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The Impact of Running Experience and Shoe Longitudinal Bending Stiffness on Lower Extremity Biomechanics: A cross-sectional study

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Abstract

Purpose: The impacts of shoe stiffness on running biomechanics are well-documented, while the specific effects on the performance of biomechanically distinct groups such as novice runners and experienced runners are still largely unexplored. The study aimed to evaluate the biomechanical effects of different shoe longitudinal bending stiffness on the lower limb during running in novice runners and experienced runners.

Methods: Twelve experienced runners and ten novice runners ran at a speed of 4.47 m/s while randomly wearing shoes with either low stiffness (5.9 Nm/rad) or high stiffness (8.6 Nm/rad). An Opensim musculoskeletal model was adopted for estimating lower limb joint angles, joint angular velocities, joint moment, joint work, peak joint reaction forces during running stance phase.

Results: Results showed that novice runners displayed greater lower limb joint angles and less joint moment, while experienced runners exhibited reduced joint angles but greater joint moment, and higher peak joint reaction forces were observed at the knee and ankle joints. Furthermore, increased shoe longitudinal bending stiffness resulted in higher peak joint reaction forces at the metatarsophalangeal joint for novice runners while lower for experienced runners.

Conclusions: Novice runners exhibit greater lower limb joint angles and reduced joint moments compared to experienced runners. Increased longitudinal bending stiffness results in higher peak joint reaction forces at the metatarsophalangeal joint for novice runners, while experienced runners show reduced forces under the same conditions. This nuanced understanding of joint dynamics underscores the need for tailored training and footwear recommendations specific to different levels of running experience.

Keywords: Novice and Experienced runners; Lower limb biomechanics; Footwear science; Joint reaction forces

1. Introduction

At the 2023 Chicago Marathon, Kelvin Kiptum set a new official world record for the men's marathon with a time of 2 hours, 0 minutes, and 35 seconds, it brings the marathon world record closer to the elusive sub-two-hour mark by just 35 seconds. Beyond the inherent talent and rigorous training of the athlete, the contribution of technologically advanced running shoes emerges as an indispensable factor. While advancements in material science have led to lighter shoes with more resilient midsoles, the integration of a carbon plate within the midsole has been identified as a key element in enhancing running economy for marathon runners[30].

Subsequent research has been focused on how longitudinal bending stiffness (LBS: stiff plates embedded in shoes) affects running lower limb mechanics to enhance athletic performance. Research conducted by Willwacher et al.[39-41] has shown that increasing LBS of the forefoot in running shoes can limit dorsiflexion at the metatarsophalangeal (MTP) joint, thereby reducing its energy loss. Further studies by Cigoja[8], Hoogkamer[14, 15], and their colleagues have found that an increase in the LBS of running shoes leads to earlier dorsiflexion of the MTP joint during the stance phase, effectively shortening the phase of negative work and allowing more time for the generation of positive work. Similar modifications have been observed at the ankle joint, where increased LBS in running shoes can delay the shift of positive work contribution from the ankle to the knee during prolonged running[9], aiding in the maintenance of a more stable work distribution and improved running economy (RE). However, the impact of LBS on biomechanical performance is not consistently observed across all studies. Some have suggested that LBS might lead to an increased peak moment at the ankle by shifting the application point of ground reaction forces anteriorly, which alters the ratio of the external ground reaction force (GRF) moment arm to the internal muscle-tendon unit moment arm at the ankle, theoretically increasing the sagittal plane moment[31]. Despite these findings, subsequent research has shown inconsistent results regarding the impact of increased LBS on peak ankle joint moment, with studies reporting mixed outcomes—some noting an increase[31], others no significant difference[3, 38, 41], and a few even observing a decrease[39].

This variability in outcomes highlights a critical aspect of running shoe research, which is the differential effects of shoe technology based on individual runner characteristics. The interaction between a runner's biomechanics and shoe design is complex, suggesting that the benefits of increased LBS may not be universally applicable across all runners, a one-size-fits-all approach to running shoe design is insufficient to cater to the diverse needs of the running population[34]. Moreover, previous studies have confirmed that running experience influences the biomechanics of a runner's lower limbs[29]. Compared to experienced runners (ER), Novice runners (NR) exhibit decreased stability in distal joints, particularly in the knee and ankle joints[16, 29]. This indicates that runners with different levels of running experience may develop distinct biomechanical adaptation patterns and face varying risks of injury, however, previous studies have not adequately explained this[22, 29]. Although it is known that runners with different running experiences exhibit distinct lower limb biomechanical responses, current research on the impact of footwear LBS on lower limb biomechanics has not taken this factor into account. Meanwhile, with the growing popularity of marathon running and the heated market for carbon plate running shoes, more NR are opting for these shoes. If the impact of a running shoe's LBS on lower limb biomechanics is related to the runner's experience, then these factors should be considered in the design and selection of running shoes.

Accordingly, the aim of this study was to explore the effects of running experience (ER and NR), the LBS of running shoes, and their interaction on the kinematics and kinetics of lower limbs. We hypothesized that NR and ER runners would exhibit different kinematic and kinetic responses when wearing running shoes with different longitudinal bending stiffnesses, particularly around the ankle and MTP joints.

