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Full Length Article

Relationship between bilateral symmetry of foot posture and lower limb musculoskeletal injuries among workers engaged in physically demanding occupations: A cross-sectional investigation

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ABSTRACT

Even though the link between foot posture and lower-extremity injuries remains controversial, there has been little research focus on bilateral foot symmetry. This study evaluated the correlation between bilateral symmetry in foot posture and lower extremity musculoskeletal injuries among workers in physically intensive occupations. A total of 248 participants with physically demanding roles were enrolled. Historical data on lower-limb musculoskeletal injuries were obtained through a review of medical records, supplemented by results from on-site consultations. The foot arch index (AI) was quantitatively measured using a 3D laser foot scanner, and foot posture was evaluated using the foot posture index-6 (FPI-6). The participants were categorized into subgroups based on bilateral symmetry assessments of their feet. Logistic regression analyses were performed for statistical comparisons after adjusting for potential confounding factors. The results indicate that abnormalities in foot posture and arch, assessed using the FPI-6 and AI, were identified in 42.3 % and 47.2 % of participants, respectively, with 20.9 % and 16.5 % demonstrating bilateral asymmetry in these parameters. When comparing bilateral and unilateral foot protonation with bilaterally normal feet, the risk adjustments revealed differences of 2.274 (95 % CI: 1.094–4.729, $P = 0.028$) and 2.751 (95 % CI: 1.222–6.191, $P = 0.015$), respectively. Furthermore, the risk adjustment for age, BMI, smoking status, physical training years, training time, training frequency, warm-up before training, relaxation after training, MIS prevention, and treatment learning for unilateral flatfoot relative to bilateral normal feet was 3.197 (95 % CI:1.235–8.279, $P = 0.017$). This study demonstrates that workers in physically demanding occupations who exhibit unilateral foot protonation or unilateral flatfoot are at an increased risk of lower-extremity musculoskeletal injuries.

1. Introduction

Musculoskeletal injury (MSI) is a frequent problem in physically demanding occupations such as the military, law enforcement, and firefighting. Reports indicate that between 28 % and 45.6 % of individuals in these professions have experienced at least one MSI incident during rigorous training sessions.[1] Epidemiological research has shown that 11.1 %–36.9 % of individuals engaged in physically strenuous occupations reported musculoskeletal injuries (MSIs) during military training sessions in China. The lower limbs are most frequently affected, with prevalence rates ranging from 54.1 % to 90.9 %.[2,3] MSIs resulting from rigorous physical training can jeopardize the ability of affected individuals to efficiently fulfill their roles, particularly in time-critical tasks. This not only escalates healthcare expenditures but also depletes human resources by rendering personnel medically unfit to perform duties or be deployed, thereby undermining operational efficiency and readiness.[4] Consequently, understanding the risk factors associated with musculoskeletal injuries is crucial for implementing effective injury prevention strategies, particularly within military and emergency response organizations.

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Foot posture, recognized as a potential determinant of lower limb injuries,[5–7] has received considerable attention in clinical settings. Historical research dating back to 1987 has emphasized the integral role of foot structure in influencing the biomechanics of all lower extremities.[8] The foot and ankle are crucial components of the kinetic chain that affect lower-limb dynamics during closed-chain movements. Numerous studies have indicated that deviations in foot posture may induce adaptive alterations in the force trajectory of the lower limbs, thereby increasing the risk of injury.[6] The foot posture index (FPI) and arch index (AI) are commonly employed metrics for evaluating foot posture, both of which demonstrate significant associations with lower-limb injuries.[9,10] Angin et al.[11,12] observed that pes planus, as measured by the FPI and AI, resulted in a reduction in the thickness of the intrinsic muscles and an increase in both the thickness and area of the extrinsic muscles. These changes lead to compensatory adaptations in the structural and functional regions of the feet, which affect the dynamic activities of the lower limbs.[13]

Compared to the general population, personnel in physically demanding occupations face significant physical challenges during training and operational activities throughout their active duty,[14] resulting in elevated incidence and prevalence of knee, hip, and other osteoarthritic conditions.[15–17] Although abnormal foot postures, particularly foot protonation and pes planus, are considered risk factors for lower-limb injuries in the general population, including athletes, there is a notable lack of information on the impact of foot morphology on MSIs and the influence of foot posture on lower-limb injuries in the context of military physical training. The absence of high-quality evidence has constrained the development of effective management strategies for foot posture in relation to the MSIs in individuals engaged in physically demanding occupations.

