength were measured using a dynamometer (J-Tech Commander Echo Wireless Muscle Testing Starter Kit, J-Tech Medical Industries, Midvale, UT, USA) (Table 1) (17,18). Knee flexion and extension and plantar flexion strength were tested using a stabilisation belt (17).

Participants were directed to use maximum effort, whilst gently holding onto the side of the plinth for stabilisation (18). Three repetitions were completed with 15 second rest intervals. The command: “Go ahead-push-push-push-push-push and relax”, was given for each contraction (18). The maximum value of three repetitions was documented and analysed for each muscle group and was multiplied by the length of the resistance moment arm (m) and normalized to body mass (kg) (19).

Navicular drop

The navicular drop test was conducted as previously described (14). The medial and lateral aspects of the talus were palpated whilst sitting, and the foot was placed in a subtalar neutral position. The navicular tuberosity was palpated, marked and the distance from the mark on the navicular to the floor was measured. A second measurement was recorded in the upright standing position. The average of three measurements of the difference between the sitting and standing heights was calculated for both feet. Additionally, participants were categorised into two groups using the summed average navicular drop of >10mm and <10mm, as measurements exceeding 10mm have previously been found to be related to injury (20).

The foot posture index (FPI)

The FPI was assessed with participants standing in a relaxed barefoot stance. Participants were instructed to remain as still as possible and were scored in accordance to the FPI-6 scale (21) and subsequently divided into foot type categories: highly supinated (-5 to -12), supinated (0 to -4), neutral (+1 to +5), pronated (+6 to +9), highly pronated (+10 to +12) (22).

Joint Motion (Supplementary Digital Content 1)

Ankle dorsiflexion, hip extension, hip internal and external rotation joint motion were assessed with the use of a smartphone application (Plaincode “clinometer”, V2.4 on a Samsung S8+ (https://play.google.com/store/apps)).

A knee to wall test was used to determine ankle dorsiflexion motion (23). Reduced ankle dorsiflexion motion has previously been suggested to be associated with compensatory pronation during running in order to achieve forefoot contact (8). This may consequently increase forces on surrounding structures. To perform this test, unshod participants faced a wall in a split stance. With one knee contacting the wall and the ipsilateral heel on the ground, participants gradually moved their foot as far away from the wall as possible, with their anterior knee maintaining contact with the wall. Participants were instructed to direct their knee anteriorly over the second toe. No additional effort was made for them to maintain a subtalar neutral position throughout the test. A smartphone was placed at the tibial tuberosity to measure the tibia angle relative to the ground. This was repeated 3 times and the average was recorded.

Hip motion has been suggested to be potentially related to injuries for two main reasons; (i) reduced motion may be reflective of shortened and therefore functionally limited hip muscles, and (ii) increased motion may signal potentially increased demands on musculature to control for excessive hip motion (24). Hip extension motion was assessed using the Modified Thomas Test (25). A resting measure of thigh position was recorded by placing a smartphone along the midline of the femur, 5cm proximal to the superior surface of the patella, whilst the participant sat with their thighs supported on a firm plinth. The participant was then instructed to move to the edge of the plinth before being guided into a supine position by the tester. To control for lumbopelvic motion, a bio-feedback pressure cuff stabilizer was placed proximal to the posterior superior iliac spines of the lower back. The smartphone was again placed in the previous measurement position and a reading was taken. The resting femur measure was subtracted from this reading to determine extension.

Hip internal and external rotation motion were measured with participants sitting with arms folded on the edge of a plinth (26). A smartphone was held against the fibula, 5cm proximal over to the lateral malleolus, and a resting value was obtained. The hip was then passively maximally rotated on the frontal plane, with care taken to minimise compensatory movements. The smartphone was repositioned, and a reading was taken. The resting value was subtracted from this reading and a resultant internal rotation measure was documented. This was repeated three times on each leg and averaged. The same procedure was repeated in the opposite direction to assess external rotation.

Good to excellent intraclass correlation coefficient values were found for inter-rater reliability (Supplementary Material 2, Table A) and intra-rater reliability (Supplementary Material 1, Table B) of each of the measures.

Asymmetry:

Asymmetry was calculated for each measure using symmetry angle (10), using the following equation:

$$Symmetry\ Angle = [(45^{\circ} - \arctan(X_{dominant}/X_{non\text{-}dominant}))/90^{\circ}] * 100\%$$

with a symmetry angle of 0% representing perfect symmetry.

Running related injury (RRI) defined

Injury history was collected via an online questionnaire, which was completed prior to testing and reviewed (by SD or AB) with each participant for accuracy, at the time of testing. An RRI was defined as "any (training or competition) musculoskeletal pain in the lower limbs that causes a restriction/stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional" (27). Recently injured participants, who had been uninjured for 3 months to 1 year prior to enrolment in the study, detailed the location of previous injuries and whether they had completed a rehabilitation programme.

Statistical Analysis:

All data were analysed with SPSS (version 23; IBM Corp, Armonk, NY). Participants were divided into three groups: recently injured (history of injury between 3 months and one year, n=116), acquired re-injury resistance (history of injury > 2 years, n=61) and never-injured runners (n=46). Differences in demographics between injury groups were assessed using one-way ANOVAs. Two-way ANOVAs (3 x 2) (group x sex) were used to evaluate differences in average bilateral and symmetry angle values for strength, navicular drop, FPI and joint motion. Post hoc testing for significant interactions was performed using Gabriel's Test to accommodate for the uneven group sample size distribution. To further investigate any interaction effects a simple slopes analysis was conducted. Data violating the assumption of homogeneity of variance were analysed using separate Kruskal Wallace Tests to evaluate differences between injury group and sex. Effect sizes were reported using partial eta squared (η^2) with 0.01, 0.06 and 0.14 representing small, medium and large effect sizes (28). A chi-square test of independence was used to examine the relationship between FPI categories and the different injury groups. A separate chi-square test of independence was used to examine the relationship between navicular drop </> 10mm and the different levels of injury. Due to equipment malfunction, the sample size for each variable sometimes varied slightly and is detailed below.

Results:

Demographics

Two hundred and seventy-four (171 males, 103 females) recreational runners participated in this study. Of these, 116 (77 males, 39 females, 42%) had been injured 3 months to 12 months prior, 61 (38 males, 23 females, 22%) had been injured over 2 years ago and 46 (29 males, 17 female, 17%) had never been injured. Fifty-one participants (38 males, 23 females, 19%) were injured in the 1- 2 years prior to participating in the study and were excluded from analysis.

This was done to ensure a clear demarcation between those who were theorised to have ‘acquired re-injury resistance’ (injured > 2 years ago) and those that were recently injured (injured 3 months- 1 year previously). Of the runners in the recently injured group, 87 % had participated in a rehabilitation programme. A breakdown of the proportion of injuries for each injury location is detailed in Table 2.

