OPEN

Published ahead of Print

Running Distance and Biomechanical Risk Factors for Plantar Fasciitis: A One-Year Prospective 4HAIE Cohort Study

Jan Plesek[1], Joseph Hamill[1,2], Michal Burda[3], Steriani Elavsky[1], Jiri Skypala[1], Jan Urbaczka[1], Julia Freedman Silvernail[1,4], David Zahradnik[1], Jaroslav Uchytil[1], and Jandacka Daniel[1]

[1]Department of Human Movement Studies, University of Ostrava, CZECH REPUBLIC; [2]Department of Kinesiology, University of Massachusetts, Amherst, MA; [3]Institute for Research and Applications of Fuzzy Modeling, University of Ostrava, CE IT4Inonovation, CZECH REPUBLIC; [4]Department of Kinesiology and Nutrition Sciences, University of Nevada Las Vegas, NV

Accepted for Publication: 20 November 2024

ACCEPTED

Downloaded from http://journals.lww.com/acsm-msse by BhDMf5ePHKav1zEoum1tQfN4a+kJLhEZgbsIHo4XMi0hCywCX1AWnYQp/IlQrHD3i3D0OdRyi7TvSFl4Cf3VC1y0abggQZXdtwnfKZBYtws= on 12/10/2024

Medicine & Science in Sports & Exercise® Published ahead of Print contains articles in unedited manuscript form that have been peer reviewed and accepted for publication. This manuscript will undergo copyediting, page composition, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered that could affect the content.

Copyright © 2024 American College of Sports Medicine

Medicine & Science in Sports & Exercise, Publish Ahead of Print
DOI: 10.1249/MSS.0000000000003617

Running Distance and Biomechanical Risk Factors for Plantar Fasciitis: A One-Year Prospective 4HAIE Cohort Study

Jan Plesek[1], Joseph Hamill[1,2], Michal Burda[3], Steriani Elavsky[1], Jiri Skypala[1], Jan Urbaczka[1], Julia Freedman Silvernail[1,4], David Zahradnik[1], Jaroslav Uchytil[1], and Jandacka Daniel[1]

[1]Department of Human Movement Studies, University of Ostrava, CZECH REPUBLIC; [2]Department of Kinesiology, University of Massachusetts, Amherst, MA; [3]Institute for Research and Applications of Fuzzy Modeling, University of Ostrava, CE IT4Inonovation, CZECH REPUBLIC; [4]Department of Kinesiology and Nutrition Sciences, University of Nevada Las Vegas, NV

Address for correspondence: Jan Plesek, University of Ostrava, 702 00, Moravska 3397, Ostrava, Czech Republic; E-mail: jan.plesek@osu.cz

ACCEPTED

Conflict of Interest and Funding Source: This work has been produced with the financial support of the European Union under the LERCO project (CZ.10.03.01/00/22_003/0000003) via the Operational Programme Just Transition and from the project Research of Excellence on Digital Technologies and Wellbeing (CZ.02.01.01/00/22_008/0004583) which is co-financed by the European Union. The baseline data refers to the project funded by the Czech Ministry of

Education, Youth and Sports, the project 4HAIE “Healthy Aging in the Industrial Environment - Program 4” (CZ.02.1.01/0.0/0.0/16_019/0000798) within its sustainability period. No potential conflict of interest was reported by the authors.

This is an open-access article distributed under the terms of the Creative Commons Attribution-Non Commercial-No Derivatives License 4.0 (CCBY-NC-ND), where it is permissible to download and share the work provided it is properly cited. The work cannot be changed in any way or used commercially without permission from the journal.

ACCEPTED

ABSTRACT

Introduction: Plantar fasciitis (PF) is one of the most common running-related injuries. **Purpose:** The aim of this prospective study was to determine the incidence of PF and identify potential risk or protective factors for PF in runners and non-runners. **Methods:** Data from 1206 participants from the 4HAIE cohort study (563 females/643 males; 715 runners/491 non-runners; 18-65 years of age) were included in the analysis. We collected biomechanical data during overground running using a 3-D motion capture system at the baseline and running distance data via retrospective questionnaires and followed the participants for 12 months following the baseline data collection. Participants were asked weekly about any sports-related injury (including PF). A binary logistic regression was performed to reveal potential associations between running distance and biomechanical risk factors and PF while controlling for running distance, sex, and age. **Results:** The total incidence of PF was 2.3% (28 PF from 1206 participants), 2.5% in runners and 2.0% in non-runners (*P* = 0.248). Runners who ran more than 40 km per week had six times higher odds of suffering PF than individuals who ran 6-20 km/week (*P* = 0.009). There was a significant association between maximal ankle adduction and PF, that is, runners with a lower abduction angle during the stance period had higher risk of PF (*P* = 0.024). No other biomechanical variables indicated significant associations with PF. **Conclusions:** Regular running with a moderate weekly volume and more toeing out of the foot relative to the shank may reduce the risk against PF in runners which may be useful for researchers, runners, coaches, and health professionals to minimize PF injury risk.

Key Words: ANKLE KINEMATICS, OVERUSE INJURY, GAIT ANALYSIS, JOGGING, LOADING RATES

ACCEPTED

INTRODUCTION

Plantar fasciitis (PF), also known as “runner´s heel”, is among the most commonly reported running-related injuries in recreational runners, second only to Achilles tendinopathy, with an incidence ranging from 4-22% incidence (mean 6.1%) (1). PF is characterized by intense inferior heel pain and discomfort, posing a substantial burden on the individual´s daily activities (2). Despite this inferior heel pain, about 40% of runners do not stop running. In addition, approximately 50% of these runners who experience heel problems do not even seek medical care or physiotherapy (3).

Unfortunately, to date, the cause and/or risk factors for PF are not well understood (2, 4). A better understanding of the underlying risk factors for PF is of paramount importance in enhancing the quality of life for those affected and minimizing its impact on a runner´s overall foot health or their training goals. A review by Wearing et al. (5) proposed several risk factors for PF: age, body mass, structural properties of the foot (low or high arch), foot and ankle biomechanics, footwear, surface, activity type and activity level. However, no single factor was reliably identified as a risk factor among the studies in this review. Therefore, there is still a lack of evidence for the combination of clinical and mechanical measures of foot and ankle function related to PF in runners (2). A prospective study by Di Caprio et al. (6), suggested that the incidence of PF in runners was related to a cavus foot arch, hindfoot and knee varus, years of participation in a regular running activity, number of kilometers per week and height of the athlete. On the contrary, the study found no significant links between plantar fasciitis (PF) and age, mass, or BMI. Importantly, the study did not examine running biomechanics nor did it include a non-running population. This group is of particular interest because less physically active/non-athletic

ACCEPTED

people may suffer from PF due to increased occupational time spent standing or walking on hard surfaces (2). Therefore, research projects should consider including groups of populations who are less physically active to further explore the various factors contributing to plantar fasciitis (PF), acknowledging that it is not solely a running-related injury.

To date, there are a few cross-sectional retrospective studies that have focused on biomechanical risk factors in runners with a history of PF (7–10). The following factors have been discussed as possible biomechanical risk factors: footstrike patterns (11), vertical loading rates (7, 9, 12, 13) and foot, ankle, and knee kinematics in the sagittal and frontal planes (7, 10, 14). However, these studies were unable to determine whether the observed biomechanical differences between resolved PF runners and healthy controls were a cause or a consequence of PF due to the retrospective designs. There remains a gap in the literature relative to prospective studies regarding running biomechanics (including 3D kinematics and kinetics of lower limb joints) and PF in runners.

Therefore, the aim of this study was to determine and compare the incidence of PF among different running distance groups and identify potential risk or protective factors for PF in runners and non-runners. We hypothesized that runners would be more likely to suffer from PF than non-runners because running groups with higher weekly running volume would have increased adjusted odds for PF. Additionally we hypothesized that running biomechanics (i.e., footstrike patterns, vertical loading rates, ankle range of motion to maximal dorsiflexion and maximal ankle adduction/abduction during stance phase (7, 11, 13, 15)) would affect the likelihood of being

ACCEPTED

diagnosed with PF within one year of follow-up when controlling for age, sex, and running distance.

METHODS

Study design and study sample size

This paper presents data from the multidisciplinary project “Healthy Aging in Industrial Environment program 4 (4HAIE)” focusing on musculoskeletal sports/physical activity/running related injuries (e.g. medial tibial stress syndrome, Achilles tendinopathy, plantar fasciitis, patellar tendinopathy, iliotibial band syndrome etc.) which includes baseline measurements and one-year prospective follow-up for each participant from air polluted or non- air polluted regions of the Czech Republic (16–18). The 4HAIE project sample size estimation was based on previous studies that focused on running-related injuries (19–21), and which indicated an injury incidence ranging between 3–85 %. This was confirmed by Kakouris et al. (1) who showed that the most common specific overuse running injuries ranged from 3-23% (i.e., medial tibial stress syndrome, plantar fasciitis, iliotibial band syndrome, Achilles tendinopathy, anterior knee pain, etc.). Power estimation was based on a model for binary logistic regression with 3 or 4 covariates (age, sex, running distance + single term addition covariate). A general guideline was to have at least 10 cases with a least frequent or expected outcome for each independent variable (covariates) in the model (22). Specifically, the incidence of PF ranged between 4-22% (mean 6.1 %) (1). For plantar fasciitis, the sample size estimation was based on a basic model with 3-4 covariates necessitating 750-1000 participants (10 cases per covariate * 3 or 4 covariates / 0.04 (expected PF incidence)). The 4HAIE study was approved by the Ethics and Research Committee of the University of

ACCEPTED

Ostrava (OU-87674190-2018) and was conducted in accordance with the principles of the Declaration of Helsinki. All participants signed an informed consent before the data collection.

