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A Comparative Analysis of Bionic and Neutral Shoes: Impact on Lower Limb Kinematics and Kinetics during Varied-Speed Running

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Abstract: The running biomechanics of running shoes have been extensively investigated. However, there is limited knowledge about the use of bionic shoes compared to neutral shoes, along with the velocities involved in their use. The aim of this study was to examine the biomechanical alterations associated with various running velocities of bionic shoes. By removing different thicknesses of the forefoot section, bionic shoes created a more natural shape—close to that of a human foot. The study included 16 heel strike runners running at 10 km/h, 12 km/h and 14 km/h in bionic shoes and neutral shoes, respectively. A two-way ANOVA and SPM1d were employed for examining kinematic and kinetic differences. Regarding the results for the shoes, increased ROM was observed for the bionic shoes for the hip ($p < 0.001$) and ankle joints ($p < 0.001$). Ankle positive work ($p < 0.001$) and negative work ($p = 0.042$) also showed significant differences. Regarding the velocity results, hip ROM ($p < 0.001$) increased and peak knee angular velocity ($p = 0.018$) increased, while knee ROM ($p = 0.023$) decreased. The interaction effects only existed in hip ($p = 0.031$) and ankle ($p = 0.008$) ROM. The results of this study suggested that the impact of running propulsion in the bionic shoes was minimal. However, with increased velocities, the bionic shoes demonstrated the ability to absorb more force, created a more stable training environment, and contributed to injury prevention for the hip and ankle joints.

Keywords: footwear; running velocity; bionic shoes; running biomechanics

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1. Introduction

Running has become a prevalent leisure sports activity among individuals pursuing a healthy lifestyle [1]. Putting aside its positive impacts on health, the negative side effects of running-related injuries should also be taken into account. The annual incidence rate for running injuries typically ranges from 37% to 56%. For long-distance runners, the literature reports injury rates ranging from 2.5 to 12.1 percent per 1000 h of running [2]. The majority of running injuries are lower extremity injuries, with a notable prevalence of knee-related injuries, followed by injuries related to the ankle and hip joints.

It has been claimed that lower limb biomechanics during running are linked to both running injury etiologies [3] and running performance [4]. The different characteristics of running shoes have been suggested as potential avenues for reducing the risk of running injuries, though the injury-preventive effects of various running shoes are not clear [5]. Running shoes, serving as the intermediary between the feet and the ground during a run, have the potential to substantially modify running biomechanics [6]. Bionic shoes refer to footwear that incorporates design elements inspired by biological systems or natural movement patterns [7]. These shoes frequently strive to improve comfort, performance, and overall biomechanical attributes [8]. Research specifically exploring the biomechanical connection between bionic shoes and conventional running footwear is limited. In one study, after a 5 km run in bionic shoes, the abduction angle of the hip was reduced significantly to a safe condition by the neuromuscular system, sensorimotor system, and proprioception to avoid injuries [9]. Using the same bionic shoes and under experimental conditions, the bionic shoes showed decreases in vertical instantaneous loading rate (VILR) before a 5 km run, which indicated a better cushioning effect or shock absorbance. After a 5 km run, the contact time of the bionic shoes was shorter, which showed the shoes' capacity to produce average vertical GRF. These findings provide evidence that bionic shoes can better prevent injuries [10,11]. However, these types of bionic shoe studies focused on modifying the soles of shoes to improve running gait, and limited attention has been given to researching bionic shoes with modified midsoles, particularly those involving changes in midsole thickness, for the study of lower extremity biomechanics. Additionally, in a previous study [12], there was little impact on foot strike pattern or stride duration when comparing with shoes with a different midsole thickness.

In addition to shoes, running velocities also influence lower limb biomechanics [13]. Overcoming the challenges encountered, Reginaldo K discovered that parameters of gait kinematics were affected by running velocity in an overall condition. For the sagittal plane, peak values of lower limb angles increased at higher running velocities, except for the peak ankle dorsiflexion angle. Parameters such as joint moments, joint work, and ground reaction forces (GRF) in gait kinetics were also affected by running velocities increasing from 2.5 m/s to 4.5 m/s (9 km/h to 16.2 km/h) [14]. SCHACHE investigated the running velocity increase from 3.50 m/s to 8.95 m/s (12.6 km/h to 32.2 km/h) and found that in the sagittal plane, the knee joint work was not influenced by the increased running velocity during the stance phase. In contrast, the ankle joint work increased from a velocity of 3.50 m/s to 5.02 m/s (12.6 km/h to 18 km/h) [15]. Jesper observed that the biggest velocity effects were found from velocities of 8 km/s to 12 km/h, and compared with the knee extension moment, the peak plantar flexion moment increased greater, which indicated that lower joints, such as the ankle joint, are burdened to a lager extent [16].

Taking into account the impact of running velocity and the choice of running shoes, William observed that the plantarflexion at touchdown underwent alterations based on both velocity and shoe type. Notably, traditional running shoes displayed a comparatively smaller plantarflexion angle. Knee angles similarly exhibited variations with velocities across all shoe conditions [17]. In a comparative study, Dustin contrasted the Nike ZoomX Vaporfly Next% 2 (VFN2) with a mass-matched control shoe, evaluating their performance at 10 km/h and 12 km/h. The study indicated that while the VFN2 improved running economy, this enhancement was less pronounced than at higher velocities of 13 km/h to 18 km/h [18]. However, there are few studies on lower limb biomechanics at different velocities and the effects of different running shoes, let alone bionic shoes.

Since studies related to running injuries and the running propulsions of bionic shoes are limited, especially for kinematics and dynamics, this study aimed to investigate the differences in lower limb biomechanics between male amateur runners wearing neutral shoes and bionic shoes at different velocities of 10 km/h, 12 km/h, and 14 km/h. The results may provide a reference for future studies and shoe designs related to running injuries and running propulsions. We set out to explore the following research questions: (1) Can using bionic shoes lead to improved running economy and injury prevention across varying velocities? (2) Does the ankle joint experience higher moments and power compared to the other two lower limb joints at different velocities? (3) Do bionic shoes have the potential to establish stable conditions and therefore safeguard joints against potential damage?

