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The Impact of Different Footwear Conditions on Lower-Limb Biomechanical Characteristics During Single-Leg Drop Landing Movements in Individuals with Functional Ankle Instability

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Featured Application: Rehabilitation professionals can utilize these findings to design tailored treatment plans that balance the need for structural support and proprioceptive training. By incorporating both shod and barefoot exercises, clinicians can optimize the rehabilitation outcomes for individuals with FAI, leading to improved athletic performance and reduced injury recurrence rates. Furthermore, the study highlights the need for future research to explore the long-term effects of various footwear conditions on proprioception and motor control in FAI rehabilitation.

Abstract: (1) Background: This study investigated the impact of different footwear conditions on the biomechanics of individuals with Functional Ankle Instability (FAI) during single-leg drop landing movements. (2) Methods: Fifteen participants with FAI and a control group were tested. Kinematics and kinetics were measured using Vicon (Model: MX13, Oxford, UK) and Kistler (Model: 9287B, Switzerland) equipment. A mixed-ANOVA analyzed the impact of footwear conditions. (3) Results: At the initial contact (IC), under the shoe-wearing condition, the FAI group exhibited a significantly smaller ankle-joint plantarflexion angle compared to the control group ($p = 0.001$). The FAI group exhibited a significantly smaller ankle-joint plantarflexion angle under the shoe-wearing condition compared to the barefoot condition at the IC ($p < 0.001$). At the IC moment, regardless of the footwear conditions in this study, the FAI group showed a larger knee flexion angle ($p = 0.028$) and a shorter time to vertical ground reaction force (T_vGRF) ($p = 0.020$) compared to the control group. (4) Conclusions: The study concluded that footwear conditions significantly influence the biomechanics of FAI individuals, with shoes enhancing ankle stability and barefoot conditions leading to biomechanics similar to healthy individuals. The effect of socks on FAI individuals was not significant. Future research should further explore the impact of footwear on FAI rehabilitation.

Keywords: Functional Ankle Instability; biomechanics; footwear; landing; rehabilitation training

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1. Introduction

Ankle sprains are among the most common injuries in sports, particularly in high-impact activities such as volleyball and basketball that involve frequent jumping and landing, with injury rates potentially reaching up to 50% [1–3]. If initial sprains are not promptly and appropriately treated, the ankle joint may suffer from chronic pain and recurrent swelling [4]. These long-term issues not only cause persistent discomfort but may also lead to a decrease in posture control and proprioceptive ability, potentially progressing to Functional Ankle Instability (FAI) [5,6]. FAI is one of the forms of Chronic Ankle Instability (CAI), characterized by recurrent ankle sprains and a sense of instability, even in the absence of apparent injury, creating a vicious cycle of repeated ankle injuries. Moreover, changes in the biomechanical characteristics of individuals with FAI can lead to injuries in other joints of the lower limb, subsequently impairing athletic performance and negatively affecting their quality of life [7,8].

Single-leg drop landing movements are common in sports and require athletes to quickly adjust the contact between the foot and the ground upon landing, effectively absorbing the impact forces generated by gravity and kinetic momentum while maintaining body balance and preparing for subsequent movements [2,9]. Research indicates that during single-leg drop landing movements, the body experiences significant ground reaction forces, typically two to seven times one's body weight [10,11]. Since the ankle joint is the terminal weight-bearing joint in the human body, this movement is closely associated with ankle sprains [12]. Different footwear conditions during this process may significantly affect ankle joint stability and motor control. For instance, barefoot landing may provide more proprioceptive feedback but offer less protection for the foot, whereas wearing shoes or socks may provide additional support and cushioning but could also affect direct contact and friction coefficients between the foot and the ground [13].

Although biomechanical research on FAI has made certain advancements [5,14,15], most studies often overlook the diversity of footwear conditions and their potential impact on biomechanical adjustments when discussing FAI. Individuals with FAI may have altered proprioception compared to healthy individuals due to previous ankle injuries [16,17]; thus, their adaptation and response to different footwear conditions during sports activities may differ. In the real world, people from different regions exhibit a variety of footwear habits, such as being barefoot or wearing socks, due to cultural, climatic, economic, and personal preferences. These different wearing conditions may have varying effects on the stability and motor control of the ankle joint in individuals with FAI [18]. However, current research on FAI often uses specific shoes and socks, failing to fully consider the different effects that various footwear conditions may have. Therefore, studying the biomechanical characteristics of individuals with FAI under different wearing conditions is of great significance for revealing the neuromuscular control mechanisms of FAI.

In light of this, the present study aims to investigate the impact of four different footwear conditions—barefoot, shoe-wearing, sock-wearing, and sock-and-shoe-wearing—on lower-limb biomechanics during single-leg drop landing movements in individuals with FAI, and to compare these effects with those observed in a healthy population. Uncovering the effects of different wearing conditions on the lower-limb biomechanics of FAI individuals during single-leg drop landing movements provides a personalized reference for the assessment and rehabilitation training of FAI. Based on existing research, this paper formulates the following two hypotheses:

H1: *Individuals with FAI will exhibit significant differences in kinematic and kinetic characteristics compared to the control group when performing single-leg drop landing movements under different footwear conditions.*

H2: *Different footwear conditions may have varying degrees of impact on the lower-limb biomechanical characteristics of individuals with FAI during single-leg drop landing movements.*