Participants

We registered 8368 clicks on the online recruitment survey. A total of 5115 applicants (potential research participants) expressed interest in participating in the 4HAIE study, by registering for a screening questionnaire. However, most of the applicants did not successfully pass the questionnaire (N=3419). The questionnaire was set up to continuously assess the entry criteria into the study. If at any step the participant stopped meeting the entry (inclusion) criteria, the questionnaire was terminated with the information that he was not a suitable candidate for the research and did not answer any further items of the questionnaire. Consequently, 381 (from 1695) applicants were excluded during phone call screening period (99 – due to loss of interest in participating; 3 - did not want to participate due to reluctance to wear FitBit; 41 - health issues; 26 - personal reasons (work constraints, pregnancy, etc.); 13 - time constrains; 9 - moving out of the research region; 68 – did not answer to phone calls (no contact); 122 other reasons). The inclusion and exclusion criteria were reported in the accompanying protocol papers (16–18). Briefly, participants were excluded for any musculoskeletal injury (surgery, pain etc.) or acute illness less than 6 weeks before the baseline measurement. Inclusion criteria included being 18-65 years old a non-smoker, residing within one of the study regions for the past five years and having no plans to move out of the area for the next year. Participating runners had to meet the WHO physical activity recommendations of 150 minutes of moderate or 75 minutes of vigorous physical activity, or an equivalent combination of moderate and vigorous intensity activity (23); and also run at least 10km per week for at least 6 months (both assessed by self-report using an online screening

ACCEPTED

questionnaire). The latter criterion was later relaxed to 6km per week due to the need to boost recruitment in the older age categories of runners whose regular weekly running volumes were lower than 10 km/week. Non-runners were capable of running but short of meeting the WHO recommendations about physical activity as self-reported during screening. In summary, for the purpose of this study, as a runner, we considered participants who ran regularly for at least six weeks and at least six km per week (16–18).

In the analysis, we included 1206 (563 females/643 males) of the 1315 4HAIE participants although only 750-1000 were required for this prospective study. Across the 12-month follow-up period, there were 62 study dropouts: 32 participants did not engage or ceased to engage with the study mobile application used for weekly reports of sports-related injury or did not respond to weekly surveys and eventually disengaged from the study (not answering reminder or follow-up phones calls) prior to finishing the 12-month monitoring period; 29 participants left the study by their own volition; and one participant succumbed to Covid-19). Data from one participant who ended participation after eight months due to a change of residence, (i.e., moving out of the study region) were included in the analysis due to his reporting of PF during the first six months in the study. As an exclusion criterion for the current study, a prospectively reported injury or pain in the foot region (N = 47) except plantar fasciitis confirmed by medical professional (N = 28) was considered. Figure 1 is a schematic of the recruitment strategy and the baseline characteristics of the sample can be seen in the Table 1.

ACCEPTED

Baseline measurement protocol

A baseline measurement was carried out across 2 consecutive days. In the evening (1st day at 6 pm), participants arrived in the Human Motion Diagnostic Centre and completed several physical activity questionnaires, anthropometric measurements (body height and mass), physiological fitness level tests (blood pressure, spirometry and graded exercise test to exhaustion). Detailed protocols are described in protocol papers by Elavsky et al. (17) and Cipryan et al. (18). For the purpose of this study, we used a Socioeconomic Survey (SES) and Physical Activity Survey. The SES consisted of questions about sociodemographic factors, basic lifestyle factors, risk perception, health status, and quality of life. We used questions asking participants to describe their physical activity at work (1 - predominantly sedentary activity or standing; 2 - predominantly walking or moderate physical activity; 3 - predominantly hard work or physically demanding activity, 4 - I do not engage in any physical activity), work load/volume (in hours/week) and to what extent did their work affect participant´s health (Likert scale; 1 – does not affect at all as minimum to 5 – affects strongly).

The Physical Activity Survey included Running Status and History questionnaire (RUNHIS) (3), the Aerobics Center Longitudinal Study survey (ACLS) (24) and Sport´s Activity questionnaire. The RUNHIS and the ACLS were used to classify runners according to their weekly running distance and footwear. From the RUNHIS questionnaire (for weekly running distance), we specifically used the question: “How many kilometers do you run per week?” Participants could choose from 7 response options (0-5km; 6-10 km; 11-20 km; 21-30 km; 31-40 km, 41-50 km; 51 and more km). If participant did not check any answer, then we used responses from the ACLS questions: “During the last two months, which of the following moderate or vigorous

ACCEPTED

activities have you performed regularly? -Jogging or running?” (Yes/No); “How many sessions per week?” and “How many kilometers in one session?” We multiplied the number of episodes and kilometers per episode, and consequently assigned corresponding running distance category (if response was “No” or “0” we selected 0-5km). The Sport´s Activity questionnaire followed RUNHIS starting with first question: “Do you regularly do any specific sports activity?” If answer was “Yes” than participants could choose more options (football/soccer, squash, table tennis, baseball/softball, skating, in-line skating, conditioning exercise, gymnastics, swimming, basketball, volleyball, floorball, ice-hockey, handball, tennis, badminton, or other). To obtain information on activity frequency the follow-up question was: “How much time do you spend a week on these activities (in hours)?”.

On the 2nd day, participants carried out an overground running protocol at their self-selected speed. For runners, this was based on self-reported usual training running speed. Non-runners were asked to set the running speed at a pace that would allow them to run comfortably as far as possible. Subsequently, each participant ran at this pace for 2 min and in the last 30 s the speed of 4 unrecorded (by motion capture system) running trials was measured with photocells. The average of the four runs then indicated their self-selected preferred speed. Overground running consisted of eight successful trials on a 17 m long runway at the participant’s self-selected speed within ±5% of the average speed from unrecorded trials. The running speed was always monitored by photo cells during the data collection. The starting position for running trials was always set at least 7 meters from the force plate. A successful running trial was considered when participant landed on the force plate with the entire right foot (approximately in the middle of the force plate) and

ACCEPTED

running speed fall within ±5% of the average speed from previously determined self-selected running speed.

Anthropometric data (body height and mass) of all participants were measured by a stadiometer (In Body 370, Biospace, South Korea) and body composition analyzer (Inbody 770, Biospace, South Korea), respectively. Body composition parameters of fat and fat-free mass (lean mass) were measured by dual-energy X-ray absorptiometry (DEXA; Hologic Discovery A, USA).

Biomechanical experimental set up and marker placement

The motion capture system consisted of three embedded force platforms (Kistler Instruments AG, Switzerland) which were encircled by ten high-speed optoelectronic cameras (Oqus, Qualisys, Inc., Sweden). Kinematic and kinetic data were synchronously collected with the sampling frequency of 240 Hz (cameras) and 2160 Hz (force platform). Four reflective, tracking markers were placed on the pelvis bilaterally on the posterior superior iliac spines, and the anterior superior iliac spines. Ten calibration markers were also positioned bilaterally on the medial and lateral malleoli, the medial and lateral femoral condyles, the greater trochanter of the femur. In addition, four light-weight rigid plates with four markers per plate were placed on the thigh and shank. Thirteen markers were placed over the right foot/running shoe according to multi-segmental Rizzoli model (25). However, for the data calculation in this study, only a triad of tracking markers on the heel over the intact shoes and two markers over the metatarsal heads (the first and fifth metatarsi) were used due to higher reliability and objectivity for data calculation compared to multi-segmental model (higher agreement among evaluators reported in previous protocol study (26). Before the biomechanics measurements, a standing calibration trial was recorded. All

ACCEPTED

participants wore standard laboratory neutral running shoes (Brooks Launch 5, Brooks Sport Inc., USA).

Data processing

All biomechanical data were processed in Qualisys Track Manager (Qualisys, Sweden). Further data processing was performed in Visual 3D software (C-motion, USA). A low–pass Butterworth filter with a cut-off frequency of 12 Hz was applied for motion and 50 Hz for force data. Three-dimensional (3-D) knee and ankle joint angles were calculated using an X-y-z Cardan rotation sequence. Knee angles were determined as relative position of shank to thigh, and ankle angles as relative position of foot to shank. The 3-D net internal ankle and knee joint moments were calculated using a Newton–Euler inverse dynamics technique (27). Loading rates were determined by calculating the first derivative of the corresponding vertical ground reaction force (VGRF) with respect to time. Consequently, the vertical instantaneous loading rate (VILR) value was obtained within the first 14% of stance as a local maximum using the same approach as Boyer et al. (28), and vertical average loading rate (VALR) was calculated as average loading rate between 20-80% of the time from initial contact to the impact peak or point of interest at 13% of stance phase (29).

The mean values from the eight running trials were calculated and used in later analysis for following biomechanical variables: strike index, VILR, VALR, maximal VGRF, running speed (based on the horizontal pelvis velocity), step frequency, step width, ankle, knee joint angles at footstrike, joint range of motion (ROM) and maximal joint angles during stance; and maximal

ACCEPTED

joint moments (9–11). A detailed biomechanical protocol, set up, data processing and marker placement (reliability and objectivity) can be seen in previous protocol papers (16, 26).

One-year follow-up

After baseline measurements, the participants wore Fitbit Charge 3 monitor (Fitbit, San Francisco, USA) for one year, during which they also completed four 2-week periods of intensive measurement that incorporated ecological momentary assessment (i.e., they received repeated surveys on affect, stress, and context during the day on their smartphones in 2-week bursts at baseline, month 4, month 8, and month 12). In terms of injury report, they were asked to report running or physical activity-related injuries via: 1) the self-initiated injury questionnaire via mobile phone application; 2) an injury survey weekly (every Sunday between 4 and 8 PM); or 3) a survey if their usual level of physical activity (monitored by Fitbit) decreased (17). In addition, the physiotherapist from the 4HAIE team called each participant to confirm/check their injury if the answer was unclear and to verify whether they sought medical help and received a medical diagnosis. A participant with plantar fasciitis (PF) was considered and included in this study only if the injury was confirmed by a medical doctor or physiotherapist. Participants were encouraged to find their usual medical doctor/orthopedist (due to large study sample size, time and travel distance, it was not feasible to undergo the medical assessment with only one specialist). In addition, participants were asked if their PF was sport related injury, if their response was positive than they were asked if the injury was running related injury.

ACCEPTED

Statistical analysis

A Shapiro-Wilk test was used to assess normality of data distribution and Levene´s test to assess homogeneity of variance. Kruskal-Wallis test was used to compare baseline characteristic and running biomechanics among running distance groups. Consequently, a two-sample Wilcoxon rank-sum test was performed for baseline characteristic between runners with PF and non-injured runners. A Fisher´s exact test was used to compare the proportions of injured individuals with PF between runners and non-runners and consequently between males and females or among running distance groups.

A binary multivariable logistic regression model was selected as the main tool for statistical analysis. As it is known that logistic regression may suffer from bias when working with rare events, a variant called the Firth's bias-reduced logistic regression, also known as penalized likelihood regression, was used to examine whether "previously proposed biomechanical risk factors" variables were associated with PF. The main dependent variable was injury status: injured (PF) and non-injured participant (Non-PF). The first analysis focused on the entire sample (N= 1206; with the exception of 62 drop outs and 47 self-reported injuries/pain in the foot region). Covariates in the basic model were sex (female, male), age, weekly running distance (5, 6). As a single term addition covariate to the basic model (tested one by one) was a history of previous PF, region (air-polluted/un air-polluted), height, mass and body mass index (BMI). For multivariable logistic regression and ease of its interpretation, we reduced the number of running distance categories from the original seven categories into four (0-5km; 6-20 km; 21-40 km; 41 and more km). Before logistic regression model fitting, the numeric variables were transformed to normal distribution using one of the following transformations: Yeo-Johnson, Box Cox, logarithmic,

ACCEPTED

square-root, arcsinh, or ordered quantile normalization. 5 times repeated 10-fold cross-validation was used to estimate the out-of-sample performance of each transformation and the best transformation was selected on the basis of the Pearson *P* test statistic for normality - see the bestNormalize package for R (30).