This study employed the FPI-6 and AI, which were assessed using a 3D laser foot scanner, to collect data on the participants' foot types and investigate the relationship between foot posture and lower-limb MSIs. These results provide a basis for establishing future injury prevention strategies to improve operational performance of military and emergency service personnel.

2. Materials and methods

2.1. Participants

For this cross-sectional study, 248 male volunteers aged 18–35 years engaged in physically demanding occupations were recruited. The participants exhibited relatively uniform characteristics in terms of age (24.02 $\pm$ 3.58 years), height (1.76 $\pm$ 0.05 m), weight (69.80 $\pm$ 8.99 kg), body mass index (22.62 $\pm$ 2.63 kg/m^2), and years of physical training (4.02 $\pm$ 3.06 years). Individuals exhibiting any of the following conditions were excluded: having deformities of the foot or ankle joints, currently using or previously used foot and ankle orthoses, or suffering from peripheral neuropathy, abnormal lower-limb sensation, or vestibular function impairment.

The sample size was determined using a chi-square design to evaluate the primary outcome, which involved assessing differences in the incidence of lower limb MSI among individuals with physically demanding occupations. This calculation was based on a previously reported annual incidence of 36 % for lower-limb MSIs,[3] with a statistical power of 80 %, significance level of 5 %, and a small effect size (0.25) to avoid undersampling.

This study was approved by the Institutional Ethics Committee (IEC) of the Tangdu Hospital, Fourth Military Medical University (XKT-Y-20221139). All participants provided informed consent prior to data collection.

2.2. Equipment and data collection

2.2.1. Investigation of MSI of the lower limb

The investigation utilized medical records from several hospitals in Xian and on-site consultation results.

A Lower Extremity Physical Training MSI Questionnaire, created by specialists at Tangdu Hospital and based on the 2022 Expert Consensus on Principles of Diagnosis and Prevention of Military Training Injuries,[18] was used to evaluate the occurrence of lower limb MSIs in participants over the previous two years. MSIs were characterized by pain, inflammation, or functional disorders affecting the bones, joints, muscles, tendons, ligaments, and associated connective tissues.[19]

Quality control of the questionnaire was ensured by an expert team consisting of two attending physicians from the Department of Rehabilitation Medicine and a deputy chief physician. The questionnaire included information on injury types (soft tissue, bone, and joint), injury sites (hip joint, knee joint, ankle joint, thigh, calf, and foot), injured tissues (skeletal muscle, ligament, tendon, cartilage, and bone), injury severity (mild, moderate, severe, and critical), ICD-10 diagnosis, and clinical treatment. In the cases with multiple injuries, the results of the first diagnosis were considered. The injuries were coded into categorical variables based on their occurrence and a descriptive analysis of the overall injury situation was performed.

2.2.2. Foot posture index-6 items (FPI-6) assessment

FPI-6: Evaluation of the FPI-6 involves both visual inspection and manual palpation by the assessor. During the evaluation, the participants stood barefoot on a flat surface in a relaxed upright position, looking straight ahead. The FPI-6 includes six criteria: (1) palpation of the talar head; (2) curvature of the supralateral and infralateral malleoli; (3) prominence of the talonavicular joint; (4) alignment of the medial longitudinal arch; (5) abduction/adduction of the forefoot; and (6) inversion/eversion of the calcaneus.[20] Each criterion is rated on a scale of -2 to 2, resulting in a total score range of -12 to 12.

After completing the test, the scores were categorized according to the following standards: a total score of -12 to -5 denoted severe supination, -4 to -1 indicated mild supination, 0 to 5 signified neutral foot posture, 6 to 9 indicated mild protonation, and 10 to 12 indicated severe protonation. To maintain consistency and precision, a trained evaluator conducted all assessments.[21]

2.3. AI assessment

A USOL 3D laser foot scanner (Kangzhilai, Wenzhou, China) was used to measure the participants' AI. The scanner offers an accuracy of up to 1.0 mm. Each foot scan was completed in approximately 2 s.