No significant differences were found for any of the demographic variables of height, weight and age between the three groups ($P > .05$, Table 3).

Normalised Strength Values (Table 4, Table 5)

No interaction effect was found between injury status and sex for the strength values. A simple main effect between injury groups existed for hip abduction strength ($P = .019$, $\eta^2 = .038$, small effect size) and plantar flexion strength ($P = .002$, $\eta^2 = .057$, small effect size). Post-hoc analyses revealed that recently injured ($P = .001$) and acquired re-injury resistance runners ($P = .010$) had significantly greater plantar flexion strength than never injured runners. Recently injured runners had significantly greater hip abduction strength compared with never-injured runners ($P = .001$). A trend towards significance existed for greater strength among recently injured compared to those with acquired re-injury resistance, although this did not reach significance ($P = .067$). A significant main effect was found for sex for all strength values with significantly greater values among males when compared to females ($P < .05$, Table 5), with the exception of plantar flexion strength, which only approached statistical significance ($P = .078$).

Joint Motion (Table 4, Table 5)

No interaction effect was found between injury status and sex for the joint motion values. No significant main effect was found for injury status. Males displayed significantly lower hip internal rotation motion (P = .038, η^2 = 0.02, small effect size) and significantly greater ankle dorsiflexion motion (P = .019, η^2 = 0.027, small effect size) compared to females.

Navicular Drop (Table 4, Table 5)

No interaction effects between injury status and sex or main effects for injury status was found for navicular drop. A significant main effect was found for sex, with males displaying significantly greater navicular drop compared to females (P = .000, η^2 = 0.062, moderate effect size, Table 5). A chi-square test of independence showed that there was no significant association between injury status and navicular drop > 10 mm, X^2 (2, N = 209) = 1.644, P = .440.

Foot Posture Index (Table 4, Table 5, Table 6)

Thera was a significant interaction effect between sex and injury status for FPI (P = .023, η^2 = .036, small effect size). Females with acquired re-injury resistance had significantly lower values of FPI (P = .007, [+4 (+1, +6)]) compared to recently injured females (+7 [+4, +8]). The median score for the acquired re-injury resistance group placed them in the “neutral” (+1 to +5) category. The median score of recently injured runners classified them as “pronated” (+6 to +11). A chi-square test of independence showed that there was no significant association between Foot Posture Index classification groups and RRI, X^2 (8, N = 212) = 3.363, P = .910 (Table 6).

Symmetry Angle (Table 7, Table 8)

No interaction effects between injury status and sex or main effects for injury status were found for symmetry angle of any variable. Females displayed greater asymmetry of knee flexion strength compared to males (P = .037, η^2= .021, small effect size).

Discussion

This study investigated the effects of injury status (recently injured, acquired re-injury resistance, never injured) and sex on lower limb strength, joint motion and functional foot alignment, as well as the between-leg asymmetry of these clinical measures. Our findings largely did not support our hypothesis that injury resistant and never injured runners would have potentially distinctive clinical features, and differences between injury groupings were mostly non-significant. However, this is with the exception of both plantar flexion and hip abduction strength. Plantar flexion strength was greater among both recently injured and acquired re-injury resistance runners compared to never-injured runners, while hip abduction strength was greater among recently injured runners compared to never injured runners only. With regard to the effect of sex, with the exception of FPI, sex had no influence on the magnitude of the between group differences, though some main effects for sex were observed. Males exhibited significantly greater strength for all muscle groups except the plantar flexor group, in addition to greater navicular drop measurements and ankle dorsiflexion motion, and significantly less hip internal rotation motion.

Contrary to our hypothesis, knee flexion, knee extension and hip extension strength were not significantly different between injury groups, suggesting that greater strength of these muscle groups is not a characteristic of acquired re-injury resistance or never injured runners. It has been suggested that increased strength may be protective against injuries due to the impact absorption properties of muscle (4), but findings to date have been mixed (7,19). Our findings have been supported by previous prospective research that found no link between hip extension, knee flexion and knee extension strength and RRI (29). However, lower knee flexion and extension strength have been found to specifically predict a higher incidence of anterior knee pain (AKP) (19) potentially indicating that strength may be related to specific injuries, which was not examined in this study.

Counterintuitively, hip abduction and plantar flexion strength were significantly greater among recently injured runners when compared to those who had never sustained an RRI. Previous studies of isometric hip abduction strength have found lower (30), higher (31) and no difference (32) in strength values among injured compared to uninjured runners. Although hip abduction strength of never-injured runners has been studied previously (10), data were not analysed statistically, thus limiting the potential for comparison. Plantar flexion strength was also greater in the acquired re-injury resistance group compared to never injured runners. Plantar flexion strength measured via portable dynamometry does not appear to have been studied previously for any injury grouping, possibly due to difficulty with positioning posed by the large forces generated by this muscle group, which was mitigated in this study by use of a stabilisation belt. Results of wider research involving isokinetic testing of plantar flexion strength has also been mixed, finding no difference between uninjured athletes and those with current medial tibial stress syndrome (MTSS) (33), higher strength in athletes with a history of MTSS (34) and lower muscle strength in symptomatic athletes with plantar fasciitis (35). Two possible explanations for the greater hip abduction strength and plantar flexion among recently injured runners observed in our study are the relatively recent participation in rehabilitation, and possible compensation as a result of injury. Firstly, gluteal and plantar flexor (36) strengthening (37) are frequent components in the rehabilitation of common RRIs, such as knee and Achilles tendon injuries. In our study, 87 % of the recently injured runners participated in a rehabilitation programme, which could have induced increases in both plantar flexion and hip abduction strength. Secondly, greater plantar flexion and hip abduction strength may be a compensatory mechanism in response to injury. Increased frontal plane hip and knee motion have been found among runners with common injuries such as patellofemoral pain syndrome (PFPS) (38) and iliotibial band syndrome (39). Therefore, for a time after injury, there may be increased muscle activity of the gluteal muscles, potentially increasing their strength in order to control for this increase in motion. A similar reasoning may hold for compensatory increases in plantar flexor strength. Interestingly, plantar flexion strength was also greater in the acquired re-injury resistance group compared to the never injured group. This may indicate that compensations as a result of previous injury may persist in excess of two years after the initial injury.

Although hypermobility and hypomobility have both been proposed to be related to musculoskeletal injury, a definitive link has not been established for RRIs (8,24,40). This is further confirmed in a recent systematic review that concluded that there was limited and low quality evidence suggesting range of motion as a risk factor for running injuries (41). Our research support this as acquired injury resistance runners and never injured runners did not display distinctive differences in dorsiflexion, hip external rotation and hip extension motion compared to recently injured runners. Notably, in relation to hip internal rotation, this finding conflicts with previous results, which found significantly higher hip internal range of motion among injured participants compared to never-injured runners (10), although different test positioning may account for the differences in results and their study had a smaller sample size (n= 40).

