Goto and Torii
BMC Sports Science, Medicine and Rehabilitation (2025) 17:27
https://doi.org/10.1186/s13102-024-01048-4

BMC Sports Science, Medicine and Rehabilitation

RESEARCH

Open Access

Epidemiology of adolescent runners: non-rearfoot strike is associated with the Achilles tendon and lower leg injury

Haruhiko Goto[1,2*] and Suguru Torii[3]

Abstract

Background Foot strike patterns during running are classified into two types: rearfoot strike (RFS) and non-rearfoot strike (NRFS). These patterns are considered biomechanical risk factors for running-related injuries (RRIs). However, limited research exists on the prevalence or incidence of RRIs associated with different foot strike patterns, particularly within training or clinical practice contexts. Therefore, this epidemiological study aimed to investigate the prevalence and injury risk ratio (IRR) of RRIs concerning different foot strike patterns.

Methods A total of 182 male Japanese adolescent runners were included. Participants completed a questionnaire regarding their RRIs over the past year and were filmed during their habitual high-intensity training sessions from the lateral side. Foot strike patterns were visually classified, with participants accordingly categorized into the RFS and NRFS groups. The prevalence and IRR for RRIs for each site were calculated in both groups. A χ^2 test was conducted to examine the relationship between RRI history and foot strike patterns.

Results A total of 95 (52.2%) and 87 (47.8%) participants were included in the RFS and NRFS groups, respectively, with 124 (68.1%) participants experiencing at least one RRI in the past year. The NRFS group was significantly associated with a history of RRI in the Achilles tendon ($P=0.01$) and the medial lower leg ($P=0.03$). The prevalence of RRI in the Achilles tendon was 9.5% and 23.0% in the RFS and NRFS groups, respectively, with an IRR of 2.427 [1.168, 5.040]. The prevalence of RRI in the medial lower leg was 27.4% and 42.5% in the RFS and NRFS groups, respectively, with an IRR of 1.554 [1.033, 2.338].

Conclusions Adolescent runners with NRFS exhibit a higher risk of Achilles tendinopathy and medial tibial stress syndrome, highlighting the need for RRI prevention strategies tailored for each foot strike pattern.

Key points

• Among 182 Japanese adolescent runners who participated in the present study, 124 (68.1%) reported one or more running-related injuries in the past year.

• The non-rearfoot strike group was significantly associated with a history of running-related injury in the Achilles tendon, with an injury risk ratio of 2.427.

• The non-rearfoot strike group was also significantly associated with a history of running-related injury in the medial lower leg, with an injury risk ratio of 1.554.

*Correspondence:
Haruhiko Goto
haruhiko.goto@jpnsport.go.jp
Full list of author information is available at the end of the article

Keywords Achilles tendinopathy, Adolescent runners, Foot strike pattern, Running-related injury, Non-rearfoot strike, Rearfoot strike

Background

Athletics face a high risk of injuries owing to both competition and daily training. Each year, more than half of middle- and long-distance runners experience at least one running-related injury (RRI), which often leads to a temporary change or cessation of training [1]. RRIs are caused by a range of intrinsic and extrinsic risk factors. Intrinsic risk factors, including excessive body mass and insufficient muscular strength, increase the likelihood of RRI [1, 2]. Extrinsic risk factors, such as excessive running mileage, hard running surfaces, and unsuitable running biomechanics, also contribute to RRI risk [2]. Notably, running biomechanics plays an important role in RRI, with an excessive vertical impact loading rate (VILR) identified as a key contributing factor in its development. Foot strike pattern can influence the magnitude of VILR, making it an important biomechanical factor contributing to the risk of RRI [3–6].

Foot strike patterns during running are classified into two types based on the initial point of contact of the foot with the running surface [7]. Rearfoot strike (RFS) occurs when the heel or the rear third of the foot makes initial contact, whereas non-rearfoot strike (NRFS) occurs when the front third of the foot lands before the heel, or when the entire foot lands simultaneously [7]. In field-based observational studies, foot strike patterns are typically assessed visually using high-speed digital video cameras, usually from a lateral perspective. Runners competing at higher levels or running at higher velocities frequently adopt the NRFS pattern in events such as the 800 m, 1500 m, 10,000 m, and half marathons [7–9]. Laboratory-based studies indicate that foot strike patterns can shift from RFS to NRFS as running vlocity increases, even within the same individual [10]. Therefore, foot strike patterns may vary depending on the competitive level, running velocity, or training experience.