During the evaluation process, the participants stood barefoot on the scanning board. The evaluator aligned the participant's heel with the red line, instructed the participant to take a step with the contralateral foot staying in the same spot, and adjust their foot posture to a relaxed state, and instructed them to look straight ahead. The scanner was used with the dedicated software to acquire 3D models of the foot with a linear precision of 1 mm. Specific foot measurements, such as length, width, and height, were automatically exported. The AI was determined by calculating the ratio of the midfoot contact area to the total foot area, and the test results were automatically generated by the analysis software.

Upon completion of the test, the AI was coded as a categorical variable based on the following standards: AI$<$0.21 is defined as cavus foot; 0.21–0.26 is defined as normal foot; 0.26–0.28 is defined as mild pes planus; 0.28–0.30 is defined as moderate pes planus; $>$0.3 is defined as severe pes planus. To ensure quality control, testing was conducted by a senior engineer and verified by another engineer.

2.4. Control variables survey

Previous studies have shown that age (in years), sex, BMI (kg/m2), smoking status, physical training years (years), training time (hours/day), training frequency (days/week), warm-up before training, relaxation after training, MIS prevention, and treatment learning are potential risk factors for MSI.[17,22] This information was collected through on-site interviews and anthropometric measurements.

Multiple logistic regression was employed for statistical modelling to mitigate the potential influence of the previously mentioned covariates. In this study, no significant differences were found in the participants' age, training frequency, pre-training warm-up, post-training relaxation, years of physical training, or MIS prevention and treatment education. Consequently, to examine the effects of FPI-6, AI, and lower-limb MSI, control variables, including BMI, sleep status, and training duration, were used to eliminate the possible confounding factors.

2.5. Quality control

In this retrospective study, data collection was conducted through expert consultations rather than relying on participants' self-reports to enhance data quality. Additionally, medical records from several designated hospitals in Xi'an were reviewed to mitigate the recall bias associated with self-reported surveys. All injury data were entered twice and cross-verified to ensure accuracy before being uploaded for analysis.

2.6. Statistical data analysis

SPSS v 26 statistical analysis software was used in this study to conduct data analysis. The data were presented as mean ± standard deviation (SD) or standard error of the mean (SEM). The Kolmogorov–Smirnov test was used to assess data distribution. Additionally, t-tests or chi-square tests were conducted to analyze the demographic characteristics of the two groups.

To examine the symmetry of the bilateral foot postures of participants, they were categorized based on the FPI-6 into bilateral supination, bilateral neutral feet, bilateral protonation, unilateral supination, and unilateral protonation groups. According to the AI, the participants were classified into bilateral cavus feet, bilateral normal arches, bilateral pes planus, unilateral cavus foot, and unilateral pes planus. Univariate analysis was conducted using percentages, and one-way ANOVA was performed to assess potential univariate associations between the outcome variables and various independent variables. To control for confounding factors, logistic regression was used to analyze the relationship between different foot postures and arches, as assessed by the FPI-6 and AI, and the incidence of lower-limb musculoskeletal injuries during physical training. Two logistic regression models are constructed. Model 1 was adjusted for BMI, sleep quality, and training duration. Model 2 was adjusted for all potential factors including age, BMI, smoking status, physical training years, training time, training frequency, warm-up before training, relaxation after training, MIS prevention, and treatment learning. The significance level for all hypothesis tests was set at $\alpha = 0.05$.

3. Results

3.1. Retrospective analysis of MSI

In this study, an initial cohort of 250 participants was analyzed. Finally, 248 participants provided valid questionnaire data, yielding a validity rate of 99.2 %. All 248 participants were male, with 69 individuals reporting lower limb musculoskeletal injuries (MSIs), resulting in an overall injury prevalence of 27.82 %.