It is hypothesised that large amounts of joint motion may potentially increase demands on stabilising muscles (24). Adaptive shortening or lengthening of muscles may also place muscles at non-optimal lengths, limiting their functional ability (40). This is a marked limitation of traditional clinic-based strength tests performed in a stationary position, which typically do not account for the interaction between joint motion and muscle action. This study found no association between general injuries and joint motion. While this is a commonly used measure in clinical practice, joint motion alone may not be able to differentiate between injury resistant and recently injured runners. The lack of association calls into question its use in the management of general RRIs, although it may be appropriate for screening for specific injuries (42) or used in combination with more dynamic muscle strength testing.

Foot alignment has been associated with changes in lower limb kinematics and loading during running (43), although the association between functional foot alignment and RRIs have been conflicting (6,44). Contrary to our hypothesis, our study found no significant differences in either navicular drop means, the proportion of runners with navicular drop >10mm, or FPI categories, suggesting that functional foot alignment largely does not appear to be protective against general RRIs. An interaction effect between injury status and sex was found for FPI. Further analysis revealed that females with acquired re-injury resistance had significantly lower values of FPI compared to recently injured runners. It is unclear why this is, but it would suggest that females injured > 2 years ago have a more neutral foot type compared to female runners recently returned to play following injury, who had feet classified as “pronated”. We had hypothesised that navicular drop > 10 mm would be associated with injury, however, assessing by cut-off point did not yield significant differences between groups in our study. This contrasts with a previous prospective study, which found this to be a risk factor for exercise related leg pain among high school runners (20). Discrepancies in results may possibly be due to our inclusion of more experienced recreational runners, a difference in age or a variation in definition of injury. Notably, our findings conflict with those of Zifchock et al. (10) who found significantly reduced Arch Height Index deviation from normal among never-injured runners,; however, our study used a larger sample size and different measurement of functional foot alignment.

No differences in asymmetry were found between different injury groupings. This is in line with previous research which found that asymmetry was not significantly different between never-injured and previously injured runners for hip strength and motion (10) or for strength values between uninjured runners and those in the early stages of PFPS (31). Limited research has found that asymmetries after injury may persist after return to play (9), despite the recommendation that asymmetries are minimised at this time point. However, for our cohort it appears that similar levels of asymmetry existed across all groups, indicating that some level of asymmetry is normal. A finding of particular interest is that greater asymmetry was not found among those injured in the past year. Another explanation could be that studies which show high levels of asymmetry are generally related to acute, traumatic injuries, such as ACL ruptures (9), which may require greater rest than typical RRIs. Our findings indicate to clinicians that some level of motion, isometric strength, FPI and navicular drop asymmetry are to be expected among runners, regardless of their injury history.

Owing to the differences in RRI risk profiles that have been noted to exist between males and females (15), both the interaction effect of injury status on sex and the main effect of sex were investigated in this study. No interaction effects were found between injury status and sex for the clinical tests, with the exception of FPI. Sex may not have been a frequent interactive factor in our study as the majority of previous research finding sex-specific differences between injured and uninjured runners subdivided injury by diagnosis or location (8,31), which was not within the scope of this study. We found that compared to females, males displayed significantly greater knee flexion strength asymmetry, dorsiflexion motion, muscle strength normalised to body mass (with the exception of plantar flexion strength, which only approached significance) and navicular drop values, in addition to lower hip internal rotation. Previous research support these findings with regard to strength (45), navicular drop (46) and hip internal rotation (47). Little previous information is available investigating the between-sex differences in knee flexion strength asymmetry. However, force production asymmetry has been found to be greater in females during jumping movements (48). Males displayed significantly greater dorsiflexion motion than females, contrasting with previous findings for healthy runners (46), although it is unclear why this difference exists.

A relatively unique component of this study was the examination of never injured runners. It was hypothesised that investigating this group may have been useful in determining if common, easily assessible measures could identify potential differences in their clinical factors that may be protective of injury. Of the two hundred and twenty three participants analysed in this study, 116 (77 males, 39 females, 42%) had been recently injured (<1 year prior), 61 (38 males, 23 females, 22%) had been injured over 2 years ago were deemed to have acquired re-injury resistance and 46 (29 males, 17 female, 17%) had never been injured. The most common location of injury was the calf, followed by the knee (Table 2), which is largely similar to what has been reported in previous literature (49).

Limitations

Despite being chosen for their suitability for use in clinical practice and potential association with common RRIs, the clinical factors examined may have limitations. This study measured isometric contraction in a fixed position. Running also requires concentric and eccentric muscle action (50). Therefore, the muscle strength values measured within our study may not represent the typical values or contraction types produced during running. Similarly, quasi-static measures of navicular drop and FPI may not accurately reflect the dynamic motion of the foot during running. However, as these measures were considered to be more accessible in clinical practice, they were selected for this study.

The retrospective design of this study limits the ability to definitively ascertain whether differences between groups (recently injured, acquired re-injury resistance, never injured) are as a result of injury or causative in nature. Compensation and post-injury rehabilitation may mask our understanding of the factors associated with injury and whilst this information was collected for the recently injured runners, this was not gathered in the acquired injury resistance group. Additionally, the injury history relied on accurate reporting from participants, meaning that it may be subject to recall bias. In an effort to minimise recall bias and due to the presence of multiple injuries, data were analysed by grouping injuries together and averaging values from both sides. This method is advantageous in assessing whether there are factors protective from general running related injuries, and not specific to a particular injury. However, this limited our ability to compare side to side differences, to examine injury-specific differences in clinical measures or to delineate between overuse and acute injuries. Future studies should prospectively track injuries to minimise the effect of recall bias, whilst allowing collection of a detailed injury history at the time of injury.

Conclusion

This study found that, in general, isometric muscle strength, joint motion, functional foot alignment, and side to side asymmetry values of these measures were not significantly different between runners who were recently injured, had acquired re-injury resistance or runners who were never injured. These findings suggest that injury resistant runners cannot be distinguished from previously injured runners using popular clinical tests, likely due to high engagement with rehabilitation. While these clinical factors may be important in the assessment and rehabilitation of injured athletes, the results of this study indicate that they have limited value in identifying future injury resistance of runners.

Acknowledgments

This publication has emanated from research supported by Science Foundation Ireland (SFI) under Grant Number SFI/12/RC/2289_P2, co-funded by the European Regional Development Fund. The authors would like to thank the participants for their time in partaking in this study.

Conflict of Interest

The authors declare that they have no conflicts of interest. The results of the present study do not constitute endorsement by ACSM. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

References

1. Van Gent RN, Siem D, Van Middelkoop M, Van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. Br J Sport Med [Internet]. 2007 [cited 2017 Oct 23];41:469–80. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2465455/pdf/469.pdf

2. Kalkhoven JT, Watsford ML, Impellizzeri FM. A conceptual model and detailed framework for stress-related, strain-related, and overuse athletic injury [Internet]. Vol. 23, Journal of Science and Medicine in Sport. 2020 [cited 2020 Sep 30]. p. 726–34. Available from: https://doi.org/10.1016/j.jsams.2020.02.002

3. Cavanagh PR, Lafortune MA. Ground reaction forces in distance running. J Biomech. 1980;13(5):397–406.

4. Ferenczi MA, Bershitsky SY, Koubassova NA, Kopylova G V., Fernandez M, Narayanan T, et al. Why muscle is an efficient shock absorber. PLoS One. 2014;9(1).