The following analysis using binary logistic regression was performed only on runners because PF is considered as a most common running-related injury and influenced by running technique (1, 10, 13, 31, 32). If a covariate from the basic model (running distance, age, or sex) was not significant then it was excluded from the model, which resulted in the second model, which we call the “simple model” in this text. This was done to maximize power due to the low number of cases PF. Subsequently, as single term addition covariates to simple model were tested the contribution of anthropometric and training variables (i.e., height, mass, BMI, running footwear). In addition, primary biomechanical variables were tested in simple model: strike index, VILR, VALR, maximal VGRF, ankle kinematics (angles), running speed (based on the horizontal pelvis velocity), and step frequency. As secondary biomechanical variables were tested: step width, knee joint angles during stance; ankle and knee maximal joint moments) (9–11).

All investigated variables were assessed for extreme outliers, that were defined as values exceeding three times the interquartile range below Q1 or above Q3. These extreme values were replaced with a missing value indicator (N/A) and were thus excluded from analyses (all missing values can be seen in the Supplemental Table 3 and 4, Supplemental Digital Content is available at http://links.lww.com/MSS/D133). In the analysis of biomechanical variables, we used the data obtained from the right lower limb (only from runners) due to the collection of complex

ACCEPTED

biomechanical data (including force data) because we do not expect any lower limb asymmetries during running in healthy people (33, 34). In addition, we excluded participants with a history of PF (resolved PF) from the analysis of running biomechanical variables because this could affect running technique itself (9, 35–37). In non-runners, logistic regression "basic model" (including sex and age) was also tested with anthropometric variables (height, mass, BMI) as single term addition covariates. The likelihood/adjusted odds of the tested variables in the models (referred to as "risk factors" in this paper) is/are represented by the odds ratio (OR) and its confidence intervals (95% CI).

Additionally, we also match-paired 14 runners PF with 14 healthy controls (by sex, age, weekly running distance, BMI, height and mass) and consequently performed one-sided paired t-test for the variable of interest (ankle kinematics in transversal plane, VILR, VALR), in order to provide comprehensive analysis and data interpretation, including the additional use of a virtual foot model to calculate ankle kinematics for better clinical interpretation of the results (Supplemental Table 3, Supplemental Figure 1B, Supplemental Figure 2B, Supplemental Digital Content is available at http://links.lww.com/MSS/D133). In the current study, a paired samples t-test with 28 participants (14 per group) would be sensitive to effects of Cohen's $d = 0.48$ with 80% power (alpha = 0.05, one-tailed t-test). This means the study would not be able to reliably detect effects smaller than Cohen's $d = 0.48$ (on the contrary, the study would be able to reliably detect possible differences from the medium effect size). Based on the previous studies (7, 9, 12), to detect an effect of $d = 0.50$ for VILR and $d = 0.89$ for VALR with minimal statistical power 80% in one-tailed t-test (two groups, alpha level = 0.05) would be sufficient 28 (14/group) or 10 (5/group) participants, respectively. The level of statistical significance was set at $P = 0.050$ for

ACCEPTED

all statistical tests. Statistical analyses were conducted using R statistical software version 4.4.1 (R Core Team) and IBM SPSS Statistics version 24 (IBM, USA).

RESULTS

Incidence of PF and baseline characteristics and measurements of the participants

According to Fisher's exact test, there were no differences in the incidence of PF between runners and non-runners over the 12-month observation period (*P* = 0.248). The incidence of PF in the entire sample was 2.3% (28 cases of PF /1206 participants; 3.0% PF in females (17 PF/563) vs. 1.7% in males (11 PF/643); *P* = 0.179). We found a 2.5% incidence of PF in runners (2.8% females (8 PF/283) vs. 2.3% males (10 PF/432); *P* = 0.808). In non-runners, the incidence was 2.0% (3.2% females (9 PF/280) vs. 0.5% males (1 PF/211); *P* = 0.049). Although no differences were found between the two groups of non-runners and runners in general, Fisher's exact test showed differences in the PF incidence among four running distance groups (*P* = 0.015; Table 1).

Thirty-one participants reported a history of PF in the baseline questionnaire (30 runners /1 non-runner); four of the runners with previous history of PF reported prospectively PF during the one-year follow-up (incidence of 11.1% prospective cases of PF in those with the previous history of PF). There were 14 new prospective cases of PF in runners. Three additional runners reported PF symptoms but the diagnosis was not confirmed by a medical professional. The latter three runners were excluded from the analysis, along with another 44 participants who reported injury or pain in the foot region. The average time between the baseline measurements and the first report of PF among the participants with PF was 149.5 days (± 109 days). In only one case of PF in runners (1/18; 5.6%) was not a running related injury identified and this participant marked this

ACCEPTED

injury as other sport related injury (this participant also reported history of PF prior to the baseline). On the other hand, one non-runner (1/10; 10%) reported PF as running related injury (indicating that this individual might start with running during one-year follow up).

For non-runners with PF, 60% were predominantly sedentary or standing at work and 40% spent their time at work predominantly walking or doing moderate physical activity (only 20% of non-runners with PF did some sport activity; 1 non-runner did conditioning exercise accompanied by swimming and 1 non-runner did only conditioning exercise). The majority of runners with PF spent their time at work predominantly sedentary or standing at work (83%), although some spent their time at work predominantly walking or doing moderate physical activity (17%). The majority of runners (56%) did not participate in any sport other than running and 46% of runners combined running with sports such as: swimming, conditioning exercise, badminton, skating, yoga and cycling (listed from most to least frequent). Non-runners reported a mean score of 2.4 (± 1.2) with regards to how they perceived their work affected their health, compared to runners with PF who reported a score of 1.5 (± 0.5) (Likert scale; ranging from 1 - least affected to 5 - most affected by work).

ACCEPTED

Risk factors of PF in total sample (non-runners and runners): Running distance, sex, age, history of plantar fasciitis, anthropometric variables and air-polluted/un air-polluted region

Age appeared to be a significant predictor for PF in the entire sample (including non-runners and runners) (Figure 2A). As age increased by each year, the probability of developing PF increased by 3.9%. Runners who ran 41 or more km/week were found to be at a 4.8 higher risk for PF than non-runners (Table 2), and 6.1 times higher risk than the 6-20 km/week runners (Table 3).

No differences were found between 41 or more km/week runners and those who ran 21-40 km/week. No significant differences in adjusted odds of attaining PF were found between non-runners (0-5 km/week) and runners in the 6-20 km (OR = 0.78; IC = 0.22 - 2.53) and 21-40 km per week groups (OR = 2.02; IC = 0.72 – 5.42). Females were twice as likely to suffer PF than males (Table 2). In addition, as a single-term additional covariate, past history of PF had significant effect on the adjusted odds of PF during the one-year follow-up period. Individuals with previous history of PF had 5.1 higher likelihood of being re-injured ($P = 0.015$; OR = 5.068; CI = 1.416 – 15.225). Height, mass, BMI and region were not significant factors for risk of PF ($P > 0.050$).

Risk factors of PF in runners: Running distance, sex, age

The second analysis showed that sex and age were not significant in "basic model for runners" ($P > 0.050$). However, weekly running distance remained significant (Table 3 and Figure 2B).

Risk factors of PF in runners: Running distance, footwear (barefoot/minimalist shoes vs. standard running shoes), biomechanical and anthropometric variables

Table 4 showed baseline characteristic of the runners and comparisons of key / primary biomechanical outcome variables between injured and non-injured runners. There were found significant differences in weekly running distance and maximal ankle adduction angle. Secondary biomechanical outcome variables according to injury status are presented in the Supplemental Table 1 (Supplemental Digital Content).

ACCEPTED

Further analysis of binary logistic regression “simple model for runners” (controlled for running distance), including biomechanical variables as single-term additional covariates, showed no effect on weekly running distance as a risk factor of PF (6-20 km/week had 5.1 – 6.0 times lower risk than 41 or more km/week). In other words, the addition of biomechanical variables did not change the fact that weekly running distance remain as a significant predictor of PF.

Interestingly, there was a significant association between maximal ankle adduction and PF ($P = 0.028$; OR = 1.178; CI = 1.017 – 1.372); runners with a lower abduction angle (lower external rotation) during the stance had higher adjusted odds of developing PF (Figure 2C) (i.e., with each additional degree towards adduction a 19% higher risk of PF if non-normalized data would be use in the analysis ($P = 0.024$; OR = 1.19; CI: 1.02 - 1.38). As one-sided paired t-test indicated that the runners with PF had lower values of the maximal ankle abduction during stance compared to the healthy matched controls (PF: -9.6° ± 5.7° vs controls: -13.9° ± 3.5°; $P = 0.031$; $d = 0.83$; Supplemental Table 2, Supplemental Digital Content). None of the other biomechanical variables were significant in the model ($P > 0.050$).

Anthropometric variables and running footwear as risk factors were not significant ($P > 0.050$) We did not control for age and sex because these variables were not significant factors in runners (as we did in the basic model) and for model parsimony, given the relative low number of PF cases in runners.

ACCEPTED

Risk factors of PF in non-runners: Sex, age, and anthropometric variables

Basic model for non-runners showed that both sex (*P* = 0.041; OR = 0.215; CI = 0.023 – 0.947) and age (*P* = 0.031; OR = 1.054; CI = 1.004 – 1.117) were significant covariates. Non-runner´s and less physically active females had nearly 5 times higher chance to suffer PF than males. In addition, no significant were found anthropometric variables in non-runners (height: *P* = 0.160; mass: *P* = 0.464; BMI: *P* = 0.913).

