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Article

A biomechanical study of lower limb distal joint asymmetry during running using bionic shoe

Jiachao Cai[1], Qian Liu[1], Hairong Chen[1,2,3], Yining Xu[1], Dong Sun[1], Ming Rong[1,*], Yaodong Gu[1]

[1] Faculty of Sports Science, Ningbo University, Ningbo 315211, China
[2] Doctoral School on Safety and Security Science, Óbuda University, 1034 Budapest, Hungary
[3] Faculty of Engineering, University of Szeged, 6724 Szeged, Hungary
*** Corresponding author:** Ming Rong, rongming@nbu.edu.cn

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Abstract: Lower limb asymmetry associated with running can reveal relevant information about sports injuries. Although the biomechanical study of bionic shoes (BS) has developed well, the understanding of how BS affects lower limb asymmetry during running is limited. The objective of this study was to compare the asymmetry between the dominant and non-dominant limbs of the participants under NS and BS conditions. The research involved the enrollment of 26 male individuals who were actively involved in running (age: 27.30 ± 3.70 years old, height: 1.72 ± 0.03 m, body mass: 66.70 ± 8.20 kg, body mass index: 22.40 ± 2.30 kg/m^2). Participants were required to run at a speed of 12 km/h wearing BS and neutral shoes (NS) respectively. Lower limb asymmetry during running was analyzed by investigating biomechanical parameters such as range of motion, peak angular velocity, peak moment, power, and work of the bilateral knee and ankle during the running stance phase. A two-way analysis of variance (ANOVA) was employed to determine the differences in joint biomechanics ($p < 0.05$) using a factorial design. Additionally, paired sample t-tests were conducted to determine the differences in symmetry angles (SA) for each of the analyzed biomechanical parameters. Compared to NS, BS optimized the asymmetry in knee ($p = 0.015$) and ankle ($p < 0.001$) angles between the dominant and non-dominant lower limbs during the push-off phase, and the BS optimized the asymmetry in knee extension work ($p = 0.049$) between the dominant and non-dominant lower limbs in the stance phase of running. However, it also resulted in increases in peak angular velocity ($p = 0.049$), power ($p = 0.018$), and work ($p = 0.035$) during dominant lower limb ankle dorsiflexion. Without considering the effects of the shoes, there would be differences in peak extension moment ($p = 0.05$) and flexion work ($p = 0.005$) of the bilateral knee during running, as well as differences in peak dorsiflexion angular velocities ($p = 0.001$) and plantarflexion work ($p = 0.039$) of the bilateral ankle. These differences can also affect the peak angular velocity in dorsiflexion and the work in plantarflexion. The findings suggest that BS improved asymmetry of the knee and ankle and demonstrated bilateral lower limb asymmetry during running. These findings provide insights into understanding sports injuries such as anterior cruciate ligament injuries of the knee and information relating to ankle sprains. The findings also offer beneficial information in the design of BS.

Keywords: bionic shoes; running injuries; asymmetry; knee; ankle; biomechanical

1. Introduction

Running, being a straightforward and easily accessible form of physical activity, has gradually gained popularity among populations worldwide. While running provides many advantages for physical health and mental well-being, it has been observed that annually, a range of 19% to 79% of runners encounter injuries associated with their running activities [1,2]. Therefore, understanding and preventing running-related injuries plays an important role in protecting the lower limbs and body from injury. Several factors that contribute to running-related injuries have been identified, such as overtraining, incorrect running form and gait, improper shoes and unsuitable running surfaces [3]. Furthermore, running-related injuries have also been influenced by lower limb asymmetry [4]. Because the influence of asymmetry on running-related injuries has been neglected, further research is necessary to understand the relationship between asymmetry and running-related injuries.

