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Biomechanical Analysis of Running Gait Patterns: The Relationship between Foot Strike Type, Injury Prevalence, and Performance Efficiency in Long-Distance Runners

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ABSTRACT

Understanding the biomechanical characteristics of running gait patterns is essential for optimizing performance and minimizing injury risk among long-distance runners. This study aimed to analyze the relationship between foot strike type classified as rearfoot, midfoot, and forefoot strike and both injury prevalence and running efficiency. A total of 60 trained long-distance runners (30 male, 30 female) were examined using 3D motion capture and ground reaction force analysis during standardized treadmill running sessions. Kinematic and kinetic parameters, including stride length, contact time, loading rate, and vertical stiffness, were compared across foot strike patterns. Statistical analysis revealed that rearfoot strikers exhibited higher vertical impact forces and greater incidence of overuse injuries, particularly in the knee and hip regions, whereas forefoot strikers demonstrated reduced impact loading but increased calf and Achilles tendon stress. Midfoot strikers showed the most balanced biomechanical profile, with moderate impact forces and optimal running economy. The findings suggest that individualized gait assessment and training interventions tailored to foot strike patterns can enhance performance efficiency while reducing injury risk in long-distance runners.

Introduction

Running is one of the most popular forms of physical activity worldwide, with long-distance running gaining particular attention due to its cardiovascular, metabolic, and psychological benefits. Despite these advantages, long-distance runners are susceptible to a wide range of musculoskeletal injuries, often attributed to repetitive loading, biomechanical inefficiencies, and individual differences in running mechanics. Among the various biomechanical factors, foot strike patterns the manner in which the foot contacts the ground during running have emerged as a critical determinant of both injury risk and performance efficiency [1].

Foot strike patterns are typically classified into three primary types: rear foot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS).

Rear foot strikers land predominantly on the heel, midfoot strikers contact the ground with the central portion of the foot, and forefoot strikers initiate contact with the ball of the foot. These patterns influence the distribution of forces throughout the lower extremities, affecting joint loading, muscle activation, and energy absorption mechanisms. Consequently, the type of foot strike not only modulates biomechanical stress but also has implications for running economy, endurance, and susceptibility to injury.

Several studies have demonstrated that rear foot strike runners typically experience higher vertical impact forces, which may increase the risk of knee and hip overuse injuries. In contrast, forefoot strike runners often display reduced impact loading at the knee but elevated stress on the calf muscles and Achilles tendon [2].

Midfoot strike runners, by comparison, tend to exhibit a more balanced biomechanical profile, with moderate loading and favorable energy transfer, suggesting a potential advantage in injury prevention and running economy.

Understanding the intricate relationships among foot strike type, biomechanical parameters, and injury prevalence is essential for designing effective training interventions. By identifying the specific patterns that contribute to increased stress or

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enhanced efficiency, coaches, physiotherapists, and athletes can implement individualized strategies to optimize performance while minimizing injury risk. Despite growing interest, gaps remain in the literature regarding the comprehensive evaluation of foot strike mechanics using modern 3D motion capture technology combined with ground reaction force analysis, particularly in populations of trained long-distance runners [3].

Therefore, the present study aims to analyze the biomechanical characteristics of running gait patterns across rear foot, midfoot, and forefoot strikers, with a focus on injury prevalence and running performance efficiency [4]. By systematically comparing kinematic and kinetic parameters among foot strike types, this research seeks to provide evidence-based insights for optimizing training protocols, informing injury prevention strategies, and enhancing overall running performance [5].

Foot Strike Patterns and Biomechanical Implications: Foot strike is commonly categorized into rear foot strike (RFS), midfoot strike (MFS), and forefoot strike (FFS). Rear foot strike runners initiate ground contact with the heel, resulting in a characteristic impact peak in vertical ground reaction forces [6]. Studies have shown that RFS can produce higher loading rates and greater stress on the knee and hip joints, potentially increasing susceptibility to patellofemoral pain, iliotibial band syndrome, and hip overuse injuries [7]. In contrast, forefoot striking shifts initial impact toward the forefoot, reducing peak vertical loading at the knee but increasing stress on the ankle plantar flexors and Achilles tendon, which may predispose athletes to calf strains or tendinopathies [8]. Midfoot strike runners generally exhibit an intermediate biomechanical profile, with reduced impact peaks compared to RFS but lower Achilles tendon loading than FFS. This pattern has been associated with more balanced force distribution, improved shock absorption, and potentially greater running economy [9]. Importantly, these biomechanical differences highlight the trade-offs inherent in each foot strike type, suggesting that individualized assessment is necessary to optimize performance and reduce injury risk.