Biomechanical differences have been identified between foot strike patterns in previous laboratory-based studies. Specifically, RFS runners demonstrate a higher VILR than NRFS runners, whereas NRFS runners demonstrate a greater force applied around the ankle joint and Achilles tendon than RFS runners in the early stance phase [3–5]. Consequently, RFS runners are often considered to have a higher risk of overall RRIs or specific RRIs, such as stress fractures in the lower-extremities, plantar fasciitis, and anterior knee pain [11]. In contrast, NRFS runners are thought to have a higher risk of RRIs associated with the Achilles tendon, ankle joint, or lower leg [4, 5].

Although laboratory studies have highlighted biomechanical disparities and potential risks for overall or a specific RRI associated with foot strike patterns, there is limited research exploring the prevalence or incidence of RRIs concerning foot strike patterns in training or clinical practice contexts. To mitigate RRIs and reduce absenteeism from athletic participation, Bahr et al. [12] outlined four key research steps: (1) establish the extent of the injury, (2) establish the etiology and mechanisms of the injury, (3) introduce a preventive measure, and (4) assess its effectiveness. Notably, these steps have been applied to other factors, such as lower-extremity muscular strength [13]. Regarding foot strike patterns, one study demonstrated that RFS runners have a higher injury rate for overall RRIs than NRFS runners [14]. In contrast, other studies found no significant relationship between foot strike pattern and overall RRIs [15, 16]. These conflicting results lead an unclear understanding of the extent to which the risk of RRIs differs between foot strike patterns. Furthermore, these previous studies did not provide injury risk ratio (IRR) and specific injury site, as outlined in the current International Olympic Committee (IOC) consensus statement for the recording and reporting of epidemiological data on injury and illness in 2020 [17]. These insufficient epidemiological data on foot strike patterns and RRIs among middle- and long-distance runners represent a crucial gap in the aforementioned steps for injury prevention.

Therefore, the present retrospective epidemiological study aimed to address this gap by reporting the prevalence and IRR for each RRI based on foot strike patterns and exploring the relationship between the overall and each RRI with foot strike patterns. The findings of the present study will contribute to a better understanding of the epidemiological characteristics of RRIs in runners. We hypothesized that NRFS runners are at a higher risk ratio for RRIs involving the Achilles tendon, ankle, or lower leg, whereas RFS runners are more likely to experience RRIs related to the knee and foot/toe.

Methods

Participants

A *priori* power analysis for χ^2 test was performed using G*Power version 3.1 (Heinrich-Heine- Universität Düsseldorf, Germany), with the following parameters: effect size (w), 0.30; α error probability (error prob), 0.05; and statistical power (1-β error prob), 0.80; degrees of freedom (df), 1. The resulting sample size was 88 participants [18].

In total, 182 male Japanese adolescent runners participated in the study (Table 1). All participants were competitive middle- and long-distance runners with no RRIs at the time of data collection.

The study was approved by the Ethics Committee of the authors' affiliation (#2022-021) and adhered to the principles of the Declaration of Helsinki. All participants provided written informed consent before participation.

Data collection—questionnaire regarding RRI

Participants completed a questionnaire on their demographics, running habits, and RRI history. Participant demographics included age [years], height [cm], and weight [kg], whereas running habits included monthly training mileage [km], daily and weekly training frequency [times per day and days per week], and personal best time (PB) in specialized events. PB was scored using the World Athletics (WA) scoring Table [19]. In cases where participants reported the PB for multiple events, the highest score was recorded.

RRI was defined as "*Any physical complaint or manifestation experienced by an athlete, irrespective of the need for medical attention or time loss from athletics activities*," as per the consensus statement for injury data collection in athletics [20]. Participants were required to report the specific site(s) on the body where they had experienced RRIs in the prior year. RRI history was aggregated, and the responses were categorized into eight sites: hip, groin, thigh (anterior/posterior), knee (anterior/posterior/medial/lateral), lower leg (anterior/posterior/medial/lateral), Achilles tendon, ankle (anterior/posterior), and foot/toe (anterior/posterior). The thigh, knee, lower leg, ankle, and foot were subcategorized into anterior, posterior, medial, and lateral sites, respectively [17]. To ensure clarity in the responses of participants, questionnaires were distributed in person by researchers, who provided explanations and instructions. Examples of answers were also provided in the questionnaire. In cases of ambiguous responses about the RRI history, an experienced researcher consulted with the participant and the coaching staff for confirmation.

Data collection—high-speed video for assessing foot strike patterns

Participants were filmed from the lateral side during habitual training sessions, where they ran at their race pace on running tracks, without specific task instructions. A high-speed digital video camera (Lumix DC-TZ95, Panasonic Corp., Osaka, Japan) with a frame rate of 240 fps was positioned on a tripod at a height of 0.8 m, perpendicular to the running direction. The camera was placed along the outer edge of the home or back straight of the running tracks, 7–10 m away from the participants. The viewing angle was set at approximately 6 m width in the running direction, using the hurdle marks on the running track as a guide, and at least three steps were captured. Data collection was conducted during daylight hours to ensure adequate light intensity for observation and recording.