In the study of sports biomechanics, symmetry applications and exploration in the analysis of both kinematics and kinetics have been observed. Research has outlined that human movement patterns and functional characteristics were not completely symmetrical [5], and there was inevitably asymmetry between the bilateral legs [6]. Indeed, numerous studies frequently employed a solitary limb to symbolize the performance of both limbs [7], as it simplified the research process and data analysis. The characteristics of lower limb asymmetry can serve as effective indicators for predicting running-related injuries [8]. During running, the asymmetry of joint moments, range of motion (ROM), angular velocity, and work can potentially indicate certain running-related injuries. For instance, findings indicated a greater knee moment in the dominant leg when contrasted with the non-dominant leg, possibly constituting a risk factor for anterior cruciate ligament (ACL) re-injury in the knee [9]. When the load on both lower limbs is imbalanced, the imbalance could lead to injuries on the side bearing more load. This suggests that the dominant leg may have a higher risk of injury [10]. The study also revealed that gait asymmetry tended to emerge following ACL reconstruction surgery [11]. Furthermore, heightened postoperative knee dysfunction escalated the likelihood of subsequent knee symptoms and knee osteoarthritis due to atypical knee loading patterns, particularly during high-impact activities [12]. These findings provided valuable information contributing to a better understanding of the biomechanics of the knee during running. The findings also contributed to a greater understanding of the influence of knee asymmetry on ACL injuries. The findings also revealed that lower limb asymmetry in athletes may be a potential source of re-injury of ankle sprains [13]. Lower limb asymmetry increases with walking speed, and the asymmetry may be magnified during running, which to some extent may affect the running process and lead to a greater risk of injuries [14]. For example, an increase of approximately 10% in the asymmetry of the area of contact between the foot and the midsole of the shoe when running has been shown to increase a runner’s metabolic cost by approximately 7.8% [14]. This can lead to faster fatigue for the runner, and the risk of injury is further increased in a fatigued state. According to previous research, the use of the symmetry angle (SA) was commonly employed to reflect the asymmetry of the lower limb joint kinematic and kinetic parameters [15]. The research indicated that even well-trained runners exhibited a certain degree of lower limb asymmetry while running, and this asymmetry became more pronounced when runners engaged in shorter distances and higher-intensity running, as indicated by SA [16].

Numerous strategies exist for preventing running-related injuries by optimizing lower limb asymmetry. In recent years, the use of shoes to prevent sports injuries has become increasingly popular, with shoes playing a key role in establishing the vital link between the foot and the ground, facilitating seamless movement. Neutral shoes

(NS) provide protection and support for the foot, but this can lead to overprotection and restriction of the foot, which reduces lower limb muscle function and increases the risk of potential musculoskeletal injuries [17–19]. Bionic shoes (BS), on the other hand, may play a role in optimizing lower limb symmetry and preventing running-related injuries due to their more unique sole structure. With the increasing emphasis on sports and health, the criteria for choosing shoes have shifted from aesthetics to functionality [20]. Drawing inspiration from biological natural evolution, a bioinspired design was considered to have the potential to improve products [21]. The research showed that inspired by the excellent cushioning and shock-absorbing properties of ostrich feet, new types of shoes with bioinspired cushioning units in the outsole have been developed [22]. By mimicking the landing pattern of cats and the unique structure of cat paws, relevant landing tools have been developed [23]. The design inspiration for climbing shoes has been successfully modeled from the foot morphology of climbing animals [24]. In recent times, the popularity of utilizing shoes designed to emulate the natural structure of the foot to avert running injuries or enhance running performance has experienced notable growth. During running, the structural changes in the shoe midsole can cause lower limb instability, especially in the knee and ankle. Compared to NS, BS, due to the unstable structure of the shoe sole, enhances muscle activation during movement [25]. Bionic shoes promote muscle activity by engaging co-contraction between antagonistic and agonistic muscles in the human body [26], thereby maintaining body balance. This increased muscle activity may alter running patterns, resulting in fewer knee and ankle injuries during running, thus acting as a potential protective mechanism [27]. Although there is a wealth of research on BS, limited research has been conducted on the effect of BS on lower limb joint asymmetry.

Based on the above, this study aimed to compare the asymmetry between the dominant and non-dominant limbs of the participants under NS and BS conditions. The differences between lower limb asymmetry during running in BS and NS were explored by analyzing ROM, peak angular velocity, peak moment, power, and work of the knee and ankle during the running stance phase. It is hypothesized that (1) the knee and ankle joints will exhibit asymmetry whether running in BS or NS, and the asymmetry would differ between BS and NS, and (2) running in BS could serve to optimize knee and ankle asymmetry when compared to NS, especially of the knee and ankle angles.

2. Materials and methods

2.1. Participants

The required sample size of 26 participants for this study (effect size of 0.5, α error probability of 0.05, and power of 0.8) was calculated using G*Power 3.1 (Franz Faul, Germany) [28]. Therefore, 26 healthy male running enthusiasts (age: 27.30 ± 3.70 years old, height: 1.72 ± 0.03m, body mass: 66.70 ± 8.20kg, body mass index: 22.40 ± 2.30 kg/m^2) were recruited for this experiment, and the participants had a weekly running mileage of no less than 30 km [29]. All participants had no health problems and/or neuromuscular disorders and/or known gait disorders. The participants had no lower limb injuries within the past six months and had never exercised in a BS before participating in this experiment. The participants' dominant leg was the right leg (dominant leg refers to the preferred leg when kicking a soccer ball). All participants used a heel-to-toe running style, their shoe size was 41, and they were all recruited from Ningbo University. Prior to the experiment, all participants obtained and signed a written consent form approved by the Institutional Review Board. Ethical procedures for the study were approved by the ethics committee based at Ningbo University. Approval Nunmber: RAGH20230220.