2. Materials and Methods

2.1. Study design and participants

This was a cross-sectional study. Participants were recruited by the researcher through online questionnaires from Ningbo university and six marathon clubs in Ningbo, China. The entire recruitment process lasted ten days (from September 4th, 2023, to September 14th, 2023). The inclusion criteria for ER are as follows: 1) an average weekly running distance exceeding 40 kilometers; 2) participation in a Class B or higher (certified by the Chinese Athletics Association for more persuasive results) full or half marathon within the past six months, with official completion proof showing a full marathon time of under 3 hours or a half marathon time of under 1 hour and 22 minutes. The inclusion criteria for

NR are: 1) an average weekly running distance of less than 10 kilometers; 2) no marathon racing experience. Additionally, there are common conditions that both groups need to meet: 1) the running shoes worn must be size 41; 2) there must be no lower limb injuries within six months prior to the study, and 3) the right leg must be the dominant leg (defined as the preferred leg for kicking). Finally, a total of 22 accessible participants were involved in this study, including 12 ER and 10 NR (Table 1). The study was conducted in strict adherence to the ethical principles of the World Medical Association (Declaration of Helsinki). Informed consent was obtained from all participants. This research received ethical approval from the Ethics Committee of Research Academy of Grand Health at Ningbo University (RAGH20231211).

Table 1. Participant demographics.

	ER (N=12)	NR (N=10)	P-value
Height(cm)	170.68(4.36)	170.23(2.77)	.836
Weight(kg)	60.56(4.17)	64.28(7.40)	.531
BMI (kg/m2)	20.79(1.32)	22.22(2.81)	.493
Weekly Mileage (km/week)	43.33(8.16)	3(2.74)	<.001

Statistical Methods: Mann-Whitney U test were used to compare variables between groups (ER and NR). Values are expressed as mean (SD). Bold values indicate statistical significance at the $p < 0.05$.

2.2. Footwear conditions

This study selected the common commercial running shoes produced by ANTA (ANTA Sports Products Limited, China) as the prototype footwear. The manufacturer embedded carbon fiber plates of two varying thicknesses into the midsole of the shoes. A digital pressure testing machine was used to bend the shoes at a rate of 100mm/min-1, and the maximum torsional moment was recorded as the forefoot bent within a range of 45°. The bending stiffness of the shoes was calculated based on the moment-angle formulas. The stiffness of the low LBS (Llbs) running shoe was calculated to be 5.0 Nm/rad and the stiffness of the high LBS (Hlbs) running shoe was 8.6 Nm/rad (Fig.1.a). Apart from differences in stiffness and weight, the two pairs of shoes are identical in all other respects.

2.3. Experimental protocol

The data collection was entirely conducted at the Sports Science Laboratory of Ningbo University, and the entire process lasted approximately three weeks (from September 27, 2023, to October 20, 2023). Participants were firstly required to warm up for 10 minutes on a treadmill at a self-selected pace while wearing two pairs of experimental shoes with different stiffnesses. If any discomfort or poor fit of the shoes was reported during the warm-up based on the participant's feedback, they will be excluded from the study. No participants experienced issues with ill-fitting shoes, and since the recruitment information was distributed before enrollment, no one was excluded during the entire testing phase. Following to the OpenSim 2392 model, 38 infrared reflective markers were placed on the participants' bony landmarks (Figure 1.b). These included 34 reflective markers with a base diameter of 16 mm and a reflective sphere diameter of 13 mm, and 4 reflective markers with a base diameter of 14 mm and a reflective sphere diameter of 10 mm, which were used specifically for the MTP joint (Figure 1.b). To minimize variability stemming from subjective placement, a single researcher consistently conducted the entire marker attachment process throughout the study. Based on the research by Rebecca and Thomas et al.[32], elliptical holes within 27 mm do not compromise the structural integrity of the shoe. Furthermore, Chris et al.[5] confirmed that with a 25 mm hole diameter, the movement of the markers is not restricted by contact with the shoe upper. Therefore, in this study, we created a circular hole with a diameter of approximately 25 mm at the MTP joint area of the shoe. Reflective markers with a base diameter of 14 mm were directly attached to the participants' feet to accurately capture the MTP joint movements during running[28]. Subsequently, participants were required to run across the collection area at a speed of 4.47m/s ± 5%[24], with the landing method chosen freely by the participants. A timing system was used to monitor speed, and GRF data were collected by a force plate (Kistler, Switzerland) located in the center of a 40-meter track at a frequency of 2000 Hz. Around the force plate, 10 infrared motion capture cameras (Vicon, Oxford Metrics Ltd, Oxford, UK) were set up to capture kinematic data during running at a frequency of 200 Hz. Additionally, we used a Delsys wireless surface electromyography (EMG) system to collect EMG signals at a frequency of 2000 Hz from the tibialis anterior, gastrocnemius, peroneus longus, vastus medialis, vastus lateralis, rectus femoris, and biceps femoris muscles. It is important to note that these EMG data are part of this study and also belong to a larger study encompassing additional outcomes and metrics. Detailed analysis of the EMG data will be reported in a subsequent study. A successful trial was defined as one in which the participant's dominant foot fully landed on the force plate without deliberate effort. For subsequent analysis, five successful trials were collected for each participant under each shoes condition (Fig.1.c).