Running Economy and Foot Strike: Running economy, defined as the oxygen cost of running at a given velocity, is influenced by biomechanical efficiency and lower limb dynamics. Foot strike patterns alter stride length, ground contact time, and vertical stiffness, all of which contribute to energy expenditure. Research indicates that midfoot striking may offer advantages in running economy due to optimized energy transfer and reduced vertical oscillation [10]. Conversely, rear foot striking, while common among recreational and elite runners, may incur higher metabolic costs due to elevated braking forces and less efficient propulsion mechanics [11].

Foot Strike and Injury Prevalence: Epidemiological studies have consistently linked foot strike patterns to injury prevalence. Rear foot strikers are more prone to knee and hip overuse injuries, whereas forefoot strikers show increased incidence of calf and Achilles tendon injuries [12]. Midfoot strike runners appear to experience a lower overall injury risk, though the evidence remains mixed and often context-dependent. Factors such as running surface, training volume, and footwear can modulate the relationship between foot strike type and injury outcomes [13].

Gaps in Current Literature: While numerous studies have explored foot strike biomechanics, gaps remain. Many prior investigations rely on over ground running or limited sample sizes, often failing to integrate comprehensive 3D motion capture with ground reaction force analysis. Additionally, longitudinal studies linking foot strike patterns to injury development and performance outcomes are scarce. This highlights the need for controlled experimental designs examining trained long-distance runners under standardized conditions to elucidate precise biomechanical mechanisms [14].

Rationale for the Present Study: The current study addresses these gaps by combining advanced 3D kinematic analysis with kinetic measurements in a cohort of trained runners. By systematically comparing rear foot, midfoot, and forefoot strikers, the research aims to identify biomechanical profiles associated with both injury prevalence and running efficiency. Such findings have practical applications in training prescription, injury prevention, and performance optimization, offering evidence-based guidance for athletes, coaches, and clinicians [15]

Literature Review / Background

Understanding the biomechanics of running gait has been a focal point in sports science research due to its implications for both performance and injury prevention. A runner’s gait is influenced by multiple factors, including foot strike pattern, joint kinematics, muscle activation, and ground reaction forces. Among these, foot strike pattern is recognized as a key modulator of lower extremity loading and running economy [16].

Table 1. Literature review [17]

Reference (APA)	Study Focus	Key Findings
Xu, Y., Yuan, P., Wang, R., Wang, D., Liu, J., & Zhou, H. (2020). Effects of foot strike techniques on running biomechanics: A systematic review and meta-analysis. Sports Health, 12(6), 505–515. https://doi.org/10.1177/1941738120934715	Systematic review of foot strike types	Rear foot strike (RFS) increases knee loading; forefoot strike (FFS) reduces knee load but increases Achilles stress; midfoot strike (MFS) shows balanced biomechanics
Bovalino, S. P., et al. (2021). Foot strike patterns during over ground distance running. Sports Medicine – Open, 7(1), 63. https://doi.org/10.1186/s40798-021-00369-9	Foot strike distribution in distance runners	RFS is the most common; FFS and MFS less prevalent; foot strike may change with fatigue
Chabot, M., et al. (2024). Influence of sudden changes in foot strikes on loading. Sensors, 24(24), 8163. https://doi.org/10.3390/s24248163	Effect of abrupt foot strike changes on loading	Sudden change in strike pattern increases injury risk, particularly in distal structures (calf, Achilles tendon)
Burke, A., et al. (2021). Risk factors for injuries in runners: A systematic review. Orthopedic Journal of Sports Medicine, 9(5), 23259671211020283. https://doi.org/10.1177/23259671211020283	Running injury risk factors	Foot strike type is significant; RFS associated with knee injuries; FFS with Achilles/calf injuries
Lieberman, D. E., et al. (2010). Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature, 463, 531–535. https://doi.org/10.1038/nature08723	Biomechanics of barefoot vs. shod running	Habitually barefoot runners tend to FFS; lower impact forces at the knee; higher distal loading on ankle and foot
Hasegawa, H., Yamauchi, T., & Kraemer, W. J. (2007). Foot strike patterns of runners at the 15-km point during an elite-level half marathon. Journal of Strength and Conditioning Research, 21(3), 888–893. https://doi.org/10.1519/R-20580.1	Long-distance race analysis	Most runners use RFS; foot strike may change during a race due to fatigue
Daoud, A. I., et al. (2012). Foot strike and injury rates in endurance runners. Medicine & Science in Sports & Exercise, 44(7), 1325–1334. https://doi.org/10.1249/MSS.0b013e3182465115	Foot strike and injury correlation	RFS linked to knee injuries; FFS linked to calf/Achilles injuries; MFS shows lowest injury incidence
Altman, A. R., & Davis, I. S. (2012). Prospective comparison of running injuries between forefoot and rear foot strikers. British Journal of Sports Medicine, 46(15), 105–111. https://doi.org/10.1136/bjsports-2011-090199	Prospective injury study	RFS runners have higher knee injury risk; FFS runners have increased lower leg injuries
Hamill, J., Derrick, T. R., & Holt, K. G. (1995). Shock attenuation and stride frequency in running. Human Movement Science, 14(1), 45–60. https://doi.org/10.1016/0167-9457(95)00005-Q	Stride frequency and impact	Higher stride frequency reduces impact forces; foot strike type interacts with stride mechanics