2.2. Experimental shoes

In this experiment, two types of shoes were used: NS and BS. Participants were randomly allocated the BS or NS shoes. Following data collection, the remaining shoe was worn, and data collection was repeated, in the same order on the following day. All testing was completed at the same time of day to avoid potential data contamination from diurnal variation. The BS used were different from previous bioinspired approaches that focused on modifying the outsole of the shoe. Instead, the shoes used in this study had directly altered shoe lasts, thickening them by 1 to 8 millimeters at the forefoot of their lasts. Based on the structural characteristics of the human foot, the final BS prototypes were designed with a reduced forefoot thickness ranging from 1 to 8 millimeters (**Figure 1**).

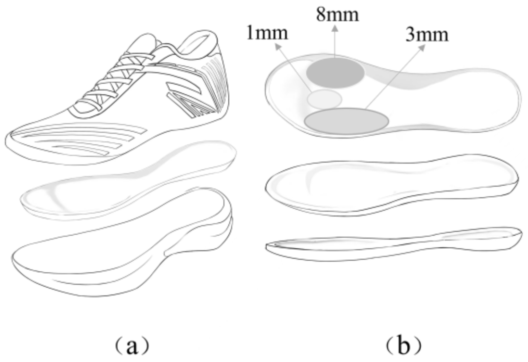

Figure 1. (a) Layered design diagram of the BS; **(b)** Location of the bioinspired design on the midsole.

2.3. The experimental process

The experiment was conducted at the Biomechanics Laboratory of Ningbo University. The participants' height and body mass were assessed using a measuring tape and calibrated weighing scale. An eight-camera infrared motion capture system (Vicon Metrics Ltd., Oxford, United Kingdom) was used to capture motion trajectories at a frequency of 1000Hz. A three-dimensional force plate (AMTI, Watertown, MA, USA) was used to collect kinetic data at a frequency of 200 Hz. Both systems were synchronized to collect data simultaneously. The infrared timing light (Brower Timing System, Draper, UT, USA) was used to control the running speed. Before the formal experiment, participants warmed up by running on a treadmill for 10 min at a self-selected speed. They were given 5 min to familiarize themselves with the experiment procedures and the environment. They wore uniform sports tights and leggings.

According to previous studies, 38 reflective markers (**Figure 2**) were placed on the trunk and lower limbs of the participants. After attaching the markers, participants were instructed to stand on the force plate with their feet parallel, assuming an anatomical position and looking straight ahead. Static data were collected during this standing posture. During the actual experimental procedure, participants were instructed to perform running tasks on a 10-meter track at a speed of 12 km/h. The track was equipped with a 3D force plate positioned in the middle. In order to accurately control the speed of each run, infrared timing lights are placed in the middle of the track at 3.3 metre intervals. An error range of 5% was allowed for the speed, meaning that the acceptable time range for each interval was between 0.95 seconds and 1.05 s [30]. During the experiment, participants were asked to run the track at a specified speed and to step on the force plate with their left and right feet separately during the run and complete 5 valid trials for each foot. A valid trial was defined as the foot landing with the heel on the force plate and lifting the toes off the ground and the foot must be within the range of the force plat when stepping on it. To guarantee data accuracy, participants were given specific instructions to maintain a normal running posture and avoid any deliberate modifications. There was a 30-second rest period between each trial to allow participants to adjust their state.