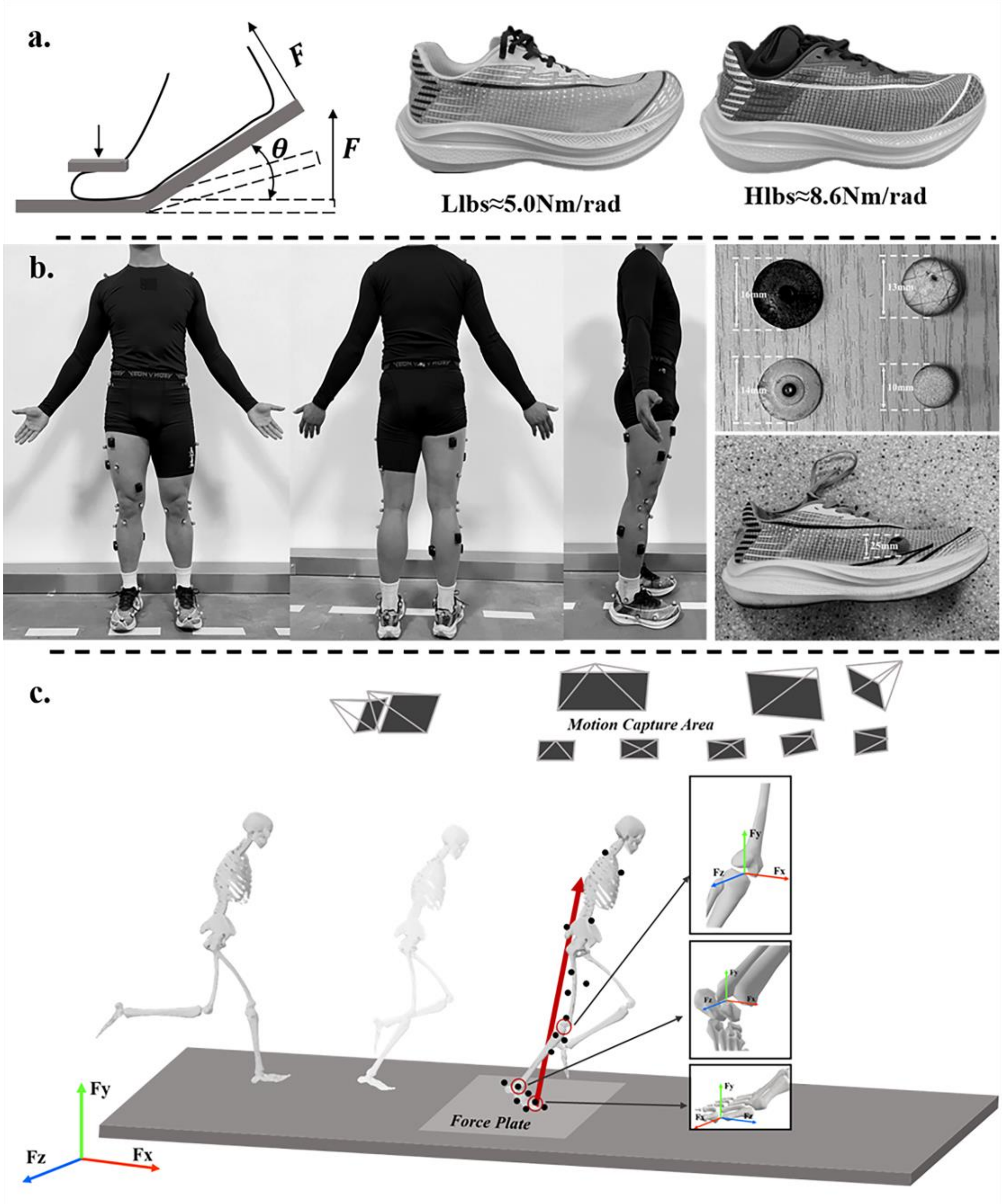

Fig 1. (a) Measurement of shoe stiffness and the specific stiffness of the experimental shoes. (b) Illustration of the placement of reflective markers, two different sizes of reflective markers and the holes for the markers on the shoes. (c) Illustration of the experimental procedure and the components of knee, ankle, and MTP joint reaction force.

2.4. Data analysis

To eliminate high-frequency noise, the collected 3D coordinate data of reflective markers and GRF data were subjected to a zero-lag fourth-order Butterworth low-pass filter, with cutoff frequencies set at 20 Hz and 50 Hz, respectively. The stance phase is defined as the period from when the right foot strike to when the toe-off. The instants of foot strike and toe-off are determined using a threshold of 20 N in vertical force. Running kinematics and kinetics, including joint angles and joint moments, were calculated using the general musculoskeletal multibody 2392 model in OpenSim (National Center for Simulation in Rehabilitation Research, Stanford, USA), which features 23 degrees of freedom and 92 muscle-tendon actuators, offering a detailed and accurate representation of the human musculoskeletal system, and has been extensively utilized in biomechanical analyses[7, 21, 33]. Following the steps are model scaling, individual body segment scaling factors were determined by comparing the distances between two markers on the segment, as measured during a static standing trial, with the distances between the same two markers on the generic model. These scaling factors were then applied to adjust segment lengths, inertial properties, and other relevant parameters. Joint angles were calculated using inverse kinematics, employing a weighted least-squares optimization that minimized the differences between the model and experimental marker positions. Joint moments for each degree of freedom in the model were determined using inverse dynamics tools. A residual reduction algorithm was applied to reduce dynamic inconsistencies in the model, thereby improving its accuracy. Considering previous studies have shown that the thickness of carbon plates significantly alters metatarsal stress [12], affecting foot stability and the efficiency of energy transfer during running, and that changes in dynamics and kinematics may also impact joint mechanical loads, we will further investigate the impact of stiffness on NR and ER by calculating peak joint reaction forces (JRF) between joints using OpenSim (Fig.1.c).