2. Material and Methods

2.1. Participants

A total of 16 male amateur heel strike runners (mean $\pm$ SD: age: 27 $\pm$ 3.7 years, height: 1.72 $\pm$ 0.03 m, body mass: 66.7 $\pm$ 8.2 kg, body mass index (BMI): 22.4 $\pm$ 2.3 kg/m^2, foot length: 255 ± 10 mm) were recruited for this study. The standard recruitment criteria for this experiment included running for at least 20 km per week [9,19]. Additionally, all participants were right leg-dominant, as determined according to their preferred leg for ball kicking. Individuals with abnormal body posture were excluded, and those with abnormally shaped or tall feet were excluded from participation. Furthermore, all participants were free from running injuries, neuromuscular disorders, and lower limb defects in the previous six months. They had all been informed of the experimental protocol and signed a consent form, and ethical approval for this study was granted by the Ethical Institutional Review Board of Ningbo University, Ningbo University [20].

2.2. Shoes

Two types of shoes were included in the test: neutral shoes and bionic shoes. The bionic shoes were designed based on the natural shape of the human foot. Taking normal shoes as a model, the only change to the normal shoes for the bionic shoes was that the midsole part was thinner, as shown by the colored part in Figure 1.

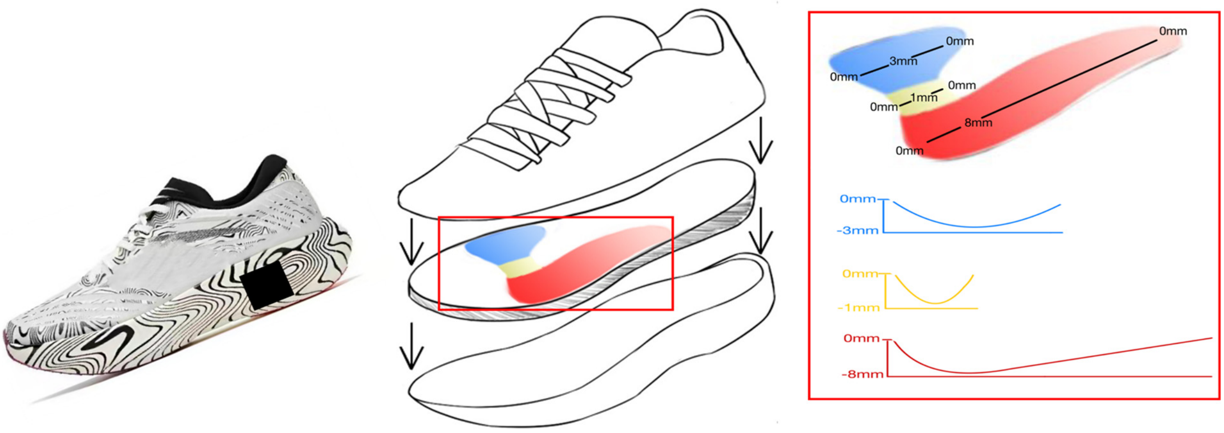

Figure 1. Shoe pictures and illustration of bionic midsole construction: bionic shoes.

By studying the anatomical structure of feet, a portion of the bionic shoes' midfoot was removed to better simulate human movement characteristics during running. Some other bionic shoes were customized based on individual's foot characteristics, which provided inspiration for our bionic shoes [21]. The thicknesses of the removed parts were 3 mm, 1 mm, and 8 mm for blue, yellow, and red separately. From the perspective of the vertical direction, looking from the heel to the toe, the middle part was the deepest for both the yellow and blue sections, with the depth decreasing towards the sides. During running, the metatarsophalangeal joints make deeper contact with the ground compared to other parts of the foot.

2.3. Experimental Procedure

The biomechanics laboratory of Ningbo University was used to conduct all of the testing. All participants were requested to wear tights and skinny pants, making sure that all 34 reflective markers (gait 2392 model in opensim [22]), as shown in Figure 2b, stayed in the same position throughout the testing procedure.

Before the formal test, static coordinates were acquired by standing on the *Y*-axis of a force platform with arms lifted to the side and eyes looking forward until all static coordinates were captured. Participants had 10 min to warm up and familiarize themselves with the shoes before the experiment begun. During the warm up session, participants were asked to accomplish the following: (a) jogging on a treadmill at a pace of 8 km/h for 10 min and (b) performing a series of lower limb stretching exercises, including hamstring stretches, calf stretches, and quadriceps stretches [21]. Running exercises were completed by participants running at different velocities controlled by Brower timing lights (Brower

Timing System, Draper, UT, USA) at 10 km/h, 12 km/h, and 14 km/h. Recreational heel strike runners choose speeds ranging from 10 km/h to 12 km/h as a "natural running pace" [9]. These velocities were chosen in a previous study to investigate the relation between running economy (RE) at endurance running speeds. The global running pattern was quantified to better understand this relation [23]. Based on existing studies in the literature, these velocities may help us understand the relationship between running injuries and bionic shoes more clearly. Participants were asked to step their right leg on to the 2 m Y-axis force platform in the middle of the track over a 10 m designed track, as shown in Figure 2a,c. The full gait cycle was defined as the moment from when the right heel touched the ground to the moment when the right toe was off the ground. Each velocity was tested on 5 times, with the error range for the running velocities being within 5% of the predefined running velocity. Participants completed the 5 trials for each velocity successfully. Participants would have a 5-min rest period, during which they changed into another pair of shoes and drank water to prepare for the next procedure.