Methods

This study employed a cross-sectional, observational design to examine the relationship between foot strike patterns, injury prevalence, and running efficiency in long-distance runners. A combination of 3D motion capture and ground reaction force analysis was utilized to quantify biomechanical parameters during standardized treadmill running sessions.

Participants: A total of 60 trained long-distance runners (30 males, 30 female) participated in this study.

Inclusion criteria were:

- ✓ Age between 18 and 35 years.
- ✓ Minimum of 3 years of consistent long-distance running experience (>30 km/week).
- ✓ Free from acute musculoskeletal injury at the time of testing.

Exclusion criteria included:

- ✓ History of lower limb surgery within the past year.
- ✓ Neurological or cardiovascular conditions affecting gait.
- ✓ Inability to complete treadmill running protocol [18].

Foot Strike Classification: Participants' foot strike patterns were determined using high-speed video analysis combined with 3D motion capture data. Foot strike was categorized as:

- ✓ **Rear foot Strike (RFS):** initial contact with the heel
- ✓ **Midfoot Strike (MFS):** initial contact with the central portion of the foot
- ✓ **Forefoot Strike (FFS):** initial contact with the ball of the foot

Classification was confirmed by at least two independent raters, and participants were assigned to groups based on their habitual foot strike during long-distance running.

Data Collection

Equipment:

- ✓ **3D Motion Capture:** 12-camera Vicon system (Vicon Motion Systems Ltd.) recorded kinematic data at 200 Hz.
- ✓ **Force Measurement:** Instrumented treadmill with embedded force plates (AMTI, USA) measured vertical and horizontal ground reaction forces at 1000 Hz.
- ✓ **Video Recording:** High-speed cameras (240 fps) synchronized with motion capture for visual verification of foot strike.

Running Protocol

- ✓ Participants completed a 10-minute warm-up at a self-selected pace.
- ✓ Standardized running trials: 5 minutes at a controlled speed (12 km/h) on the treadmill to ensure consistent measurement conditions.
- ✓ Adequate rest periods (2–3 minutes) were provided between trials to prevent fatigue.

Measured Variables: The following kinematic and kinetic parameters were analyzed:

- ✓ Stride length (m)
- ✓ Ground contact time (ms)
- ✓ Vertical ground reaction force (vGRF) peak (N)
- ✓ Loading rate (N/s)
- ✓ Vertical stiffness (kN/m)
- ✓ Ankle, knee, and hip joint angles at initial contact and midstance

Additionally, injury prevalence over the past 12 months was assessed using a structured questionnaire, documenting:

- ✓ Injury type (overuse vs. acute)
- ✓ Location (knee, hip, ankle, calf)
- ✓ Duration and severity

Running economy was estimated using treadmill-derived oxygen consumption (VO_2) measurements during submaximal running trials, expressed as $ml \cdot kg^{-1} \cdot min^{-1}$.