$$JRF = \sqrt{F_x^2 + F_y^2 + F_z^2}\ , \tag{1}$$

For each stance phase, peak joint angles, peak joint moment, and peak JRF were extracted. Joint power was obtained by multiplying joint moment by joint angular velocity. Joint work was then derived from the integral of the joint power curve over time. The selection of these peak values is predicated on their significance in biomechanical analysis, as they encapsulate the maximal mechanical demands imposed on the joints during running. These peak metrics are critical indicators of joint loading, providing valuable insights into potential injury mechanisms and biomechanical performance. To minimize the potential confounding effects of variations in bodyweight, enabling a more precise and unbiased comparison of biomechanical outcomes between the groups, peak joint moment was normalized by body mass (Nm/kg), while joint work and JRF were normalized to body weight (×BW).

2.5. Statistical analysis

For each participant, each computed parameter was calculated as the mean of the values obtained in the five considered trials. Statistical analysis was conducted using IBM SPSS Statistics version 25.0 (IBM, Armonk, NY, USA). The Shapiro–Wilk test was applied to check the normality of data distribution and Levene’s test for homogeneity of variances was used for homogeneity assessment. The tests confirmed that the data were normally distributed and satisfied the assumption of homogeneity of variances. Data were then analyzed using a two-way analysis of variance (ANOVA), with ER and NR as between-subject factors, and Hlbs shoes and Llbs shoes as within-subject factors. For the comparison between ER and NR, data from both shoe conditions were combined for each runner group, allowing us to examine the overall impact of running experience on biomechanical parameters while accounting for variations due to shoe conditions. Generalized eta-squared (η_p^2) was utilized to measure the effect size for the ANOVA (small: $\eta_p^2 > 0.02$; medium: $\eta_p^2 > 0.13$; and large: $\eta_p^2 > 0.26$)[2]. The significance level was set at $p \leqslant 0.05$. If significant interaction effects were found, post hoc comparisons were performed using the Bonferroni correction to identify the specific differences, with the significance level adjusted to $P \leqslant 0.0125$.

3. Results

3.1. Joint kinematics, peak joint angular velocity and peak joint moment

Significant group effects were observed in joint angles, with NR showing significantly smaller hip ($p<0.001, \eta_p^2 = 0.483$) and knee ($p<0.001, \eta_p^2 = 0.515$) extension-flexion and ankle ($p<0.001$, $\eta_p^2 = 0.485$) and MTP ($p=0.002$, $\eta_p^2 = 0.123$) joint dorsiflexion-plantarflexion compared to ER (Table 2). Significant shoe effects were also found at the MTP joint ($p<0.001, \eta_p^2=0.183$), where increased shoe stiffness led to decreased angles of dorsiflexion-plantarflexion at the joints (Fig.2).

Significant group effects were observed in the peak angular velocities of the knee joint, ankle joint, and MTP joint. The peak angular velocities of the knee joint, ankle joint, and MTP joint in NR were significantly greater than those in ER, with p-values less than 0.001 for all comparisons. The increased stiffness also significantly reduces the angular velocity of the MTP ($p=0.023, \eta_p^2=0.051$).

In terms of the peak moment of joints, significant inter-group effects were observed at the ankle and MTP joints, with NR having lower peak moment at the ankle compared to ER ($p<0.001, \eta_p^2=0.144$), but higher peak moment at the MTP joint ($p<0.001, \eta_p^2=0.294$). A significant shoe effect was also observed in the peak moment at the hip joint.

Table 2. Lower limb joints kinematics, joint angular velocity and peak joint moment of NR and ER with Hlbs and Llbs Shoes during running.

	ER (N=12)		NR (N=10)		Group effects		Shoe effects		Interaction	
	Hlbs	Llbs	Hlbs	Llbs	P	η_p^2	P	η_p^2	P	η_p^2
Hip Ext-Fle (degree)	36.97(2.92)	38.43(4.28)	44.44(3.52)	44.89(3.65)	**<.001**	.483	.121	.017	.411	.005
Knee Ext-Fle (degree)	17.09(1.53)	18.44(3.41)	26.63(5.80)	26.36(4.41)	**<.001**	.515	.459	.004	.263	.009
Ankle Dorsi-Planta (degree)	22.77(5.07)	23.97(4.87)	35.83(9.12)	37.26(7.52)	**<.001**	.485	.274	.009	.922	.000
MTP Dorsi-Planta (degree)	17.25(5.52)	19.09(4.87)	14.23(3.76)	17.43(3.59)	**.002**	.123	**<.001**	.183	.359	.005
Hip joint angular velocity(rad/s)	8.47(1.64)	8.27(0.61)	8.04(0.85)	8.12(0.67)	.103	.021	.755	.001	.423	.005
Knee joint angular velocity(rad/s)	5.32(0.59)	5.71(1.09)	8.62(2.70)	8.65(2.29)	**<.001**	.399	.537	.003	.595	.002
Ankle joint angular velocity(rad/s)	7.50(1.69)	7.97(2.19)	11.16(3.02)	12.05(2.71)	**<.001**	.382	.122	.018	.631	.002
MTP joint angular velocity(rad/s)	5.46(0.83)	5.83(1.57)	8.04(3.41)	8.31(3.92)	**<.001**	.201	**.023**	.051	.523	.001
Peak hip moment (Nm/kg)	2.70(0.51)	3.10(1.42)	2.69(0.50)	2.90(0.47)	.460	.004	**.036**	.034	.513	.003
Peak knee moment (Nm/kg)	2.38(0.32)	2.46(0.74)	2.34(0.62)	2.35(0.63)	.468	.004	.651	.002	.730	.001
Peak ankle moment (Nm/kg)	3.90(0.21)	3.96(0.22)	3.47(0.75)	3.51(0.70)	**<.001**	.144	.618	.002	.881	.000
Peak MTP moment (Nm/kg)	0.83(0.27)	0.93(0.29)	1.28(0.32)	1.24(0.31)	**<.001**	.294	.576	.003	.203	.013