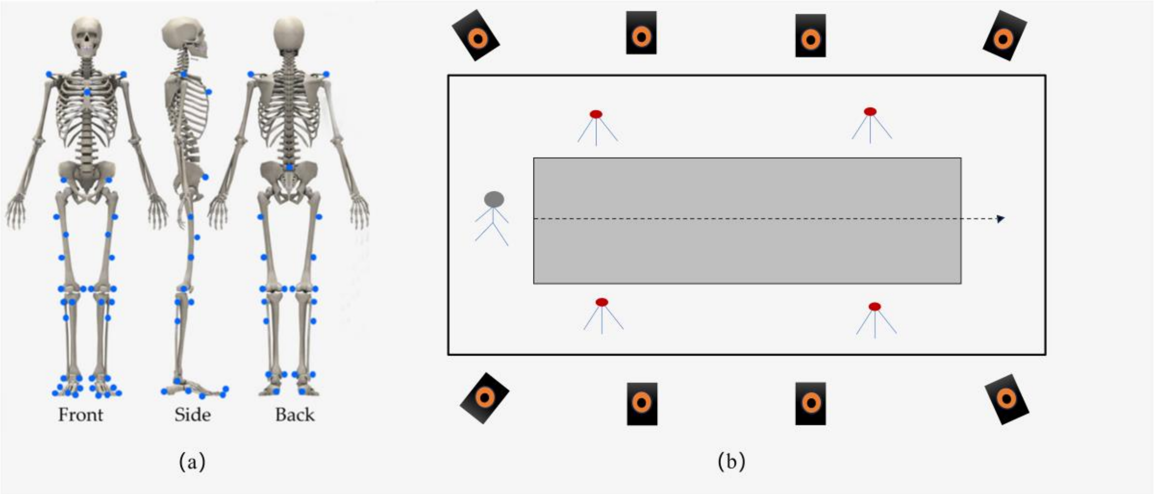

Figure 2. (a) shows the marked front, side, and back views with blue-colored markers; **(b)** represents the experimental flowchart for collecting kinematic and kinetic data during the running and standing phases.

2.4. Data analysis

The experimental study focused on the sagittal plane of the knee and ankle. Previous research has indicated that there is significant variation in the sagittal plane of the lower extremities when running [25,31]. The marker trajectories were filtered using a zero-lag fourth-order Butterworth low-pass filter at 12Hz. The C3D file data was converted to the format recognized by OpenSim 3.2016 (.mot and .trc) using Matlab R2018b and then imported into OpenSim for data processing [26,32]. During data processing, the musculoskeletal model (gait 2392) from OpenSim was used. The model was scaled in static calibration using the subject’s marker point positions and weights. The model was scaled in static calibration using the subject’s marker point positions and weights. The static weights for each marker were manually adjusted based on the root mean square (RMS) error value (less than 0.02) between the experimental and virtual markers in the model. The scaling model was applied to the data calculations after adjusting it to the appropriate position. The joint angles were calculated using the inverse kinematics (IK) computation tool in OpenSim, while the joint moments were calculated utilizing the inverse dynamics (ID) computation tool in OpenSim.

In the data analysis process, SA was used to assess the symmetry between the dominant and non-dominant limbs of the participants. The calculation method for SA was as follows:

$$\mathrm{SA} = \frac{\left(45^{\circ} - \arctan\left(\frac{X_{left}}{X_{right}}\right)\right)}{90^{\circ}} \times 100\%.$$

If

$$\left(45^{\circ} - \arctan\left(\frac{X_{left}}{X_{right}}\right)\right) > 90^{\circ}.$$

Then

$$\mathrm{SA} = \frac{(45^{\circ} - \arctan\left(\frac{X_{left}}{X_{right}}\right) - 180^{\circ})}{90^{\circ}} \times 100\%.$$

X_{left} represents the kinematic or dynamic variables of the left lower limb, while X_{right} represents the kinematic or dynamic variables of the right lower limb. A value of 0% indicates complete symmetry between the left and right lower limbs, while a value of 100% indicates complete asymmetry [33].

2.5. Statistical analysis

SPSS 26.0 (SPSS, Chicago, IL, USA) software was used for statistical analysis.

Descriptive statistics, including mean and standard deviation (SD), were provided. Tests for normality and homogeneity of variance were conducted on all SA data using Shapiro-Wilk and Levene's tests respectively before the analysis. A two-way analysis of variance (ANOVA) was conducted to analyze the joint angles and angular velocities, peak moment, power, and work of the knee and ankle during the running stance phase. This analysis aimed to examine the main effects of "shoe" and "leg" factors, as well as their interaction effects. In the presence of significant interaction effects, simple effect comparisons were conducted. Post-hoc analyses were performed using pairwise comparisons with Bonferroni correction to further examine the significant effects of the interaction between shoe and leg. The significance level for Main A and Main B was set at $p = 0.05/2 = 0.025$ after the Bonferroni adjustment. A paired sample t-test was used to assess the changes in lower limb joint SA when wearing different running shoes. The statistical analysis was performed using MATLAB version 2018b (MathWorks Inc.). The significance level was set at $\alpha = 0.05$, where $p < 0.05$ indicates a statistically significant difference.

Due to the one-dimensional time-varying nature of joint kinematics and dynamics [34], a one-dimensional statistical parametric mapping (SPM1D) approach was used to apply a paired-sample t-test. The method compared joint angles, angular velocities, moments, and power during the running stance phase. The significance level was set at $\alpha = 0.05$, where $p < 0.05$ indicates a statistically significant difference.

