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Effects of longitudinal bending stiffness on joint range of motion and peak angle velocity during the stance phase of running

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Abstract

Running has become one of the most popular sports because of its low cost and ease of joining. Longitudinal bending stiffness (LBS) is a footwear property that plays a vital role in runners' athletic performance. A total of 16 healthy male recreational runners (running time ≥ 6 months, weekly running distance ≥ 10 km) were recruited for this study. After warming up and getting familiar with the experimental environment, the subjects wore three types of LBS running shoes (shoe 1: 2.7 Nm/rad, shoe 2: 5.0 Nm/rad, shoe 3: 8.6 Nm/rad) in random order and ran at a speed of 10km/h. The Visual3D three-dimensional motion analysis software was used to analyze the joint angles of the hip, knee, ankle, and metatarsophalangeal (MTP) joints during the running stance period, and the joint range of motion (ROM) and peak angle velocity were further obtained. This study found that ankle and knee ROM and peak angle velocity were significantly greater than S1 when wearing S2 and S3. MTP joint ROM and peak angle velocity were significantly smaller than S2 and/or S1 when wearing S3. This provides a basis for understanding how LBS affects lower limb joint ROM and peak angle velocity. It also provides suggestions for recreational runners on the choice of running shoes.
Keywords: running, longitudinal bending stiffness, joints, angle, angle velocity

1. Introduction

Although running is popular, it has a disadvantage that cannot be ignored, that is, the risk of running-related injuries (RRI) is extremely high [1]. These injuries may involve the hip, knee, ankle, and other parts of the body, and require careful and steady training as well as proper body position and equipment to reduce the risk of injury and maximize the benefits of running. Various studies have examined the prevalence of injuries in runners, with the prevalence ranging from 3.2% to 84.9%, a large variation that differences in study design, injury definitions, victim characteristics, and follow-up periods can explain [2].

Longitudinal bending stiffness (LBS) refers to the hardness or stiffness of the shoe when it is bent in the longitudinal direction (i.e., from heel to toe). The LBS of running shoes not only affects the biomechanical characteristics of running, but also affects the subjective feelings of runners [3]. Wang Yu [4] found in his study on the effects of different LBS insoles on subjective comfort and jogging biomechanics that changing the LBS of sports shoe insoles can change the LBS of the entire shoe and affect the subjective comfort of the wearer. The smaller the LBS, the better the overall comfort, and the more people tend to choose such shoes; changes in the insole LBS can affect the eversion angular velocity of the ankle joint, the eversion angle of the knee joint, and the extension angle of the metatarsophalangeal joint during jogging. Choosing sports shoes with appropriate LBS can protect the knee joint, ankle joint, and metatarsophalangeal joint to a certain extent and reduce the chance of injury; changes in the insole LBS can affect the position of the center of pressure point and joint torque during jogging, which can improve running economy. In addition, Ma et al. [5] found that changes in LBS affect the plantar flexion speed during the extension phase of running; the lower the stiffness, the faster the speed; it also affects the plantar flexion speed during the cushioning phase of running; the higher the LBS, the faster the speed; and increasing LBS can increase the stability of the movement of the inner foot during running. In addition, Chen et al. [6] found that LBS directly affects the performance of various sports such as running, jumping, sprinting, and multidirectional sports, and prevents metatarsophalangeal joint loss by limiting metatarsophalangeal joint hyperextension. In addition, it was concluded that running shoe LBS mainly affects the kinematic parameters of the metatarsophalangeal joint and ankle joint. Higher running shoe LBS has a shock-absorbing effect by increasing the ankle contact angle, and higher stiffness running shoes have the smallest ankle eversion angle before and after running, while low stiffness running shoes have the largest ankle eversion angle. Low stiffness running shoes have higher propulsion force, but excessive reliance on knee joint work may pose a risk of injury [7].