All recorded images from the data collection were processed using QuickTime for Windows (Apple Inc., CA, USA). Subsequently, an experienced researcher visually classified foot strike patterns based on a previous study: RFS, where the rear third part of the foot lands first; and NRFS, where the rest of the foot makes initial contact (Fig. 1) [7, 16]. In addition, no participants changed their foot strike patterns during the filmed sessions.

Their running velocities during data collection were calculated and presented as m/s based on the manually measured lap times readout for each 100–200 m by their coaching staff.

Data analyses

Before the analysis, each foot strike was assessed twice, and the weighted kappa (κ) was calculated to assess the

Table 1 Participant demographics

Group	*N*	Age [years]	Height [cm]	Body mass [kg]	WA score [points]	Monthly running mileage [km]	Training frequency [days per week]	Training frequency [times per day]	Running velocity during data collection [m/s]
NRFS	87	16.82 ± 0.77*	170.92 ± 4.70	54.33 ± 4.84	787.10 ± 133.13*	420.98 ± 156.63*	6.36 ± 0.58	1.82 ± 0.44	5.74 ± 0.43*
RFS	95	16.32 ± 0.88	169.86 ± 5.65	53.92 ± 5.46	686.01 ± 189.13	353.43 ± 141.56	6.18 ± 0.72	1.67 ± 0.43	5.56 ± 0.54
Total	182	16.55 ± 0.86	170.37 ± 5.24	54.12 ± 4.74	734.34 ± 171.98	385.72 ± 152.35	6.27 ± 0.66	1.74 ± 0.44	5.65 ± 0.49

NRFS Non-rearfoot strike, *RFS* Rearfoot strike, *WA* World Athletics,

*$P < 0.01$ vs. RFS group

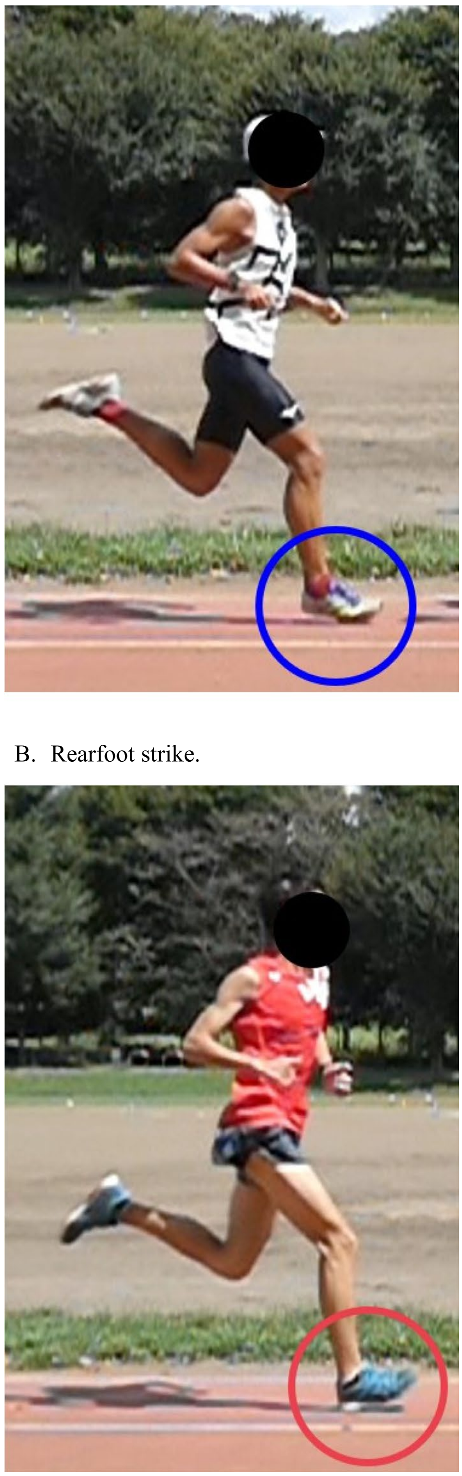

Fig. 1 Foot strike patterns for each group

reliability of the visual foot strike assessment. The reliability was interpreted as almost perfect when κ was ≥ 0.81.

Participant demographics and running habits were presented as the means ± standard deviations. An independent Student's *t*-test or Welch's *t*-test was used to compare the participant demographics between the two groups for normally and non-normally distributed data, respectively. Effect sizes were described using Cohen's coefficient (d), with associations interpreted as trivial ($d < 0.20$), small ($0.20 \leq d < 0.50$), moderate ($0.50 \leq d < 0.80$), or large ($0.80 \leq d$).