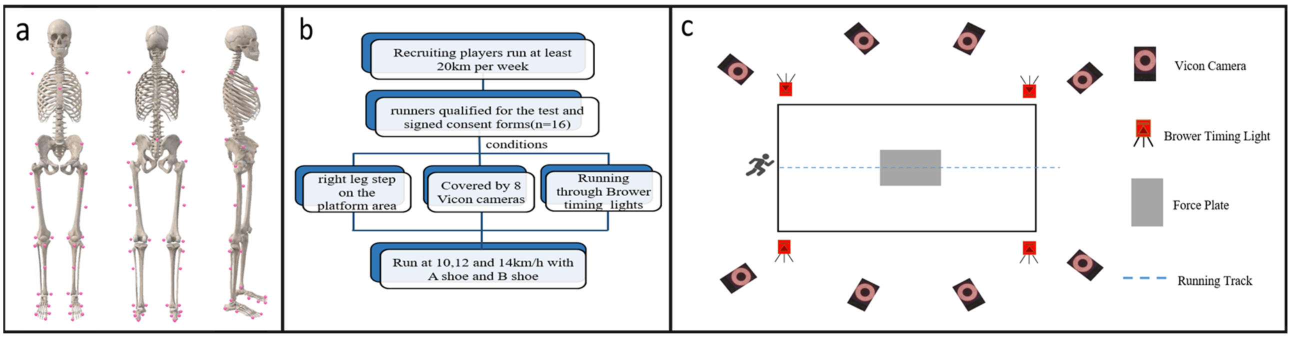

Figure 2. (**a**) The front, back, and side positions of markers. Pink dots: markers. (**b**) Experimental flow. (**c**) Illustration of experimental design for collecting the kinematic data during the running stance phase.

The kinematic and kinetic data were collected at a frequency of 200 Hz using a Vicon motion capture system (Oxford Metrics, Ltd., Oxford, UK) and 1000 Hz using a force plat form (Kistler, Winterthur, Switzerland) [24]. Brower timing lights (Brower Timing System, Draper, UT, USA) were used to control the running velocities in the experiment.

2.4. Data Collection and Processing

C3D files were produced by using Vicon Nexus software (version 1.8.5A, Vicon Metrics Ltd., Oxford, UK), which detected the kinematics and kinetics. As for the gaps of markers' trajectories, the raw motion data were visually checked and manually filled (using 'pattern fill' according to the shape of another trajectory without a gap to fill the selected gap) to avoid intermittent trajectories. A kind of pipeline of Nexus was set to export raw C3D files. The kinematic and kinetic data were filtered by using a fourth-order zero-phase low-pass Butterworth filter with a cut-off frequency of 10 Hz and 20 Hz respectively for the denoising process of the marker trajectories [25].

During this study, biomechanical parameters were processed and calculated using Opensim 4.3 (Stanford University, Stanford, CA, USA). For gathering data on joint kinematics and kinetics, the modeling procedure was performed as follows: (1) Using OpenSim simulation software 4.3 (Stanford University, Stanford, CA, USA), the kinematic and kinetic data were collected and translated to the trc. (marker trajectory) and mot. (forceplate data) formats, which can be recognized by MATLAB. (2) Opensim 4.3 was used to import the personal static model. Then, we obtained the anthropometric model of each participant. (3) The inverse kinematics (IK) and inverse dynamics (ID) tool was used to calculate kinematic and kinetic data. The standard inverse dynamic method was operated to calculate the internal joint angles, joint moments, and joint power. The kinetic data were normalized for everyone's body mass. Joint kinematic and kinetic data were time-normalized to 101 data points per stand phase using MATLAB version R2016a (The Math Works, Natick, MA, USA) [26].

2.5. Statistical Analysis

Descriptive statistics are presented as means and standard deviations (Mean ± SD).

A two-factor analysis of variance (two-way ANOVA) was used (shoe × velocity) to test for group differences in terms of the shoes (bionic shoes vs. neutral shoes) and to evaluate if there were any group differences in terms of the velocities tested (10 km/h vs. 12 km/h vs. 14 km/h). Firstly, based on the ANOVA assumptions examination (normality and homogeneity of residuals), a two-way ANOVA was used to evaluate the main effects of 'shoe' and 'velocity' factors and the interaction of the two factors. The interaction effect was significant ($p < 0.05$), and simple effect comparisons were calculated. Post-verification comparisons with a Bonferroni correction were carried out post hoc to further analyze the significant effects of the running velocities, the shoes, and their interaction. Statistical calculations were carried out using SPSS version 26.0 software (SPSS, Chicago, IL, USA).

The kinematic and kinetic data during the running stance phase were compared using SPM1D (Statistical Parametric Mapping 1D), a method for analyzing data from one-dimensional (1D) spatial domains [27]. For SPM1D, descriptive data for each moment were time-normalized to the stance phase (101 data points per stance phase). All SPM1d analyses were conducted in MATLAB 2016a using the new version, spm1d 8 [28]. (www.spm1d.org, accessed on 2 May 2022).

3. Results

3.1. Shoe Effects

Regarding the results for the shoes, significant differences were found at the hip and ankle joints, as shown in Table 1. In both V1 (10 km/h) and V2 (12 km/h), the angle range of motion (ROM)of the bionic shoes showed significant differences in hip extension (F = 9.476, $p < 0.001$) and ankle dorsiflexion (F = 33.570; $p < 0.001$) compared with the neutral shoes. The positive work (F = 15.079; $p < 0.001$) and negative work (F = 4.342; $p = 0.042$) of the ankle while wearing the bionic shoes at V1 velocity also showed bigger values compared with the neutral shoes. At V2 velocity, the positive work of the ankle (F = 15.079; $p < 0.001$) also showed significant differences with the bionic shoes compared with the neutral shoes.

3.2. Velocity Effects

Regarding the velocities, significant differences were also found at both hip, knee, and ankle joints, as shown in Table 1. The specific statistical differences are as follows: (1) The ROM of hip extension and knee flexion showed significant differences due to running velocity ($p < 0.05$). (2) The peak moment, maximum power, and positive work of the hip and ankle were significantly different due to running velocity ($p < 0.05$). (3) The peak angular velocity of the knee and negative power of the ankle were significantly increased due to running velocity ($p < 0.05$). As running velocity increased, hip ROM showed a significant increase and knee ROM showed a significant decrease, while the results for ankle ROM showed differed between the bionic shoes and neutral shoes. The peak moment, maximum power, and positive work of hip and ankle showed great increases, as did the peak angular velocity of the knee and negative power of the ankle. When the participants ran at V3 compared to V1 and V2, significant differences were observed in terms of the positive work of the hip and ankle, as well as for the maximum power of the hip. Compared to V1, when the participants ran at V3, the peak moment and maximum power of the hip, as well as the positive work of the ankle, showed significant differences, regardless of shoe conditions.