2. Materials and Methods

2.1. Participants

Utilizing G*Power 3.1.9 software and in alignment with previous studies [9] as well as the statistical methods employed in this research, the required sample size was estimated. The power, Type I error rate (α), and effect size were set to 0.95, 0.05, and 0.4, respectively. Calculations indicated a sample size of 24 individuals, with an additional 20% to account for potential invalid samples, resulting in a minimum sample size of 29 individuals. Following the selection criteria established by the International Ankle Consortium [19], 15 participants with unilateral FAI were recruited for the experimental group (FAI group), comprising eight males and seven females, through scores on the Cumberland Ankle Instability Tool (CAIT) and in conjunction with anterior drawer test methods. A control group of 15 individuals with no history of ankle injuries was matched based on gender, morphological characteristics, and athletic background to the FAI group participants, and the corresponding unaffected side was chosen for matching (Table 1). Prior to the experiment, all participants were informed of the testing procedures and signed informed consent forms. The study was approved by the Ethics Committee of Soochow University (Ethics Approval Number: SUDA20221005H03).

Table 1. Basic information of subjects ($\bar{x} \pm$ SD).

Parameter	FAI Group (n = 15)	Control Group (n = 15)	p
Age (year)	24.2 ± 0.9	24.1 ± 1.3	0.740
Height (cm)	172.6 ± 7.3	170.9 ± 9.7	0.599
BMI (kg/m^2)	22.8 ± 1.6	22.3 ± 2.7	0.485
CAIT Score	19.3 ± 2.2	29.0 ± 0.8	<0.001 *

Note: * $p < 0.05$.

Inclusion Criteria for the FAI Group: ① At least one instance of a unilateral ankle sprain, with the initial sprain occurring at least 12 months prior to the trial and presenting with inflammatory symptoms (pain, swelling, etc.) that interrupted physical activity for at least one day; ② Participants without a history of severe lower-limb injuries, except for ankle sprains [20]; ③ CAIT score ≤ 24 [21]; ④ FAI present in only one ankle.

Exclusion Criteria for the FAI Group: ① History of lower-limb surgery [20]; ② Acute musculoskeletal injury to other joints in the lower limb within the month prior to the formal trial; ③ Bilateral FAI [20]; ④ Congenital joint deformity; ⑤ Positive anterior drawer test result or talar tilt; ⑥ CAIT score > 24.

Inclusion Criteria for the Control Group: ① CAIT score ≥ 28 [21]; ② Gender, morphological characteristics, and athletic background matched with the FAI group participants.

Exclusion Criteria for the Control Group: ① CAIT score < 28; ② History of musculoskeletal surgery on the lower limb; ③ Acute joint injury within the month prior to the trial; ④ Inability to complete assessments as required or missing data during the trial.

2.2. Experimental Equipment and Materials

(1) Vicon Infrared 3D Motion Capture and Analysis System

The system comprises eight infrared cameras (Model: MX13, Oxford, UK) MX Net, MX Control, a PC host, a calibration kit, and standard accessories. The sampling frequency was set at 100 Hz, utilizing the CGM 23 lower-limb model within the Vicon system [9].

(2) Three-dimensional Force Plate

At the center of the area covered by the motion capture system's infrared cameras, two Kistler three-dimensional force platforms (90 cm × 60 cm × 10 cm, Model: 9287B, Switzerland) were embedded in the ground. The sampling frequency was 1000 Hz. An analog-to-digital converter was used to synchronize the data collection from the Kistler force platforms with the Vicon motion capture system.

(3) Experimental Footwear and Socks

To ensure the standardization and reproducibility of the experiment, the footwear and socks used were commercially available, standard, low-cut multifunctional rubber-soled sports shoes and matching thin-bottomed cotton socks [22]. All shoes and socks were fitted according to each participant's size to ensure comfortable wear.

2.3. Experimental Procedure

2.3.1. Experimental Preparation

Participants were dressed in uniform experimental footwear, socks, and clothing provided by the laboratory. After completing a warm-up, 28 marker points with a diameter of 14 mm were affixed to their bodies (Figure 1) following the CGM23 lower-limb model, with marker placements at the bilateral anterior superior iliac spines, bilateral posterior superior iliac spines, lateral and medial condyles of the knee, lateral and medial malleoli, calcanei, and the bases of the second metatarsals. Furthermore, markers were positioned at the upper and lower thirds of the left thigh and lower leg, as well as the upper and lower thirds of the right thigh and lower leg, ensuring a detailed and anatomically accurate representation of the lower limb for motion analysis. Subsequently, they familiarized themselves with the single-leg drop landing movements. To minimize experimental error, the application of all marker points was performed by a single individual.

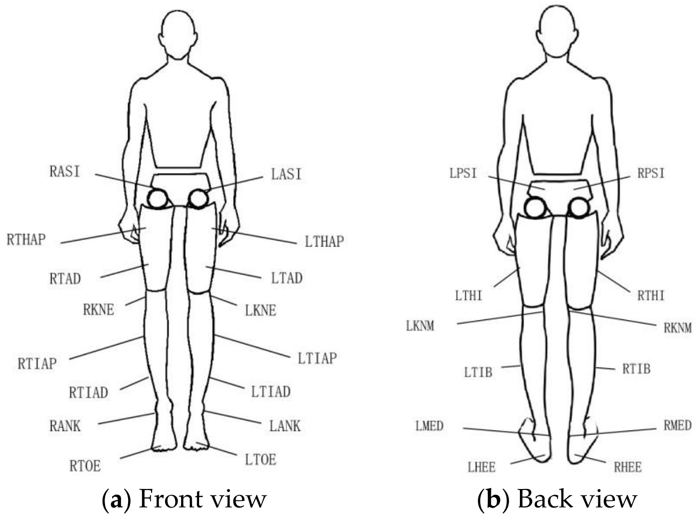

Figure 1. CGM 23 marker-point pasting (**a**) Front view, (**b**) Back view.