Statistical Analysis

- ✓ **Descriptive statistics:** means ± standard deviations for all biomechanical variables
- ✓ **Between-group comparisons:** One-way ANOVA with Bonferroni post-hoc tests to compare RFS, MFS, and FFS groups
- ✓ **Correlation analysis:** Pearson's correlation coefficients assessed relationships between foot strike, loading parameters, and injury prevalence
- ✓ **Regression models:** Multiple linear regression analyzed predictive value of biomechanical variables on injury risk and running economy
- ✓ **Significance level:** $p < 0.05$ for all statistical tests

Data analyses were performed using SPSS v26 (IBM Corp., Armonk, NY) and visualized with Graph Pad Prism 9.

Results

Participant Characteristics:

The study included 60 trained long-distance runners, equally distributed by sex (30 males, 30 females). The mean age was 26.4 ± 4.2 years, with an average weekly running volume of 42.7 ± 8.5 km. Participants were classified into three-foot strike groups based on habitual running pattern:

- ✓ Rear foot Strike (RFS): 28 runners (46.7%)
- ✓ Midfoot Strike (MFS): 16 runners (26.7%)
- ✓ Forefoot Strike (FFS): 16 runners (26.7%)

No significant differences were observed in age, body mass, or running experience among the groups ($p > 0.05$), confirming comparability.

Kinematic Parameters

Stride length and ground contact time varied significantly across foot strike types:

- ✓ **Stride length:** MFS runners demonstrated slightly longer strides (1.38 ± 0.06 m) than RFS (1.33 ± 0.07 m) and FFS (1.35 ± 0.05 m), although post-hoc comparisons indicated differences were not statistically significant ($p = 0.08$).
- ✓ **Ground contact time:** RFS runners exhibited the longest contact time (275 ± 15 ms), compared to MFS (260 ± 12 ms) and FFS (245 ± 10 ms). ANOVA revealed significant differences ($F(2,57) = 9.72$, $p < 0.001$), with FFS runners achieving the shortest contact time.

Joint kinematics at initial contact indicated:

- ✓ **Ankle dorsiflexion:** highest in RFS (12.5 ± 3.1°), lowest in FFS (2.8 ± 2.4°), reflecting heel vs. forefoot landing mechanics.
- ✓ **Knee flexion:** slightly greater in MFS (20.2 ± 2.9°) than RFS (18.5 ± 3.0°) and FFS (19.0 ± 2.6°), though differences were not statistically significant [19].

Kinetic Parameters

Vertical ground reaction force (vGRF) peak:

- ✓ RFS: 3.2 ± 0.3 × body weight (BW)
- ✓ MFS: 2.8 ± 0.2 × BW
- ✓ FFS: 2.5 ± 0.2 × BW

ANOVA indicated a significant main effect of foot strike on vGRF ($F(2,57) = 18.45$, $p < 0.001$). Post-hoc comparisons showed RFS > MFS > FFS.

Loading rate:

- ✓ RFS exhibited the highest loading rate (82.5 ± 9.2 BW/s), followed by MFS (63.4 ± 8.1 BW/s) and FFS (55.1 ± 7.6 BW/s), confirming significant differences ($p < 0.001$).

Vertical stiffness:

- ✓ MFS runners displayed the highest vertical stiffness (16.8 ± 1.2 kN/m), suggesting optimized elastic energy storage and return. RFS and FFS groups had slightly lower stiffness (15.2 ± 1.5 kN/m and 15.7 ± 1.3 kN/m, respectively).

Running Economy

Estimated running economy (VO_2, ml·kg^{-1}·min^{-1}) at 12 km/h:

- ✓ RFS: 41.5 ± 2.7
- ✓ MFS: 39.8 ± 2.5
- ✓ FFS: 40.2 ± 2.8

MFS runners exhibited slightly better running economy, although differences did not reach statistical significance ($p = 0.07$).

Injury Prevalence

Self-reported injuries over the previous 12 months:

- ✓ **RFS:** 18/28 (64%) reported at least one overuse injury, primarily affecting the knee (36%) and hip (21%).
- ✓ **MFS:** 6/16 (37.5%) reported injuries, distributed across knee, ankle, and lower leg.
- ✓ **FFS:** 7/16 (43.7%) reported injuries, with calf (25%) and Achilles tendon (18.7%) most common.

Chi-square analysis indicated a significant association between foot strike type and injury location (χ^2 (4) = 12.76, p=0.013). RFS was strongly associated with knee and hip injuries, whereas FFS was more linked to calf and Achilles tendon problems [20].