Notably, the most common sites of injury were the knee joint (49.28 %) and ankle joint (26.09 %), followed by the foot (11.59 %), calf (8.70 %), hip joint (2.90 %), and thigh joint (1.44 %). Soft tissue injuries were the most prevalent type of musculoskeletal injury (MSI), affecting 72.46 % of injured individuals (50 participants). Among the tissues, muscle injuries were the most common (47.83 %), followed by bone (17.39 %), cartilage (15.94 %), ligament (11.59 %), and tendon (7.25 %) injuries (Table 1).

3.2. Baseline characteristics of participants

Participants with lower limb MSI were assigned to the injury group (n = 69) and the remaining participants were included in the non-injury group (n = 179).

Table 1
Retrospective analysis of MSI.

Injury category	Incidence N, %
Injury type	
Soft tissue	50 (72.5)
Bone	19 (27.5)
Injury site	
Hip joint	2 (2.9)
Thigh	1 (1.4)
Knee joint	34 (49.3)
Calf	6 (8.7)
Ankle joint	18 (26.1)
Foot	8 (11.6)
Injured tissue	
Muscle	33 (47.8)
Ligament	8 (11.6)
Tendon	5 (7.2)
Cartilage	11 (15.9)
Bone	12 (17.4)
Severity of injury	
Mild	40 (58.0)
Moderate	25 (36.2)
Severe	4 (5.8)
Critical	0 (0.0)

Table 2
Baseline characteristics of participants.

	Injury group n = 69	Non-injury group n = 179	$t/\chi2$	P
Age (years)	23.55 ± 2.66	24.21 ± 3.86	1.30	0.196
Height (m)	1.76 ± 0.05	1.76 ± 0.06	0.16	0.875
Weight (kg)	69.62 ± 12.46	69.87 ± 7.27	0.129	0.848
BMI			4.63	0.031
< 24 kg/m^2	43 (62.32)	136 (75.98)		
≥24 kg/m^2	26 (37.68)	43 (24.02)		
Smoking status			0.274	0.601
yes	36 (52.2)	100 (55.9)		
no	33 (47.8)	79 (44.1)		
Physical training years			2.61	0.127
< 5 years	42 (60.87)	128 (71.51)		
≥5 years	27 (39.13)	51 (28.49)		
Sleep quantity			6.325	0.012
≤6 h/night	51 (73.9)	156 (87.2)		
> 6 h/night	18 (26.1)	23 (12.8)		
Training time			26.84	< 0.001
6 h/day	31 (44.9)	141 (78.8)		
7 h/day	38 (55.1)	38 (21.2)		

Note: BMI, body mass index; FPI-6, foot posture index-6; AI, arch index.

Significant statistical differences were noted between the injured and non-injured groups regarding BMI, sleep duration, and training duration ($P < 0.05$). Conversely, no significant variations were observed in age, height, weight, smoking habits, or years of physical training ($P > 0.05$) (Table 2).

3.3. FPI-6-based foot posture

Evaluations of the participants' podiatric alignment were conducted using the FPI-6. Of the 248 participants analyzed, 143 had normal alignment, whereas 105 displayed deviations from the typical alignment, resulting in a detection rate of 42.3 % for atypical alignments. Foot protonation was identified in 38.3 % of the cases (95 of 248), with the majority (77.9 % or 74 of 95) being mild. In contrast, the occurrence of foot supination was significantly lower, detected in merely 4.0 % of the cases (10 of 248), as detailed in Fig. 1.

In the study cohort, 53 participants exhibited bilateral asymmetrical foot postures, with 94.3 % (50 of 53) displaying unilateral protonation.

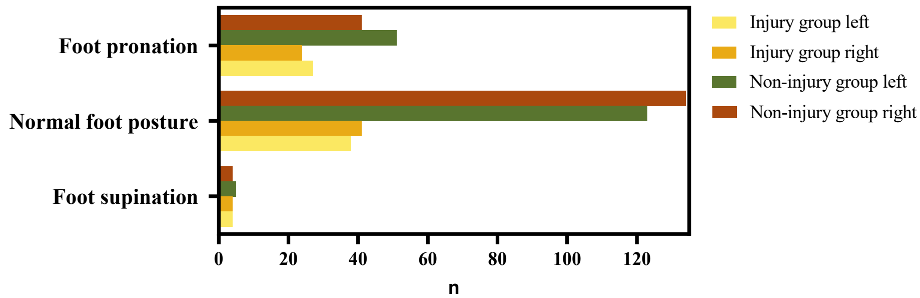

Fig. 1. Distribution of FPI-6-based foot posture between the two groups.