5. Mason-Mackay AR, Whatman C, Reid D. The effect of reduced ankle dorsiflexion on lower extremity mechanics during landing: A systematic review. J Sci Med Sport [Internet]. 2017 [cited 2020 Feb 17];20:451–8. Available from: http://dx.doi.org/10.1016/j.jsams.2015.06.006

6. Pérez-Morcillo A, Gómez-Bernal A, Gil-Guillen VF, Alfaro-Santafé J, Alfaro-Santafé JV, Quesada JA, et al. Association between the Foot Posture Index and running related injuries: A case-control study. Clin Biomech [Internet]. 2019 [cited 2019 Mar 25];61:217–21. Available from: https://doi.org/10.1016/j.clinbiomech.2018.12.019

7. Mucha MD, Caldwell W, Schlueter EL, Walters C, Hassen A. Hip abductor strength

and lower extremity running related injury in distance runners: A systematic review. J Sci Med Sport [Internet]. 2017 Apr [cited 2019 Jan 24];20(4):349–55. Available from: http://dx.doi.org/10.1016/j.jsams.2016.09.002

8. Becker J, James S, Wayner R, Osternig L, Chou LS. Biomechanical Factors Associated with Achilles Tendinopathy and Medial Tibial Stress Syndrome in Runners. Am J Sports Med [Internet]. 2017 [cited 2018 Dec 11];45(11):2614–21. Available from: https://journals-sagepub-com.dcu.idm.oclc.org/doi/pdf/10.1177/0363546517708193

9. Ithurburn MP, Paterno M V., Ford KR, Hewett TE, Schmitt LC. Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics. Am J Sports Med. 2015 Nov 1;43(11):2727–37.

10. Zifchock RA, Davis I, Higginson J, McCaw S, Royer T. Side-to-side differences in overuse running injury susceptibility: A retrospective study. Hum Mov Sci [Internet]. 2008 [cited 2017 Oct 23];27:888–902. Available from: https://ac.els-cdn.com/S0167945708000560/1-s2.0-S0167945708000560-main.pdf?_tid=616c3714-0cc8-11e8-90ea-00000aacb35d&acdnat=1518091720_04b365b16f60f183368d4e0ea9f20ca0

11. Fredericson M, Cookingham CL, Chaudhari AM, Dowdell BC, Oestreicher N, Sahrmann ‡shirley A. Hip abductor weakness in distance runners with iliotibial band syndrome. Clin J Sport Med [Internet]. 2000 [cited 2019 Feb 26];10(3):169–75. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.477.4812&rep=rep1&type=pdf

12. Saragiotto BT, Yamato TP, Hespanhol Junior LC, Rainbow MJ, Davis IS, Lopes AD. What are the main risk factors for running-related injuries? Sport Med. 2014;44(8):1153–63.

13. Lun V, Meeuwisse WH, Stergiou P, Stefanyshyn D. Relation between running injury and static lower limb alignment in recreational runners. Br J Sports Med [Internet]. 2004 [cited 2020 Jun 13];38(5):576–80. Available from: www.bjsportmed.com

14. Buist I, Bredeweg SW, Lemmink KAPM, Van Mechelen W, Diercks RL. Predictors of running-related injuries in novice runners enrolled in a systematic training program: A prospective cohort study. Am J Sports Med [Internet]. 2010 [cited 2019 Feb 25];38(2):273–80. Available from: http://ajs.

15. de Wijer A, van Cingel R, Staal JB, Nijhuis-van der Sanden MWG, van der Worp MP, ten Haaf DSM. Injuries in Runners; A Systematic Review on Risk Factors and Sex Differences. PLoS One [Internet]. 2015 [cited 2017 Nov 2];10(2):e0114937. Available from: http://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0114937&type=printable

16. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39(2):175–91.

17. Mentiplay BF, Perraton LG, Bower KJ, Adair B, Pua YH, Williams GP, et al. Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: A reliability and validity study. PLoS One [Internet]. 2015 [cited 2017 Nov 22];10(10). Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4624940/pdf/pone.0140822.pdf

18. Thorborg K, Petersen J, Magnusson SP, Hölmich P. Clinical assessment of hip strength using a hand-held dynamometer is reliable. Scand J Med Sci Sport [Internet]. 2010 Jun 23 [cited 2019 May 2];20(3):493–501. Available from: http://www.ncbi.nlm.nih.gov/pubmed/19558384

19. Luedke LE, Heiderscheit BC, Williams DSB, Rauh MJ. Association of Isometric Strength of Hip and Knee Muscles With Injury Risk in High School Cross Country Runners. Int J Sports Phys Ther [Internet]. 2015 [cited 2019 Feb 26];10(6):868–76. Available from: http://www.ncbi.nlm.nih.gov/pubmed/26618066%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC4637921

20. Bennett JE, Reinking MF, Rauh MJ. The relationship between isotonic plantar flexor endurance, navicular drop, and exercise-related leg pain in a cohort of collegiate cross-country runners. Int J Sports Phys Ther [Internet]. 2012 [cited 2019 Mar 22];7(3):267–78. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3362985/pdf/ijspt-07-267.pdf

21. Redmond AC, Crosbie J, Ouvrier RA. Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index. Clin Biomech [Internet]. 2006 [cited 2018 Feb 8];21(1):89–98. Available from: http://www.clinbiomech.com/article/S0268-0033(05)00180-4/pdf

22. Teyhen DS, Stoltenberg BE, Collinsworth KM, Giesel CL, Williams DG, Kardouni CH, et al. Dynamic plantar pressure parameters associated with static arch height index during gait. Clin Biomech. 2009;24(4):391–6.

23. Konor MM, Morton S, Eckerson JM, Grindstaff TL. Reliability of three measures of ankle dorsiflexion range of motion. Int J Sports Phys Ther [Internet]. 2012 [cited 2017

Dec 14];7(3):279–87. Available from:
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3362988/pdf/ijspt-07-279.pdf

24. Cannon A, Finn K, Yan Z. Comparison of hip internal rotation and external rotation between intercolleagiate distance runners and non-running college students. Int J Sports Phys Ther [Internet]. 2018 [cited 2020 Nov 5];13(6):956–62. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6253754/pdf/ijspt-13-956.pdf

25. Vigotsky AD, Lehman GJ, Beardsley C, Contreras B, Chung B, Feser EH. The modified Thomas test is not a valid measure of hip extension unless pelvic tilt is controlled. PeerJ. 2016 Aug 11;2016(8):e2325.