The prevalence for overall and each RRI with at least 10 occurrences in total and both groups were calculated by dividing the number of RRI by the number of participants, and they were presented in percentage. The IRR with a 95% confidence interval (CI) between the two groups was defined as the ratio of the prevalence of NRFS to that of RFS; a value of < 1 indicates a higher prevalence in the NRFS group than in the RFS group [17, 18, 21].

In addition, a χ^2 test was conducted to examine the relationship between the overall and specific sites of the RRIs and foot strike patterns. The effect size in the χ^2 test was described using the phi coefficient (ϕ) with association levels interpreted as small ($\phi < 0.10$), medium ($0.10 \leq \phi < 0.50$), or large ($0.50 \leq \phi$).

All statistical analyses were conducted using SPSS version 28 (IBM Corp., Armonk, NY, USA), and statistical significance was set at $P < 0.05$.

Results

Reliability of assessment for foot strike patterns

The reliability of the visual foot strike assessment was interpreted as almost perfect (κ ≥ 0.81), with a value of 0.97 [0.93, 1.00].

Participant demographics

In total, 182 runners participated in the study, with 95 (52.2%) and 87 (47.8%) included in the RFS and NRFS groups, respectively. Participant demographics, their running habits, and the running velocity during data collection were presented in Table 1. The NRFS group exhibited significantly higher values for age, WA scores for PBs, monthly running mileage, and running velocity during fata collection than those of the RFS group ($P < 0.01$ for all parameters). The effect size for these differences ranged from small to moderate ($d = 0.60$, 0.62, 0.45 and 0.36, respectively). The running velocity observed during data collection corresponded to participants' race paces for the 1500 m and 5000 m PB times in both groups. Most participants reported their PBs for the 1500 m and 5000 m. The distribution of participants

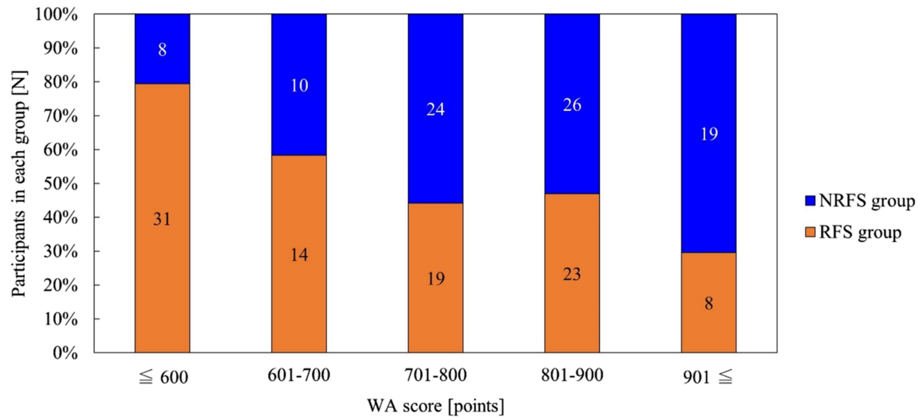

Fig. 2 Number and population of non-rearfoot and rearfoot strike groups for each World athletics score

across the WA scores for each group is depicted in Fig. 2, which illustrates the following trend: the higher the PB, the larger the population in the NRFS group.

Prevalence and IRR of RRI for each foot strike pattern

In total, 124 (68.1%) participants experienced one or more RRIs in the prior year (Tables 2). The most frequent site of RRI was the lower leg (37.4%), followed by the knee (24.7%), Achilles tendon (15.9%), and foot/toe (15.9%).

In the RFS group, 60.0% of the participants experienced RRI, compared to 77.0% in the NRFS group. The χ^2 test revealed a significant association between foot strike pattern and the prevalence of overall RRIs, with the NRFS group (Table 3) exhibiting a higher frequency of overall RRIs ($P=0.01$). The IRR for the overall RRIs was 1.284 [1.050, 1.568].

For specific RRI sites, the χ^2 test revealed a significant association between the foot strike pattern and the

Table 2 Prevalence of running-related injuries

A. Prevalence of running-related injuries at each site

Site for RRI	NRFS group [N (%)]	RFS group [N (%)]	Total [N (%)]
Hip	3 (3.5 %)	1 (1.1 %)	4 (2.2 %)
Groin	1 (1.2 %)	1 (1.1 %)	2 (1.1 %)
Thigh	5 (5.7 %)	1 (1.1 %)	6 (3.3 %)
Knee	22 (25.3 %)	23 (24.2 %)	45 (24.7 %)
Lower leg	39 (44.8 %)	29 (30.5 %)	68 (37.4 %)
Achilles tendon	20 (23.0 %)	9 (9.5 %)	29 (15.9 %)
Ankle	2 (2.3 %)	0 (0.0 %)	2 (2.2 %)
Foot/toe	14 (16.1 %)	15 (15.5 %)	29 (15.9 %)