The purpose of this study is to compare the range of motion (ROM) and peak angle velocity of the hip, knee, ankle and metatarsophalangeal (MTP) joints of the lower limbs during the stance phase of running when recreational runners wear different LBS running shoes, in order to explore the LBS suitable for recreational runners from a biomechanical perspective, and to provide a reference for further reducing sports injuries and improving sports performance.

2. Materials and Methods

2.1 Participants

A total of 16 adult males were recruited for the study (participant information is shown in Table 1). The recruitment criteria for recreational runners in this experiment were: continuous running for at least 6 months and at least 10 kilometers per week. The dominant limb refers to the leg that is preferred for kicking a ball. The dominant limb of all participants is the right lower limb. All participants had no health problems and/or neuromuscular diseases and/or known gait disorders, and had no lower limb injuries in the past six months. All participants were informed of the purpose, methods, and procedures of the test before the test and signed the informed consent form.

Table 1. Demographic information

N	16
Age	23.13±1.17
Height	175.21±1.62
Weight	75.72±3.61
Cumulative running time（months）	8.23±1.12
Weekly running distance	15.47±2.34

2.2 The Experimental Shoes

The specific details of the running shoes used in this experiment are shown in Figure 1. In order to eliminate the influence of other design parameters of the shoes on the mechanical properties of the shoes, the experimental shoes used in this study were all provided by a third-party organization and the LBS values of the running shoes were measured by a third-party organization using a rotating axis material testing machine (Instron ElectroPuls E1000, Norwood, MA, USA) to ensure that the other mechanical properties of the three pairs of running shoes were the same except for the LBS. The customized running shoes requirements are as follows: (1) In terms of material composition, the outsoles of the three pairs of running shoes are made of rubber with the same material properties, the midsoles are made of EVA cushioning materials and carbon fiber plate support materials with the same material properties, and the uppers are made of artificial leather with the same material properties; (2) In terms of appearance and size, the heel height of the three pairs of running shoes is 4.2 cm, and the forefoot thickness is 2.6 cm; (3) In terms of LBS, this study selected the LBS based on previous studies [8, 9].

Figure 1. The information of shoes (S1: shoe 1, S2: shoe 2, S3: shoe 3)

2.3 The Experimental Process

Before the formal test, the subjects entered the laboratory to fill in basic information. After filling in the basic information, the subjects warmed up by running for 10 minutes at the speed they felt most comfortable. After completing the warm-up, participants will use the results of a random draw to determine the order in which they will wear their running shoes in the formal experiment. In the first step of the formal test, each subject was asked to stand on a force platform to collect static coordinates. During the test, the subjects were asked to run on a specified track wearing the first pair of shoes. The subjects were asked to complete a full gait cycle on the force platform (Kistler, Winterthur, Switzerland) located in the middle of the track. In this test, a full gait cycle was defined as the time from the right heel strike to the right forefoot leaving the ground. The force platform recorded the ground reaction force during running at a frequency of 1000 Hz to determine a complete gait cycle. The motion data of the stance phase was recorded at a frequency of 200 Hz using an infrared 3D motion capture system with eight cameras (Vicon Metrics Ltd., Oxford, UK). The force platform and the infrared motion capture system were synchronized to collect motion data. In order to obtain the running speed of the subjects in a timely manner, a Brower infrared timing light (Brower Timing System, Draper, UT, USA) was used to control the speed. The subject must successfully complete five attempts for each pair of shoes.