Table 2. Summary of Biomechanical Data by Foot Strike Type

Parameter	Rear foot Strike (RFS)	Midfoot Strike (MFS)	Forefoot Strike (FFS)	Notes
Participant Characteristics	n = 28; Age = 26.2 ± 4.1 yr; Mass = 68.5 ± 7.2 kg; Height = 1.74 ± 0.06 m	n = 16; Age = 26.8 ± 4.5 yr; Mass = 69.1 ± 6.8 kg; Height = 1.75 ± 0.05 m	n = 16; Age = 26.5 ± 4.0 yr; Mass = 67.8 ± 7.5 kg; Height = 1.73 ± 0.06 m	Groups matched for age, mass, height
Stride Length (m)	1.33 ± 0.07	1.38 ± 0.06	1.35 ± 0.05	MFS slightly longer stride
Ground Contact Time (ms)	275 ± 15	260 ± 12	245 ± 10	FFS shortest contact time
Ankle Angle at Initial Contact (°)	12.5 ± 3.1	7.1 ± 2.5	2.8 ± 2.4	RFS dorsiflexed; FFS plantar flexed
Knee Flexion at Initial Contact (°)	18.5 ± 3.0	20.2 ± 2.9	19.0 ± 2.6	Minor differences
Vertical Ground Reaction Force (vGRF, ×BW)	3.2 ± 0.3	2.8 ± 0.2	2.5 ± 0.2	RFS highest peak impact
Loading Rate (BW/s)	82.5 ± 9.2	63.4 ± 8.1	55.1 ± 7.6	RFS highest; FFS lowest
Vertical Stiffness (kN/m)	15.2 ± 1.5	16.8 ± 1.2	15.7 ± 1.3	MFS optimal stiffness
Running Economy (VO_2, ml·kg^{-1}·min^{-1})	41.5 ± 2.7	39.8 ± 2.5	40.2 ± 2.8	MFS slightly better economy
Injury Prevalence (past 12 months)	18/28 (64%); knee 36%, hip 21%	6/16 (37.5%); mixed locations	7/16 (43.7%); calf 25%, Achilles 18.7%	RFS highest knee/hip injuries; FFS distal injuries

Explanation of the table:

- ✓ **Participant Characteristics:** Shows sample size, age, mass, and height per foot strike group.
- ✓ **Kinematic Parameters:** Includes stride length, ground contact time, and joint angles.
- ✓ **Kinetic Parameters:** Vertical ground reaction force, loading rate, and vertical stiffness.
- ✓ **Running Economy:** VO_2 as a measure of metabolic cost at submaximal running.
- ✓ **Injury Prevalence:** Self-reported injuries over 12 months, broken down by location.

Correlation and Regression Analysis

Pearson correlation analyses revealed:

- ✓ vGRF peak positively correlated with injury prevalence (r=0.54, p<0.001)

- ✓ Loading rate correlated with knee injury frequency (r=0.47, p=0.002)
- ✓ Vertical stiffness showed a moderate negative correlation with overall injury prevalence (r=-0.35, p=0.01)

Multiple linear regression models indicated:

- ✓ vGRF peak and loading rate together predicted 42% of variance in injury prevalence ($R^2 = 0.42$, $p < 0.001$).
- ✓ Vertical stiffness and stride parameters accounted for 31% of variance in running economy ($R^2 = 0.31$, $p = 0.004$).

Summary of Key Findings:

- ✓ **RFS runners:** higher vertical impact forces, longer contact time, greater knee/hip injury prevalence
- ✓ **MFS runners:** balanced biomechanical profile, moderate loading, optimal vertical stiffness, lower injury prevalence
- ✓ **FFS runners:** reduced impact at knee/hip, shorter contact time, higher calf/Achilles stress

These results suggest that midfoot striking provides a biomechanical advantage in terms of injury prevention and running efficiency, while both rear foot and forefoot striking exhibit trade-offs affecting specific injury sites [21].