Among those with symmetrical foot postures, 6 participants had bilateral supination, while 46 demonstrated bilateral protonation.

The data in Table 3 show no statistically significant differences in the distribution of foot posture types or symmetry between the injured and non-injured groups on either side ($P > 0.05$). However, there was a significant difference in the subgroup distribution of bilateral foot postures between the two groups ($P < 0.05$). Details regarding the prevalence and distribution of various FPI-6-determined foot postures are presented in Table 3.

3.4. AI-based foot arch

Examination of the foot arches revealed that 48.4 % of the participants exhibited abnormalities, distributed between 37.5 % with pes planus and 9.7 % with cavus feet (Fig. 2). Of the 41 individuals with bilateral arch asymmetry, a significant majority (73.2 %, 30 of 41) showed unilateral pes planus, while the occurrence of bilateral flat feet was notably high at 25.4 %.

The analysis revealed a significantly higher frequency of symmetrical arches in the non-injured group than in the injured group ($P < 0.05$). The participants were further classified according to their bilateral arch types, as outlined in Table 3, and significant differences were found in the distribution patterns between the groups ($P < 0.05$). The distribution patterns are listed in Table 4.

Table 3
Frequency and distribution of different types of FPI-6-based foot posture.

	Injury group n = 69	Non-injury group n = 179	*P*
Foot posture symmetry			
Bilateral symmetry	48 (69.6)	148 (82.7)	0.023
Bilateral asymmetry	21 (30.4)	31 (17.3)	
Bilateral foot posture subgroup			0.025
Bilateral feet supination	3 (4.3)	4 (2.2)	
Bilateral normal feet	29 (42.0)	114 (63.7)	
Bilateral feet pronation	16 (23.2)	30 (16.8)	
Unilateral foot supination	2 (2.9)	1 (0.6)	
Unilateral foot pronation	19 (27.5)	30 (16.8)	

Table 4
Incidence and categorization of various AI-derived foot arch types.

	Injury group n = 69	Non-injury group n = 179	*P*
Foot arch symmetry			0.012
Bilateral symmetry	51 (73.9)	156 (87.2)	
Bilateral asymmetry	18 (26.1)	23 (12.8)	
Bilateral arch subgroup			0.037
Bilateral cavus feet	3 (4.3)	10 (5.6)	
Bilateral normal feet arch	27 (39.1)	104 (58.1)	
Bilateral pes planus	21 (30.4)	42 (23.5)	
Unilateral cavus foot	4 (5.8)	7 (3.9)	
Unilateral pes planus	14 (20.3)	16 (8.9)	

3.5. Relationship between foot posture, arch, and lower limb MSI

In this study, there were significant differences in BMI, sleep duration, and training time between the injured and non-injured groups ($P < 0.05$). To eliminate the influence of confounding factors, a logistic regression analysis was performed. Factors such as age, height, weight, smoking status, and years of physical training that did not correlate with lower limb MSI were excluded as confounders in Model 1. In Model 2, all potential factors were adjusted.

The results of the two models were similar. Bilateral asymmetry in the FPI-6-assessed foot posture was associated with an increased risk of lower-extremity MSI in those with physically demanding jobs compared to bilateral symmetry (Model 1: OR = 2.236, 95 % CI: 1.112–4.498, $P = 0.024$; Model 2: OR = 2.274, 95 % CI: 1.094–4.729, $P = 0.028$). Additionally, for those with bilateral protonation and unilateral protonation versus bilateral normal feet, the adjusted risk differences in model 2 were 2.314 (95 % CI: 1.013–5.287, $P = 0.047$) and 2.751 (95 % CI: 1.222–6.191, $P = 0.015$), respectively.