26. Bierma-Zeinstra SMA, Bohnen AM, Ramlal R, Ridderikhoff J, Verhaar JAN, Prins A. Comparison between two devices for measuring hip joint motions. Clin Rehabil. 1998;12(6):497–505.

27. Yamato T, Saragiotto B, Hespanhol Junior L, Yeung S, Lopes A. Definitions Used To Define A Running-Related Musculoskeletal Injury: A Systematic Review. J Orthop Sport Phys Ther. 2015;45(5):375–80.

28. Tomczak M, Tomczak E. The need to report effect size estimates revisited. An overview of some recommended measures of effect size. Trends Sport Sci [Internet]. 2014 [cited 2020 Aug 5];1(21):19–25. Available from: http://www.wbc.poznan.pl/Content/325867/5_Trends_Vol21_2014_ no1_20.pdf

29. Torp DM, Donovan L, Gribble PA, Thomas AC, Bazett-Jones DM, Beard MQ. No baseline strength differences between female recreational runners who developed an injury and injury free runners during a 16-week formalized training program. Phys Ther Sport [Internet]. 2018 Nov [cited 2019 Jan 25];34:1–7. Available from: https://linkinghub.elsevier.com/retrieve/pii/S1466853X18300865

30. Becker J, Nakajima M, Wu WFW. Factors Contributing to Medial Tibial Stress Syndrome in Runners: A Prospective Study. Med Sci Sports Exerc [Internet]. 2018 Oct [cited 2019 Mar 1];50(10):2092–100. Available from: http://insights.ovid.com/crossref?an=00005768-201810000-00014

31. Plastaras C, McCormick Z, Nguyen C, Rho M, Nack SH, Roth D, et al. Is Hip Abduction Strength Asymmetry Present in Female Runners in the Early Stages of Patellofemoral Pain Syndrome? Am J Sports Med [Internet]. 2016 [cited 2019 Jan 24];44(1):105–12. Available from: https://journals-sagepub-com.dcu.idm.oclc.org/doi/pdf/10.1177/0363546515611632

32. Esculier JF, Roy JS, Bouyer LJ. Lower limb control and strength in runners with and without patellofemoral pain syndrome. Gait Posture [Internet]. 2015 Mar [cited 2018 Nov 15];41(3):813–9. Available from: http://www.ncbi.nlm.nih.gov/pubmed/25800001

33. Saeki J, Nakamura M, Nakao S, Fujita K, Yanase K, Morishita K, et al. Ankle and toe muscle strength characteristics in runners with a history of medial tibial stress syndrome. J Foot Ankle Res [Internet]. 2017 [cited 2019 Mar 22];10:16. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5387355/pdf/13047_2017_Article_197.pdf

34. Gehlsen GM, Seger A. Selected measures of angular displacement, strength, and flexibility in subjects with and without shinsplints. Res Q Exerc Sport [Internet]. 1980 Oct [cited 2020 Apr 2];51(3):478–85. Available from: http://www.tandfonline.com/doi/abs/10.1080/02701367.1980.10608070

35. Kibler WB, Goldberg C, Chandler TJ. Functional biomechanical deficits in running

athletes with plantar fasciitis. Am J Sports Med [Internet]. 1991 Jan 23 [cited 2020 Apr 2];19(1):66–71. Available from: http://www.ncbi.nlm.nih.gov/pubmed/1672577

36. Mascaró A, Cos MÀ, Morral A, Roig A, Purdam C, Cook J. Load management in tendinopathy: Clinical progression for Achilles and patellar tendinopath. Apunt Med l'Esport. 2018 Jan 1;53(197):19–27.

37. Ferber R, Kendall KD, Farr L. Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. J Athl Train [Internet]. 2011 [cited 2019 Apr 17];46(2):142–9. Available from: www.nata.org/jat

38. Noehren B, Pohl MB, Sanchez Z, Cunningham T, Lattermann C. Proximal and distal kinematics in female runners with patellofemoral pain. Clin Biomech [Internet]. 2012 [cited 2017 Oct 20];27(4):366–71. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3984468/pdf/nihms563691.pdf

39. Noehren B, Davis I, Hamill J. ASB Clinical Biomechanics Award Winner 2006. Prospective study of the biomechanical factors associated with iliotibial band syndrome. Clin Biomech [Internet]. 2007 [cited 2017 Oct 23];22(9):951–6. Available from: https://ac.els-cdn.com/S0268003307001404/1-s2.0-S0268003307001404-main.pdf?_tid=d1e2d054-b7df-11e7-ac55-00000aab0f6c&acdnat=1508755938_c690d5b76e161749467db4d115c71a2f

40. Kendall F, Kendall McCreary E, Geise Provance P, McIntyre Rodgers M, Romani W. Muscles: Testing and Function with Posture and Pain. 5th ed. Baltimore: Lippincott Williams & Wilkins; 2005.

41. Christopher SM, McCullough J, Snodgrass SJ, Cook C. Do alterations in muscle strength, flexibility, range of motion, and alignment predict lower extremity injury in runners: a systematic review. Arch Physiother [Internet]. 2019 [cited 2019 Feb

22];9(1):2. Available from: https://doi.org/10.1186/s40945-019-0054-7

42. Winkelmann ZK, Anderson D, Games KE, Eberman LE. Risk factors for medial tibial stress syndrome in active individuals: An evidence-based review. J Athl Train. 2016 Dec 1;51(12):1049–52.

43. Williams DSB, Tierney RN, Butler RJ. Increased medial longitudinal arch mobility, lower extremity kinematics, and ground reaction forces in high-arched runners. J Athl Train [Internet]. 2014 [cited 2019 May 21];49(3):290–6. Available from: www.natajournals.org

44. Nohr EA, Parner ET, Sørensen H, Buist I, Rasmussen S, Lind M, et al. Foot pronation is not associated with increased injury risk in novice runners wearing a neutral shoe: a 1-year prospective cohort study. Br J Sports Med [Internet]. 2013 [cited 2017 Nov 6];48(6):440–7. Available from: http://bjsm.bmj.com/content/bjsports/early/2013/06/12/bjsports-2013-092202.full.pdf

45. Bishop P, Cureton K, Collins M. Sex difference in muscular strength in equally-trained men and women. Ergonomics [Internet]. 1987 [cited 2020 Apr 2];30(4):675–87. Available from: https://www.researchgate.net/publication/19552903

46. Van Der Worp MP, De Wijer A, Staal JB, Van Der Sanden MWGN. Reproducibility of and sex differences in common orthopaedic ankle and foot tests in runners. BMC Musculoskelet Disord [Internet]. 2014 [cited 2020 Mar 31];15(1). Available from: http://www.biomedcentral.com/1471-2474/15/171

47. Czuppon S, Prather H, Hunt DM, Steger-May K, Bloom NJ, Clohisy JC, et al. Gender-Dependent Differences in Hip Range of Motion and Impingement Testing in Asymptomatic College Freshman Athletes. PM R. 2017;9(7):660–7.