2.3.2. Single-Leg Drop Landing Movement Test Protocol

The single-leg drop landing movement test was designed based on previous research by Meng et al. [2], where participants stood naturally on a 30 cm high jump box with their feet shoulder-width apart. During the test, participants placed their hands on their waist to avoid the inertia generated by arm swinging. Under four different footwear conditions (barefoot, sock-wearing, shoe-wearing, and sock-and-shoe-wearing), participants were required to perform single-leg drop landing tasks, all adopting a "toe-heel" landing pattern (Figure 2) [23]. In each test condition, participants had to complete three successful single-leg drop landings. The results of the three trials for each participant were averaged to reduce random errors and enhance the reliability of the data.

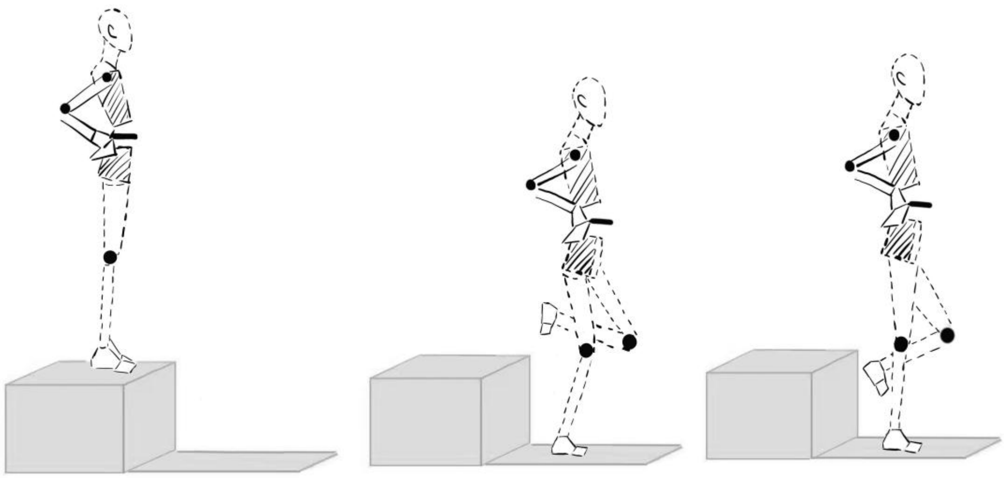

Figure 2. Action diagram.

Participants performed a single leg drop landing from a 30 cm high platform onto a force plate.

2.4. Data Processing

The primary outcome measures in this study include the following: ① The joint angles of the hip, knee, and ankle in the sagittal and frontal planes at the initial contact (IC) and at the peak vertical ground reaction force (vGRF), measured in degrees (°); ② The peak vGRF normalized to body weight (BW); ③ The time to peak vGRF (T_vGRF), measured in milliseconds (ms); ④ The vertical load rate (LR), measured in body weight per millisecond (BW/ms); ⑤ The lower-limb stiffness (k_{leg}), measured in body weight per meter (BW/m). The specific calculation formulas for LR and k_{leg}, as indicated in [2], are shown in Equations (1) and (2) below, where ΔL represents the change in lower-limb length, measured in meters (m):

$$\mathrm{LR} = \text{peak vGRF}/\text{T\_vGRF}, \tag{1}$$

$$k_{leg} = \text{peak vGRF}/\Delta\mathrm{L}. \tag{2}$$

The raw data collected by the Vicon system were subjected to kinematic and inverse dynamic analysis using Visual3D (Version 6, C-Motion, Inc., Germantown, MD, USA) software. A fourth-order low-pass Butterworth filter was utilized to smooth the three-dimensional coordinate data at 10 Hz and the force platform data at 50 Hz. The calculation of the lower-limb joint angles was performed using the Euler angle method. The instant of ground contact was defined as the initial moment when the vGRF exceeded 10 N [9].

2.5. Statistical Analysis

Data analysis was conducted using SPSS 26, with descriptive statistics presented as mean ± standard deviation ($\bar{x}$ ± SD). The Shapiro–Wilk test was used to assess the normality of the data distribution. If the data were normally distributed, an independent samples *t*-test was used to compare the basic information of the subjects. If the data were not normally distributed, the Mann–Whittney U test was applied. A 2 × 2 × 2 mixed analysis of variance (mixed ANOVA) with factors [Group (FAI and control) × sock-wearing (with and without) × shoe-wearing (with and without)] was used to analyze the collected kinematic and kinetic data. The criterion for statistical significance was set at α = 0.05.

3. Results

3.1. Hip Joint Angles of the Two Groups

No statistically significant differences were observed in the hip-joint angle measurements between the two groups of participants (p > 0.05) (Table 2).

Table 2. Hip joint angles of the two groups.