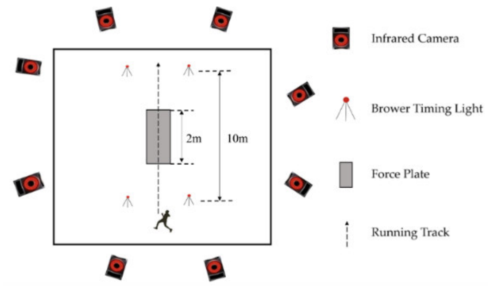

Figure 2. Experimental flow chart

2.4 Data Analysis

Kinematic data preprocessing was performed in Vicon Nexus software, and five complete support periods were captured for each test group of each subject. The support period was defined as the interval from right heel strike to left toe lift-off. The frame number corresponding to the right heel strike (the first frame with a force value exceeding 20 N) and the frame rate corresponding to the left toe lift-off (the last frame with a force value exceeding 20 N) were determined by the vertical ground reaction force value [10]. The missing marker points in the support period were completed, and the wrong or redundant marker points in the support period were deleted. Then, a file containing the support period marker point trajectory and ground reaction force data (.c3d format) was exported for subsequent processing.

The exported files were further processed using the biomechanical analysis software Visual3D (C-Motion, Germantown, USA), and the static data of the subjects collected were selected to create a static model. After the static model was created, the joint angles were calculated using the "Compute Model-Based Data" command. The calculated data were filtered using the "Lowpass Filter" command, and the kinematic data cutoff frequency was 14 Hz, which was used for the denoising process of the marker trajectory. The joint angles of each frame during the support phase were exported in .txt format using the "Export Signals to ASCII File" command in the "Script/Pipeline Processing" window. The ROM and peak angle velocity of the joints were calculated and summarized in Excel (Microsoft, SFO, USA).

2.5 Statistical Analysis

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

Descriptive statistics were provided as means and standard deviations (SD). Tests for normality and homogeneity of variances (Shapiro–Wilk and Levene's, respectively) were conducted on all data before the analysis. One-way ANOVA was performed to determine the effects of LBS on joint ROM and peak angle velocities during running. The level of statistical significance was set at $p < 0.05$.

3. Results

3.1 ROM

The effects of LBS on joint ROM are shown in Table 2.

The knee flexion and extension ROM when running in S2 and S3 are significantly greater than those in S1(P=0.001). The ankle dorsiflexion and plantarflexion ROM when running in S2 and S3 are significantly greater than those in S1 (p =0.001). The MTP dorsiflexion ROM when running in S3 is significantly smaller than this in S1 (p =0.001). The MTP plantarflexion ROM when running in S3 is significantly smaller than this in S1 and S2(p=0.001).

Table 2. The effects of LBS on joint ROM

(a. Significantly different from S1, b. Significantly different from S2, c. Significantly different from S3.)

ROM（°）		S1	S2	S3
Hip	Extension	40.01±8.92	41.90±7.83	44.28±8.50
Knee	Flexion	21.36±4.34bc	27.75±2.67a	28.06±4.85a
	Extension	15.03±9.29bc	19.23±5.52a	19.91±8.35a
Ankle	Dorsiflexion	14.25±1.57bc	18.53±0.98a	18.78±0.92a
	Plantarflexion	32.90±4.01bc	38.43±4.79a	38.12±4.97a
MTP	Dorsiflexion	15.90±3.89	17.20±4.22c	13.40±1.33b
	Plantarflexion	15.65±4.42c	12.60±3.47c	8.88±2.34ab

3.2 Peak Angle Velocity

The effects of LBS on joint peak angle velocity are shown in Table 3.

The knee flexion and extension peak angle velocity when running in S2 and S3 are significantly greater than those in S1 (p=0.001). The ankle dorsiflexion and plantarflexion peak angle velocity when running in S2 and S3 are significantly greater than those in S1 (p =0.001). The MTP plantarflexion ROM when running in S3 is significantly smaller than this in S1 and S2 (p =0.001).

Table 3. The effects of LBS on joint peak angle velocity

(a. Significantly different from S1, b. Significantly different from S2, c. Significantly different from S3.)