48. Bailey CA, Sato K, Burnett A, Stone MH. Force-production asymmetry in male and female athletes of differing strength levels. Int J Sports Physiol Perform. 2015;10(4):504–8.

49. Francis P, Whatman C, Sheerin K, Hume P, Johnson MI. The proportion of lower limb running injuries by gender, anatomical location and specific pathology: A systematic review [Internet]. Vol. 18, Journal of Sports Science and Medicine. 2019 [cited 2019 Mar 1]. p. 21–31. Available from: http://www.jssm.org

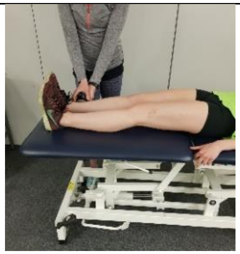
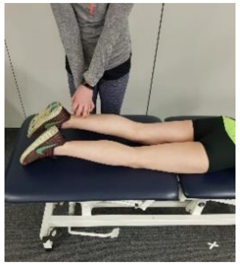
50. Novacheck TF. The biomechanics of running [Internet]. Vol. 7, Gait and Posture. 1998 [cited 2018 Nov 15]. p. 77–95. Available from: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.467.9707&rep=rep1&type=pdf

List of Supplemental Content:

Supplementary Digital Content 1.docx

Supplementary Digital Content 2.docx

Table 1 Portable dynamometry manual muscle strength testing protocols.

Movement Tested	Stabilisation Belt	Patient Position	Dynamometer Position Protocol	Image of testing
Hip Abduction	N/A	Supine, knees in extension, hips in neutral	Positioned 5cm proximal to the lateral malleolus (17).	
Hip Extension	N/A	Prone, knee extended, hips in neutral.	Positioned on the posterior calf complex, in line with a mark that is 5cm proximal to the medial malleolus (17).	
Plantar Flexion	Around the plinth and the sole of the subject's shoe.	Prone, knees bent to 90 degrees of flexion and foot in plantar grade.	Positioned between the belt and the metatarsal heads of the sole of the foot.	

Knee Extension	A suction plug was used to fix the stabilisation belt to a concrete wall structure, allowing the tester to fasten the stabilisation belt around the anterior aspect of the shank, proximal to the ankle joint (18).	Seated position with hips and knees flexed to 90 degrees.	Positioned between the anterior shank and the belt, and participants was instructed to kick out against it.	
Knee Flexion	A suction plug was used to fix the stabilisation belt to a concrete wall structure, allowing the tester to fasten the stabilisation belt around the anterior aspect of the shank, proximal to the ankle joint.	Seated position, again with hips and knees flexed to 90 degrees. Note: For the purpose of clear visibility the other leg was staggered behind the testing leg. This was done in practice with both feet in parallel.	Positioned between the posterior shank and the belt, posterior aspect of the shank, proximal to the ankle joint (18).	

Abbreviations: N/A: not applicable.

Table 2 The location of injuries among the recently injured group.

Injury Location	Number of injuries at this location	Percentage of injuries at this location (%)
Calf	30	20.4
Knee	19	12.9
Posterior thigh	18	12.2
Shin	12	8.2
Foot	11	7.5
Lateral thigh	10	6.8
Ankle	7	4.8
Lower Back	9	6.1
Hip	9	6.1
Buttock	7	4.8
Medial thigh	5	3.4
Heel	5	3.4
Anterior thigh	2	1.4
Toes	2	1.4
Sacroiliac Joint	1	0.7

Table 3 Table of subject demographics.

		Recently Injured				Acquired Re-injury Resistance				Never-injured				p value
	Total n	Males, females	Group	Males	Females	Males, females	Group	Males	Females	Males, females	Group	Males	Females	
			(Mean ± SD)	(Mean ± SD)	(Mean ± SD)		(Mean ± SD)	(Mean ± SD)	(Mean ± SD)		(Mean ± SD)	(Mean ± SD)	(Mean ± SD)	
Age (years)	223	77 M, 39 F	43.11 ± 8.67	43.34 ± 9.16	42.67 ± 7.72	38 M, 23 F	44.70 ± 8.64	45.58 ± 8.13	43.26 ± 9.43	29 M, 17 F	41.76 ± 10.41	43.34 ± 11.41	39.06 ± 8.06	.989
Weight (kg)	223	77 M, 39 F	72.93 ± 11.78	78.30 ± 9.26	62.34 ± 8.65	38 M, 23 F	72.63 ± 13.15	79.56 ± 10.55	61.19 ± 8.03	29 M, 17 F	72.90 ± 14.05	80.81 ± 10.69	59.41 ± 7.02	.494
Height (m)	223	77 M, 39 F	1.73 ± 0.09	1.77 ± 0.06	1.64 ± 0.07	38 M, 23 F	1.74 ± 0.10	1.79 ± 0.07	1.66 ± 0.08	29 M, 17 F	1.72 ± 0.10	1.77 ± 0.08	1.63 ± 0.07	.243

Abbreviated Terms: n- number of participants, SD- standard deviation.

Table 4 Descriptive statistics for each clinical measure.