Variables	FAI	Control	Main Effect			Interaction Effect			
	Affected Side	Matched Side	Group	Shoe	Sock	Group × Shoe	Group × Sock	Shoe × Sock	Group × Shoe × Sock
IC									
Hip Flexion/Extension Angle (°)									
Barefoot	20.49 ± 6.17	23.11 ± 6.19	p = 0.111	p = 0.704	p = 0.051	p = 0.460	p = 0.603	p = 0.687	p = 0.994
Sock	19.05 ± 4.94	22.36 ± 8.93	F = 2.702	F = 0.147	F = 4.150	F = 0.562	F = 0.277	F = 0.166	F < 0.001
Shoe	19.96 ± 5.28	23.63 ± 7.44							
Sock and Shoe	17.96 ± 5.18	22.35 ± 8.08	Eta^2 = 0.088	Eta^2 = 0.005	Eta^2 = 0.129	Eta^2 = 0.20	Eta^2 = 0.010	Eta^2 = 0.006	Eta^2 < 0.001
Hip Adduction/Abduction Angle (°)									
Barefoot	−5.48 ± 3.03	−4.99 ± 3.53	p = 0.959	p = 0.905	p = 0.584	p = 0.683	p = 0.721	p = 0.782	p = 0.961
Sock	−5.42 ± 2.79	−5.39 ± 4.11	F = 0.003	F = 0.014	F = 0.306	F = 0.171	F = 0.130	F = 0.078	F = 0.002
Shoe	−5.17 ± 2.75	−5.14 ± 5.10							
Sock and Shoe	−5.44 ± 3.15	−5.76 ± 5.71	Eta^2 < 0.001	Eta^2 = 0.001	Eta^2 = 0.011	Eta^2 = 0.006	Eta^2 = 0.005	Eta^2 = 0.003	Eta^2 < 0.001
Peak vGRF moment									
Hip Flexion/Extension Angle (°)									
Barefoot	25.82 ± 7.11	27.45 ± 6.22	p = 0.164	p = 0.120	p = 0.100	p = 0.284	p = 0.787	p = 0.670	p = 0.690
Sock	23.25 ± 6.56	27.06 ± 7.47	F = 2.041	F = 2.572	F = 2.887	F = 1.193	F = 0.075	F = 0.186	F = 0.162
Shoe	23.67 ± 4.31	27.06 ± 7.47							
Sock and Shoe	22.44 ± 4.03	26.02 ± 8.65	Eta^2 = 0.068	Eta^2 = 0.084	Eta^2 = 0.093	Eta^2 = 0.041	Eta^2 = 0.003	Eta^2 = 0.007	Eta^2 = 0.006

Table 2. *Cont.*

Variables	FAI	Control	Main Effect			Interaction Effect			
	Affected Side	Matched Side	Group	Shoe	Sock	Group × Shoe	Group × Sock	Shoe × Sock	Group × Shoe × Sock
Hip Adduction/Abduction Angle (°)									
Barefoot	−4.56 ± 3.90	−4.64 ± 4.11	p = 0.864	p = 0.154	p = 0.266	p = 0.876	p = 0.858	p = 0.701	p = 0.294
Sock	−5.38 ± 3.69	−4.69 ± 5.00	F = 0.030	F = 2.148	F = 1.290	F = 0.025	F = 0.033	F = 0.150	F = 1.141
Shoe	−4.01 ± 3.05	−3.30 ± 3.81							
Sock and Shoe	−4.21 ± 3.45	−4.66 ± 6.14	Eta^2 = 0.001	Eta^2 = 0.071	Eta^2 = 0.044	Eta^2 = 0.001	Eta^2 = 0.001	Eta^2 = 0.005	Eta^2 = 0.039

Note: Hip flexion (+)/extension (−), hip adduction (+)/abduction (−).

3.2. Knee Joint Angles of the Two Groups

At the IC, a statistically significant difference between groups was observed in the knee flexion angle, with the FAI group exhibiting a larger knee flexion angle compared to the control group (p = 0.028) (Table 3).

Table 3. Knee joint angles of the two groups.

Variables	FAI	Control	Main Effect			Interaction Effect			
	Affected Side	Matched Side	Group	Shoe	Sock	Group × Shoe	Group × Sock	Shoe × Sock	Group × Shoe × Sock
IC									
Knee Flexion/Extension Angle (°)									
Barefoot	8.77 ± 4.14	6.89 ± 2.82	p = 0.028 *	p = 0.190	p = 0.348	p = 0.309	p = 0.405	p = 0.508	p = 0.909
Sock	7.53 ± 3.47	6.36 ± 3.06	F = 5.355	F = 1.808	F = 0.913	F = 1.075	F = 0.715	F = 0.449	F = 0.013
Shoe	9.72 ± 4.11	6.58 ± 3.93							
Sock and Shoe	9.14 ± 3.70	6.70 ± 3.25	Eta^2 = 0.161	Eta^2 = 0.061	Eta^2 = 0.032	Eta^2 = 0.037	Eta^2 = 0.025	Eta^2 = 0.016	Eta^2 < 0.001
Knee varus/valgus Angle (°)									
Barefoot	0.12 ± 3.52	0.67 ± 2.17	p = 0.107	p = 0.513	p = 0.940	p = 0.194	p = 0.794	p = 0.332	p = 0.783
Sock	0.33 ± 3.59	1.35 ± 2.88	F = 2.772	F = 0.438	F = 0.006	F = 1.774	F = 0.069	F = 0.974	F = 0.078
Shoe	−0.48 ± 3.95	1.50 ± 2.38							
Sock and Shoe	−0.86 ± 3.22	1.12 ± 2.49	Eta^2 = 0.090	Eta^2 = 0.015	Eta^2 < 0.001	Eta^2 = 0.060	Eta^2 = 0.002	Eta^2 = 0.034	Eta^2 = 0.003
Peak vGRF moment									
Knee Flexion/Extension Angle (°)									
Barefoot	27.90 ± 6.11	25.59 ± 8.33	p = 0.264	p = 0.806	p = 0.096	p = 0.817	p = 0.732	p = 0.223	p = 0.735
Sock	24.31 ± 4.94	23.34 ± 5.25	F = 1.297	F = 0.061	F = 2.972	F = 0.055	F = 0.119	F = 1.551	F = 0.117
Shoe	26.35 ± 6.31	24.31 ± 7.34							
Sock and Shoe	25.84 ± 5.05	23.83 ± 5.81	Eta^2 = 0.044	Eta^2 = 0.002	Eta^2 = 0.096	Eta^2 = 0.002	Eta^2 = 0.004	Eta^2 = 0.052	Eta^2 = 0.004
Knee varus/valgus Angle (°)									
Barefoot	0.36 ± 5.35	0.51 ± 5.20	p = 0.593	p = 0.347	p = 0.379	p = 0.480	p = 0.798	p = 0.624	p = 0.791
sock	1.01 ± 6.80	1.91 ± 5.24	F = 0.292	F = 0.914	F = 0.800	F = 0.513	F = 0.067	F = 0.246	F = 0.072
Shoe	−0.48 ± 5.82	0.87 ± 5.34							
Sock and Shoe	−0.14 ± 7.11	1.26 ± 5.16	Eta^2 = 0.010	Eta^2 = 0.032	Eta^2 = 0.028	Eta^2 = 0.018	Eta^2 = 0.002	Eta^2 = 0.009	Eta^2 = 0.003