DISCUSSION

The aim of this study was to determine the incidence of PF and identify possible risk factors of PF in runners and non-runners. This study prospectively assessed previously proposed biomechanical risk factors in runners for PF (footstrike patterns, vertical loading rates, ankle range of motion to maximal dorsiflexion and maximal ankle adduction/abduction during stance phase) and identified a weekly running distance that was associated with greater adjusted odds of developing PF. First, we hypothesized that runners would be more likely to suffer from PF than non-runners (31, 32). Second, we hypothesized that running biomechanics variables (footstrike patterns, vertical loading rates, ankle kinematics) (7, 9–12, 15) would affect the likelihood of being classified as having PF during one-year of follow-up. The results provided only partial support for the first hypothesis since we found that non-runners were four times less likely to develop PF than runners who ran more than 40 km per week. No differences were found in the likelihood of incurring PF between non-runners and runners who ran less than 41 km per week (6-20 km/week and 21-40 km/week). Several researchers (31, 32) stated that the typical patients with PF are between 40 and 60 years old (in the general population) but might be younger if they are runners (with incidence reaching up to 10%). This is in line with the results of the current study which

ACCEPTED

showed that younger individuals had lower risk for PF than older individuals when controlling for sex and running distance. Contrary to the abovementioned studies, we found a two times higher risk in females than in males. In addition, this study showed that individuals with the previous history of PF had 5 times higher risk of re-injury. This is in accordance with a prospective study which reported that a previous running-related injury was a significant risk factor for a new running-related injury during 12 week follow up (38).

The incidence of PF in the population of runners was 2.5% across the one-year follow-up which appeared to be lower than the previously reported average PF incidence of 6.1% in populations of runners (1). This incidence is lower even though we used real-time injury reporting via mobile phone application which is less affected by recall bias (39, 40). This low incidence rate could reflect a low compliance with injury reporting and could be influenced by our criterion of including PF cases only when confirmed by medical care professionals. As shown by Wiegand et al. (3), approximately 40% of runners with PF continue running and almost 50% do not seek medical care. Furthermore, most previous studies have only focused on runners who had a higher weekly running volume (more than 20 km/week) which may have increased the risk of developing PF and higher incidence of PF. Surprisingly, this study found a relatively high incidence of PF (2%) in non-runners, who appeared to be less active than groups of runners. A previous systematic review and meta-analysis by van Leeuwen et al. (2), found that non-athletes with increased occupational standing or walking time on hard surfaces were 30% more likely to suffer from PF than those with sedentary occupations. The non-runners in the current study were more physically active at work than runners, and they reported their work to be more influential on their health than the runners. In addition, the absence of regular exercise in the aforementioned review was also

ACCEPTED

associated with an increased prevalence of PF. Yet, self-reporting as a recreational runner/jogger was not associated with increased prevalence of PF (2). These facts may explain the relatively high incidence of PF in non-runners in the current study.

The current study indicated no differences in the risk of PF between female and male runners. This is consistent with the results from injury data on 166 runners collected during a two-year prospective study by Di Caprio and colleagues (6). The different results regarding sex (total sample vs. runners) in our study leads us to speculate that a female´s risk of PF is not as related to running as a male´s risk because the incidence of PF in female non-runners and female runners is almost the same (3.2% vs. 2.7%) and different in males (0.5% vs. 2.1%). Consistent with Di Caprio et al. (6), we found no relationship between PF risk and runners´ age, mass and BMI.

Another important finding, consistent with previous research, was that weekly running distance had an influence on the risk of developing PF. Our study indicated that runners who ran 6-20 km per week had six times lower risk for PF than runners who ran 41 or more km per week while controlling for sex and age (Table 3). The Di Caprio et al. prospective study (6) also found differences in weekly running distance in injured runners with PF running 61 km/week (± 23 km/week) on average and non-injured runners running 41 km/week (± 25 km/week). A review by Saragiotto et al. (41) summarized the main-factors for running-related injuries and they noted that weekly running distance above 64 km/week was a risk factor for non-specific running injuries in general. Interestingly, a recent study found an association between running distance and the quality of collagen fibers of the Achilles tendon (MRI assessment of water content and collagen orientation) (42). It has been shown that runners who ran 41 km/week or more had greater than

ACCEPTED

two times higher likelihood of being in the group with an adverse Achilles tendon quality (the longest T2* relaxation time) (42). Biomechanically speaking, Achilles tendon and plantar fascia are connected and have similar structural properties (5, 43–45). Their extensibility counter each other indicating balanced mechanical interaction between the Achilles tendon and plantar fascia in ankle - foot motion (45).

These findings are equivalent to the data supporting the benefits of running as a key lifestyle “medicine” for longevity. Here, the data indicate an optimal running dose of less than 48 km/week is more appropriate for health due to an observed trend of a reversed J-shape curve in all-cause death and coronary heart disease data (i.e., more than 48 km/week progressively attenuated the health benefits and became detrimental for cardiovascular health) (46). In line with Lee et al. (46) and in light of the results of this study, we argue that a running dose of about 40 km/week could represent a reasonably safe limit for developing PF where the benefits of running outweigh potential risks at least for recreational runners.

The etiology of running-related injuries is multifactorial in nature and includes both intrinsic (age, sex, biomechanics) and extrinsic factors (weekly running distance). To date, the biomechanical risk factors of PF have been previously studied only with retrospective cross-sectional designs with small groups and matching runners with and without PF. This prospective cohort study has shown that it is important that the statistical models include meaningful covariates (such as weekly running distance) when testing the contribution of biomechanical variables. Our second hypothesis, that running biomechanics would affect the likelihood to suffer PF, was also partially confirmed. We found a significantly lower maximal ankle adduction (internal rotation) in

ACCEPTED

runners who did not suffer PF compared to injured group (i.e., non-injured runners had higher abduction angle).

Ankle abduction is a one component of the complex ankle motion known as pronation that occurs with increasing dorsiflexion and eversion in the ankle after initial contact and reaches a maximum about 25-40% of stance phase during running which is the same time as the maximum of ankle abduction) (47, 48). The term “pronation” is often inter-changeable with “eversion” (49). Excessive pronation was extensively studied in late 20th and early 21th century as first running paradigm for overall running related injuries (50). Greater pronation was also suggested as a potential risk factor for plantar fasciitis (5, 48, 51). However, a cross-sectional retrospective study by Pohl et al. (2009) found no differences in ankle eversion/pronation between twenty-five female runners with a history of PF and group of 25 age and mileage matched runners without history of PF. Similar results for peak eversion/pronation angle during stance (i.e., no differences between groups) were reported in the study by Wiegand et al. (2022) where they cross-sectionally compared three groups of runners (acute, chronic PF and healthy controls). The results of the current study appear to be in agreement with these studies regarding the ankle angles in the sagittal and frontal planes. Nonetheless, this study is the first to prospectively investigate three-dimensional ankle angle motion. It appears that a lower maximal adduction/higher maximal ankle abduction angle (ankle toe out), which naturally increases after foot strike along with increasing pronation (maximal abduction occurred around 31.1% in PF and 38.7% in the control group), may be a protective factor against PF.

ACCEPTED

An explanation for this protective phenomenon could be that soft tissues similar to the plantar fascia such as the Achilles tendon or the patellar ligament are physiologically active tissues (52, 53). Therefore, these tissues may be positively or negatively related to regular running and specific running techniques by their structure (54). For example, the plantar fascia, patellar ligament or Achilles tendon can improve function after specific eccentric strength or stretching program/training (55–59). Collagen synthesis occurs approximately 48 hours after physical loading of a given tissue and if the loading is optimal and the training dose is not repeated too early (52), there could be an improvement in plantar fascia structure with adequate loading. According to our research, the protective role of external foot rotation (abduction) with respect to shank may suggest that dynamic movements in the transverse plane may specifically stimulate physiological processes (strengthening; i.e "supercompensation" phenomenon of the collagen turnover after running) leading ultimately to a lower incidence of PF injury to this most loaded foot structure.

Based on a recent systematic review (13), we expected higher vertical ground reaction forces in runners with PF compared to runners without PF. Willwacher et al. (13) suggested that VALR and VILR might be possible biomechanical risk factors for PF, although this suggestion was made based on retrospective studies in small groups of runners (7, 12). Johnson et al. (12) showed that 22 resolved PF injured runners had 17-21% higher loading rates than matched healthy controls matched by sex and running speed. Similarly, Pohl et al. (7) observed increased VILR in 25 female runners with a history of PF compared to 25 age and mileage-matched controls. Since in this study, we studied a large cohort of runners during the one-year follow up and we controlled for weekly running distance, age, and sex in the logistic regression models, it is apparent that loading rate parameters should be reconsidered as risk factors for PF in runners. In addition, in

ACCEPTED

terms of active (propulsive) vertical GRF, Chang et al. (14) found that chronic PF runners (symptomatic over three months) displayed lower propulsive forces than paired healthy runners. The authors suggested that this could be a compensative mechanism in response to experienced pain. However, we did not find any association between maximal propulsive GRF or VGRF and PF risk.

In summary, this study did not confirm the recently proposed biomechanical risk factors of PF such as forefoot strike as suggested by Chen et al. (11). Footstrike represented by the strike index and ankle angle at initial foot-ground contact, did not show any association with the risk of PF. In addition, a recent study by Wiegand et al. (10) showed that runners with PF (symptoms within the past two weeks) had a greater range of motion in the knee in the sagittal plane during the loading phase of stance than resolved PF runners (with no symptoms for at least four weeks) and healthy controls. The current study did not observe any differences in sagittal plane ankle and knee biomechanics (angles, moments) between runners with PF and non-injured individuals. Overall, it appears that most discrete variables of running biomechanics may not be sufficient to indicate the risks factors of incurring PF in runners and may be more indicative of changes occurring as a result of the injury (except maximal ankle abduction).

Several limitations and strengths of this study should be mentioned. First, we did not collect data about the participant’s foot arch, ankle flexibility and did not control for this in the statistical models. Second, participants were tested in uniform laboratory shoes which could be considered as both strength and limitation. While the use of uniform laboratory shoes ensured uniform testing conditions, the participants did not wear our laboratory-neutral cushioned running shoes during

ACCEPTED

the one-year follow-up period. Third, we did not include information about running volume and running intensity before injury occurred (absence of time to event analysis). Fourth, participants with PF were not assessed by only one medical doctor and we had no information about PF severity. Fifth, we did not present multi-segment foot kinematics data due to lower reliability and objectivity of marker placement (lower intra and inter-rater reliability of marker placement (26). In addition, it is well-known that when running in shoes, the foot can move independently of the shoe. Therefore, without analysis of running in a barefoot condition, it is very difficult to determine with certainty how the foot moved when running in shoes (10). Sixth, we analyzed kinetic data only from right limb. Lastly, the current study only assessed and presented discrete biomechanical variables. For a greater insight, future studies should perform an analysis of continuous biomechanical variables and coordination patterns. In spite of these limitations, this study represents the first large prospective cohort study to date involving runners and non-runners investigating biomechanical risk factors for PF in the context of other relevant correlates.