Table 1. Mean (SD)of ROM, peak angular velocity, maximum power, positive work, and negative work of the stance phase for the three velocity conditions of the different shoes.

Joint	Variables	Shoes	V			*p*		
			V1	V2	V3	S	V	S × V
Hip	ROM (°)	A	**38.88 ± 3.50**	**43.19 ± 5.33**	43.97 ± 4.39	F = 9.476	F = 27.946	F = 6.539
		B	**29.22 ± 6.24** [ac]	**35.94 ± 5.70** [ab]	43.30 ± 6.60 [bc]	***p* < 0.001** *	***p* < 0.001** *	***p* = 0.031** *
	Peak angular velocity (rad s^{-1})	A	2.28 ± 1.29	2.04 ± 1.19	**1.03 ± 1.34**	F = 2.615	F = 1.626	F = 1.047
		B	2.57 ± 1.33	2.17 ± 1.48	**2.29 ± 1.43**	***p* = 0.05** *	*p* = 0.206	*p* = 0.358
	Peak moment (N m kg^{-1})	A	−3.18 ± 0.59 [c]	−3.53 ± 0.60	−3.96 ± 0.62 [c]	F = 0.305	F = 7.076	F = 0.003
		B	−3.28 ± 0.47 [c]	−3.62 ± 0.51	−4.04 ± 0.98 [c]	*p* = 0.583	***p* = 0.002** *	*p* = 0.997
	Maximum power (W)	A	9.43 ± 2.52 [c]	11.03 ± 2.43 [b]	13.68 ± 2.34 [bc]	F = 0.923	F = 18.594	F = 0.024
		B	9.93 ± 2.13 [c]	11.48 ± 2.19 [b]	14.43 ± 2.15 [bc]	*p* = 0.341	***p* < 0.001** *	*p* = 0.977
	Positive Work (J kg^{-1})	A	0.66 ± 0.18 [c]	0.82 ± 0.21 [b]	1.15 ± 0.22 [bc]	F = 0.172	F = 21.872	F = 0.402
		B	0.72 ± 0.17 [c]	0.88 ± 0.17	1.10 ± 0.29 [c]	*p* = 0.680	***p* < 0.001** *	*p* = 0.671
	Negative Work (J kg^{-1})	A	−0.13 ± 0.09	−0.12 ± 0.08	−0.08 ± 0.08	F = 0.761	F = 0.597	F = 0.216
		B	−0.14 ± 0.10	−0.13 ± 0.10	−0.12 ± 0.11	*p* = 0.472	*p* = 0.443	*p* = 0.806
Knee	ROM (°)	A	34.01 ± 4.07	33.65 ± 4.94	28.58 ± 6.05	F = 0.025	F = 4.057	F = 0.680
		B	34.08 ± 4.28	32.07 ± 5.37	30.72 ± 5.34	*p* = 0.874	***p* = 0.023** *	*p* = 0.511
	Peak angular velocity (rad s^{-1})	A	4.22 ± 0.73	4.87 ± 1.01	5.12 ± 1.03	F = 3.101	F = 4.330	F = 0.139
		B	3.73 ± 0.80	4.20 ± 1.28	4.81 ± 1.41	*p* = 0.084	***p* = 0.018** *	*p* = 0.871
	Peak moment (N m kg^{-1})	A	2.11 ± 0.40	2.22 ± 0.24	2.18 ± 0.30	F = 0.028	F = 0.340	F = 0.054
		B	2.14 ± 0.46	2.19 ± 0.39	2.22 ± 0.33	*p* = 0.868	*p* = 0.713	*p* = 0.947
	Maximum power (W)	A	11.89 ± 3.54	14.17 ± 2.84	13.95 ± 4.28	F = 0.186	F = 1.231	F = 0.306
		B	13.07 ± 4.06	13.53 ± 3.51	14.71 ± 4.70	*p* = 0.668	*p* = 0.300	*p* = 0.738
	Positive Work (J kg^{-1})	A	0.44 ± 0.11	0.49 ± 0.12	0.45 ± 0.15	F = 0.102	F = 0.220	F = 0.528
		B	0.44 ± 0.14	0.44 ± 0.11	0.47 ± 0.13	*p* = 0.751	*p* = 0.804	*p* = 0.593
	Negative Work (J kg^{-1})	A	−0.25 ± 0.07	−0.28 ± 0.07	−0.26 ± 0.06	F = 1.123	F = 1.074	F = 0.183
		B	−0.22 ± 0.07	−0.25 ± 0.09	−0.25 ± 0.07	*p* = 0.294	*p* = 0.349	*p* = 0.834
Ankle	ROM (°)	A	**37.93 ± 4.45**	**40.28 ± 5.23**	35.23 ± 5.93	F = 33.570	F = 0.479	F = 5.294
		B	**27.01 ± 6.11**	**26.94 ± 6.93**	33.28 ± 6.06	***p* < 0.001** *	*p* = 0.622	***p* = 0.008** *
	Peak angular velocity (rad s^{-1})	A	9.15 ± 3.25	9.80 ± 3.88	10.14 ± 4.06	F = 0.064	F = 0.608	F = 0.170
		B	9.56 ± 3.36	9.29 ± 3.16	10.96 ± 4.24	*p* = 0.802	*p* = 0.548	*p* = 0.844
	Peak moment (N m kg^{-1})	A	−2.82 ± 0.38	−3.09 ± 0.40	−3.27 ± 0.36	F = 2.829	F = 3.975	F = 0.046
		B	−2.68 ± 0.49	−2.88 ± 0.52	−3.04 ± 0.54	*p* = 0.098	***p* = 0.025** *	*p* = 0.955
	Maximum power (W)	A	14.40 ± 2.64 [c]	17.89 ± 4.16	19.21 ± 4.31 [c]	F = 0.723	F = 10.938	F = 0.836
		B	12.85 ± 3.11 [c]	15.72 ± 3.37	20.22 ± 6.16 [c]	*p* = 0.399	***p* < 0.001** *	*p* = 0.439
	Positive Work (J kg^{-1})	A	**0.84 ± 0.13**	**1.00 ± 0.17**	1.01 ± 0.19	F = 15.079	F = 10.565	F = 2.824
		B	**0.61 ± 0.18** [c]	**0.71 ± 0.14** [b]	0.98 ± 0.26 [bc]	***p* < 0.001** *	***p* < 0.001** *	*p* = 0.068
	Negative Work (J kg^{-1})	A	**−0.59 ± 0.13**	−0.70 ± 0.16	−0.73 ± 0.19	F = 4.342	F = 8.373	F = 0.868
		B	**−0.46 ± 0.12** [c]	−0.61 ± 0.15	−0.71 ± 0.15 [c]	***p* = 0.042** *	***p* = 0.001** *	*p* = 0.426