3. Results

3.1. Knee joint

From the data presented in **Table 1**, compared to the non-dominant leg, the dominant leg exhibited higher peak knee moment ($p = 0.005$), extension power ($p = 0.001$), and extension work ($p = 0.005$) during the running stance phase. Additionally, when wearing the BS, these three parameters were larger than the NS. There was no interaction effect between shoes and legs.

3.2. Ankle joint

Drawing from the data presented in **Table 1**, when participants wore different shoes during running, the peak dorsiflexion angular velocity of the ankle on the non-dominant leg was significantly greater than that of the dominant leg ($p = 0.049$). Additionally, it was found that the maximum dorsiflexion power and dorsiflexion work of the ankle on the dominant leg was significantly greater than those of the non-dominant leg ($p = 0.018$, $p = 0.035$). At the running stance phase, the peak angular velocity of ankle dorsiflexion on both sides was shown to be significantly greater in the non-dominant leg than in the dominant leg ($p = 0.001$). It was also evident that the maximum dorsiflexion power ($p = 0.009$), minimum plantarflexion power, and plantarflexion work of the ankle on the dominant leg were significantly larger than those of the non-dominant leg ($p = 0.029$, $p = 0.039$). There was no interaction effect between shoes and legs.

3.3. The effects of shoes on the SA of knee and ankle

3.3.1. Knee joint

According to the data presented in **Table 2**, a notable difference was observed in the SA of knee work among the participants when running with different shoes ($p = 0.049$). Compared to the NS, the knee extension work had a smaller SA in the BS, this indicating better symmetry between the dominant and non-dominant lower limbs when wearing BS. Although not revealing any significant differences in the SA of peak angular velocity and maximum power, the experimental results suggest that the SA of knee peak angular velocity and maximum power were smaller in the BS compared to the NS, indicating better symmetry in BS. This suggests a potential role in optimizing knee asymmetry in the dominant and non-dominant lower limbs.

According to the SPM results shown in **Figure 3**, during the running stance phases, there were significant differences in the knee angle SA of BS and NS within the 80%–100% phase ($p = 0.015$). The knee moment SA of BS and NS exhibited significant differences within the 0%–2% phase ($p = 0.043$) and the 23%–25% ($p = 0.045$). The knee power SA of BS and NS exhibited significant differences within the 0%–2% phase($p = 0.043$) and the 23%–27% phase($p = 0.018$). Compared to NS, BS had a smaller SA in all the above three parameters, indicating better symmetry in BS. These findings are worthy of further investigation and study.

3.3.2. Ankle joint

As indicated in **Table 2**, a noteworthy difference was observed in the SA of the bilateral ankle ROM was observed when running with different shoes. Although the significance level was not below 0.05, the ankle ROM had a smaller SA in the BS compared to the NS, indicating a potential role in optimizing asymmetry in ankle ROM between dominant and non-dominant lower limbs and suggesting a direction for further research. Additionally, it was found that when wearing BS, the SA of the ankle ROM and peak moment were also smaller, although their significance levels were below 0.05. This trend suggests a potential for improving asymmetry and warrants additional further investigation.

Referring to the SPM outcomes depicted in **Figure 3**, the ankle angle SA of the BS and NS showed significant differences in the 9%–14% phase(p = 0.001), 49%–60% phase($p < 0.001$) and 77%–100% phase($p < 0.001$) when the participants performed the experimental run. Compared to NS, BS had a smaller SA in ankle angle, indicating, better symmetry in BS.

Table 1. Descriptive Results of ROM, Angular Velocity, Moment, Power, and Work for BS and NS Conditions in the Knee and Ankle.