B. Prevalence of running-related knee injury

Subcategorized site for RRI	NRFS group [N (%)]	RFS group [N (%)]	Total [N (%)]
Anterior knee	5 (5.7 %)	7 (7.4 %)	12 (6.6 %)
Posterior knee	0 (0.0 %)	0 (0.0 %)	0 (0.0 %)
Medial knee	2 (2.3 %)	1 (1.1 %)	3 (1.7 %)
Lateral knee	2 (2.3 %)	1 (1.1 %)	3 (1.7 %)

C. Prevalence of running-related injuries in the lower leg

Subcategorized site for RRI	NRFS group [N (%)]	RFS group [N (%)]	Total [N(%)]
Posterior lower leg	3 (3.5 %)	3 (3.3 %)	6 (3.3 %)
Medial lower leg	37 (42.5 %)	29 (30.5 %)	63 (34.6 %)

NRFS Non-rearfoot strike, *RFS* Rearfoot strike, *RRI* Running related injury

Table 3 Relationship between running-related injuries and foot strike patterns

Group	Yes [*N*]	No [*N*]	Total [*N*]	Prevalence [%]
NRFS	67	20	87	77.0
RFS	57	38	95	60.0
Total	124	58	182	68.1

$\chi^2[1]=6.053$, $P=0.01$, $\varphi=0.182$
IRR: 1.284 [1.050, 1.568]

IRR Injury risk ratio, *NRFS* Non-rearfoot strike, *RFS* Rearfoot strike

Table 4 Relationship between running-related injuries around the Achilles tendon and foot strike patterns

Group	Yes [N]	No [N]	Total [N]	Prevalence [%]
NRFS	20	67	87	23.0
RFS	9	86	95	9.5
Total	29	153	182	15.9

$\chi^2[1] = 6.192$, $P = 0.01$, $\varphi = 0.184$
IRR: 2.427 [1.168, 5.040]

IRR Injury risk ratio, *NRFS* Non-rearfoot strike, *RFS* Rearfoot strike

Table 5 Relationship between running-related injuries around the medial lower leg and foot strike patterns

Group	Yes [N]	No [N]	Total [N]	Prevalence [%]
NRFS	37	50	87	42.5
RFS	26	69	95	27.4
Total	63	119	182	34.6

$\chi^2[1] = 4.612$, $P = 0.03$, $\varphi= 0.159$
IRR: 1.554 [1.033, 2.338]

IRR Injury risk ratio, *NRFS* Non-rearfoot strike, *RFS* Rearfoot strike

prevalence of RRI for the Achilles tendon and medial lower leg, both of which were more frequent in the NRFS group than in the RFS group (Tables 4 and 5) ($P=0.01$ and 0.03, respectively). The IRR for both sites of the RRI were 2.427 [1.168, 5.040] and 1.554 [1.033, 2.338], respectively.

Discussion

To the best of our knowledge, the present study represents the first epidemiological investigation on the prevalence and IRR of each RRI among foot strike patterns, categorized by injury site following the consensus statement for recording and reporting injuries [17, 20]. The present study also explores the association of foot strike patterns with the prevalence of RRIs among male Japanese adolescent runners.

The number of participants in the RFS and NRFS groups was similar (95 and 87, respectively). The running velocity in both groups during data collection corresponded to the racing velocity they typically achieve in their respective events. Thus, the conditions reflect their habitual foot strike patterns. Among the participant demographics, age, monthly mileage, WA scores for PBs, and running velocity during data collection were significantly higher in the NRFS group than in the RFS group. This trend is consistent with previous findings suggesting that as runners reach highly competitive levels, the proportion of NRFS runners increases in middle- and long-distance running events [7–9]. The higher age, monthly running mileage, and running velocity observed in the NRFS group suggest that these participants were more competitive, with more advanced and greater experience. Overall, these results indicate that participants in the present study were representative of the general population of adolescent middle- and long-distance runners, in terms of both foot strike patterns and competitive levels.

In the present study, a total of 124 (68.1%) runners experienced one or more RRIs in the prior year. The prevalence of overall RRIs was generally similar to a previous study indicating that 53–83% of middle- and long-distance runners experienced "*any complaints*" or RRIs, with or without periods of absence from athletic activity over a year [1]. Consequently, the present result demonstrate that middle- and long-distance running is associated with a high incidence of RRI, even among Japanese male adolescent runners.