Note: * in the table indicate statistical significance, $p < 0.05$. A means bionic shoes and B means neutral shoes. "[a]" represents significant differences between V1 and V2, "[b]" represents significant differences between V2 and V3, "[c]" represents significant differences between V1 and V3. Bold parts represent significant differences. V1 represents 10 km/h, V2 represents 12 km/h, and V3 represents 14 km/h. S means main effect of shoes, V means main effect of velocities, and S × V means interaction effect.

3.3. SPM1D Effects

Regarding the results of SPM1D, as shown in the blue rectangle parts in Figures 3 and 4, significant differences were also found for both hip, knee, and ankle joints. Regarding the hip joint, when using the bionic shoes, the extension angle decreased by 57–100% (p = 0.035), and extension angle velocity decreased by 28–70% (p < 0.001). The flexion moment increased by 22–28% (p = 0.008) and 51–100% (p < 0.001) respectively, while the extension moment decreased by 0–22% (p = 0.018) and 28–43% (p = 0.002) respectively. Flexion power was increased by 20–46% (p < 0.001), and extension power was decreased by 69–100% (p < 0.001). At the knee joint, when using the bionic shoes, the flexion angle was observed to increase by 10–38% (p = 0.010), while the extension angle increased by 57–100% (p = 0.001). The extension angle velocity increased by 20–78% (p < 0.001), and a 98–100% decrease in flexion angle velocity was observed (p = 0.047). The extension knee moment increased by 19–35% (p < 0.001), and the flexion knee moment decreased by 50–100% (p < 0.001); decreased flexion power was observed at 22–26% (p = 0.015) and 71–100% (p < 0.001), and extension power increased by 30–66% (p < 0.001). At the ankle joint, when wearing the bionic shoes, the dorsiflexion angle increased by 37–50% (p = 0.035), and the plantarflexion angle decreased by 65–100% (p = 0.003). The dorsiflexion angle velocity was observed to increase over the stance phase by 30–40% (p < 0.001), and a decrease in plantarflexion angle velocity of 18–25% (p = 0.003) and 42–97% (p < 0.001) were found; the ankle moment decreased by 23–60% (p < 0.001) and increased by 68–90% (p < 0.001). Decreased plantarflexion was detected while wearing the bionic shoes at 28–42% (p < 0.001) and 88–100% (p < 0.001), while dorsiflexion increased by 46–83% (p < 0.001).

3.4. Interaction Effects

As shown in Table 1, the interaction between the shoe conditions and the velocities induced a significant effect on the angle ROM of hip extension (F = 6.539, p = 0.031) and ankle dorsiflexion (F = 5.294, p = 0.008). At both V1 (10 km/h) and V2 (12 km/h), the angle range of motion (ROM)of the bionic shoes showed a significant increase in the hip and ankle joints.

3.5. Pairwise Comparison Effects

For the results of the pairwise comparisons in the post-examination, significant differences were also found at the hip, knee, and ankle joints, as shown in Figures 3 and 4. When considering the neutral shoes' impact on the hip joint, significant differences in extension angle during the final stance phase were observed at 83–100% (p = 0.006) in V1, 70–100% (p = 0.002) in V2, and 78–100% (p = 0.004) in V3. However, no significant differences were noted with the bionic shoes. Hip angle velocity showed significant differences in the neutral shoes at V1, V2, and V3, while significant differences for the bionic shoes were only observed at V3 compared to V1 and V2. The hip moment also exhibited significant differences, along with smaller values, during the final stance phase around 60–100% (p < 0.001) when comparing the bionic shoes to the neutral shoes at V1 and V2. Hip power showed significant differences in both the neutral shoes and bionic shoes at V1, V2, and V3. In terms of the knee joint, significant joint angle differences were displayed during the initial stance phase both in the neutral shoes and bionic shoes at V1, V2, and V3. Knee angle extension showed significant increases in the bionic shoes compared with the neutral shoes in the final stance phase around 65–100% (p < 0.001). The knee angle extension velocities were significantly different, showing faster velocities in the neutral shoes compared to the bionic shoes at 20–75% (p < 0.001) in V1 and 25–75% (p < 0.001) in V2. Both knee moment and knee power displayed noteworthy disparities in the context of shoe results around the 40% (p < 0.001) stance phase. Notably, the bionic shoes exhibited larger values compared to the neutral shoes. In terms of the ankle joint, ankle angle velocity showed significant differences in the final stance phase around 80–100% (p < 0.001) at all velocities except for V2 versus V3 in the bionic shoes. Significant distinctions were observed in both ankle moment and ankle power across all velocities. Notably, the data from the bionic shoes revealed a greater number of differences, particularly during the middle and final stance phases around 50–80% ($p < 0.001$). In the final stance phase around 60–100% ($p < 0.001$), ankle moment and ankle power showed a larger value in the bionic shoes compared with the neutral shoes.

