World Journal of Physical Education and Sports
www.worldsportsjournal.com
Online ISSN:
Received: 02-01-2025, Accepted: 02-02-2026, Published: 17-02-2026
Volume 2, Issue 1, Jan-Mar, 2026, Page No. 9-12

Three-dimensional kinematic analysis of knee joint loading during forefoot versus rearfoot strike patterns in recreational runners: Implications for injury prevention

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Abstract
Background: Running-related injuries affect 50–70% of recreational runners annually, with the knee joint accounting for the greatest proportion of injury sites. Foot strike pattern specifically forefoot strike (FFS) versus rearfoot strike (RFS) is hypothesized to substantially modulate knee joint loading mechanics; however, comparative three-dimensional kinematic data in recreational runners remain limited.
Objective: To quantitatively compare knee joint kinematic parameters peak valgus angle, internal rotation, and knee flexion angle at initial contact between forefoot and rearfoot strikers during overground running at preferred pace.
Method: Thirty recreational runners (15 forefoot, 15 rearfoot strikers; confirmed by force plate analysis; Mage = 26.7 ± 3.9 years; weekly mileage 25–50 km) underwent three-dimensional kinematic analysis using a 10-camera Vicon motion capture system at 200 Hz with 16-marker lower extremity protocol. Statistical comparisons employed independent samples t-tests with Bonferroni correction. This study uses a simulated dataset created for academic training purposes.
Key Results: FFS runners demonstrated significantly lower peak knee valgus angles (4.2° ± 1.8° vs. 7.1° ± 2.4°; $p = 0.001$) but higher ipsilateral hip adduction loads. RFS runners exhibited greater knee flexion at initial contact (14.3° ± 3.1° vs. 7.8° ± 2.6°; $p < 0.001$) and higher peak vertical ground reaction force loading rates.
Conclusion: Foot strike pattern produces distinct knee joint loading profiles with differential injury risk implications. Neither pattern is universally superior; individualized biomechanical screening is recommended for injury prevention programming.

Keywords: Biomechanics, foot strike, knee kinematics, running injury, valgus, motion capture

Introduction

Running remains one of the most globally practised forms of physical exercise, with conservative estimates placing the number of regular recreational runners at over 600 million worldwide [1]. Despite its well-documented cardiovascular, metabolic, and psychological benefits, running is associated with high rates of overuse injury with epidemiological data consistently reporting incidence rates of 50–70% among recreational participants over a single training year [2]. The knee joint is the most commonly injured anatomical site, encompassing diagnoses including patellofemoral pain syndrome (PFPS), iliotibial band syndrome (ITBS), and medial compartment osteoarthritis all mechanically linked to aberrant knee joint loading during the stance phase of running [3].

Foot strike pattern specifically the point of initial ground contact relative to the centre of mass has emerged as a central mechanical variable in running injury biomechanics research over the past two decades [4]. The rearfoot strike (RFS) pattern, in which the heel contacts the ground first, characterizes approximately 75–80% of recreational runners wearing conventional cushioned footwear [5]. The forefoot strike (FFS) pattern, gaining widespread attention following Lieberman *et al.*'s seminal 2010 paper [6], involves initial contact at the ball of the foot or toes, producing distinct tibial shock transient, ankle kinematics, and ground reaction force profiles.

The biomechanical consequences of foot strike pattern for the knee joint are mechanistically plausible: FFS produces greater ankle dorsiflexion and ankle joint energy absorption, potentially redistributing loading proximally to the knee and hip [7]. Conversely, RFS produces characteristic impact transients with steep loading rates linked to tibial stress fractures and patellofemoral pain, while knee flexion at initial contact influences quadriceps demand and patellar compression force [8].

Despite the theoretical framework, comparative three-dimensional kinematic studies examining knee-specific parameters particularly coronal plane kinematics (valgus/varus) and transverse plane rotation between naturally-occurring FFS and RFS groups in recreational runners are methodologically limited [9]. Many existing studies have employed laboratory-induced strike pattern changes rather than natural strike classification, and most have prioritized sagittal plane kinematics at the expense of clinically relevant coronal plane parameters that predict PFPS and ITBS risk [10].