No significant associations were observed between the bilateral symmetry of the AI-based foot arch and lower limb MSI after adjusting

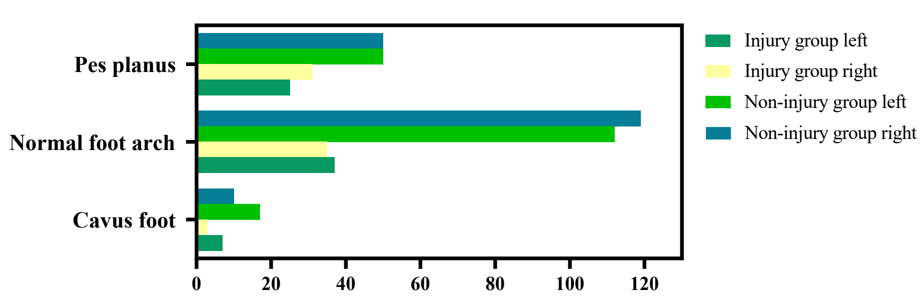

Fig. 2. Distribution of AI-based foot posture between the two groups.

Table 5
Logistic regression for foot posture, arch and lower limb MSI.

Variable of interest		n (%)	Model 1		Model 2	
			OR (95 % CI)	P	OR (95 % CI)	*P*
FPI-6-based foot posture						
Symmetry	Bilateral symmetry	196 (79.0)	0		0	
	Bilateral asymmetry	52 (21.0)	2.236 (1.112–4.498)	0.024	2.274 (1.094–4.729)	0.028
Bilateral foot posture subgroup	Bilateral normal feet	143 (57.7)	0		0	
	Bilateral feet pronation	46 (18.5)	2.565 (1.141–5.768)	0.023	2.314 (1.013–5.287)	0.047
	Bilateral feet supination	7 (2.8)	2.287 (0.403–12.987)	0.350	2.219 (0.374–13.184)	0.381
	Unilateral foot pronation	49 (19.8)	2.774 (1.280–6.011)	0.010	2.751 (1.222–6.191)	0.015
	Unilateral foot supination	3 (1.2)	7.530 (0.609–93.119)	0.116	8.409 (0.631–112.034)	0.107
AI-based foot posture						
Symmetry	Bilateral symmetry	207 (83.5)	0		0	
	Bilateral asymmetry	41 (16.5)	2.105 (0.990–4.477)	0.053	2.193 (0.992–4.851)	0.052
Bilateral arch subgroup	Bilateral normal feet arch	131 (52.8)	0			
	Bilateral flat feet	63 (25.4)	1.946 (0.941–4.024)	0.073	2.062 (0.969–4.388)	0.060
	Bilateral cavus feet	13 (5.2)	1.607 (0.363–7.100)	0.532	1.690 (0.358–7.963)	0.507
	Unilateral pes planus	30 (12.1)	3.050 (1.243–7.485)	0.015	3.197 (1.235–8.279)	0.017
	Unilateral cavus foot	11 (4.4)	1.929 (0.437–8.513)	0.386	2.346 (0.483–11.386)	0.290

Note: CI: confidence interval.
Model 1 was adjusted for BMI, sleep quality, and training time.
Model 2 was adjusted for age, BMI, smoking status, physical training years, training time, training frequency, warm-ups before training, relaxation after training, MIS prevention, and treatment learning.

for confounding factors in either model (Model 1: OR = 2.131, 95 % CI:0.999–4.548, $P = 0.051$; Model 2: OR = 2.193, 95 % CI: 0.992–4.851, $P = 0.052$). The adjusted risk difference after adjusting for confounding factors for unilateral pes planus compared with bilateral normal feet was 3.197 (95 % CI:1.235–8.279, $P = 0.017$). Further details are presented in Table 5.

4. Discussion

This study aimed to improve injury prevention strategies for physically demanding occupations by examining the relationship between foot posture and lower-limb MSIs. The results of this study indicate that foot alignment is a significant risk factor for lower limb MSIs. Specifically, individuals in physically demanding roles who exhibited unilateral pes planus or unilateral foot protonation had a higher incidence of lower-limb MSIs than those with bilateral normal foot alignment, suggesting that foot symmetry should be considered while examining the relationship between foot posture and lower-limb MSIs.