Joint	**Variables**	**NS**		**BS**		***p***		
		Left	**Right**	**Left**	**Right**	**S**	**L**	**S × L**
Knee	ROM (°)	31.81 ± 7.56	31.64 ± 5.93	31.31 ± 4.99	32.98 ± 5.54	0.720	0.522	0.430
	Peak Angular Velocity (rad/s)	−10.62 ± 1.74	−10.98 ± 1.80	−10.97 ± 1.77	−11.15 ± 1.29	0.424	0.400	0.771
	Peak Moment (Nm/kg)	1.67 ± 1.05	2.10 ± 0.42	1.73 ± 1.16	2.21 ± 0.27	0.582	**0.005**	0.882
	Maximum Power (w/kg)	5.43 ± 2.60	5.58 ± 2.33	6.06 ± 2.38	6.01 ± 2.23	0.254	0.907	0.830
	Minimum Power (w/kg)	−10.61 ± 4.18	−13.35 ± 3.82	−11.26 ± 4.83	−14.05 ± 3.00	0.384	**0.001**	0.974
	Positive Work (J/kg)	0.24 ± 0.13	0.26 ± 0.11	0.25 ± 0.12	0.28 ± 0.09	0.480	0.258	0.948
	Negative work (J/kg)	−0.36 ± 0.14	−0.43 ± 0.13	−0.39 ± 0.15	−0.48 ± 0.16	0.162	**0.005**	0.817
Ankle	ROM (°)	41.91 ± 6.79	41.13 ± 7.37	43.70 ± 4.37	43.72 ± 7.75	0.092	0.774	0.757
	Peak Angular Velocity (rad/s)	3.01 ± 11.36	−2.01 ± 12.60	9.17 ± 2.83	0.14 ± 13.17	**0.049**	**0.001**	0.340
	Peak Moment (Nm/kg)	−3.05 ± 0.40	−3.12 ± 0.54	−3.09 ± 0.41	−3.23 ± 0.39	0.380	0.195	0.668
	Maximum Power (w/kg)	15.04 ± 4.04	16.51 ± 3.98	16.31 ± 3.48	19.08 ± 4.92	**0.018**	**0.009**	0.412
	Minimum Power (w/kg)	−12.57 ± 3.39	−13.62 ± 3.02	−12.89 ± 2.95	−14.54 ± 3.25	0.306	**0.029**	0.619
	Positive Work (J/kg)	0.92 ± 0.20	0.96 ± 0.19	0.98 ± 0.18	1.05 ± 0.21	**0.035**	0.163	0.766
	Negative Work (J/kg)	−0.64 ± 0.20	−0.68 ± 0.14	−0.64 ± 0.15	−0.74 ± 0.18	0.358	**0.039**	0.343

Note: Statistical significance was set to $p < 0.05$. Bold indicates statistical significance. S=shoe, L=leg, S × L=Interaction of shoe and leg.

Table 2. Descriptive results of SA in ROM, angular velocity, moment, and power for BS and NS conditions in the knee and ankle.

Joint	Variables	NS	BS	*p*
Knee	ROM (100%)	4.50 ± 3.46	4.73 ± 3.30	0.809
	Peak Angular Velocity (100%)	5.88 ± 3.50	4.98 ± 4.38	0.345
	Peak Moment (100%)	13.96 ± 25.42	14.99 ± 25.83	0.175
	Maximum Power (100%)	9.72 ± 9.78	7.77 ± 8.41	0.247
	Minimum Power (100%)	13.28 ± 10.96	13.41 ± 11.64	0.927
	Positive Work (100%)	11.94 ± 10.35	8.45 ± 9.75	**0.049**
	Negative Work (100%)	11.43 ± 8.12	11.82 ± 9.65	0.781
Ankle	ROM (100%)	5.04 ± 3.65	3.95 ± 4.68	0.305
	Peak Angular Velocity (100%)	38.70 ± 44.66	52.99 ± 41.36	0.253
	Peak Moment (100%)	4.11 ± 1.84	3.00 ± 2.63	0.060
	Maximum Power (100%)	5.70 ± 4.07	6.89 ± 5.02	0.243
	Minimum Power (100%)	7.46 ± 4.31	6.77 ± 3.62	0.490
	Positive Work (100%)	4.37 ± 3.74	5.19 ± 4.39	0.402
	Negative Work (100%)	6.35 ± 3.58	7.12 ± 3.98	0.273

Note: Statistical significance was set to $p < 0.05$. Bold indicates statistical significance.