Tummary of Biomechanical Data by Foot Strike Type

Participant Characteristics	Rearfoot Strike (RFS)	Midfoot Strike (MFS)	Forefoot Strike (FFS)
n	*n* = 28	*n* = 16	*n* = 16
Age (year)	26.2 ± 4.1	26.8 ± 4.5	26.5 ± 4.0
Mass (kg, (cm)	68.5 ± 7.2	69.1 ± 6.8	67.8 ± 7.5
Height (m (m)	1.74 ± 0.06	1.75 ± 0.05	1.73 ± 0.06
Kinematic Parameters			
Stride Length (m)	1.33 ± 0.07	1.38 ± 0.06	1.35 ± 0.05
Ground Contact time (ms)	275 ± 15	260 ± 12	245 ± 10
Ankle Angle at initial contact	12.5 ± 3.1	7.1 ± 2.5	2.8 ± 2.4
Knee Flexion at initial contact	18.5 ± 3.0	20.2 ± 2.9	19.0 ± 2.6
Running Economy			
VO_2 (ml-kg^{-11-})	41.5 ± 2.7	39.8 ± 2.5	40.2 ± 2.8
Injury Prevalence	18/28 (64 %)	6/16 (37.5 %)	7/16 (43.7 %)
Knee (21 %)	36 I Inee	Mixed	Calf
Hip (21 %)	21 I Hip	Mered	21 I Aakes

Discussion

The present study examined the biomechanical characteristics of running gait patterns and their relationship with injury prevalence and running efficiency among trained long-distance runners. By systematically analyzing rear foot (RFS), midfoot (MFS), and forefoot (FFS) strike patterns using 3D motion capture and ground reaction force analysis, several key insights emerged regarding the trade-offs between performance optimization and injury risk [22].

Biomechanical Implications of Foot Strike Patterns: Consistent with previous research (Xu et al.,2020; Bovalino et al.,2021), rear foot strikers in this study demonstrated higher vertical ground reaction forces (vGRF) and loading rates, which were strongly associated with knee and hip overuse injuries. The prolonged ground contact time observed in RFS runners may further exacerbate joint loading and contribute to repetitive stress injuries. Conversely, forefoot strikers exhibited reduced peak vGRF at the knee, suggesting a protective effect on proximal lower limb structures; however, increased calf and Achilles tendon stress indicates a shift of mechanical load distally, which may predispose runners to tendon and muscle injuries in the lower leg. These findings highlight the inherent biomechanical trade-offs associated with different foot strike patterns. Midfoot strikers displayed a balanced biomechanical profile, with moderate impact forces, optimal vertical stiffness, and relatively short ground contact times. This pattern appears to distribute mechanical loads more evenly across the lower extremities, potentially reducing injury risk while maintaining running efficiency. The slightly improved running economy in MFS runners further supports the notion that midfoot striking may optimize both energy utilization and joint protection, providing practical guidance for coaches and athletes seeking to enhance performance while minimizing injuries [23].

Comparison with Existing Literature: The current findings align with previous studies that identified RFS as a common pattern among recreational and elite runners and associated it with knee-related overuse injuries (Burke et al., 2021). Similarly, the increased distal stress observed in FFS runners corroborates earlier reports of higher Achilles tendon loading (Chabot et al., 2024). Importantly, this study adds to the literature by quantifying vertical stiffness and demonstrating its negative correlation with injury prevalence, suggesting that enhanced elastic energy storage and transfer may mitigate injury risk.

Implications for Training and Injury Prevention: The observed associations between foot strike, biomechanical parameters, and injury prevalence have several practical implications:

- ✓ **Individualized Gait Assessment:** Runners may benefit from personalized evaluation of foot strike and biomechanical characteristics to identify potential injury risk [24].
- ✓ **Targeted Interventions:** For RFS runners, strength and conditioning programs focusing on knee and hip stabilizers may reduce overuse injury risk. FFS runners may require calf and Achilles tendon conditioning to accommodate increased loading.
- ✓ **Foot Strike Modification:** Gradual transition strategies from RFS to MFS or FFS, if desired, should be implemented carefully to avoid overloading distal structures.
- ✓ **Monitoring Loading Metrics:** Use of vGRF, loading rate, and vertical stiffness measurements can guide training intensity and recovery protocols, potentially reducing injury incidence.

Limitations of the Study

While the study provides valuable insights, several limitations should be considered:

- ✓ **Sample Size:** Although adequate for statistical analysis, larger samples would enhance generalizability.
- ✓ **Treadmill Running:** Biomechanics on a treadmill may differ from over ground running, potentially affecting foot strike behavior and loading patterns.
- ✓ **Cross-Sectional Design:** Causal relationships between foot strike and injury cannot be definitively established. Longitudinal studies are needed to track injury development over time.
- ✓ **Self-Reported Injuries:** Injury data relied on participant recall, which may introduce reporting bias.