For overall RRIs, the χ^2 test revealed a significant correlation between foot strike patterns and the prevalence of overall RRIs, with a higher frequency observed in the NRFS group. This result might be attributed to the fact that the NRFS group exhibited a significantly higher competitive level and longer running mileage than the RFS group. Notably, this finding contrasts with the study by Daoud et al., [13] which demonstrated that RFS collegiate runners had a 2.5 times higher rate of RRIs compared to that of NRFS runners. In addition to foot strike patterns, various factors contribute to RRIs, including body mass index (BMI) [22], muscular strength of the lower-extremities [23], and running mileage [2, 24]. Therefore, in the present study, foot strike patterns may play a different role in the development of overall RRIs among Japanese adolescent runners compared to collegiate runners reported in the previous study.

In terms of specific RRI, the lower leg was the most frequent site (37.4%), followed by the knee (24.7%), Achilles tendon (15.9%), and foot/toe (15.9%). These injury sites align with a previous study [1], suggesting that participants in the present study were representative of the general population in terms of specific RRI site, the competitive level, and the foot strike pattern.

Regarding the relationship between specific RRI sites and foot strike patterns, RRIs involving the Achilles tendon and medial lower leg were significantly more frequent in the NRFS group. This finding was partially consistent with the results of Goto et al., [16] who reported a significant association between NRFS and achillodynia but not with medial tibial pain. Previous laboratory-based biomechanical studies indicated that NRFS was associated with a 1.2–1.4 times greater ankle plantar flexion torque and/or Achilles tendon force than RFS [3–5] and that the transition from RFS to NRFS increased triceps surae muscle activity [25]. These data suggested higher risk of Achilles tendinopathy among NRFS runners, and the present study provides epidemiological support for these earlier findings [3–5, 25]. However, in the present study, the IRR for RRI of the Achilles tendon was 2.427, considerably exceeding the biomechanical differences in ankle joint force or torque between foot strike patterns reported in previous studies [3–5]. Given that the NRFS group in the present study ran significantly longer mileage, and potentially at higher intensity, than the RFS group, the elevated IRR might reflect the combined effects of these factors, rather than purely mechanical differences.

In the present study, RRIs around the medial lower leg were also associated with foot strike patterns. Most of these injuries were considered cases of medial tibial stress syndrome (MTSS) [26, 27], which is thought to be influenced by excessive eccentric stress on the planter flexor muscle or greater pronation of the ankle joint [27, 28]. As NRFS results in increased ankle plantar flexion torque and triceps surae muscle activity [3–5, 25], this could explain its association with MTSS. The findings of the present study regarding RRIs at specific anatomical sites differ from those of Daoud et al., [14] who found no association between foot strike patterns and Achilles tendinopathy or MTSS in male collegiate long-distance runners. Similarly, Goto et al. [16] reported no significant association between foot strike patterns and medial tibial pain. These inconsistencies could be attributed to the age or training experience of participants across studies. In the present study, participants in the NRFS group were significantly older, and had a higher monthly running mileage and better WA scores than those in the RFS group. As competitive levels of participants were not significantly different or were not reported in previous studies [14, 16], demographic variations may explain these inconsistencies. For example, Achilles tendon properties change with growth and athletic training [29, 30], suggesting that the magnitude of RRI risk may vary by age or training experience, even for the same foot strike pattern. Moreover, MTSS may be a more common RRI for adolescent runners [27]. Therefore, the influence of foot strike patterns on MTSS development might be more pronounced in younger athletes, contributing to different results observed in the present study. Given that foot strike patterns can vary depending on competitive level or running velocity [7–10], and that the NRFS group in the present study had significantly longer running mileage than that of the RFS group, mileage alone cannot account for the difference in RRI site between the groups. If running mileage were the sole factor, both groups would exhibit RRIs at the same anatomical sites. Consequently, it is likely that RRIs in the Achilles tendon and medial lower leg are specifically associated with foot strike patterns. These findings suggest that targeted prevention strategies should be developed to address the distinct biomechanical demands and injury risks associated with each foot strike pattern and the developmental stage the athletes.

Unlike the RRI around the Achilles tendon and lower leg, the RRI for the knee and foot/toe were not significantly associated with foot strike patterns. Common knee RRIs, such as iliotibial band syndrome or patellofemoral pain, as well as common foot/toe RRIs such as plantar fasciitis, are associated with risk factors such as a higher body mass or BMI [22], limited joint range of motion [22], and insufficient lower extremity muscle strength [13, 23]. Biomechanical differences between foot strike patterns were primarily observed during the first half of the stance phase, especially during initial contact [4, 5]. Therefore, the influence of foot strike patterns on RRIs at the knee and foot/toe may be less pronounced than that for other anatomical sites.