Values are expressed as mean (SD). Bold values indicate statistical significance at the $p < 0.05$.

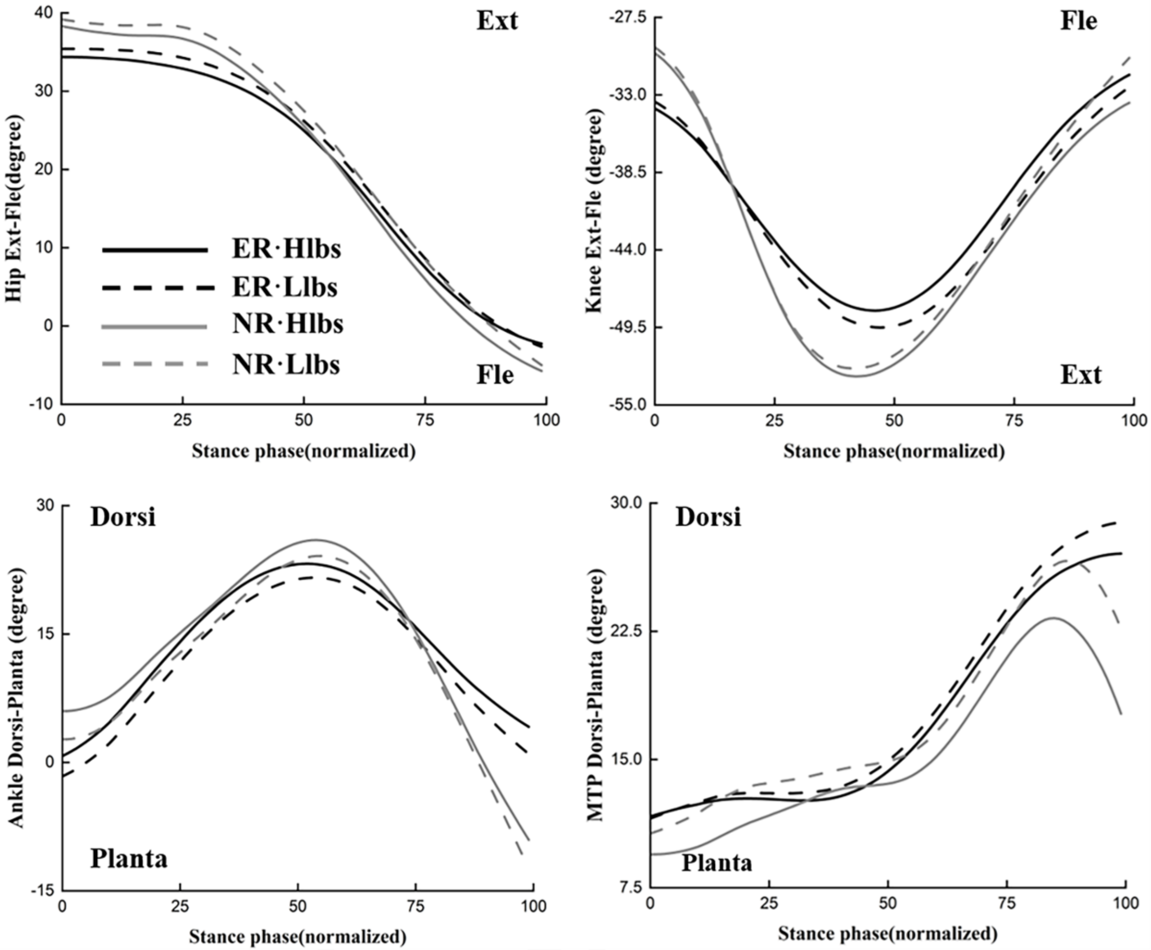

Fig 2. Mean lower limb joint angle time-normalized.

3.2. Joint work

The results indicated significant group effects in the work done by the hip, knee, and MTP joints between ER and NR (Table 3). Compared to NR, ER exhibited higher positive work at the hip joint (p=0.008, η_p^2=0.055) and significantly reduced negative work at the knee (p<0.001, η_p^2=0.246) joints, and this decrease occurs more often during the touchdown period (Fig.3). At the MTP joint, NR were observed to have more positive work. Significant shoe effects were also present at the ankle and MTP joints, where increased stiffness led to an increase in positive work (p=0.023, η_p^2=0.040) and a decrease in negative work (p=0.013, η_p^2=0.048) at the MTP joint.