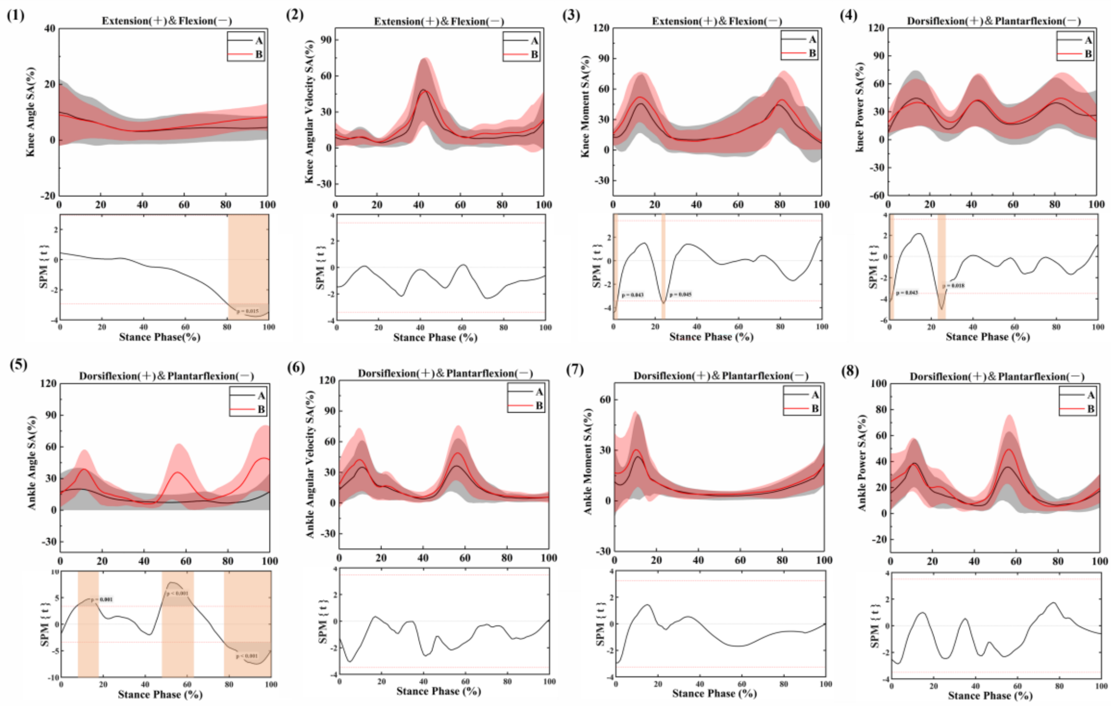

Figure 3. Descriptive results of Angle, Angular Velocity, Moment, and Power in the Knee and Ankle SPM between the Bionic Shoe and Neutral Shoe during Stance Phase. (1) Knee Angle SA; (2) Knee Angular Velocity SA; (3) Knee Moment SA; (4) Knee Power SA; (5) Ankle Angle SA; (6) Ankle Angular Velocity SA; (7) Ankle Moment SA; (8) Ankle Power SA. A = Bionic Shoe, B = Neutral Shoe.

4. Discussion

This study investigated how asymmetry between the dominant and non-dominant limbs changed when participants ran in NS and BS. The differences in bilateral knee were shown in peak moment, power, and work, while the differences in bilateral ankle were shown in peak angular velocity, power, and work. This provided further evidence to further corroborate the asymmetry present in the bilateral lower limbs [35,36]. SA was based on the study of the variation of these parameters. BS was found to decrease the SA of knee work, peak angular velocity, power, and the SA of ankle ROM, peak moment, and plantarflexion power. Among these parameters, BS exerted a pronounced effect on the work in knee extension. Additionally, in the analysis of the relevant parameters of BS and NS by SPM, significant differences in angle were found between the two shoes. The results showed that the knee angle of BS had a lower SA during the running stomp-off phase, indicating better symmetry of BS compared to NS. Whereas, the ankle angle of the BS exhibited lower SA throughout the stance phase, representing a better symmetry compared to the NS. It was also found that the kinematic and kinetic parameters of the knees and ankles were not perfectly aligned with the changes in SA, which precisely mirrored previous studies [35,36].

The kinetic parameters of the knee and ankle indicated that the peak extension moments of the bilateral knee with BS were significantly greater than those with NS. The research found that unstable shoes can lead to increased strength in the lower limb muscles [37], improved muscle control, and enhanced movement ability [38]. Therefore, compared to NS, wearing BS may influence neuromuscular control during running, exacerbating the difference in muscle strength between the two, and resulting in differences in peak extension moments of the bilateral knee. The power and work during ankle dorsiflexion also showed significant differences due to the different shoes. Compared to NS, BS exhibited significantly higher power and work in both ankles, with the dominant leg showing greater values than the non-dominant leg. Previous studies have shown that when running barefoot, there was greater energy absorption and work in the ankle compared to wearing NS [39]. The rationale behind the heightened ankle dorsiflexion power while running in BS could be attributed to the fact that the midsole of BS closely mimics the foot’s structure, thus emulating the mechanics of barefoot running. Compared to the additional cushioning and support that NS would provide, BS makes the ankle absorb more ground impact and reaction forces, resulting in more power and work. During the analysis of the research results, we unexpectedly observed a significant increase in peak angular velocity of the left ankle when wearing BS compared to NS. We supposed this notable difference may be attributed to the unique influence of the BS midsole structure on ankle movement. The distinctive midsole design could potentially lead to a more flexible and unrestricted ROM in the ankle, consequently resulting in a relative increase in peak angular velocity.