Note: Knee Flexion (+)/Extension (−), knee varus (+)/valgus (−); *: $p < 0.05$.

3.3. Ankle Joint Angles of the Two Groups

At the IC for the ankle-joint plantarflexion angle, an interaction effect of Group × Shoe was observed (p = 0.022). Simple effects revealed that compared to the barefoot condition, individuals with FAI exhibited a significantly smaller ankle-joint plantarflexion angle under the shoe-wearing condition (p < 0.001). Furthermore, under the shoe-wearing condition, the FAI group demonstrated a significantly smaller ankle-joint plantarflexion angle compared to the control group (p = 0.001) (Table 4).

Table 4. Ankle joint angles of the two groups.

Variables	FAI	Control	Main Effect			Interaction Effect			
	Affected Side	Matched Side	Group	Shoe	Sock	Group × Shoe	Group × Sock	Shoe × Sock	Group × Shoe × Sock
IC									
Ankle Dorsiflexion/Plantarflexion Angle (°)									
Barefoot	−21.34 ± 7.57	−24.92 ± 5.00	p = 0.008 *	p = 0.001 *	p = 0.415	p = 0.022 *	p = 0.490	p = 0.417	p = 0.514
Sock	−22.49 ± 6.58	−23.93 ± 6.61	F = 8.070	F = 14.973	F = 0.685	F = 5.922	F = 0.490	F = 0.680	F = 0.437
Shoe	−14.65 ± 8.01	−22.33 ± 6.03							
Sock and Shoe	−16.04 ± 3.69	−23.53 ± 6.71	Eta^2 = 0.224	Eta^2 = 0.348	Eta^2 = 0.024	Eta^2 = 0.175	Eta^2 = 0.017	Eta^2 = 0.024	Eta^2 = 0.015
Ankle Inversion/Eversion Angle (°)									
Barefoot	4.07 ± 3.16	3.03 ± 2.48	p = 0.296	p = 0.077	p = 0.991	p = 0.620	p = 0.833	p = 0.835	p = 0.731
Sock	4.20 ± 4.40	2.79 ± 2.62	F = 1.135	F = 3.372	F < 0.001	F = 0.252	F = 0.045	F = 0.044	F = 0.120

Table 4. *Cont.*

Variables	FAI	Control	Main Effect			Interaction Effect			
	Affected Side	Matched Side	Group	Shoe	Sock	Group × Shoe	Group × Sock	Shoe × Sock	Group × Shoe × Sock
Shoe	3.15 ± 2.77	2.33 ± 3.62							
Sock and Shoe	3.21 ± 2.83	2.40 ± 3.03	$Eta^2 = 0.039$	$Eta^2 = 0.107$	$Eta^2 < 0.001$	$Eta^2 = 0.009$	$Eta^2 = 0.002$	$Eta^2 = 0.002$	$Eta^2 = 0.004$
Peak vGRF moment									
Ankle Dorsiflexion/Plantarflexion Angle (°)									
Barefoot	12.13 ± 4.21	13.13 ± 5.13	$p = 0.091$	$p = 0.057$	$p = 0.631$	$p = 0.461$	$p = 0.920$	$p = 0.504$	$p = 0.962$
Sock	11.37 ± 2.41	12.43 ± 2.91	$F = 3.062$	$F = 3.931$	$F = 0.236$	$F = 0.559$	$F = 0.010$	$F = 0.457$	$F = 0.002$
Shoe	12.45 ± 3.47	14.26 ± 3.65							
Sock and Shoe	12.48 ± 3.81	14.48 ± 3.38	$Eta^2 = 0.099$	$Eta^2 = 0.123$	$Eta^2 = 0.008$	$Eta^2 = 0.020$	$Eta^2 < 0.001$	$Eta^2 = 0.016$	$Eta^2 < 0.001$
Ankle Inversion/Eversion Angle (°)									
Barefoot	1.59 ± 2.84	2.43 ± 3.57	$p = 0.566$	$p = 0.201$	$p = 0.537$	$p = 0.154$	$p = 0.785$	$p = 0.911$	$p = 0.655$
Sock	0.89 ± 3.51	2.43 ± 4.55	$F = 0.337$	$F = 1.718$	$F = 0.390$	$F = 2.147$	$F = 0.076$	$F = 0.013$	$F = 0.204$
Shoe	1.38 ± 2.78	1.51 ± 4.07							
Sock and Shoe	1.22 ± 3.58	1.18 ± 3.85	$Eta^2 = 0.012$	$Eta^2 = 0.058$	$Eta^2 = 0.014$	$Eta^2 = 0.071$	$Eta^2 = 0.003$	$Eta^2 < 0.001$	$Eta^2 = 0.007$