Table 3. Lower limb joints work of NR and ER with Hlbs and Llbs Shoes during running.

		ER (N=12)		NR(N=10)		Group effects		Shoe effects		Interaction	
		Hlbs	Llbs	Hlbs	Llbs	P	η_p^2	P	η_p^2	P	η_p^2
Hip	positive work(J/kg^{-1})	1.00(0.15)	1.00(0.27)	0.85(0.35)	0.91(0.35)	**.008**	.055	.361	.007	.881	.000
	negative work(J/kg^{-1})	-0.12(0.03)	-0.18(0.04)	-0.045(0.05)	-0.044(0.04)	**<.001**	.123	.729	.000	.632	.000
Knee	positive work(J/kg^{-1})	0.24(0.06)	0.28(0.13)	0.24(0.11)	0.26(0.11)	.768	008	.211	.013	.549	.003
	negative work(J/kg^{-1})	-0.37(0.07)	-0.40(0.12)	-0.59(0.21)	-0.58(0.23)	**<.001**	.246	.673	.001	.576	.003
Ankle	positive work(J/kg^{-1})	0.93(0.21)	0.97(0.31)	0.78(0.32)	0.97(0.31)	.155	.016	**.003**	.037	.155	.016
	negative work(J/kg^{-1})	-0.87(0.25)	-0.90(0.29)	-0.93(0.28)	-0.90(0.29)	.510	.004	.900	.000	.510	.000
MTP	positive work(J/kg^{-1})	0.009(0.003)	0.005(0.009)	0.08(0.06)	0 .04(0.04)	**<.001**	.341	**.023**	.040	.088	.049
	negative work(J/kg^{-1})	-0.17(0.05)	-0.23(0.11)	-0.16(0.11)	-0.20(0.07)	.323	.008	**.013**	.048	.767	.001

Values are expressed as mean (SD). Bold values indicate statistical significance at the $p < 0.05$.

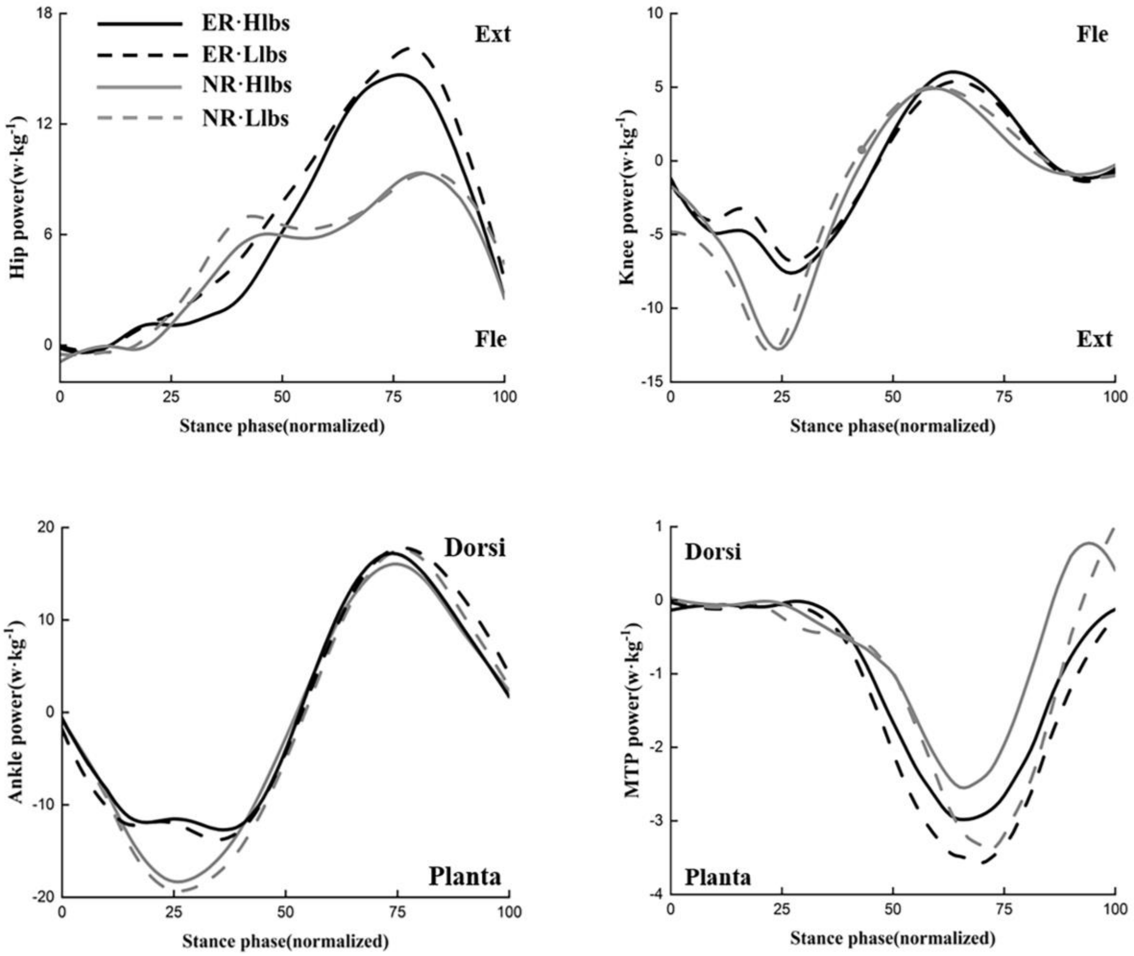

Fig 3. Mean lower limb joint power time- and weight-normalized.