CONCLUSIONS

In general, there were no differences in PF incidence between runner and non-runner less physically active populations. The current study reported that females are generally twice as likely to suffer from PF than males and older individuals are at a greater risk for PF (increasing odds by 4% every year). In addition, runners who ran 41 or more km/week have a 4-6 times higher risk for a PF injury than non-runners or runners who ran moderately (6-20 km/week) with no difference in the likelihood of developing PF between male and female runners at any given age. Lastly, previously proposed running biomechanics risk factors (e.g., loading rates) did not appear to influence the likelihood of suffering PF in runners with the exception of greater ankle abduction

ACCEPTED

during stance which may be a protective factor against PF. The information in this study regarding optimal weekly running dose and running biomechanics, could be useful for the researchers, clinicians, health professionals, coaches and runners whose aim is to minimize the risk of PF.

Acknowledgments

This work has been produced with the financial support of the European Union under the LERCO project (CZ.10.03.01/00/22_003/0000003) via the Operational Programme Just Transition and from the project Research of Excellence on Digital Technologies and Wellbeing (CZ.02.01.01/00/22_008/0004583) which is co-financed by the European Union. The baseline data refers to the project funded by the Czech Ministry of Education, Youth and Sports, the project 4HAIE "Healthy Aging in the Industrial Environment - Program 4" (CZ.02.1.01/0.0/0.0/16_019/0000798) within its sustainability period. No potential conflict of interest was reported by the authors. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine. The 4HAIE study was approved by the Ethics and Research Committee of the University of Ostrava (OU-87674190-2018) and was conducted in accordance with the principles of the Declaration of Helsinki. All participants signed an informed consent before the data collection. Data can also be requested to create a meaningful research study. Guidelines on how to request data are published on the project 4HAIE website. Data description presented in the article can be found at www.4HAIE.cz.

ACCEPTED

ACCEPTED

REFERENCES

1. Kakouris N, Yener N, Fong DTP. A systematic review of running-related musculoskeletal injuries in runners. *J Sport Heal Sci*. 2021;10(5):513–22.
2. VanLeeuwen KDB, Rogers J, Winzenberg T, Van Middelkoop M. Higher body mass index is associated with plantar fasciopathy/'plantar fasciitis': Systematic review and meta-analysis of various clinical and imaging risk factors. *Br J Sports Med*. 2016;50(16):972–81.
3. Wiegand K, Mercer JA, Navalta JW, Pharr J, Tandy R, Freedman Silvernail J. Running status and history: a self-report study. *Phys Ther Sport*. 2019;39:8–15.
4. Beeson P. Plantar fasciopathy: revisiting the risk factors. *Foot Ankle Surg*. 2014;20(3):160–5.
5. Wearing SC, Smeathers JE, Urry SR, Hennig EM, Hills AP. The pathomechanics of plantar fasciitis. *Sport Med*. 2006;36(7):585–611.
6. DiCaprio F, Buda R, Mosca M, Calabrò A, Giannini S. Foot and lower limb diseases in runners: assessment of risk factors. *J Sport Sci Med*. 2010;9(4):587–96.
7. Pohl M, Hamill J, Davis IS. Biomechanical and anatomic factors associated with a history of plantar fasciitis in female runners. *Clin J Sport Med*. 2009;19(5):372–6.
8. Ribeiro AP, Trombini-Souza F, Tessutti VD, Lima FR, João SMA, Sacco ICN. The effects of plantar fasciitis and pain on plantar pressure distribution of recreational runners. *Clin Biomech (Bristol)*. 2011;26(2):194–9.
9. Ribeiro AP, João SMA, Dinato RC, Tessutti VD, Sacco ICN. Dynamic patterns of forces and loading rate in runners with unilateral plantar fasciitis: a cross-sectional study. *PLoS One*. 2015;10(9):e0136971.
10. Wiegand K, Tandy R, Freedman Silvernail J. Plantar fasciitis injury status influences foot

mechanics during running. *Clin Biomech (Bristol)*. 2022;97:105712.

11. Chen TLW, Wong DWC, Wang Y, Lin J, Zhang M. Foot arch deformation and plantar fascia loading during running with rearfoot strike and forefoot strike: a dynamic finite element analysis. *J Biomech*. 2019;83:260–72.
12. Johnson CD, Tenforde AS, Outerleys J, Reilly J, Davis IS. Impact-related ground reaction forces are more strongly associated with some running injuries than others. *Am J Sports Med*. 2020;40(28):3072–80.
13. Willwacher S, Kurz M, Robbin J, et al. Running-related biomechanical risk factors for overuse injuries in distance runners: a systematic review considering injury specificity and the potentials for future research. *Sport Med*. 2022;52(8):1863–77.
14. Chang R, Rodrigues PA, Van Emmerik REA, Hamill J. Multi-segment foot kinematics and ground reaction forces during gait of individuals with plantar fasciitis. *J Biomech*. 2014;47(11):2571–7.
15. Plesek J, Skypala J, Hamill J, et al. Ankle kinematics and plantar fasciitis in runners: a one-year prospective 4HAIE study. *ISBS Proceedings Archive*. Salzburg: NMU Commons; 2024. p. 764–7. Available from: https://commons.nmu.edu/isbs/vol42/iss1/215.
16. Jandacka D, Uchytil J, Zahradnik D, et al. Running and physical activity in an air-polluted environment: the biomechanical and musculoskeletal protocol for a prospective cohort study 4HAIE (Healthy Aging in Industrial Environment — Program 4). *Int J Environ Res Public Health*. 2020;17(9142):9142.
17. Elavsky S, Jandačková V, Knapová L, et al. Physical activity in an air-polluted environment: behavioral, psychological and neuroimaging protocol for a prospective cohort study (Healthy Aging in Industrial Environment study – Program 4). *BMC Public Health*.

ACCEPTED

2021;21(1):126.

18. Cipryan L, Kutac P, Dostal T, et al. Regular running in an air-polluted environment: Physiological and anthropometric protocol for a prospective cohort study (Healthy Aging in Industrial Environment Study - Program 4). *BMJ Open*. 2020;10(12):e040529.

19. VanGent RN, Siem D, Van Middeloop 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 Sports Med*. 2007;41:469–80.

20. VanMiddelkoop M, Kolkman J, VanOchten J, Bierma-Zeinstra SMA, Koes BW. Risk factors for lower extremity injuries among male marathon runners. *Scand J Med Sci Sports*. 2008;18(6):691–7.

21. Kluitenberg B, Van Middelkoop M, Diercks R, Van der Worp H. What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. *Sport Med*. 2015;45(8):1143–61.

22. Peduzzi P, Concato J, Kemper E, Holford TR, Feinstem AR. A simulation study of the number of events per variable in logistic regression analysis. *J Clin Epidemiol*. 1996;49(12):1373–9.

23. WHO. Global recommendations on physical activity for health. *World Health Organization*. 2010.

24. Kohl HW, Blair SN, Paffenbarger RS, Macera CA, Kronenfeld JJ. A mail survey of physical activity habits as related to measured physical fitness. *Am J Epidemiol*. 1988;127(6):1228–39.

25. Leardini A, Benedetti MG, Berti L, Bettinelli D, Nativo R, Giannini S. Rear-foot, mid-foot and fore-foot motion during the stance phase of gait. *Gait Posture*. 2007;25(3):453–62.

ACCEPTED

26. Malus J, Skypala J, Silvernail JF, et al. Marker placement reliability and objectivity for biomechanical cohort study: Healthy Aging in Industrial Environment (HAIE—Program 4). *Sensors (Basel)*. 2021;21(5):1830.

27. Robertson, E., Gordon D, Caldwell GE, Hamill J, Kamen G, Whittlesey SN. *Research Methods in Biomechanics*. 2nd ed. Champaign: Human Kinetics; 2014. 428 p.

28. Boyer ER, Rooney BD, Derrick TR. Rearfoot and midfoot or forefoot impacts in habitually shod runners. *Med Sci Sports Exerc*. 2014;46(7):1384–91.

29. Samaan CD, Rainbow MJ, Davis IS. Reduction in ground reaction force variables with instructed barefoot running. *J Sport Heal Sci*. 2014;3(2):143–51.

30. Peterson RA. Finding Optimal Normalizing Transformations via bestNormalize. *R J*. 2021;13(1):310–29.

31. Agyekum EK, Ma K. Heel pain: a systematic review. *Chin J Traumatol*. 2015;18(3):164–9.

32. Rhim HC, Kwon J, Park J, Borg-Stein J, Tenforde AS. A systematic review of systematic reviews on the epidemiology, evaluation, and treatment of plantar fasciitis. *Life (Basel)*. 2021;11(12):1287.

33. Hamill J, Bates BT, Knutzen KM. Ground reaction force symmetry during walking and running. *Res Q Exerc Sport*. 1984;55(3):289–93.

34. Brown AM, Zifchock RA, Hillstrom HJ. The effects of limb dominance and fatigue on running biomechanics. *Gait Posture*. 2014;39(3):915–9.

35. Knurr KA, Kliethermes SA, Stiffler-Joachim MR, Cobian DG, Baer GS, Heiderscheit BC. Running biomechanics before injury and 1 year after anterior cruciate ligament reconstruction in Division I collegiate athletes. *Am J Sports Med*. 2021;49(10):2607–14.

ACCEPTED

36. Silbernagel KG, Willy R, Davis I. Preinjury and postinjury running analysis along with measurements of strength and tendon length in a patient with a surgically repaired Achilles tendon rupture. *J Orthop Sports Phys Ther*. 2012;42(6):521–9.

37. Blyton SJ, Snodgrass SJ, Pizzari T, Birse SM, Likens AD, Edwards S. The impact of previous musculoskeletal injury on running gait variability: a systematic review. *Gait Posture*. 2023;101:124–33.

38. Hespanhol Junior LC, Pena Costa LO, Lopes AD. Previous injuries and some training characteristics predict running-related injuries in recreational runners: a prospective cohort study. *J Physiother*. 2013;59(4):263–9.

39. Stone AA, Shiffman S, Atienza AA, Nebeling L. *The science of real-time data capture: self-reports in health research*. New York: Oxford University Press; 2007. 416 p.

40. Bittel KM, O'Briant KY, Ragaglia RM, et al. Associations between social cognitive determinants and movement-related behaviors in studies using ecological momentary assessment methods: systematic review. *JMIR Mhealth Uhealth*. 2023;11:e44104.

41. 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.

42. Jandacka D, Jandackova VK, Juras V, et al. Achilles tendon structure is associated with regular running volume and biomechanics. *J Sports Sci*. 2023;41(4):381–90.

43. Orner S, Kratzer W, Schmidberger J, Grüner B. Quantitative tissue parameters of Achilles tendon and plantar fascia in healthy subjects using a handheld myotonometer. *J Bodyw Mov Ther*. 2018;22(1):105–11.