Note: Ankle Dorsiflexion (+)/Plantarflexion (−), Ankle Inversion (+)/Eversion (−); *: $p < 0.05$.

3.4. Peak vGRF, LR, and k_{leg} of the Two Groups

Statistical differences between groups were observed for the T_vGRF, with the FAI group exhibiting a shorter T_vGRF compared to the control group ($p = 0.020$) (Table 5).

Table 5. Peak vGRF, LR and k_{leg} of the two groups.

Variables	FAI	Control	Main Effect			Interaction Effect			
	Affected Side	Matched Side	Group	Shoe	Sock	Group × Shoe	Group × Sock	Shoe × Sock	Group × Shoe × Sock
Peak vGRF (BW)									
Barefoot	2.67 ± 0.76	2.63 ± 1.08	$p = 0.315$	$p = 0.737$	$p = 0.346$	$p = 0.599$	$p = 0.689$	$p = 0.104$	$p = 0.694$
Sock	3.10 ± 1.04	2.85 ± 0.57	$F = 1.046$	$F = 0.115$	$F = 0.919$	$F = 0.284$	$F = 0.164$	$F = 2.820$	$F = 0.158$
Shoe	2.91 ± 1.01	2.66 ± 0.63							
Sock and Shoe	2.91 ± 0.84	2.61 ± 0.55	$Eta^2 = 0.036$	$Eta^2 = 0.004$	$Eta^2 = 0.032$	$Eta^2 = 0.010$	$Eta^2 = 0.006$	$Eta^2 = 0.092$	$Eta^2 = 0.006$
T_vGRF (ms)									
Barefoot	68.00 ± 21.11	76.00 ± 26.40	$p = 0.020$ *	$p = 0.114$	$p = 0.261$	$p = 0.139$	$p = 0.536$	$p = 0.375$	$p = 0.553$
Sock	61.33 ± 14.07	69.33 ± 13.87	$F = 6.092$	$F = 2.659$	$F = 1.317$	$F = 2.317$	$F = 0.392$	$F = 0.812$	$F = 0.361$
Shoe	63.33 ± 14.47	84.67 ± 27.22							
Sock and Shoe	66.67 ± 16.33	80.00 ± 25.91	$Eta^2 = 0.179$	$Eta^2 = 0.087$	$Eta^2 = 0.045$	$Eta^2 = 0.076$	$Eta^2 = 0.014$	$Eta^2 = 0.028$	$Eta^2 = 0.013$
LR (BW/ms)									
Barefoot	0.04 ± 0.02	0.04 ± 0.03	$p = 0.132$	$p = 0.312$	$p = 0.348$	$p = 0.410$	$p = 0.680$	$p = 0.223$	$p = 0.240$
Sock	0.05 ± 0.02	0.04 ± 0.01	$F = 2.403$	$F = 1.060$	$F = 0.911$	$F = 0.699$	$F = 0.174$	$F = 1.554$	$F = 1.438$
Shoe	0.05 ± 0.02	0.04 ± 0.02							
Sock and Shoe	0.05 ± 0.02	0.04 ± 0.02	$Eta^2 = 0.079$	$Eta^2 = 0.036$	$Eta^2 = 0.032$	$Eta^2 = 0.024$	$Eta^2 = 0.006$	$Eta^2 = 0.053$	$Eta^2 = 0.049$
k_{leg} (BW/m)									
Barefoot	20.94 ± 7.84	21.97 ± 9.19	$p = 0.941$	$p = 0.888$	$p = 0.562$	$p = 0.252$	$p = 0.837$	$p = 0.052$	$p = 0.470$
Sock	23.44 ± 9.91	25.62 ± 6.74	$F = 0.006$	$F = 0.020$	$F = 0.344$	$F = 1.370$	$F = 0.043$	$F = 4.117$	$F = 0.537$
Shoe	24.03 ± 10.81	23.88 ± 8.34							
Sock and Shoe	23.57 ± 8.99	21.20 ± 5.41	$Eta^2 < 0.001$	$Eta^2 = 0.001$	$Eta^2 = 0.012$	$Eta^2 = 0.047$	$Eta^2 = 0.002$	$Eta^2 = 0.128$	$Eta^2 = 0.019$

Note: * $p < 0.05$.