Of the 248 participants, 27.82 % reported injuries, a lower rate compared to the 34.2 % reported in other studies.[2,23] The knee (49.28 %) and ankle (26.09 %) were the most commonly injured areas, which differs from the findings of Psaila et al. who found that the foot was the most frequently injured area during basic physical training.[17] This difference might be because the study by Psaila et al. involved new recruits, whereas our participants had 6–7 years of physical training.

Standardized and accurate measurement methods are crucial for assessing and defining foot posture. Currently, various clinical approaches are employed to evaluate arch height, ranging from basic manual measurements to advanced techniques, such as videography and force plate analysis. The 3D scanning technology used in this study provided a more precise and robust method for investigating foot shape characteristics than traditional manual anthropometric methods.[24] Concurrently, the FPI-6 was used to assess foot posture, offering a quick, straightforward, and comprehensive evaluation of foot posture types. One advantage of the FPI-6 is its ability to interpret aggregate scores in relation to the hindfoot and forefoot segments, either separately or across the three body planes,[25] with moderate to good reliability.[26] Two different methods were used to diagnose foot posture in this study.

The relationship between foot posture and lower extremity injuries remains controversial. Throughout the kinetic chain, a pronated foot posture is associated with increased medial tibial stress injury, heightened subtalar motion, increased leg stiffness, tibial shock, and patellofemoral pain during running.[27] These findings were confirmed by Levy et al.,[28] who conducted a study at the United States Military Academy (USMA) at West Point and analyzed the arch height of cadets using 3D foot scans. They revealed significant correlations between pes planus and the frequency of injuries sustained by cadets over a four-year period. Only 33 individuals were identified as having pes planus. Furthermore, 559 sea, air, and land trainees examined by Kaufman et al. found a significant correlation between foot arch height and stress fractures, indicating that both pes planus and pes cavus could increase the risk of lower limb MSI, particularly among recruits.[29] Notably, Kaufman et al. focused on recruits who had completed basic training and did not control for confounding factors in their analysis. In contrast, Esterman et al. found that flat feet seemed to offer some protection against training injuries in Royal Australian Air Force recruits, although this benefit diminished after adjusting for confounding variables.[30] In a 12-week prospective study of 89 recreational runners, Hespanhol Junior found no significant association between the plantar arch index (measured using photographs) and the incidence of lower limb injuries.[31] Moreover, in a more recent and extensive prospective study, Knapik et al. examined whether selecting individually appropriate running shoes based on the medial longitudinal foot arch influenced the injury risk during United States Army Basic Combat Training. They concluded that there was little difference in injury risk when selecting shoes based on plantar shape, even after controlling for other injury risk factors.[32]

Our findings align with earlier studies by Hespanhol et al.[31] and Knapik et al.,[32] which indicated that individuals with flat feet or high arches do not have a heightened risk of injury. Moreover, there was no significant variation in the distribution of foot posture types (including foot protonation, normal foot posture, and foot supination) between participants with and without sustained injuries.

Although the standardized methods employed in foot posture assessment are extensive, the consideration of bilateral symmetry has been largely overlooked. Kisacik et al. indicated that unilateral flatfoot and the corresponding increase in foot protonation contributed to the augmentation of pelvic tilt and asymmetry of the spine. These observations have been corroborated by other studies suggesting that unilateral pes planus and protonation can lead to discrepancies in leg length. This misalignment stresses the weight-bearing joints of the lower extremities and lumbar spine, potentially altering spinopelvic alignment.[33,34] Such deviations can result in substantial structural and functional deficits affecting both standing and ambulatory activities,[35,36] thereby escalating the risk of injuries to the lower extremities. In this analysis, subgroups based on foot posture demonstrated that unilateral foot protonation and pes planus were associated with an increased risk of lower-limb musculoskeletal injuries (MSIs), with odds ratios (OR) of 2.751 and 3.197, respectively. An increased risk was confirmed after controlling for multiple confounding factors. Tateuchi et al.[37] highlighted the role of calcaneal eversion in altering three-dimensional movement patterns during unilateral weight bearing, suggesting that even slight deviations in the arch structure, such as low arches, can significantly shift the load and cause medial hip rotation. Additionally, Resende et al.[38] found that unilateral protonation not only influences knee dynamics but also enhances hip adduction on the contralateral side, contributing to a complex pattern of biomechanical changes that may accelerate the progression of lower-limb injuries.[37] These findings underscore the critical impact of rearfoot alignment in modifying the load on skeletal structures during ambulation, which intensifies lower limb asymmetry and potentially increases the risk of musculoskeletal injuries.