44. Stecco C, Corradin M, Macchi V, et al. Plantar fascia anatomy and its relationship with Achilles tendon and paratenon. *J Anat*. 2013;223(6):665–76.

ACCEPTED

ACCEPTED

45. Shiotani H, Takahashi K, Honma Y, et al. Mechanical linkage between Achilles tendon and plantar fascia accounts for range of motion of human ankle-foot complex. *Med Sci Sports Exerc*. 2023;55(1):66–73.

46. Lee D, Brellenthin AG, Thompson PD, Sui X, Lee IM, Lavie CJ. Running as a key lifestyle medicine for longevity. *Prog Cardiovasc Dis*. 2017;60(1):45–55.

47. McClay I, Manal K. A comparison of three-dimensional lower extremity kinematics during running between excessive pronators and normals. *Clin Biomech (Bristol)*. 1998;13(3):195–203.

48. Warren BL. Plantar fasciitis in runners treatment and prevention. *Sport Med*. 1990;10(5):338–45.

49. Nigg BM, Baltich J, Hoerzer S, Enders H. Running shoes and running injuries: mythbusting and a proposal for two new paradigms: 'preferred movement path' and 'comfort filter.' *Br J Sports Med*. 2015;49(20):1290–4.

50. Nigg BM. The role of impact forces and foot pronation: a new paradigm. *Clin J Sport Med*. 2001;12(1):57–9.

51. Ribeiro AP. Biomechanical aspects of the static and dynamic patterns of the feet of runners with plantar fasciitis and their relationship with sports shoes. In: Taiar R, editor. *Contemporary Advances in Sports Science*. London: IntechOpen; 2021. p. 336.

52. Kjaer M, Langberg H, Miller BF, et al. Metabolic activity and collagen turnover in human tendon in response to physical activity. *J Musculoskelet Neuronal Interact*. 2005;5(1):41–52.

53. Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Nat Rev Rheumatol*. 2010;6(5):262–8.

54. Jandacka D, Jandackova VK, Juras V, et al. Achilles tendon structure is associated with regular running volume and biomechanics. *J Sports Sci*. 2023;41(4):381–90.

55. Breda SJ, Oei EHG, Zwerver J, et al. Effectiveness of progressive tendon-loading exercise therapy in patients with patellar tendinopathy: a randomised clinical trial. *Br J Sports Med*. 2021;55(9):501–9.

56. Rabusin CL, Menz HB, Mcclelland JA, et al. Efficacy of heel lifts versus calf muscle eccentric exercise for mid-portion Achilles tendinopathy (HEALTHY): a randomised trial. *Br J Sports Med*. 2021;55(9):486–92.

57. Boonchum H, Bovonsunthonchai S, Sinsurin K, Kunanusornchai W. Effect of a home-based stretching exercise on multisegmental foot motion and clinical outcomes in patients with plantar fasciitis. *J Musculoskelet Neuronal Interact*. 2020;20(3):411–20.

58. Huffer D, Hing W, Newton R, Clair M. Strength training for plantar fasciitis and the intrinsic foot musculature: a systematic review. *Phys Ther Sport*. 2017;24:44–52.

59. Siriphorn A, Eksakulkla S. Calf stretching and plantar fascia-specific stretching for plantar fasciitis: a systematic review and meta-analysis. *J Bodyw Mov Ther*. 2020;24(4):222–32.

ACCEPTED

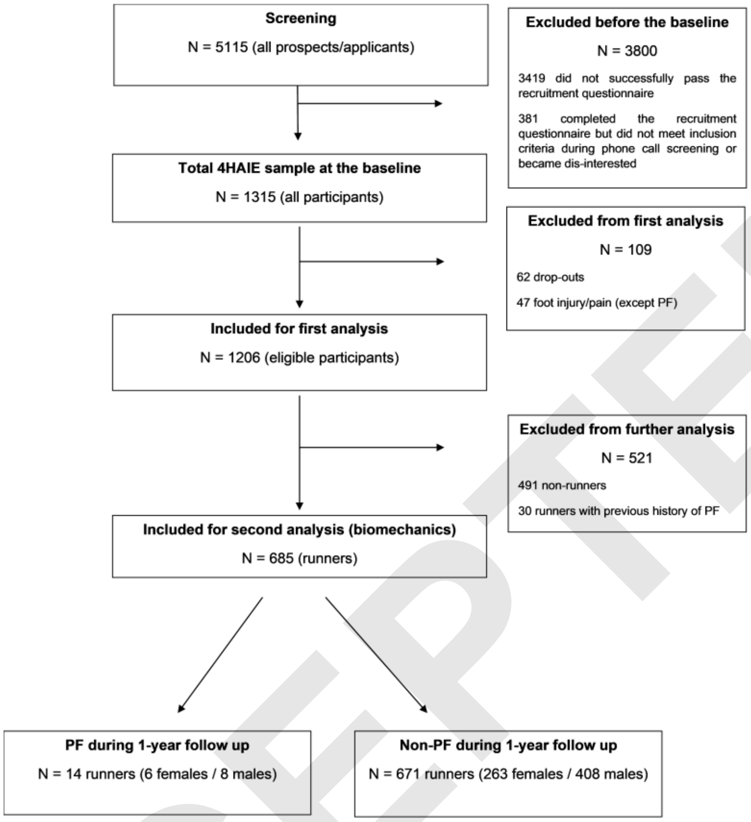
FIGURE LEGENDS

Figure 1. Flow chart of recruitment and analysis.

Figure 2. Binary logistic regression models. (A) Basic model for entire sample (N=1206) including sex, age, and running distance. (B) Basic model for runners (N=685). (C) Simple model for runners (N=680) including transformed (center-scaled) maximal ankle adduction and running distance groups (6-20km, 21-40 km, 41 and more km per week).

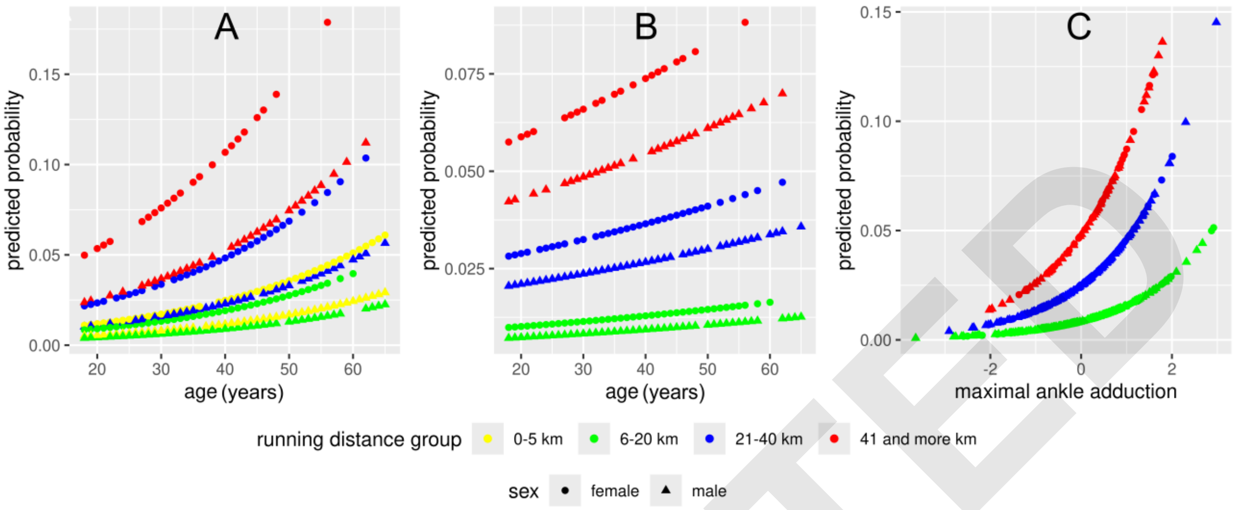
ACCEPTED

Figure 1



ACCEPTED

Figure 2



ACCEPTED

Table 1 Baseline characteristics, measurements of the participants and PF incidence (N = 1206).

	Non-runners **(0-5 km/week)** N = 491	**Runner Group 1** **(6-20 km/week)** N = 369	**Runner Group 2** **(21-40 km/week)** N = 241	**Runner Group 3** **(41 ≥ km/week)** N = 105	***P* – value**
Sex: female/male (%)	57% / 43%	44% / 56%	36% / 64%	33% / 67%	<0.001*
Age (years)	41.0 (27.0 – 52.0)	36.0 (24.0 – 44.0)	40.0 (32.0 – 45.0)	42.0 (32.0 – 47.0)	<0.001*
Running distance from ACLS (km/week)	-	14.0 (10.0 – 18.0)	27.5 (22.5 – 32.0)	50.0 (40.0 – 63.0)	<0.001*
BMI (kg/m^2)	25.1 (22.4 – 28.8)	24.1 (21.7 – 26.4)	23.8 (21.6 – 25.4)	22.4 (21.3 – 24.1)	<0.001*
Height (cm)	172.2 (165.7 – 179.7)	174.8 (169.2 – 181.1)	176.9 (170.5 – 183.1)	175.2 (169.1 – 182.4)	<0.001*
Body mass - DXA (kg)	77.7 (67.3 – 90.2)	76.6 (66.5 – 85.9)	77.1 (65.6 – 85.3)	72.0 (65.3 – 78.5)	0.001*
Body fat mass - DXA (kg)	26.0 (21.2 – 33.1)	20.9 (17.6 – 25.6)	19.3 (16.4 – 23.2)	16.3 (14.2 – 18.9)	<0.001*
Body lean mass - DXA (kg)	49.8 (42.3 – 60.6)	54.1 (45.4 – 62.6)	57.8 (47.0 – 64.3)	55.7 (47.2 – 62.0)	<0.001*
Body fat percentage - DXA (%)	34.8 (29.5 – 39.5)	28.3 (24.3 – 32.6)	25.8 (22.4 – 29.8)	23.3 (20.0 – 26.6)	<0.001*
Number of steps per day during walking/running	9672.4 (7760.2 – 11767.5)	12207.6 (9533.4 – 15048.5)	14603.5 (11545.2 – 17394.8)	17885.5 (15000.6 – 20645.1)	<0.001*
VO$_2$Max (mL/(kg·min)	33.6 (28.0 – 39.4)	44.1 (38.0 – 49.9)	47.9 (41.8 – 52.8)	50.5 (45.5 – 55.8)	<0.001*
Footwear: Standard Running / Minimalist Shoes (%)	-	98% / 2%	95% / 5%	93% / 7%	0.038*
PF incidence					
Number of prospective PF cases (N (%))	10 (2.0%)	4 (1.1%)	7 (2.9%)	7 (6.7%)	0.015*
Number of retrospective previous PF cases before baseline (N (%))	1 (0.2%)	9 (2.4%)	10 (4.2%)	11 (10.5%)	<0.001*

ACCEPTED

Data are presented as a median (Q1-Q3) and as N or percentage. Running distance values are from ACLS questionnaire (89% (438/490) of non-runners did not answer because they did not run). * - statistically significant differences between groups.