This study aims to provide a comprehensive three-dimensional kinematic profile of the knee joint in recreational forefoot and rearfoot strikers during overground running at preferred pace, using gold-standard optical motion capture methodology. The findings will contribute evidence to guide individualized biomechanical screening and gait retraining protocols in recreational running injury prevention.

Literature Review

The biomechanical literature on foot strike and knee loading spans three primary domains: (i) ground reaction force characteristics, (ii) joint kinematics and kinetics, and (iii) clinical injury associations. A systematic understanding of the evidence base across these domains is essential for contextualizing the present investigation.

Lieberman *et al* [6]. established that FFS runners generate lower impact transients and reduced tibial shock acceleration compared to RFS runners, particularly when barefoot. Subsequent work by Milner *et al* [11]. demonstrated that high vertical loading rates characteristic of RFS are prospective predictors of tibial stress fracture in female distance runners, establishing a mechanistic injury pathway independent of total training load. These loading rate differences have been replicated across multiple cohorts and footwear conditions [12].

With respect to the knee joint specifically, Bonacci *et al* [13]. compared knee kinematics during FFS and RFS in recreational triathletes, reporting greater knee flexion at initial contact in RFS runners but no significant difference in coronal plane kinematics. However, this study employed a 2D sagittal analysis and was conducted during treadmill not overground running, limiting ecological validity.

The role of dynamic knee valgus an inward collapse of the knee during loading characterized by combined hip adduction and internal rotation, tibial internal rotation, and knee valgus angulation as an injury risk factor for PFPS and ACL injury has been extensively documented [14]. Dierks *et al* [15]. demonstrated that recreational runners with PFPS exhibited greater peak knee abduction moments and hip adduction angles compared to pain-free controls, emphasizing the proximal origins of distal knee loading pathology.

The interaction between foot strike pattern and knee valgus biomechanics remains insufficiently characterised in the peer-reviewed literature. Conceivably, the altered foot contact mechanics in FFS including increased ankle inversion at initial contact could modulate the transmission of ground reaction forces through the kinetic chain in ways that either increase or decrease dynamic knee valgus [16]. This mechanistic uncertainty underscores the clinical and scientific relevance of the present three-dimensional kinematic investigation.

Methodology

1. Research design

A cross-sectional, observational comparative design was employed. Participants were stratified into naturally-occurring FFS and RFS groups confirmed by instrumented force plate analysis. Ethical approval was obtained from the institutional ethics committee.

2. Participants

Thirty recreational runners (Mage = 26.7 ± 3.9 years; 17 male, 13 female; weekly mileage 25–50 km) with no running-related injury in the preceding six months were recruited by purposive sampling. Foot strike classification was determined during habitual overground running using embedded Kistler force plates (2000 Hz), with RFS defined as initial contact at or posterior to 33% of foot length, and FFS as initial contact anterior to this threshold. This yielded n = 15 per group.

3. Motion capture protocol

Three-dimensional kinematics were captured using a 10-camera Vicon Nexus system operating at 200 Hz. A 16-marker lower extremity protocol was employed (bilateral ASIS, PSIS, lateral thigh, medial/lateral femoral epicondyle, lateral shank, medial/lateral malleolus, heel, and first/fifth metatarsal heads). Participants completed five overground running trials at self-selected preferred pace on a 20-metre track. Three valid trials per participant were averaged for analysis. Kinematic data were filtered using a 4th-order Butterworth low-pass filter at 12 Hz.

4. Outcome variables

Primary outcomes: (i) Peak knee valgus angle (°) during stance phase; (ii) Knee flexion angle at initial contact (°); (iii) Peak knee internal rotation (°). Secondary outcomes: peak vertical ground reaction force loading rate (BW/s) and ankle dorsiflexion at initial contact.

5. Statistical analysis

Independent samples t-tests with Bonferroni correction for multiple comparisons were performed using SPSS v.28. Effect sizes were computed using Cohen's d. Statistical significance was set at $\alpha = 0.05$ (corrected to $\alpha = 0.017$ per comparison after Bonferroni adjustment).

Note: This study uses a simulated dataset created for academic training purposes.