The present study had some limitations. First, the results were based on a questionnaire, which introduces the possibility of recall bias. Accurately assessing the time lost from athletic activities as an indicator of RRI severity was also difficult [30]. Participants may have varied in their interpretation of what constitutes an RRI, with some accepting "*any complaint*" as an injury, while others may view such issues as simply "part of the sport." Furthermore, as foot strike patterns are associated with the competitive level [7–9], future analyses should consider factors other than foot strike patterns, such as running mileage and training load, footwear, or running surfaces, all of which have been correlated with RRI occurrence [24]. A long-term prospective study and multivariate analysis with a larger sample size, including female athletes, is needed to comprehensively investigate the role of training-related factors—such as foot strike patterns—in RRIs. The other limitation is that the present study assessed foot strike patterns visually. Although the reliability of the visual foot strike assessment was almost perfect, the camera was positioned at a relatively far distance, and no markers were attached to the participants' shoes. Future studies should use foot strike angles calculated using markers attached to the foot to evaluate the relationship between foot strike patterns and RRIs, even in field-based situations.

Conclusions

To the best of our knowledge, the present study is the first to investigate the prevalence and IRR of RRI for each foot strike pattern among male Japanese adolescent runners. The prevalence of overall RRIs for all participants was 68.1%. Although the NRFS group exhibited a longer monthly running mileage than the RFS group, they also demonstrated higher IRRs for RRI around the Achilles tendon and medial lower leg, with 2.427 and 1.554 times greater IRRs than those of the RFS group, respectively. These findings suggest the need for introducing foot strike pattern-specific preventive measures to mitigate RRIs in athletes.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-024-01048-4.

Supplementary Material 1.

Acknowledgements

The authors thank Mr. Yano K. and Mr. Haseba Y., who are ex-colleagues of the author Goto H., for helping in recruiting the participants. All pictures used for the figures were taken by the authors themselves. The authors declare that they have no conflicts of interest, and the data supporting the findings of the present study are available from the corresponding author upon reasonable request. The experiments complied with the current laws of the country in which they were performed.

Authors' contributions

H. G.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing original draft. S. T.: Supervision, Writing- review and editing the manuscript.

Funding

No funding or grant was received for conducting the present study.

Data availability

The datasets that support the findings of the current study are available from the authors upon reasonable request and with permission from Japan Institute of Sports Sciences.

Declarations

Ethics approval and consent to participate

The study was approved by the Ethics Committee of the Japan Institute of Sports Sciences (#2022-021) and conducted in accordance with the principles of the Declaration of Helsinki. All participants provided written informed consent before participation.

Consent for publication

The corresponding author has read the journal policies and submitted this manuscript in accordance with those policies. All participants provided written informed consent for the publication and usage of their picture and/or figure in the manuscript.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Sports Sciences, Japan Institute of Sports Sciences, 3-15-1 Nishigaoka, Kita-Ku, Tokyo 115-0056, Japan. [2]Graduate School of Sport Sciences, Waseda University, Saitama, Japan. [3]Faculty of Sport Sciences, Waseda University, Saitama, Japan.

Received: 27 June 2024 Accepted: 30 December 2024
Published online: 26 February 2025