ACCEPTED

Table 2 Binary multivariable logistic regression (Basic model for all eligible participants: N=1206).

Variable	***P***	**OR**	**95% CI for OR**	
			Lower	Upper
Sex (reference: females)				
Males	**0.049***	0.448	0.193	0.996
Age	**0.022***	1.039	1.005	1.075
Running distance (reference: 0-5 km/week)				
6-20 km/week	0.531	0.775	0.222	2.529
21-40 km/week	0.335	2.017	0.723	5.423
41 and more km/week	**0.004***	4.764	1.680	13.088

Note: 109 participants as were excluded from the first analysis (62 drop-outs and 47 foot injury/pain). Bolded values with * represent statistically significant risk factor for PF. Abbreviations: OR – Odds ratio; CI – confidential interval.

ACCEPTED

Table 3 Binary multivariable regression (Basic model for runners: N=685).

Variable	***P***	**OR**	**95% CI for OR**	
Sex (reference: female)				
Males	0.546	0.720	0.253	2.143
Age	0.619	1.012	0.965	1.063
Running distance (reference: 6-20 km/week)				
21-40 km/week	0.102	2.905	0.810	12.380
41 and more km/week	**0.009***	6.109	1.581	26.999

Note: Bolded values with * represent statistically significant risk factor for PF. Abbreviations: OR – Odds ratio; CI – confidential interval.

ACCEPTED

Table 4 Baseline characteristics and primary biomechanical variables of overground running (N = 685).

	PF runners N = 14	**Non-PF runners** N = 671	***P - value***
Characteristics			
Sex (female/male)	6/8	263/408	0.788
Age (years)	41.5 (31.5 – 44.7)	38.0 (27.0 – 45.0)	0.409
Weekly running distance (km/week)	32.0 (22.5 – 39.0)	20.0 (12.0 – 30.0)	0.011*
BMI (kg/m^2)	22.3 (21.8 – 23.9)	23.7 (21.5 – 25.7)	0.073
Height (cm)	177.9 (173.4 – 184.0)	175.8 (169.3 – 182.0)	0.356
Mass (kg)	70.5 (61.5 – 78.5)	73.8 (64.2 – 83.2)	0.353
Spatiotemporal variables			
Running speed (m/s)	3.18 (2.96 – 3.33)	2.94 (2.68 – 3.22)	0.060
Cadence (steps/minute)	160.2 (158.0 – 163.8)	160.2 (153.7 – 166.5)	0.686
Kinematics (°)			
Ankle angle at IC	73.96 (65.19 – 77.91)	74.23 (68.20 – 77.55)	0.825
Max ankle dorsiflexion	86.54 (85.17 – 87.70)	85.88 (83.05 – 88.82)	0.544
Ankle ROM (IC-Max dorsiflexion)	11.78 (8.85 – 20.74)	11.70 (8.54 – 17.05)	0.742
Max ankle eversion	-14.72 (-16.89 – -10.83)	-15.42 (-18.70 – -12.11)	0.356
Max ankle adduction	-6.05 (-7.61 – -3.69)	-7.99 (-10.89 – -5.60)	0.031*
Strike index and ground reaction forces			
Strike index (%)	8.77 (4.16 – 30.61)	9.90 (4.87 – 17.73)	0.630
VILR (BW/s)	79.33 (65.45 – 85.09)	70.08 (56.56 – 84.66)	0.247
VALR (BW/s)	56.01 (49.18 – 65.59)	49.97 (40.37 – 60.13)	0.168
Max propulsive VGRF (BW)	2.39 (2.26 – 2.64)	2.37 (2.20 – 2.53)	0.310

Data are presented as median (Q1-Q3). Sagittal plane: Ankle dorsiflexion (+)/plantar flexion (-). Frontal plane: ankle inversion (+)/eversion (-). Transversal plane: ankle adduction (+) / abduction (-). Abbreviations: IC – initial contact, ROM –range of motion. * - statistically significant differences between groups.

ACCEPTED

SUPPLEMENTAL DIGITAL CONTENT

SDC 1: Supplemental Digital Content.docx

ACCEPTED

SUPPLEMENTAL TABLE 1. Secondary outcome biomechanical variables according to injury status.

	PF runners N = 14	**Non-PF runners** N = 671	***P* - value**
Spatiotemporal variables			
Step width (m)	0.08 (0.06 – 0.11)	0.09 (0.07 – 0.11)	0.457
Kinematics (angles)			
Sagittal plane (°)			
Knee angle at IC	-13.11 (-16.02 – -7.68)	-10.97 (-14.07 – -7.85)	0.350
Max knee flexion during stance	-39.80 (-44.02 – -37.91)	-41.01 (-44.14 – -37.17)	0.892
Knee ROM	27.25 (24.41 – 32.16)	29.61 (26.94 – 32.56)	0.281
Frontal plane (°)			
Ankle angle at IC	-2.95 (-6.63 – -0.04)	-3.12 (-7.21 – 0.84)	0.826
Ankle ROM to maximal eversion	10.06 (9.20 – 15.95)	11.91 (9.19 – 15.17)	0.671
Knee angle at IC	-0.10 (-1.36 – 2.49)	-0.24 (-2.58 – 2.02)	0.484
Maximal knee adduction	1.23 (-1.18 – 3.44)	1.99 (1.01 – 3.05)	0.457
Transversal plane (°)			
Ankle angle at IC	-17.38 (-18.30 – -14.76)	-18.39 (-21.33 – -15.52)	0.273
Ankle ROM to maximal adduction	-11.28 (-13.08 – - 7.19)	-10.06 (-12.36 – - 8.17)	0.593
Knee angle at IC	-10.31 (-13.00 – -7.75)	-8.95 (-12.52 – -5.92)	0.424
Maximal knee internal rotation	5.89 (2.45 – 7.83)	4.23 (1.06 – 8.57)	0.672
Knee ROM to max internal rotation	14.70 (18.40 – 12.88)	13.41 (16.76 – 10.51)	
Kinetics (moments/torques)			
Sagittal plane (N*m)			
Max ankle plantar flexion	-2.45 (-2.62 – -2.33)	-2.35 (-2.63 – -2.12)	0.290
Max knee extension	2.81 (2.49 – 3.12)	2.61 (2.30 – 2.96)	0.094
Frontal plane (N*m)			
Max ankle inversion	0.61 (0.45 – 0.67)	0.51 (0.37 – 0.67)	0.428
Max knee abduction	-0.75 (-0.77 – -0.65)	-0.63 (-0.82 – -0.46)	0.243
Max knee adduction	0.15 (0.05 – 0.21)	0.09 (0.05 – 0.14)	0.092
Transversal plane (N*m)			
Max ankle adduction	0.04 (0.02 – 0.08)	0.04 (0.02 – 0.07)	0.662

ACCEPTED

Max knee internal rotation	0.46 (0.42 – 0.56)	0.49 (0.41 – 0.59)	0.694

Note: Data are presented as median and Q1-Q3. ROM – range of motion).

ACCEPTED

SUPPLEMENTAL TABLE 2. Paired t-test comparison between 14 PF runners and 14 match-paired healthy controls (matched by sex, age, weekly running distance, BMI, height and mass).

	PF	**Controls**	***P***	***d***
Characteristics				
Sex (female/male)	6/8	6/8		
Age (years)	39.4 ± 10.4	39.9 ± 10.5	0.914	0.04
Weekly running distance (km/week)	32.8 ± 14.2	33.0 ± 14.5	0.974	0.01
BMI (kg/m^2)	22.4 ± 2.1	22.4 ± 1.3	0.983	0.01
Height (cm)	177.8 ± 8.4	176.8 ± 8.9	0.764	0.12
Mass (kg)	70.9 ± 9.4	70.3 ± 9.4	0.862	0.06
Spatiotemporal variables				
Running speed (m/s)	3.05 ± 0.39	3.00 ± 0.43	0.294	0.19
Cadence (steps/minute)	160.0 ± 5.4	161.1 ± 9.9	0.360	-0.14
Kinematics				
Maximal ankle eversion (°)	-14.5 ± 6.2	-16.9 ± 5.1	0.200	0.43
Maximal ankle adduction / internal rotation (°)	-5.9 ± 3.4	-9.1 ± 3.4	**0.004***	0.94
Maximal ankle abduction, virtual foot (°)	-9.6 ± 5.7	-13.9 ± 3.5	**0.031***	0.91
Kinetics				
VILR (BW/s)	77.5 ± 18.9	69.8 ± 14.5	0.115	0.46
VALR (BW/s)	55.7 ± 12.7	50.9 ± 11.6	0.117	0.39

Data are presented as a mean (SD). *P* – statistical significance for paired t-tests (two-sided for characteristics and one-sided for biomechanics); *d* - Cohen´s d. * - statistically significant differences.

ACCEPTED

SUPPLEMENTAL TABLE 3. Numbers of missing values in all participants (N=1206).

	Non-runners	**6-20 km / week**	**21-40 km / week**	**41 and more km / week**
N (%)	491 (100 %)	369 (100 %)	241 (100 %)	105 (100 %)
Sex	0 (0.00 %)	0 (0.00 %)	0 (0.00 %)	0 (0.00 %)
Age	0 (0.00 %)	0 (0.00 %)	0 (0.00 %)	0 (0.00 %)
Running distance RUNHIS	0 (0.00 %)	0 (0.00 %)	0 (0.00 %)	0 (0.00 %)
Running distance ACLS	439 (89.4 %)	9 (3.7 %)	1 (0.95 %)	31 (8.40 %)
BMI	2 (0.41 %)	1 (0.27 %)	0 (0.00 %)	0 (0.00 %)
Height	2 (0.41 %)	1 (0.27 %)	0 (0.00 %)	0 (0.00 %)
Mass	2 (0.41 %)	1 (0.27 %)	0 (0.00 %)	0 (0.00 %)
VO2max	56 (11.41 %)	25 (6.78 %)	15 (6.22 %)	7 (6.67 %)
Body mass - DXA	6 (1.22 %)	3 (0.81 %)	4 (1.66 %)	2 (1.90 %)
Body fat mass - DXA	6 (1.22 %)	3 (0.81 %)	4 (1.66 %)	2 (1.90 %)
Body lean mass - DXA	6 (1.22 %)	3 (0.81 %)	4 (1.66 %)	2 (1.90 %)
Body fat percentage	6 (1.22 %)	3 (0.81 %)	4 (1.66 %)	2 (1.90 %)
Daily number of steps Fitbit data	58 (11.81 %)	49 (13.28 %)	20 (8.30 %)	7 (6.67 %)

Note: Data are presented as N (%).