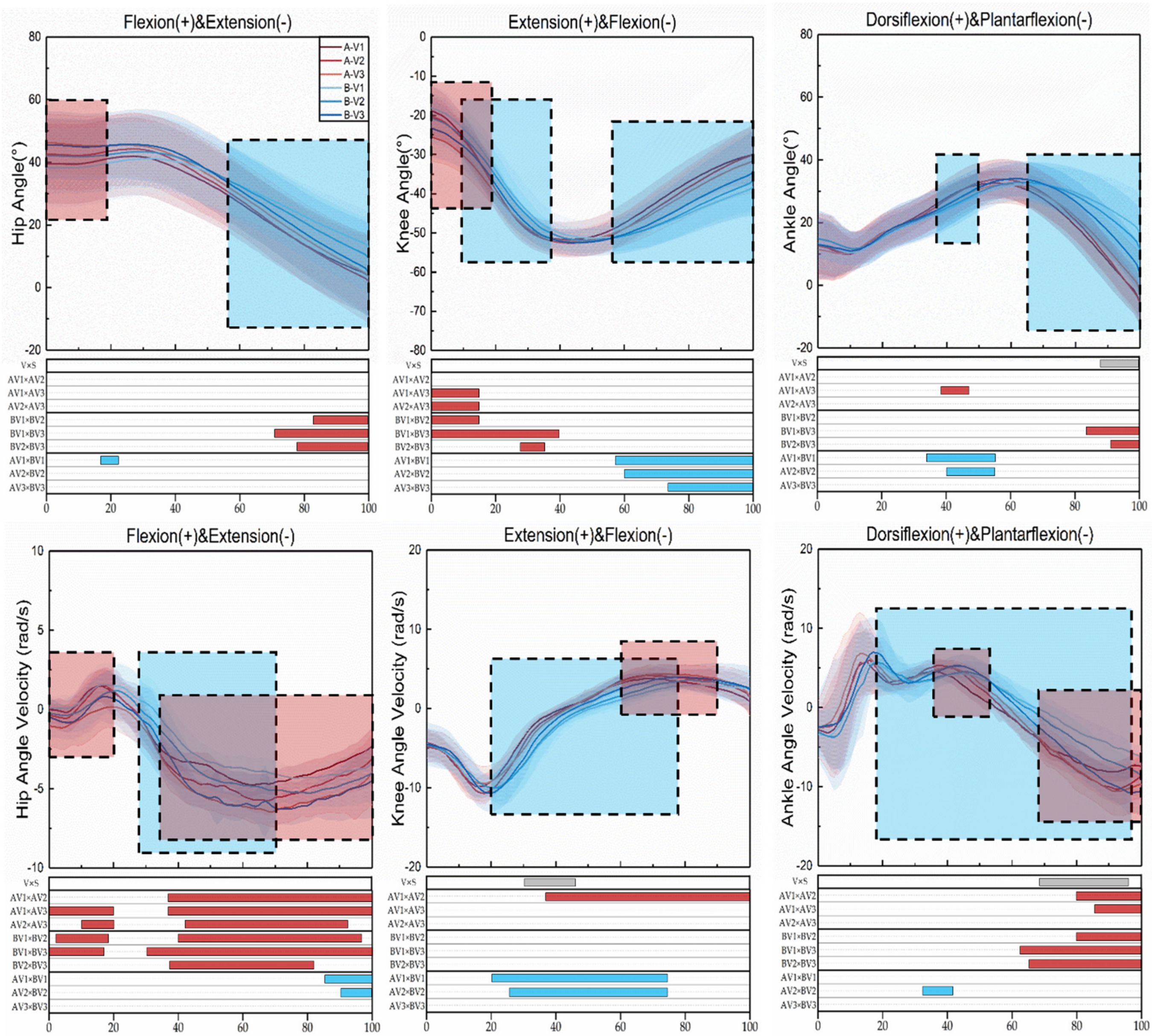

Figure 3. Lower limb joint angle and angle velocity waveforms of mean and standard deviation over the stance phase for neutral shoes and bionic shoes. The shaded red rectangles represent the main effects of the velocities ($p < 0.05$). The shaded blue rectangles represent the main effects of the shoes ($p < 0.05$). At the bottom of the figure, the gray horizontal bars represent interaction effects ($p < 0.05$), the red horizontal bars represent pairwise comparison effects in terms of the velocities ($p < 0.05$), and the blue horizontal bars represent pairwise comparison effects in terms of the shoes ($p < 0.05$).