References

1. Hollander K, Rahlf AL, Wilke J, Edler C, Steib S, Junge A, Zech A. Sex-specific differences in running injuries: a systematic review with meta-analysis and meta-regression. Sports Med. 2021;51(5):1011–39.
2. Souza RB. An evidence-based videotaped running biomechanics analysis. Phys Med Rehabil Clin N Am. 2016;27(1):217–36.
3. Hashizume S, Yanagiya T. A forefoot strike requires the highest forces applied to the foot among foot strike patterns. Sports Med Int Open. 2017;1(2):E37–42.
4. Kuhman D, Melcher D, Paquette MR. Ankle and knee kinetics between strike patterns at common training speeds in competitive male runners. Eur J Sport Sci. 2016;16(4):433–40.
5. Kulmala JP, Avela J, Pasanen K, Parkkari J. Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. Med Sci Sports Exerc. 2013;45(12):2306–13.
6. Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, D'Andrea S, Davis IS, Mang'eni RO, Pitsiladis Y. Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature. 2010;463(7280):531–5.
7. Hanley B, Tucker CB, Bissas A, Merlino S, Gruber AH. Footstrike patterns and race performance in the 2017 IAAF World Championship men's 10,000 m final. Sports Biomech. 2024;23(3):314–23.
8. Hasegawa H, Yamauchi T, Kraemer WJ. Foot strike patterns of runners at the 15-km point during an elite-level half marathon. J Strength Cond Res. 2007;21(3):888–93.
9. Hayes P, Caplan N. Foot strike patterns and ground contact times during high-calibre middle-distance races. J Sports Sci. 2012;30(12):1275–83.
10. Breine B, Malcolm P, Frederick EC, De Clercq D. Relationship between running speed and initial foot contact patterns. Med Sci Sports Exerc. 2014;46(8):1595–603.
11. Futrell EE, Jamison ST, Tenforde AS, Davis IS. Relationships between habitual cadence, footstrike, and vertical load rates in runners. Med Sci Sports Exerc. 2018;50(9):1837–41.
12. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. Br J Sports Med. 2005;39(6):324–9.
13. Noehren B, Schmitz A, Hempel R, Westlake C, Black W. Assessment of strength, flexibility, and running mechanics in men with iliotibial band syndrome. J Orthop Sports Phys Ther. 2014;44(3):217–22.
14. Daoud AI, Geissler GJ, Wang F, Saretsky J, Daoud YA, Lieberman DE. Foot strike and injury rates in endurance runners: a retrospective study. Med Sci Sports Exerc. 2012;44(7):1325–34.
15. Molloy JM. Factors influencing running-related musculoskeletal injury risk among U.S. military recruits. Mil Med. 2016;181(6):512–23.
16. Goto H, Torii S. Foot strike patterns and running-related injuries among high school runners: a retrospective study. J Sports Med Phys Fit. 2022;62(12):1668–74.
17. International Olympic Committee Injury and Illness Epidemiology Consensus Group, Bahr R, Clarsen B, Derman W, Dvorak J, Emery CA, Finch CF, Hägglund M, Junge A, Kemp S, Khan KM, Marshall SW, Meeuwisse W, Mountjoy M, Orchard JW, Pluim B, Quarrie KL, Reider B, Schwellnus M, Soligard T, Stokes KA, Timpka T, Verhagen E, Bindra A, Budgett R, Engebretsen L, Erdener U, Chamari K. International Olympic Committee consensus statement: methods for recording and reporting of epidemiological data on injury and illness in sports 2020 (including the STROBE extension for sports injury and illness surveillance (STROBE-SIIS)). Orthop J Sports Med. 2020;8(2):2325967120902908.
18. Field A. Discovering statistics using IBM SPSS statistics. 5th ed. London: SAGE; 2017.
19. World Athletics. In: World Athletics scoring tables updated for 2022. 2022. https://worldathletics.org/news/news/scoring-tables-2022. Accessed 30 Sep 2024.

20. Timpka T, Alonso JM, Jacobsson J, Junge A, Branco P, Clarsen B, Kowalski J, Mountjoy M, Nilsson S, Pluim B, Renström P, Rønsen O, Steffen K, Edouard P. Injury and illness definitions and data collection procedures for use in epidemiological studies in Athletics (track and field): consensus statement. Br J Sports Med. 2014;48(7):483–90.
21. Bahr R. No injuries, but plenty of pain? On the methodology for recording overuse symptoms in sports. Br J Sports Med. 2009;43:966–72.
22. Trojian T, Tucker AK. Plantar fasciitis. Am Fam Physician. 2019;99(12):744–50.
23. Verrelst R, Willems TM, De Clercq D, Roosen P, Goossens L, Witvrouw E. The role of hip abductor and external rotator muscle strength in the development of exertional medial tibial pain: a prospective study. Br J Sports Med. 2014;48(21):1564–9.
24. Damsted C, Glad S, Nielsen RO, Sørensen H, Malisoux L. Is there evidence for an association between changes in training load and running-related injuries? A systematic review. Int J Sports Phys Ther. 2018;13(6):931–42.
25. Shih Y, Lin KL, Shiang TY. Is the foot striking pattern more important than barefoot or shod conditions in running? Gait Posture. 2013;38(3):490–4.
26. Shaw A, Newman P, Witchalls J, Hedger T. Externally validated machine learning algorithm accurately predicts medial tibial stress syndrome in military trainees: a multicohort study. BMJ Open Sport Exerc Med. 2023;9(2): e001566.
27. Yates B, White S. The incidence and risk factors in the development of medial tibial stress syndrome among naval recruits. Am J Sports Med. 2004;32(3):772–80.
28. Burrus MT, Werner BC, Starman JS, Gwathmey FW, Carson EW, Wilder RP, Diduch DR. Chronic leg pain in athletes. Am J Sports Med. 2015;43(6):1538–47.
29. Kubo K, Kanehisa H, Kawakami Y, Fukanaga T. Growth changes in the elastic properties of human tendon structures. Int J Sports Med. 2001;22(2):138–43.
30. Murphy MC, Glasgow P, Mosler AB. Self-reported measures of training exposure: can we trust them, and how do we select them? Br J Sports Med. 2021;55(16):891–2.

Publisher's Note