3.3. Joint reaction force

Compared to NR, ER showed higher peak JRF at the knee ($p<0.001$, $\eta_p^2=0.409$) and ankle

($p<0.001$, $\eta_p^2=0.185$), while NR had higher peak JRF at the MTP joint ($p=0.001$, $\eta_p^2=0.206$) than ER (Table 4).

Table 4. Lower limb joints peak JRF of NR and ER with Hlbs and Llbs Shoes during running

	ER (N=12)		NR(N=10)		Group effects		Shoe effects		Interaction	
	Hlbs	Llbs	Hlbs	Llbs	P	η_p^2	P	η_p^2	P	η_p^2
Knee (BW)	16.19(1.35)	15.82(1.25)	13.95(0.91)	14.27(1.08)	**<.001**	.409	.901	.000	.119	.022
Ankle (BW)	17.84(1.91)	17.92(1.80)	15.39(1.71)	15.71(1.89)	**<.001**	.185	.558	.002	.736	.000
MTP(BW)	3.44(0.40)	3.63(0.42)	3.91(0.29)	3.77(0.74)	**.001**	.206	.082	.062	.781	.000

Values are expressed as mean (SD). Bold values indicate statistical significance at the $p < 0.05$.

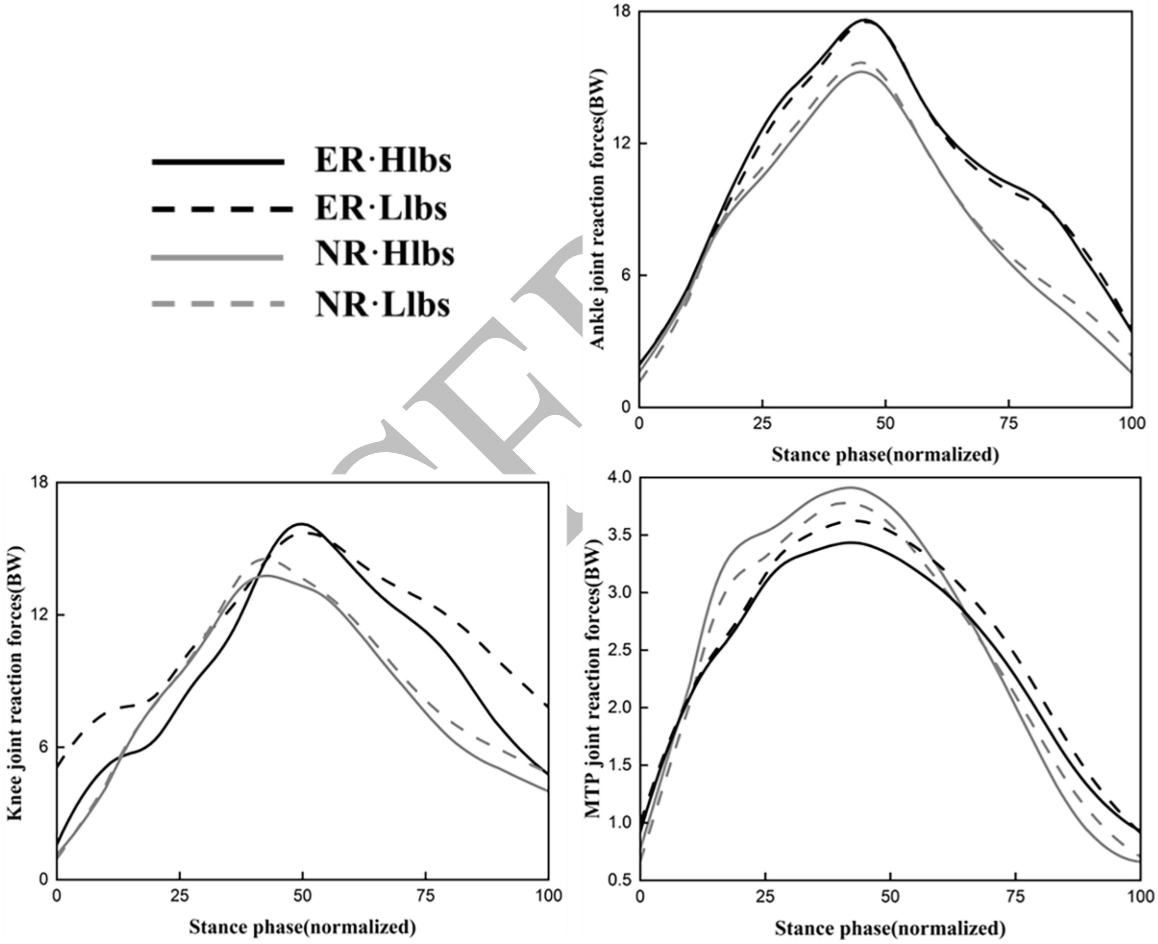

Fig 4. Mean lower limb joint reaction forces time- and weight-normalized.