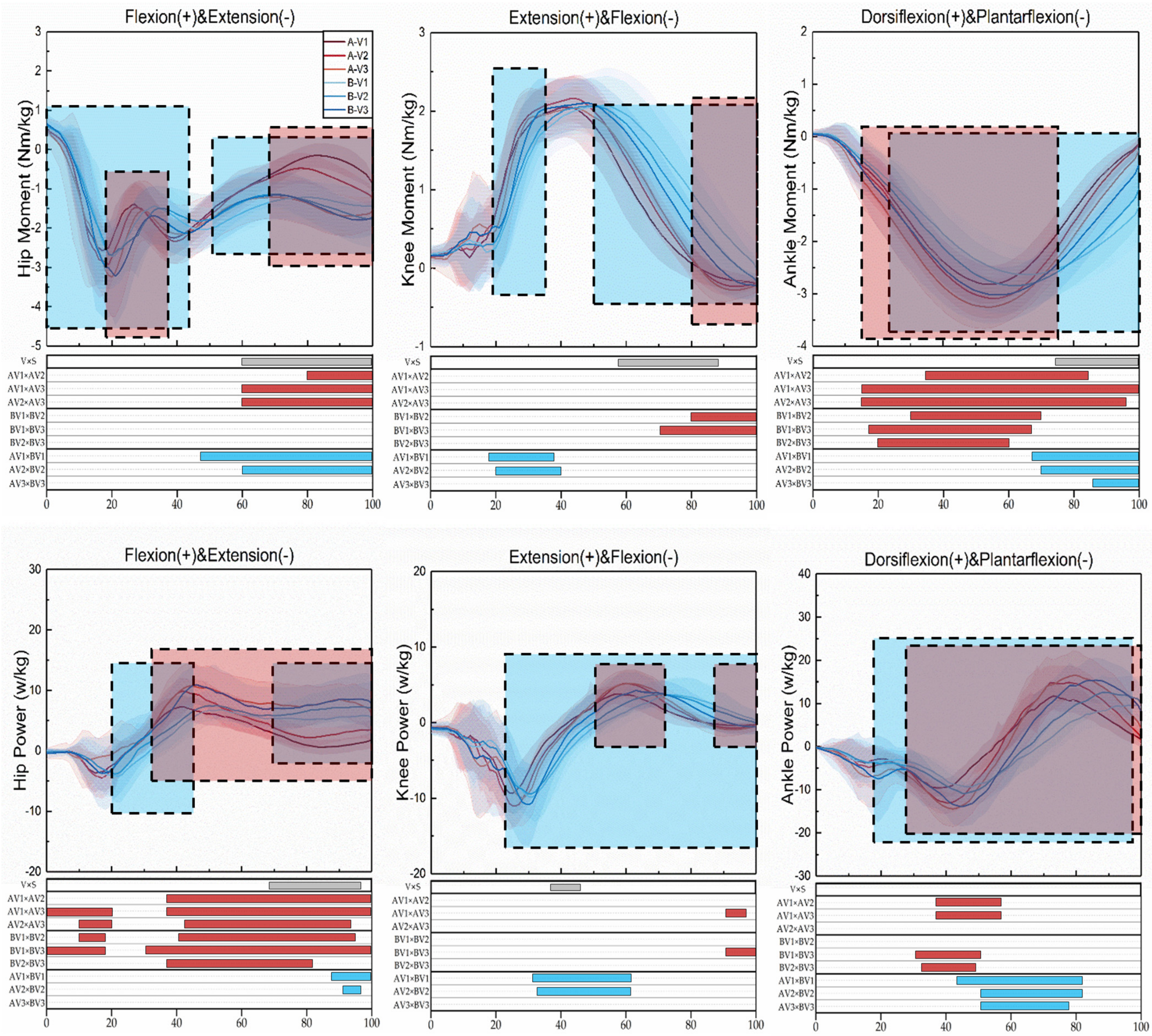

Figure 4. Lower limb moment and power waveforms of mean and standard deviation over the stance phase for the neutral shoes and bionic shoes. The shaded red rectangles represent the main effects of the velocities ($p < 0.05$). The shaded blue rectangles represent the main effects of the shoes ($p < 0.05$). At the bottom of the figure, the gray horizontal bars represent the interaction effects ($p < 0.05$), the red horizontal bars represent pairwise comparison effects in terms of velocities ($p < 0.05$), and the blue horizontal bars represent pairwise comparison effects in terms of shoes ($p < 0.05$).

4. Discussions

The purpose of the present study was to investigate the effects of wearing bionic shoes on lower limb biomechanics when running at various speeds compared with the effects of wearing neutral shoes. Given that the results indicate that the bionic shoes had a minimal impact on running performance, bionic shoes may have the potential to be beneficial in preventing running injuries. Running from 8 km/h to 12 km/h leads to elevated moments and power in the lower limb joints, with the primary alterations being observed in the knee and ankle joints [29]. While few studies have explored biomechanics when using bionic running shoes, we believe that our scientific research can provide novel perspectives and ideas combined with the existing literature.

4.1. Shoe Effects

Regarding the effects of the shoes, larger values were observed for hip extension ROM and ankle dorsiflexion ROM when the bionic shoes were worn, as shown in Figure 3, while the neutral shoes showed smaller ROM values for hip extension and ankle dorsiflexion. Regarding the training conditions, one would expect increases in joint ROM and/or joint moments to achieve a better training effect [30]. Another study also stated that an injured runner showed a significant more restricted ROM in the hip joints than uninjured runners [31]. Larger hip and ankle ROM during running may be a protective way to avoid injuries. In this study, the overall peak angular velocity values of the hip and ankle joints were smaller in the bionic shoes, and hip instability is considered as an essential mechanism for lower limb injuries [32]. For example, during the standing phase of gait, the gluteus medius muscle eccentrically controls hip adduction, while the posterolateral fibers assist in the eccentric control of internal hip rotation [33]. The deep external rotators of the hip, including the piriformis and quadratus femoris, play a critical role in hip stabilization. Their primary function is to eccentrically control the internal rotation of the hip during the standing phase of gait [34]. A comparison between the smaller hip extension moment values in the neutral shoes and the bionic shoes is shown in Figure 4. Ireland investigated the hypothesis that reduced hip muscle strength contributes to injuries in runners [35]. The bionic shoes appeared to provide better protection for the hip joint. Larger joint ROM and smaller joint angular velocity in the hip and ankle joints in the bionic shoes may consume more time and generate less effective propulsion. This finding of our study is inconsistent with the concept proposed by others that bionic shoes can provide better propulsion under certain conditions. Another finding of our study is the fact that both the positive and negative work performed by the joint ankle was bigger in the bionic shoes than in the neutral shoes. The vital cause of the ankle joint generating propulsive force during running has been investigated both experimentally and through environmental simulation experiments [36]. Under the same velocity conditions, the bionic shoes needed to generate more ankle power to achieve the same effects as the neutral shoes. Overall, the values for peak moment, maximum power, and the positive work and negative work of the hip in the bionic shoes were smaller than in the neutral shoes. The bionic shoes seemed to provide more protection to the hip joint.