		Recently Injured				Acquired Re-injury Resistance				Never-injured			
Clinical Test	Total n	Males, females	Group	Males	Females	Males, females	Group	Males	Females	Males, females	Group	Males	Females
			Mean ± SD*	Mean ± SD*	Mean ± SD*		Mean ± SD*	Mean ± SD*	Mean ± SD*		Mean ± SD*	Mean ± SD*	Mean ± SD*
Hip abduction strength (Nm/kg)	211	73 M, 34 F	1.75 ± 0.33	1.84 ± 0.30	1.56 ± 0.30	37 M, 22 F	1.64 ± 0.28	1.70 ± 0.27	1.54 ± 0.27	28 M, 17 F	1.56 ± 0.29	1.59 ± 0.31	1.51 ± 0.25
Hip extension strength (Nm/kg)	211	73 M, 34 F	1.98 ± 0.50	2.07 ± 0.50	1.80 ± 0.46	37 M, 22 F	1.90 ± 0.41	1.95 ± 0.42	1.82 ± 0.38	28 M, 17 F	1.82 ± 0.44	1.88 ± 0.47	1.72 ± 0.39
Plantar flexion strength (Nm/kg)	211	73 M, 34 F	0.61 ± 0.23	0.64 ± 0.22	0.57 ± 0.23	37 M, 22 F	0.60 ± 0.20	0.61 ± 0.19	0.59 ± 0.23	28 M, 17 F	0.48 ± 0.17	0.51 ± 0.15	0.44 ± 0.19
Knee flexion strength (Nm/kg)	209	72 M, 34 F	1.40 ± 0.33	1.50 ± 0.32	1.19 ± 0.26	37 M, 22 F	1.37 ± 0.31	1.47 ± 0.32	1.23 ± 0.24	28 M, 16 F	1.31 ± 0.74	1.39 ± 0.38	1.16 ± 0.30
Knee extension strength (Nm/kg)	210	73 M, 34 F	1.37 ± 0.39	1.49 ± 0.35	1.10 ± 0.34	37 M, 22 F	1.35 ± 0.43	1.47 ± 0.45	1.15 ± 0.30	28 M, 16 F	1.23 ± 0.47	1.35 ± 0.49	1.03 ± 0.36
Navicular drop (mm)	206	68 M, 37 F	8.4 ± 2.8	8.7 ± 2.7	7.8 ± 2.8	35 M, 20 F	8.6 ± 3.3	9.6 ± 3.4	6.7 ± 1.9	29 M, 17 F	8.8 ± 3.1	9.5 ± 3.3	7.5 ± 2.6
Foot Posture Index	212	70 M, 37 F	7 (4. 8)	6 (4, 8)	7 (4, 8)	36 M, 23 F	5 (3, 7)	6 (4, 8)	4 (1, 6)	29 M, 17 F	6 (4, 8)	6 (5, 8)	5 (3, 8)
Hip IR motion (degrees)	210	70 M, 38 F	39.1 ± 6.0	38.1 ± 6.3	41.0 ± 5.2	36 M, 20 F	40.5 ± 5.8	40.5 ± 5.6	40.7 ± 6.2	29 M, 17 F	40.1 ± 6.8	39.9 ± 6.6	42.7 ± 7.0
Hip ER motion (degrees)	210	70 M, 38 F	36.9 ± 6.2	35.5 ± 5.7	39.4 ± 6.4	36 M, 20 F	36.2 ± 6.18	36.2 ± 6.5	36.3 ± 5.7	29 M, 17 F	35.0 ± 5.2	34.8 ± 5.2	35.3 ± 5.2
Hip extension motion (degrees)	210	70 M, 38 F	12.1 ± 7.7	11.7 ± 8.1	12.8 ± 7.0	36 M, 20 F	12.6 ± 7.7	11.7 ± 8.9	14.2 ± 4.5	29 M, 17 F	12.3 ± 7.1	12.8 ± 6.4	11.5 ± 8.3
Ankle DF motion (degrees)	210	70 M, 38 F	40.4 ± 3.4	40.4 ± 3.3	40.3 ± 3.6	36 M, 20 F	40.0 ± 3.9	41.0 ± 4.7	38.2 ± 4.9	29 M, 17 F	39.5 ± 3.4	39.8 ± 3.3	38.8 ± 3.7

Abbreviated Terms: n- number of participants, M- males, F- females, SD- standard deviation, IR- internal rotation, ER- external rotation, DF- dorsiflexion. * Denotes that median (first quartile, third quartile) was reported.

Table 5 Results of the Two Way ANOVA investigating the differences in means between the different injury groups and sex for each clinical measure

Clinical Measure	***P value-injury status***	***Effect size-injury status***	***P value-sex***	***Effect size-sex***	***P value-injury status*sex***	***Effect size-injury status* sex***
Hip abduction strength	.019*	.038	.000*	.069	.143	.019
Hip extension strength	.285	.012	.008*	.034	.660	.004
Plantar flexion strength	.002*	.057	.078	.015	.794	.003
Knee flexion strength	.471	.007	.000*	.125	.678	.004
Knee extension strength	.257	.013	.000*	.141	.826	.002
Navicular drop	.836	.002	.000*	.089	.126	.002
Foot Posture Index	.179	.017	.065	.016	.023*	.036
Hip extension motion	.839	.002	.484	.021	.472	.007
Hip IR motion	.270	.013	.038*	.024	.477	.008
Hip ER motion	.076	.025	.095	.014	.102	.022
Ankle DF motion	.215	.015	.019*	.027	.148	.019
Hip abduction strength SA	.467	.007	.805	.000	.085	.024
Hip extension strength SA	.422	.008	.196	.008	.527	.006
Plantar flexion strength SA	.422	.008	.629	.001	.492	.007
Knee flexion strength SA	.572	.005	.037*	.021	.950	.001
Knee extension strength SA	.240	.014	.574	.002	.736	.003
Navicular drop SA	.861	.001	.632	.001	.338	.011
Foot Posture Index SA	.343	.004	.311	.011	.943	.001

Hip IR motion SA	.497	0.007	.578	.002	.206	.015
Ankle DF motion SA	0.636	0.004	.753	.003	.411	.003

*Abbreviation: SA- symmetry angle, IR- internal rotation, ER- external rotation, DF- dorsiflexion. *Indicates a significant difference between groups.*

Table 6 Foot Posture Index breakdown of the injury groups.

	Recently Injured		Acquired Re-injury Resistance		Never Injured	
	n	%	n	%	n	%
Neutral	26	29	38	51	17	37
Pronated	53	58	22	29	20	43
Highly Pronated	7	8	6	8	5	11
Supinated	3	3	6	8	2	4
Highly Supinated	3	3	2	3	2	4

Abbreviation: n- number of participants

Table 7 Descriptive statistics of symmetry angle values for each clinical measure.