The effect of BS on knee SA was mainly reflected in the angle and extension work, with better symmetry of these two parameters and greater knee extension work while wearing BS. The bionic midsole design at the forefoot reduces arch collapse, providing enhanced support and promoting a more uniform force distribution across the knee. Simultaneously, this design could stimulate the muscles of the lower limb to a greater extent during the push-off phase, thereby amplifying neuromuscular control and strength [27]. This heightened perceptual experience aligned with the previously mentioned research findings, where improved muscular control corresponded to heightened muscle engagement and effort. This enhanced perceptual experience may optimize bilateral knee performance during the push-off phase, resulting in a more symmetrical knee angle between the dominant and non-dominant lower limbs. Additionally, studies indicated a strength disparity between the dominant and non-dominant legs, with the biceps femoris muscle activating earlier than the semitendinosus muscle during the stance phase [40,41], this difference may contribute to increased knee extension work. Compared with NS, wearing BS increased the work of the non-dominant leg, which improved the imbalance of bilateral lower limbs work to some extent and resulted in better SA of knee extension work.

The influence of BS on ankle SA primarily focused on three parameters: ROM, angle and peak moment. Compared to the NS, the ankle ROM was greater and the angle symmetry was better in the BS. The main significant difference in ankle angle remained in the push-off phase between the two shoes. One potential rationale for this phenomenon was that the instability in the forefoot of BS enabled runners to subtly extend the duration of dorsiflexion during the push-off phase. This resulted in an increased dorsiflexion angle and an expanded ROM in the ankle. To maintain stability, the neuromuscular system adjusted the ROM in the ankle to ensure relative safety and reduce the likelihood of ankle sprains to some extent. Previous studies suggested that the presence of unstable elements can augment muscular control and potentially lead to heightened sagittal plane mobility in the ankle at the stance phase [42]. The barefoot-like midsole design of BS forced the ankles and surrounding muscles to engage more actively in the push-off phase, which may affect the runner’s motor control and posture, resulting in better symmetry of the ankle angle, and it may also be a potential mechanism for driving better knee angle symmetry while wearing the BS. Additionally, the barefoot-like midsole design of BS received more impact from the ground compared to the NS, resulting in an increased peak moment of ankle dorsiflexion and better symmetry. Indeed, this mechanism could potentially contribute to optimizing the asymmetry of knee work to some extent. The BS midsole design implemented in this study can be used to enhance neuromuscular strength and improve the asymmetry of the lower limb knee and ankle [26,43], thereby preventing running-related injuries.

The current study had several limitations. This experiment was conducted in-depth primarily on running enthusiasts, and the next step would be to expand the participant’s population categorization to include, for example, professional elite runners. Second, the participants of this experiment were healthy males and the findings may not apply to females and injured runners. Third, due to our relatively small sample size, we may not have captured all individual variations, potentially contributing to the observed significant increase in peak angular velocity of the left ankle when wearing BS. Fourth, it is necessary to conduct further studies to verify the impact of BS on muscle activity. Fifth, due to the limitations associated with a single force plate, the experimental results are derived from a combination of two to three tests, and speed errors may have a certain impact on the outcomes. Therefore, our future research will be conducted with a larger sample size and a more comprehensive experimental design to address this limitation.

5. Conclusions

This study aimed to examine the effects on dominant and non-dominant limb asymmetry when running while wearing NS and BS conditions. Firstly, it was observed that the angles of the knee and ankle of the dominant and non-dominant lower limbs showed better symmetry during the push-off phase when wearing BS. The second major finding was that the BS increased the bilateral knee work and resulted in better symmetry than those observed using NS. In addition, the BS increased ROM at the ankle bilaterally and also showed a tendency to improve the asymmetry of the peak moments. This study has advanced and enhanced our understanding of how to reduce knee ACL injuries and ankle sprains. At the same time, the results of the study provide some valuable information for the design of running shoes, especially some theoretical support for the midsole design of BS.

Author contributions: Conceived the presented idea, developed the framework, and wrote the manuscript, JC, QL and HC,provided critical feedback and contributed to the final version, YX, DS, MR and YG. All authors were involved in the final direction of the paper and contributed to the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

Availability of data and materials: The data that support the findings of this study are available on reasonable request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Ethical approval: All participants obtained and signed a written consent form approved by the Institutional Review Board. The study was conducted in accordance with the Declaration of Helsinki, and was approved from the Ethics Committee of Ningbo University (Approval Number: RAGH20230220).

Conflict of interest: The authors declare no conflict of interest.

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