4.2. Velocity Effects

Regarding the increased velocity effects, hip ROM and ankle ROM increased to varying extents [37], while the bionic shoes and neutral shoes also yielded different results. In our study, from 10 km/h to 14 km/h, knee ROM while wearing the bionic shoes showed a greater decrease than for the neutral shoes. Previous studies have implied that in bionic shoes, a reduction in joint ROM served to strengthen muscle control, which may increase the activation of relative muscle groups and reduce the risk of falling [38]. Other studies [39,40] have also found that the unstable element of the midsole could strengthen muscle control. In our study, the peak angular velocity of the knee joint showed a significant increase, which indicated a shorter time to complete the running gait. As explained by previous studies, at higher gait velocities, a greater amount of power is required to propel the body forward, leading to this outcome [41]. Another finding is that ankle ROM and knee ROM in the bionic shoes showed greater decreases, while ankle ROM increased, and knee ROM showed a smaller decrease in the neutral shoes. Hence, we observed a magnitude decrease in the proportional contribution of ankle ROM in the bionic shoes compared with the neutral shoes when the velocity increased. Previous studies have also associated sprinting ability with specific ankle plantar–flexor properties [42]. These characteristics contributed to enhanced force generation and power output in the bionic shoes during the propulsion phase of sprinting, allowing for greater velocity and acceleration. Simultaneously, the neuromuscular system, sensorimotor system, and proprioception were enhanced passively to adjust the ROM of the low limbs, especially for ankle ROM, to an inherently safer range to avoid injury [43]. From V2 to V3, hip ROM in the neutral shoes showed a magnitude increase, while no significant differences were found in this regard in the bionic shoes. This finding may indicate that from jogging running to training running, the bionic shoes brought a more stable condition for the hip joint for runners to achieve their training effect. With increasing running velocity, the peak ankle moment increased more than the peak knee moment. Recent indications suggest that as running velocity increases, there is a greater burden placed on the plantar flexors of the ankle joint compared to the extensors of the knee joint [44]. This finding suggests that when running at an excessive pace, the structures located in the posterior part of the lower leg and underneath the foot are potentially more vulnerable to injury compared to the structures in the anterior part of the knee [16]. In general, the maximum power and the positive work and negative work of the hip and ankle joints were affected by increases in running velocity. In particular, the maximum power of the hip and ankle, hip positive work, and ankle work (both positive and negative) were all significantly affected by running velocity under all the conditions tested. When running velocity increased, the positive work performed by the hip and ankle showed a significant increase, while no significant changes were observed in the knee joint. Previous studies have also found that accelerated velocity appears to be particularly dependent on the performance of the hip and ankle joints [45]. Furthermore, for the ankle joint in the bionic shoes, positive work, negative work, and maximum power showed larger values than in the neutral shoes at slower velocities but showed little differences compared with the neutral shoes at faster velocities. This may indicate that the bionic shoes were good at absorbing power and that they are more suitable for running at a training velocity or a faster velocity since the ankle plantar–flexor muscles play a significant role in generating the primary contribution among the major muscles of the lower limbs to vertical and forward acceleration during the stance phase of sprinting [46,47].

4.3. SPM1D Effects

Regarding the SPM1D results, all joint angles exhibited a greater change in the bionic shoes compared to the neutral shoes during the propulsion phase (the latter half of the stance phase), indicating a larger range of joint motion to activate the relevant muscles [30]. While the angular velocity in the bionic shoes was faster than the neutral shoes during the intermediate phase of the hip and knee joints and the mid to last phase of the ankle joints, the joint power results also showed a significant increase in the bionic shoes. These results were consistent with those in previous studies indicating that the ankle and knee joint moment angular velocity curves shift right and upward, leading to increased joint power during the push-off phase of contact, and the rise in power output could partly account for the increased energy expenditure [48]. During the running stance phase, hip moment and knee moment in the bionic shoes showed smaller values than in the neutral shoes, demonstrating that the bionic shoes provided a more stable condition for the hip joint, and Braz. J also found that inflexible runners exhibited a higher peak knee moment compared to flexible runners [49].

4.4. Pairwise Comparison Effects

Regarding the pairwise comparison effects, differences were also observed in all joints. During the last stance phase, the hip angle demonstrated significant pairwise velocity differences when wearing the neutral shoes, while no significant differences were observed with the bionic shoes. This implies that bionic shoes aid in maintaining a stable hip joint and could be suitable for rehabilitation training [50]. During the initial stance phase, the knee angle exhibited significant differences in velocity. Both in the neutral shoes and bionic shoes, the hip angle velocity and hip power exhibited numerous significant pairwise velocity differences, indicating the strong influence of velocity on hip angle velocity and hip power. At V1 and V2, knee angle velocity was slower in the bionic shoes compared to the neutral shoes, consistent with the findings for knee power, indicating that the bionic shoes required less knee power to achieve a reduction in energy consumption. During the last stance phase, significant differences in ankle angle velocity were observed, attributed to the effects of varying velocities. Throughout the entire stance phase, the angles of the ankle joint did not exhibit significant changes [51]. At all velocities and during the mid to last phase, ankle power exhibited a greater value in the bionic shoes compared to the neutral shoes, suggesting that the ankle generated more power in the bionic shoes to achieve similar effects in the neutral shoes. In both the hip and ankle joints, the hip moment in the bionic shoes displayed lower values during the last stance phase compared to V1 and V2, and this corresponds to the findings for ankle moment across all velocities. Reduced joint moments appeared to offer improved protection for the joints.

4.5. Limitations

The current study has several limitations. Firstly, our investigation focused exclusively on the stance phase of running, given its close association with running-related injuries and running performance, as reported by the authors of [52,53]. However, it is important to note that footwear and running velocity can significantly impact lower limb biomechanics during the swing phase of gait. Secondly, we only investigated three particular velocities in a narrow range; more distinct lower limb biomechanical results may arise at slower or faster velocities, such as 8 km/h or 16 km/h. Thirdly, only heel strike runners were recruited for this study. Runners with different landing styles may have varying levels of adaptation to bionic shoes because the modifications to the midsole of such shoes are intended to enhance propulsion during running. When worn by forefoot strikers, bionic shoes may potentially showcase their functionality more effectively. Finally, the participants involved in this study were exclusively healthy male recreational runners. As a result, the findings of our study may not be applicable to females or injured runners. It is crucial to consider these factors in future research endeavors.

5. Conclusions

In this study, the bionic shoes showcased significantly bigger values in both ankle positive work and negative work than the neutral shoes across all velocities. This suggests that bionic shoes do not yield superior running performance compared to neutral shoes. Decreased peak angular velocities were shown across the different velocities, and the bionic shoes effectively established a stable state at the hip joint, thereby contributing to injury prevention. Overall, bionic shoes have the potential to yield enhanced running performance by manifesting reduced growth in ROM and power, especially when operating at higher velocities. This study provides an exemplar, highlighting the necessity for the production of various types of bionic shoes to assess their efficacy in improving running performance and preventing running injuries. The present study's findings contribute to our understanding of footwear and running biomechanics, providing valuable information for protecting lower limb joints and improving running propulsion. Future studies should examine the effects of running in bionic shoes over a larger range of velocities to better understand the impact of shoe design on running biomechanics and performance.

Author Contributions: All authors have made substantial contributions to the manuscript. J.P., H.C. and M.L. were responsible for the conception and design of the study. Z.Z. was responsible for providing shoes. J.P. and M.L. were responsible for data acquisition and data processing. J.P., H.C., D.S. and Y.X. were responsible for data analysis and interpretation and drafting the article. H.C., M.L. and Y.L. critically revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: Author Zhiyi Zheng was employed by the company ANTA. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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