4. Discussion

4.1. Impact of Different Footwear Conditions on Lower-Limb Biomechanical Characteristics in Individuals with FAI

The findings of this study indicate that the lower-limb biomechanical characteristics of individuals with FAI are significantly influenced by the conditions of footwear worn during single-leg drop landing movements. Specifically, at the IC, individuals with FAI exhibited a significantly smaller ankle-joint plantarflexion angle under the shoe-wearing condition compared to the control group. This result supports Hypothesis 1, which posits that there would be significant differences in the kinematic characteristics of the lower-limb joints between individuals with FAI and the control group under different footwear conditions. This phenomenon suggests that wearing shoes provides additional structural support and stability for the ankle joint of individuals with FAI, reducing excessive motion during the landing process and enhancing ankle joint stability, thereby decreasing the risk of injury. This may be attributed to the impaired proprioceptive function and reduced neuromuscular control capacity of the ankle joint in individuals with FAI due to previous injuries, affecting their muscle reaction time and coordination and thus diminishing their perception of joint position and movement [24,25]. In such cases, wearing shoes may offer necessary structural support, helping to limit the abnormal motion of the ankle joint, keep the joint in a neutral position, and provide stability to the foot.

Furthermore, regardless of the condition, individuals with FAI showed a larger knee flexion angle compared to the healthy population, but no significant differences were observed in the hip-joint angle indicators. This suggests that they may preferentially utilize the buffering capacity of the knee joint to alleviate the impact on the ankle joint during landing [26]. This strategy may help reduce the risk of re-injury to the ankle joint during sports activities for individuals with FAI but may also increase the load on the knee joint, potentially leading to additional stress and injury risk to the knee joint in the long term [27]. Concurrently, the shorter T_vGRF observed in individuals with FAI compared to the healthy population indicates a quicker attainment of peak vGRF upon landing, which may be a mechanism they adopt to rapidly stabilize body posture and reduce ankle joint loading. Additionally, the lack of significant differences in the peak vGRF, LR, and k_{leg} indicators in this study's results also supports the above discussion, indicating the unique adaptability of individuals with FAI in their landing strategies, relying more on the knee flexion angle to maintain the overall lower-limb mechanical performance stability [28]. This result highlights that in rehabilitation training, in addition to focusing on the movement strategies of the ankle and knee joints, consideration should also be given to how to improve the overall lower-limb mechanical performance of individuals with FAI through training, thereby enhancing their sports efficiency and reducing the risk of injury.

However, it is noteworthy that under barefoot conditions, there was no significant difference in the ankle-joint plantarflexion angle between individuals with FAI and the healthy population. This finding suggests that despite the compromised stability of the ankle joint in individuals with FAI, they can still exhibit biomechanical characteristics similar to those of the healthy population in barefoot conditions. This may imply that barefoot activity provides a more natural environment for individuals with FAI, aiding in the re-establishment of the proprioceptive system around the ankle joint, thereby improving posture control and coordination. However, due to previous injuries, individuals with FAI may have reduced proprioception and neuromuscular control of the ankle joint, which could affect their performance in movements without external support [25,29]. This is consistent with Moisan et al. [17], who suggested that individuals with CAI might derive significant biomechanical benefits from wearing shoes, reducing the ankle-joint plantarflexion angle and providing additional support and stability. Gardner et al. [30] further confirmed through experimentation that moderate ankle joint support can promote the utilization of the knee and hip joints to share the load during single-leg drop landing movements, thereby optimizing muscle coordination and joint control. Therefore, for individuals with FAI, wearing appropriate footwear during tasks such as landing may enhance foot stability and provide necessary support, enabling more precise neuromuscular feedback and adjustment during movement, optimizing movement mechanics, and reducing the risk of injury.

Thus, footwear conditions play a crucial role in the movement process of individuals with FAI. Wearing shoes may assist individuals with FAI in more easily controlling the motion of the ankle joint, while barefoot conditions may help them approximate the biomechanical characteristics of the healthy population in certain aspects, especially in training for proprioception and balance capabilities. As Abdelraouf et al. [31] demonstrated, footwear conditions are an undeniable factor when assessing ankle–foot kinematics and dynamics. This emphasizes the need to consider the impact of footwear conditions comprehensively and to customize treatment plans according to the individual circumstances and needs of individuals with FAI.

4.2. Impact of Different Footwear Conditions on the Biomechanical Adaptability of Individuals with FAI

The results of this study reveal significant biomechanical changes in individuals with FAI under different footwear conditions, reflecting their adaptive adjustments to varying support conditions. Compared to the barefoot group, the FAI group showed a reduced ankle-joint plantarflexion angle when landing under the shoe-wearing condition, indicating that with additional support, FAI patients can better control ankle motion, minimize excessive joint activity, and thereby enhance movement stability and reduce the risk of injury [32,33], which aligns with Hypothesis 2 of this study. Concurrently, the biomechanical characteristics of FAI patients under the shoe-wearing condition further suggest that by increasing the encapsulation and stability of the foot, they may optimize their adaptability to better meet the challenges of movement. The research by Fu et al. [34] also supports the significant effect of wearing shoes in enhancing ankle joint function during movement, demonstrating a clear advantage of wearing shoes in this regard.

Moreover, the similar ankle joint angles observed between individuals with FAI and healthy individuals during single-leg drop landing movements under barefoot conditions suggest that, due to their poorer postural stability and proprioception [35], barefoot conditions may better activate and utilize their inherent foot functions, thus promoting a movement pattern closer to that of healthy individuals. This is consistent with the findings of Gu et al. [13], which show that barefoot exercise significantly adjusts lower-limb biomechanical functions, not only promoting the development of small muscle groups in the foot, increasing their cross-sectional area, but also potentially providing additional foot stability and sock absorption. This could be extremely beneficial for the rehabilitation of individuals with FAI, as barefoot training may help them enhance foot proprioception, balance, and posture control.