Future Research Directions

Future investigations should focus on:

- ✓ Longitudinal studies tracking the incidence of injuries among different foot strike groups over multiple training seasons.
- ✓ Integration of wearable technology to measure biomechanical parameters in natural running environments.
- ✓ Exploring interactions between foot strike, footwear type, running surface, and fatigue to understand context-dependent risk factors.
- ✓ Intervention studies examining whether modifying foot strike patterns can improve running economy and reduce injuries without introducing compensatory loading problems. Overall, the findings indicate that foot strike type exerts significant influence on biomechanical loading, injury prevalence, and running efficiency. Midfoot striking emerges as a biomechanically advantageous pattern that balances load distribution and energy utilization. Rear foot and forefoot striking demonstrate specific trade-offs: RFS increases proximal joint stress, whereas FFS elevates distal tendon loading. These insights emphasize the importance of individualized biomechanical assessment and targeted training interventions in optimizing performance and reducing injury risk in long-distance runners [25].

Practical Implications and Recommendations

The findings of this study provide valuable guidance for athletes, coaches, and clinicians working with long-distance runners. Several practical applications can be derived:

- ✓ **Individualized Gait Assessment:** Each runner should undergo a biomechanical evaluation to determine habitual foot strike pattern, stride characteristics, and joint loading. Identifying potential high-risk mechanics enables targeted interventions.
- ✓ **Strength and Conditioning Programs:**

- ✓ **Rear foot Strikers (RFS):** Emphasis on strengthening the quadriceps, hip abductors, and core muscles to reduce knee and hip overuse injuries.
- ✓ **Forefoot Strikers (FFS):** Focus on calf strengthening, Achilles tendon conditioning, and ankle stability exercises to accommodate higher distal loading.
- ✓ **Midfoot Strikers (MFS):** Maintenance programs to preserve optimal load distribution

and prevent compensatory changes during fatigue [26].

- ✓ **Gradual Foot Strike Modification:** Runners seeking to alter their foot strike pattern should implement progressive transition strategies, gradually increasing training volume to allow musculoskeletal adaptation and prevent secondary injuries [27].
- ✓ **Monitoring Biomechanical Metrics:** Use of vertical ground reaction force (vGRF), loading rate, and vertical stiffness during training sessions can provide real-time feedback, enabling coaches to adjust intensity or technique to minimize injury risk [28].
- ✓ **Integration with Running Equipment:** Footwear selection should complement individual foot strike patterns. For example, cushioned shoes may mitigate impact in RFS runners, whereas minimalist or flexible footwear may support FFS or MFS mechanics.
- ✓ **Education and Awareness:** Athletes should be educated about the trade-offs associated with different foot strike types. Understanding how biomechanics influence injury risk and performance encourages adherence to preventive and performance-enhancing strategies [29].

Conclusion

This study provides a comprehensive biomechanical analysis of running gait patterns in trained long-distance runners, emphasizing the relationship between foot strike type, injury prevalence, and running efficiency. Key findings include:

- ✓ Rear foot strikers (RFS) experience higher vertical impact forces and loading rates, with increased incidence of knee and hip overuse injuries.
- ✓ Forefoot strikers (FFS) exhibit reduced proximal joint loading but elevated stress on the calf and Achilles tendon.
- ✓ Midfoot strikers (MFS) demonstrate the most balanced biomechanical profile, with moderate impact forces, optimal vertical stiffness, and favorable running economy.

These results highlight that foot strike type significantly influences both injury risk and performance outcomes. Individualized gait assessment, targeted conditioning programs, and careful consideration of training volume and footwear are essential for optimizing performance and minimizing injuries. The study underscores the importance of integrating biomechanical insights into coaching and rehabilitation practices for long-distance runners.

Future research should focus on longitudinal studies, real-world running environments, and intervention-based designs to further elucidate the complex interactions between foot strike mechanics, training adaptations, and injury prevention. By tailoring training and rehabilitation strategies to individual biomechanical profiles, athletes can achieve improved performance while minimizing injury risk, ultimately enhancing long-term health and running longevity.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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