4. Discussion

This study explored the biomechanical differences between ER and NR in terms of joint moment, angular velocities, and JRF. ER are characterized by lower joint activity and higher joint moment, while NR display larger joint angles and higher angular velocities. Additionally, the study observes how increased shoe stiffness impacts the MTP joint, noting increased joint moment in NR with stiffer shoes. These findings contribute to a deeper understanding of biomechanical behavior in response to changes in shoe stiffness among different runner groups.

Previous studies only discussed joint activity during running and overlooked the crucial factor of joint moment. According to Belli et al.[4, 13], the extensor muscles of the ankle and knee joints (such as the gastrocnemius, soleus, and quadriceps) may be the cause of "joint stiffness", and with increased proficiency, the hip extensors (gluteal and hamstring muscle groups) become the primary driving muscles, which could explain the higher positive work observed at the hip joint. Previous research has also confirmed that ER have more powerful lower limb muscles[13, 22]. The increase in joint moment and lower joint activity could represent an adaptive change to reduce energy consumption during running and improve energy transfer efficiency. The higher peak JRF at the hip, knee, and ankle also indirectly support this point. In contrast, the larger joint angles and angular velocities and smaller joint moment of NR may indicate weaker lower limb muscle strength, leading to poorer joint mechanical control, lower energy transfer efficiency, and higher angular velocities as a compensatory mechanism to offset the reduction in joint moment, thus maintaining joint work production.

No previous studies have found differences in the biomechanics of the MTP joint between NR and ER runners during running. However, with advances in shoe technology and the study of the chemical interaction between footwear and running, the MTP joint is increasingly being investigated[7, 19, 20]. This study's results contribute to filling this gap. In this study, NR and ER showed opposite kinematic and dynamic results at the MTP joint compared to the hip, knee, and ankle joints. NR exhibited lower MTP joint activity and higher joint moment. As the stiffness of the running shoes increased, the MTP joint moment in NR also showed an increase. Previous research has shown that curved carbon fiber plates reduce the dorsiflexion moment by shifting the point of GRF closer to the MTP joint while limiting dorsiflexion angular velocity[11, 27]. However, this was not found in NR, as they often lack the finely tuned neuromuscular control possessed by ER[26]. As Malisoux et al.[23]pointed out, the foot mechanics of NR are often uncoordinated. Combined with stiffer shoes, this might lead to excessive compensation at the toe joint, thereby increasing moment. This lack of refinement could lead to less efficient use of the carbon plates in their shoes. Rather than reducing the load on the MTP joint, the stiffness of the shoe might actually require NR to exert more effort in this area to achieve effective propulsion. This could be due to an over-reliance on forefoot mechanics to compensate for less efficient overall stride mechanics and lower limb coordination, which has been noted in other contexts as NR athletes work to improve their running technique.

Although most previous studies have shown that NR are more prone to injuries[16, 37], this study's results show that ER exhibit higher peak JRFs at the knee and ankle joints. This could be related to the smaller joint activity and higher moment during motion, as these often represent higher joint stiffness to prevent excessive bending during the contact phase, especially at the ankle joint. Previous research[12, 17, 18] has shown that a stronger triceps surae muscle-tendon unit enhances the work efficiency of the ankle joint because it maintains muscle contraction within an ideal range, allowing rapid muscle stretching. NR have lower force efficiency during running because they usually exhibit poorer posture and weaker muscle support around these joints (i.e., larger joint activity and smaller joint moment). From the perspective of joint work, more of the impact is absorbed by the hip joint in ER, while in NR, it is more concentrated on the knee joint, consistent with the findings of Agresta et al[1]. The results may explain why ER are more prone to stress fractures and joint wear, while NR are more likely to exhibit abnormal movement patterns due to improper loading patterns around the joints, thereby increasing the risk of injury. Changes in shoe stiffness did not affect inter-joint contact forces, but a different pattern was found at the MTP joint, characterized by an increase in peak JRF in NR as shoe stiffness increased, while a decrease was observed in ER. Since the muscles of NR are not well-developed, the increased JRF at the MTP might lead to metatarsal pain and increase the risk of stress fractures[6, 10, 25].

It must be acknowledged that this study has some limitations. Firstly, we only used two types of shoes with different stiffness levels, which do not fully represent the range of all existing running shoes. Secondly, we analyzed data from only the dominant limb of each participant, leaving the bilateral comparison unexamined. Future studies should include data from both limbs to verify if similar results are observed. Additionally, the chosen running speed may not reflect the natural running speeds of all participants, varying speeds might yield different or more pronounced results. Lastly, this study investigated only the acute effects of shoe stiffness and running experience on lower limb biomechanics. Further research with a broader variety of shoe types, more diverse participant populations, and extended monitoring periods to evaluate how shoe longitudinal bending stiffness affects injury risk in runners across diverse populations and extended periods[35, 36, 42].

Conclusions

NR exhibited greater reduced limb joint angles and smaller joint moment, while ER showed reduced joint angles but greater joint moment, with higher peak JRF at the knee and ankle joints. Furthermore, increased shoe stiffness led to higher peak JRF at the MTP joint for NR, while ER displayed the opposite trend, with increased shoe stiffness resulting in lower peak JRF at the MTP joint. This nuanced understanding of joint dynamics underscores the need for tailored training and footwear recommendations to mitigate injury risks specific to different levels of running experience.

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