Furthermore, for the special group of individuals with FAI, wearing shoes may provide better support and protection for the ankle joint, which is crucial for improving movement stability and reducing the risk of injury [17]. However, this additional physical support may also affect foot proprioception, as wearing shoes might limit direct sensory feedback from the foot to the ground, affecting the individual's perception of ground conditions. Meanwhile, barefoot exercise may help improve foot proprioception and muscle strength [36], bringing the foot function of individuals with FAI closer to that of healthy individuals in certain aspects. The biomechanical characteristics in barefoot conditions may assist individuals with FAI in perceiving and controlling foot movements better during the rehabilitation process, thereby promoting a more natural movement pattern. However, barefoot exercise may also deprive individuals with FAI of the physical protection offered by shoes, increasing the risk of ankle injury, especially when the ankle joint is already compromised. Research by Zech et al. [37] indirectly supports this viewpoint, suggesting that the choice of footwear conditions should be determined based on the individual's specific needs. Moreover, according to the results of this study, the larger knee flexion angle and shorter T_vGRF observed in individuals with FAI compared to healthy individuals during single-leg drop landing movements persist, indicating that individuals with FAI may adopt specific landing strategies under the footwear conditions employed in this study. Therefore, for individuals with FAI, the choice between wearing shoes or being barefoot should be based on their individual circumstances and rehabilitation goals, as well as their adaptability and stability under different movement conditions.

However, this study did not observe changes in the lower-limb biomechanical indicators of individuals with FAI during single-leg drop landing movements under sock-wearing conditions, which may be related to the type of socks selected for this study. Future research should consider the potential impact of different sock designs and materials on the biomechanical characteristics of individuals with FAI.

In summary, footwear is a complex balancing issue for individuals with FAI, requiring a comprehensive consideration of biomechanical support, proprioception, psychological factors, and individual rehabilitation goals. Wearing shoes undoubtedly provides the necessary physical support and protection for individuals with FAI, which is essential for improving movement stability and reducing the risk of injury. However, barefoot conditions may assist individuals with FAI in better perceiving and controlling foot movements during the rehabilitation process, promoting the development of more natural movement patterns. Future research should delve into the mechanisms of proprioceptive changes under different footwear conditions and how these changes affect the motor control and rehabilitation outcomes of individuals with FAI. Additionally, research should consider the development and evaluation of personalized rehabilitation programs for individuals with FAI, which may combine the advantages of both shoe-wearing and barefoot training to achieve optimal rehabilitation effects.

4.3. Clinical Recommendations

In clinical treatment and rehabilitation training for individuals with FAI, it is recommended to consider the impact of different footwear conditions on their biomechanical characteristics. Experimental research and rehabilitation plans should account for various conditions, including barefoot, shoe-wearing, sock-wearing, and sock-and-shoe-wearing, to determine the most suitable type of footwear for individual needs. It is suggested to combine the advantages of both shoe-wearing and barefoot training, adopting a progressive approach that transitions from basic balance exercises to more complex movements, while also providing necessary psychological support and education. It is recommended to monitor the progress of individuals with FAI and adjust the training program based on changes in their adaptability and stability.

4.4. Limitations

This study provides preliminary insights into the impact of footwear conditions on the biomechanical characteristics of individuals with FAI, but it has some limitations. (1) The small sample size may limit the generalizability of the results, and the study primarily focuses on single-leg drop landing movements, not covering a broader range of movement types. (2) The study does not thoroughly explore the specific effects of different designs and materials of shoes and socks on the biomechanical characteristics of individuals with FAI, nor does it address the long-term impact of footwear conditions on proprioception and psychological state. (3) The conclusions drawn are primarily based on experimental settings, and their applicability to real-world sports scenarios remains to be validated. Future research should aim to expand the sample size, include a more diverse array of movement scenarios, conduct in-depth studies on the effects of different types of footwear, and engage in long-term effectiveness tracking assessments.

4.5. Perspectives

This study's findings offer a novel perspective on the role of footwear in FAI rehabilitation, emphasizing the need for tailored approaches that balance biomechanical support and sensory feedback. The distinct biomechanical adaptations observed under various footwear conditions could guide future research towards developing more nuanced rehabilitation protocols. Importantly, these insights may also be instrumental for sports medicine professionals in crafting individualized treatment plans that enhance both performance and injury prevention in athletes with FAI. By considering the specific biomechanical implications of different footwear types, future studies can further our understanding of how best to support the unique needs of this patient population, ultimately contributing to the broader field of sports medicine and rehabilitation.

5. Conclusions

The biomechanical characteristics of the lower limbs in individuals with FAI are significantly influenced by various footwear conditions. Wearing shoes offers crucial structural support, enhancing the stability of the ankle joint and mitigating the risk of injury, particularly during single-leg drop landing movements. At the same time, biomechanical characteristics under barefoot conditions indicate that individuals with FAI may achieve biomechanical levels akin to those of healthy individuals by improving proprioception, posture control, and coordination. However, regardless of the footwear conditions in this study, individuals with FAI exhibit a larger knee flexion angle and a shorter T_vGRF during single-leg drop landing movements compared to healthy individuals. Additionally, wearing socks did not significantly affect individuals with FAI. Therefore, the selection of footwear is a nuanced balance that must be carefully considered for individuals with FAI, tailored to their specific circumstances, rehabilitation objectives, and adaptability and stability under diverse sports conditions. Future research should further investigate the changes in proprioception under different footwear conditions and their impact on motor control and rehabilitation outcomes, assisting individuals with FAI in making optimal footwear choices during the rehabilitation process to achieve personalized rehabilitation effects.

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