Our analysis revealed that participants with bilateral foot protonation, assessed using the FPI-6, were 2.3 fold more likely to experience lower limb musculoskeletal injuries than those with a neutral foot posture. Research has indicated that protonation leads to significant biomechanical alterations, including protonation of the subtalar and midtarsal joints during load-bearing activities, which in turn increases the tension in specific foot and leg muscles.[39–43] This condition may compromise foot stability and increase the risk of falls and repetitive strain injuries.[44,45] Furthermore, protonation affects the alignment of the pelvic and lower limb structures, potentially altering both static and dynamic postures and rendering these structure more susceptible to injuries.[36] Further research emphasized the influence of foot protonation on static posture and its subsequent effects on dynamic movement. Poor forefoot alignment at the initial ground contact generates substantial protonation torque, leading to a notable increase in the magnitude and duration of protonation throughout the gait cycle.[38] Dodelin et al.[46] demonstrated that a pronated foot alters the kinetic chain of the entire lower limb during motion. Notable changes include increased pelvic tilt, heightened internal rotation of the knee, pronounced forefoot abduction, and rearfoot eversion in patients with pronated feet. These biomechanical alterations are associated with an elevated risk of musculoskeletal conditions, especially because excessive knee internal rotation has been identified as a risk factor for the development of knee and tibial stress disorders.[47,48] This finding suggests that persistent bilateral foot protonation may induce a range of dynamic and static biomechanical changes that may exacerbate the risk of injury.

4.1. Limitations and prospects

Although this study has contributed several insights, its limitations also merit attention. Primarily, the analysis was confined to static foot-type measurements and the dynamic aspects of foot functionality were neglected. It is important to recognize that static measurements of foot posture may not provide a complete understanding of the mobility tasks.[49,50] It is crucial to further integrate the assessment of dynamic lower-limb activities to enhance the predictive accuracy of injury risks. Moreover, injuries in some cases may provoke changes in foot posture,[51,52] necessitating ongoing research to examine whether changes in foot posture correlate with specific types of injuries and whether interventions aimed at correcting foot posture can reduce injury rates in physically demanding roles.

5. Conclusion

In summary, this study found that 20.9 % of the physically demanding personnel exhibited asymmetrical foot postures, whereas 42.3 % had abnormal foot postures. Additionally, physically demanding job roles that involve unilateral foot protonation or pes planus present a heightened risk of MSIs, after accounting for confounding factors. Consequently, preventive measures should be specifically tailored to address these foot types, potentially leading to enhanced efficacy in preventing injuries.

Ethical approval

This study was approved by the Institutional Ethics Committee (IEC) of the Institution for National Drug Clinical Trials at the Tangdu Hospital, Fourth Military Medical University (XKT-Y-20221139). All participants provided informed consent prior to data collection.

CRediT authorship contribution statement

Chunhua Liao: Writing – original draft, Supervision, Conceptualization. **Jing Liu:** Writing – original draft, Investigation, Data curation. **Shuanglong Hou:** Methodology, Investigation. **Wendong Zhang:** Resources, Investigation. **Xin Zhao:** Investigation. **Zhipan Hou:** Investigation. **Honglei Quan:** Investigation. **Zhaohui Tian:** Investigation. **Rui Liu:** Writing – review & editing, Conceptualization. **Yuting Zhao:** Writing – review & editing, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Liu Rui reports financial support was provided by Xi'an Municipal Bureau of Science and Technology. Liu Rui reports financial support was provided by Research and Academic Office of Air Force Military Medical University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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