		Recently Injured				Acquired Re-injury Resistance				Never-injured			
Clinical Measure	**Total n**	**Males, Females**	**Group**	**Males**	**Females**	**Males, Females**	**Group**	**Males**	**Females**	**Males, Females**	**Group**	**Males**	**Females**
			Mean ± SD	**Mean ± SD**	**Mean ± SD**		**Mean ± SD**	**Mean ± SD**	**Mean ± SD**		**Mean ± SD**	**Mean ± SD**	**Mean ± SD**
Hip abduction strength SA	211	73 M, 34 F	2.53 ± 2.07	2.52 ± 2.16	2.54 ± 1.90	37 M, 22 F	2.56 ± 2.35	2.97 ± 2.44	1.88 ± 2.06	28 M, 17 F	2.84 ± 2.04	2.53 ± 1.64	3.35 ± 2.53
Hip extension strength SA	211	73 M, 34 F	2.66 ± 2.32	2.65 ± 2.52	2.68 ± 1.83	36 M, 20 F	3.30 ± 2.70	3.62 ± 2.85	2.77 ± 2.39	28 M, 17 F	2.73 ± 2.57	3.01 ± 2.46	2.35 ± 2.76
Plantar flexion strength SA	211	73 M, 34 F	6.98 ± 4.82	7.24 ± 4.47	6.41 ± 5.54	37 M, 22 F	7.61 ± 5.74	7.38 ± 5.26	8.01 ± 6.60	28 M, 17 F	7.85 ± 6.19	7.32 ± 6.01	8.72 ± 6.57
Knee flexion strength SA	209	72 M, 34 F	17.38 ± 5.31	16.77 ± 5.61	18.65 ± 4.41	37 M, 22 F	16.71 ± 5.71	15.91 ± 5.03	18.04 ± 6.60	28 M, 16 F	17.96 ± 6.14	17.45 ± 6.05	18.85 ± 6.40
Knee extension strength SA	210	73 M, 34 F	4.03 ± 3.18	3.78 ± 2.90	4.58 ± 3.70	37 M, 22 F	5.13 ± 3.43	5.12 ± 3.05	5.15 ± 4.07	28 M, 16 F	4.41 ± 3.56	4.39 ± 3.24	4.43 ± 4.16
Navicular drop SA	206	68 M, 37 F	6.12 ± 5.07	5.54 ± 4.28	7.19 ± 6.20	35 M, 20 F	6.33 ± 4.32	6.15 ± 4.68	6.66 ± 3.70	29 M, 17 F	6.04 ± 5.68	6.43 ± 5.51	5.37 ± 6.05
Foot Posture Index SA	212	70 M, 37 F	4.04 ± 13.12	3.63 ± 12.28	4.80 ± 14.73	36 M, 23 F	1.59 ± 4.56	0.75 ± 1.92	2.91 ± 6.78	29 M, 17 F	2.29 ± 4.56	1.94 ± 3.59	2.89 ± 5.95
Hip IR motion SA	210	70 M, 38 F	3.79 ± 2.81	3.63 ± 2.90	4.09 ± 2.63	36 M, 20 F	3.86 ± 3.58	4.35 ± 3.88	2.98 ± 2.84	29 M, 17 F	3.19 ± 2.69	3.14 ± 2.86	3.27 ± 2.45
Hip ER motion SA	210	70 M, 38 F	4.24 ± 3.40	4.85 ± 3.80	3.12 ± 2.13	36 M, 20 F	4.12 ± 4.65	4.50 ± 5.21	3.43 ± 3.45	29 M, 17 F	4.29 ± 3.65	4.49 ± 3.89	3.95 ± 3.29
Ankle DF motion SA	210	70 M, 38 F	1.95 ± 1.91	1.88 ± 1.67	2.07 ± 2.32	36 M, 20 F	1.85 ± 1.41	1.67 ± 1.28	2.16 ± 1.59	29 M, 17 F	2.23 ± 1.48	2.25 ± 1.57	2.21 ± 1.35
Hip extension motion SA	210	70 M, 38 F	17.18 ± 26.34	19.02 ± 28.61	13.79 ± 21.51	37 M, 22 F	16.63 ± 25.71	20.09 ± 30.84	10.42 ± 9.93	29 M, 17 F	17.18 ± 29.63	10.58 ± 17.74	28.42 ± 41.29

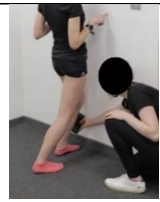
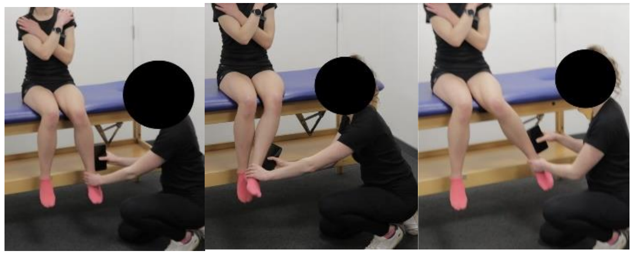
Abbreviation: n- number of participants, SD- standard deviation, SA- symmetry angle, M- males, F- females, IR- internal rotation, ER- external rotation, DF- dorsiflexion.

Table 8 Results of non-parametric tests investigating the differences in means between the different injury groups and sex for each clinical measure.

Clinical Measure	*P* value- injury status	Effect size- injury status	*P* value- sex	Effect size- sex
Hip ER motion SA	.508	.003	.064	.011
Hip extension motion SA	.960	.009	.160	.005

Abbreviation: n- number of participants, SD- standard deviation, M- males, F- females, ER- external rotation, SA- symmetry angle.

Supplementary Digital Content 1: Joint motion testing protocols.

Movement Tested	Patient Starting Position	Test Movement	Smartphone Placement	Image of Testing
Dorsiflexion motion	Standing in a split stance facing a wall, with both heels in contact with the ground (23).	Knee actively advanced forward over second toe (8, 23).	Tibial tuberosity	
Hip extension motion	Sitting on the edge of a firm plinth	Participant guided into supine lying with legs over the edge of the plinth with the bio-feedback pressure cuff stabilize placed proximal to the posterior superior iliac spines of the lower back.	Midline of the femur, 5cm proximal to the superior surface of the patella (25).	
Hip internal and external rotation motion	Sitting with arms folded on the edge of a plinth	The hip was then passively maximally rotated on the frontal plane, with care taken to minimise compensatory movements (26).	Lateral fibula, 5cm proximal to the lateral malleolus.	

Abbreviations: N/A: not applicable.

Supplementary Digital Content 2: Reliability Data

Table A. The inter-rater reliability of summed values of each of the outcome measures.

Measure	Intraclass correlation coefficient	Lower bound- upper bound	Standard error of measurement	Minimum detectable change
Navicular drop (mm)	.848	.855 - .981	1.311	3.63
FPI	.961	.893 - .996	2.2	6.10
Hip abduction strength (Nm/kg)	.898	.707 - .964	0.21	0.58
Plantar flexion strength (Nm/kg)	.834	.526 - .924	0.88	2.44
Hip extension strength (Nm/kg)	.906	.732 - .967	0.33	0.91
Knee flexion strength (nm/kg)	.912	.748 - .969	0.75	2.08
Knee extension strength (nm/kg)	.942	.548 - .945	0.36	1.00
Hip internal rotation motion (°)	.963	.901 - .986	3.32	9.21
Hip extension motion (°)	.877	.672 - .954	2.94	8.14
Hip external rotation motion (°)	.761	.360 - .911	2.06	5.71
Dorsiflexion motion (°)	.797	.457 - .924	1.80	4.99

Table B. The intra-rater reliability of asymmetry angle values of each of the outcome measures.

Measure	Intraclass Correlation Coefficient	Lower Bound- Upper Bound	Standard Error of Measurement	Minimum Detectable Change
Navicular drop	.946	.852 - .981	1.19	3.30
FPI	.990	.971 - .996	2.3	6.38
Hip abduction strength	.850	.585 - .946	0.21	0.58
Plantar flexion strength	.831	0.533 - .939	0.85	2.36
Hip extension strength	.906	.732 - .967	0.33	0.91
Knee flexion strength	.912	.748 - .969	0.75	2.08
Knee extension strength	.942	.548 - .945	0.36	1.00
Hip internal rotation motion	.952	.871 - .982	5.5	15.25

Hip extension motion	.906	.732 - .967	0.33	0.91
Hip External rotation motion	.937	.832 - .977	4.87	13.50
Dorsiflexion motion	.933	.820 - .975	5.11	14.16

Abbreviations: FPI- Foot Posture Index