Results and Discussion

Table 1: Group participant characteristics

Variable	FFS Group (n=15)	RFS Group (n=15)
Age (years)	25.9 ± 3.7	27.4 ± 4.0
Height (m)	1.73 ± 0.07	1.72 ± 0.08
Body Mass (kg)	68.4 ± 9.1	70.2 ± 8.6
Weekly Mileage (km)	38.4 ± 8.3	36.9 ± 9.1
Running Speed (m/s)	3.28 ± 0.31	3.22 ± 0.28

Source: Simulated dataset created for academic training purposes (2026)

Table 2: Primary Kinematic Outcome Comparison: FFS vs. RFS

Kinematic Variable	FFS (Mean ± SD)	RFS (Mean ± SD)	Cohen's d	p-value
Peak Knee Valgus Angle (°)	4.2 ± 1.8	7.1 ± 2.4	0.75	0.001**
Knee Flexion at IC (°)	7.8 ± 2.6	14.3 ± 3.1	0.91	< 0.001**
Peak Knee Internal Rotation (°)	6.9 ± 2.2	5.4 ± 1.9	0.50	0.024*
VGRF Loading Rate (BW/s)	58.4 ± 12.3	82.1 ± 18.7	0.79	0.001**

Source: Simulated training dataset (2026). IC = Initial Contact; VGRF = Vertical Ground Reaction Force. *p < 0.05; **p < 0.01

FFS runners demonstrated significantly lower peak knee valgus angles (4.2° ± 1.8° vs. 7.1° ± 2.4°; d = 0.75; p = 0.001), consistent with reduced dynamic knee valgus loading that is associated with PFPS and ACL injury risk profiles. The mechanistic explanation likely involves the more lateral and anterior foot contact in FFS, which alters the moment arm of the ground reaction force vector relative to the knee joint centre, reducing the abduction moment driving valgus collapse [17].

Conversely, RFS runners exhibited significantly greater knee flexion at initial contact (14.3° vs. 7.8°; d = 0.91; $p < 0.001$), which represents the largest effect size observed. Greater knee flexion at initial contact is associated with higher quadriceps demand for impact absorption, increased patellofemoral contact force, and elevated cumulative patellofemoral stress a well-established biomechanical pathway to PFPS [18].

Table 3: Secondary kinematic and ankle variables

Variable	FFS (Mean ± SD)	RFS (Mean ± SD)	Cohen's d	p-value
Ankle Dorsiflexion at IC (°)	−8.4 ± 3.1	12.6 ± 4.3	2.51	< 0.001**
Peak Hip Adduction (°)	10.3 ± 3.4	7.8 ± 2.9	0.47	0.039*

Source: Simulated training dataset (2026). *p < 0.05; **p < 0.01

The finding of significantly greater peak hip adduction in FFS runners is notable and represents a potential counter-balancing injury risk factor elevated hip adduction angles are consistently associated with ITBS and contribute to the dynamic valgus moment at the knee through proximal mechanisms [19]. This observation supports the conclusion that FFS is not universally biomechanically superior and that injury risk must be assessed holistically across the entire lower extremity kinetic chain.

Conclusion

Three-dimensional kinematic analysis reveals that forefoot and rearfoot strike patterns produce distinctly different knee joint loading profiles in recreational runners, each carrying specific injury risk implications. FFS reduces dynamic knee valgus protective against PFPS and ACL injury but increases hip adduction, a risk factor for ITBS. RFS produces greater knee flexion at initial contact and higher VGRF loading rates, implicating patellofemoral and tibial stress pathways.

These findings support the conclusion that neither foot strike pattern is universally biomechanically optimal. Clinical recommendations for foot strike modification should be individualized based on the runner's specific injury history, symptom pattern, and biomechanical screen findings rather than based on general population-level guidance. Gait retraining interventions targeting specific kinematic parameters rather than wholesale strike pattern changes represent the more evidence-informed injury prevention approach.

Limitations include the cross-sectional design, absence of kinetic data (joint moments and powers), and the non-clinical recreational sample. Future research should prospectively examine injury incidence in FFS and RFS cohorts, include joint kinetics analysis, and evaluate the effects of individualized gait retraining on injury rates over competitive training seasons.

Ethical Statement

This article was prepared as an original academic training document. The dataset is explicitly simulated for educational purposes. No real participants, biomechanical datasets, or institutional data were reproduced. All identifiers are placeholders.

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