ACCEPTED

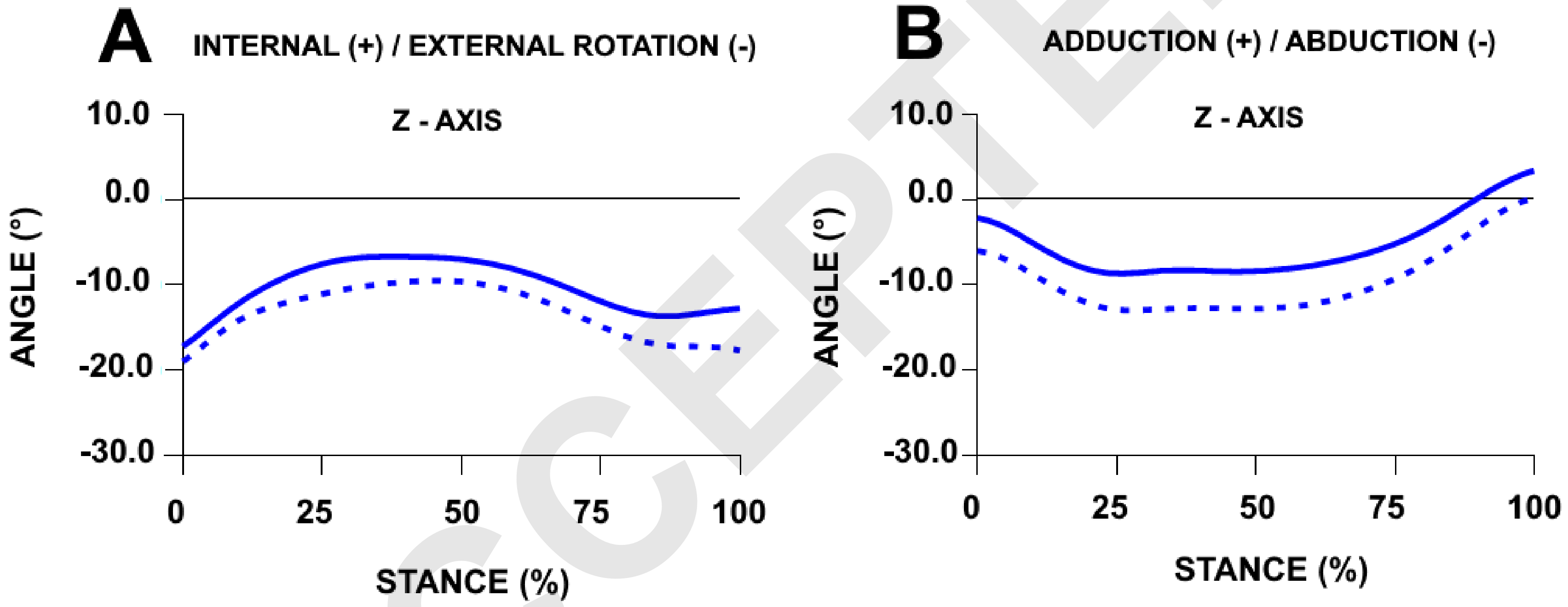
SUPPLEMENTAL TABLE 4. Numbers of missing biomechanical values in runners (N=685).

name	**Injured PF**	**Non-injured**
N (%)	14 (100%)	671 (100%)
Pelvis velocity	0 (0.00 %)	2 (0.30 %)
Strike index	0 (0.00 %)	6 (0.89 %)
VILR	0 (0.00 %)	4 (0.60 %)
VALR	0 (0.00 %)	3 (0.45 %)
VGRF Max	0 (0.00 %)	3 (0.45 %)
Step frequency (cadence)	0 (0.00 %)	7 (1.04 %)
Step width	0 (0.00 %)	6 (0.89 %)
Ankle angle IC Sagittal plane	0 (0.00 %)	5 (0.75 %)
Ankle angle IC Frontal plane	0 (0.00 %)	5 (0.75 %)
Ankle angle eversion max	0 (0.00 %)	5 (0.75 %)
Ankle maximal dorsiflexion	0 (0.00 %)	5 (0.75 %)
Ankle ROM to max dorsiflexion	0 (0.00 %)	5 (0.75 %)
Knee angle IC Sagittal plane	1 (7.14 %)	2 (0.30 %)
Knee maximal flexion	1 (7.14 %)	2 (0.30 %)
Knee ROM to max flexion	1 (7.14 %)	2 (0.30 %)
Knee angle IC Frontal	1 (7.14 %)	2 (0.30 %)
Knee maximal adduction	1 (7.14 %)	2 (0.30 %)
Knee ROM to adduction	1 (7.14 %)	2 (0.30 %)
Maximal knee extension moment	1 (7.14 %)	2 (0.30 %)
Maximal knee adduction moment	1 (7.14 %)	2 (0.30 %)
Maximal knee abduction moment	1 (7.14 %)	2 (0.30 %)
Maximal ankle plantar flexion moment	0 (0.00 %)	5 (0.75 %)
Knee adduction max	1 (7.14 %)	2 (0.30 %)
Knee internal rotation max	1 (7.14 %)	2 (0.30 %)
Maximal ankle adduction	0 (0.00 %)	5 (0.75 %)
Ankle angle IC Transversal plane	0 (0.00 %)	5 (0.75 %)
Knee angle IC Z Transversal plane	1 (7.14 %)	2 (0.30 %)
Knee angle ROM to maximal internal rotation	1 (7.14 %)	2 (0.30 %)
Maximal ankle inversion moment	0 (0.00 %)	6 (0.89 %)
Maximal knee internal rotation moment	1 (7.14 %)	3 (0.45 %)
Maximal ankle adduction moment	0 (0.00 %)	6 (0.89 %)
Ankle ROM Frontal plane	0 (0.00 %)	2 (0.30 %)
Footwear data	0 (0.00 %)	4 (0.60 %)

Note: Data are presented as N (%).

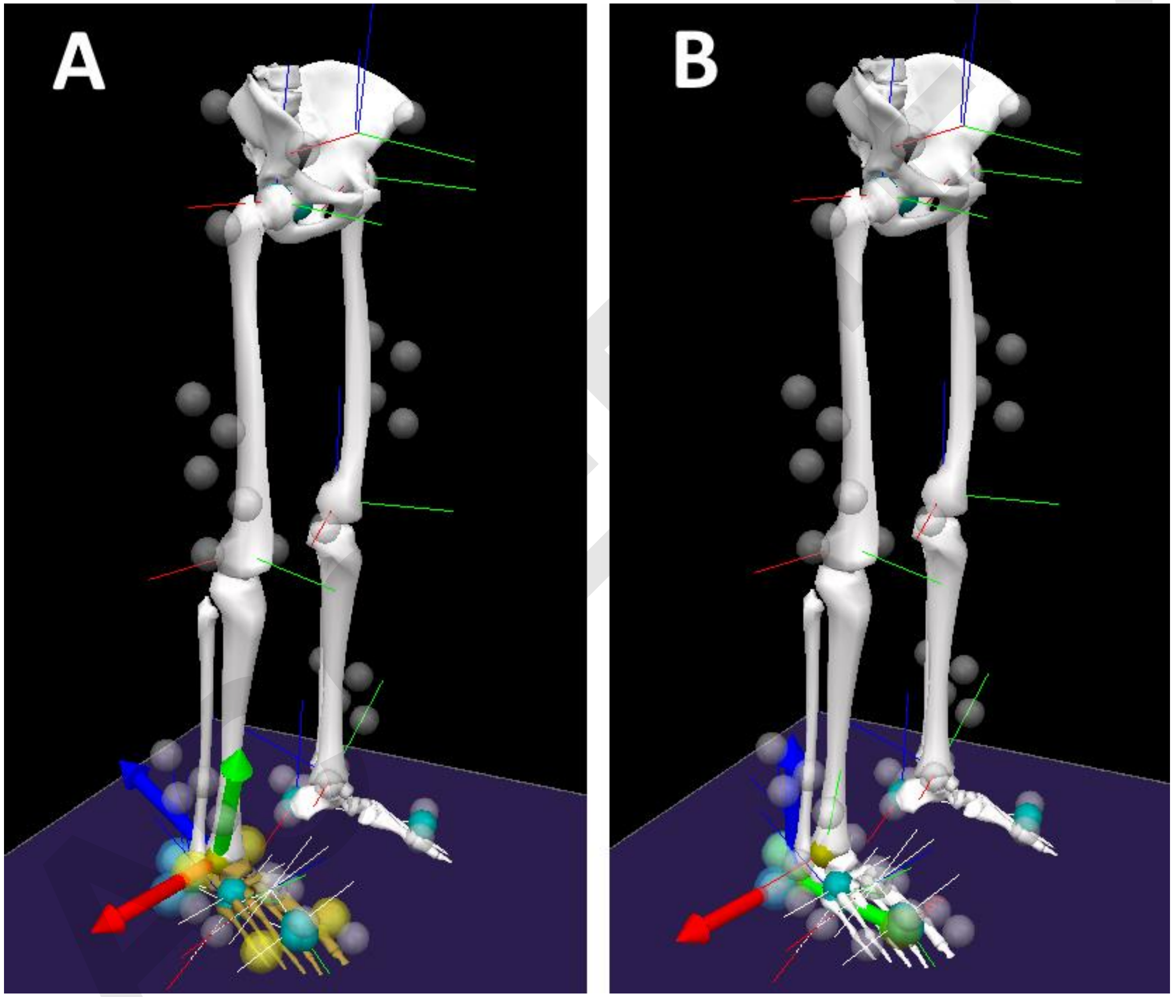
ACCEPTED

SUPPLEMENTAL FIGURE 1. A - Ankle angle (rotation around Z axis) using non-virtual foot model. B - Ankle angle (rotation around Z axis; transversal plane) using virtual foot model. PF runners – solid line; controls – dash line.



ACCEPTED

SUPPLEMENTAL FIGURE 2. Model of the lower extremities in Visual 3D. A – Non-virtual foot model. B – Virtual foot model. Red arrow – X axis; green arrow – Y axis; and blue arrow – Z axis.



ACCEPTED