Peak angle velocity（rad/s）		S1	S2	S3
Hip	Extension	6.16±0.97	6.18±0.46	5.94±0.49
Knee	Flexion	4.12±1.47bc	7.32±1.28a	9.37±1.28a
	Extension	4.12±1.47bc	6.32±1.28a	7.37±1.28a
Ankle	Dorsiflexion	5.71±0.79bc	7.24±2.05a	7.10±1.87a
	Plantarflexion	4.80±0.66bc	7.38±0.51a	7.45±0.84a
MTP	Dorsiflexion	3.53±0.49	3.78±2.46	3.35±0.63
	Plantarflexion	8.44±1.58c	7.13±1.68c	4.23±1.32ab

4. Discussion

This study compared the hip, knee, ankle, and MTP joints of recreational runners during the running stance phase under three different LBS. Mainly observe the changes in joint ROM and peak angle velocity to explore the effects of different LBS on lower limb biomechanics. The study found that different LBS will affect the biomechanical characteristics of recreational runners during running.

In this study, the effects of running shoes on the biomechanical characteristics of the lower limbs were mainly concentrated on joint ROM and peak angular velocity. The knee ROM and ankle peak angular velocity were shown to be greater in S3 and S2 than in S1. Increasing the LBS of running shoes will change the way the foot contacts the ground, which may cause runners to adjust their gait to adapt to the physical characteristics of the shoe. This adjustment may include changing the way the foot strikes the ground [11], thereby affecting the range of motion of the knee joint during the running cycle. The greater the LBS of the running shoe, the more obvious the rebound effect of the sole after each step. This elastic reaction not only reduces energy loss but also provides additional power when the foot strikes the ground, thereby increasing the angular velocity of the ankle joint [9]. The reason why the ROM of the ankle and knee with high LBS is greater than that with low LBS is primarily due to the mechanical properties of the materials and the design of the joint structure [12]. Higher LBS generally provides better support and stability to the ankle, reducing unwanted movements and improving the efficiency of motion. This enhanced stability allows the joint to function more effectively within its designed range of motion [13], thus potentially increasing the overall ROM compared to joints with lower stiffness, which might allow for excessive and less controlled movements, leading to a decreased effective ROM.

The reason why the range of motion of the MTP is smaller in cases of high LBS compared to low LBS is primarily due to the rigidity and limited flexibility of the structures involved. High longitudinal bending stiffness indicates that the material or structure (such as a shoe or orthotic) is more resistant to bending [14]. This increased resistance restricts the natural movement and flexion of the metatarsophalangeal joint, thereby reducing its range of motion [15]. In contrast, low longitudinal bending stiffness allows for greater flexibility and bending, enabling a larger range of motion in the joint [16].

High LBS running shoes can reduce energy loss and improve the efficient conversion and transfer of energy, which requires the ankle joint to complete its action cycle more quickly when running. This efficiency improvement is usually reflected in the acceleration of the ankle joint during the stage of pushing the ground, thereby increasing the angular velocity.

5. Conclusion

This study found that ankle and knee ROM and peak angle velocity were significantly greater than S1 when wearing S2 and S3. MTP joint ROM and peak angle velocity were significantly smaller than S2 and/or S1 when wearing S3. This provides a basis for understanding how LBS affects lower limb joint ROM and peak angle velocity. It also provides suggestions for recreational runners on the choice of running shoes.

6. References

[1] L. Ceyssens, R. Vanelderen, C. Barton, P. Malliaras, and B. Dingenen, "Biomechanical risk factors associated with running-related injuries: a systematic review," Sports medicine, vol. 49, 1095-1115, 2019.

[2] N. Kakouris, N. Yener, and D. T. Fong, "A systematic review of running-related musculoskeletal injuries in runners," Journal of sport and health science, vol. 10, no. 5, 513-522, 2021.

[3] Q. Liu et al., "Running Velocity and Longitudinal Bending Stiffness Influence the Asymmetry of Kinematic Variables of the Lower Limb Joints," Bioengineering, vol. 9, no. 11, 607, 2022.

[4] Y. Wang, "Effects of Insole with Different Bending Stiffness on Subjective Comfort and Jogging Biomechanics," Chinese Master's Theses Full-text Database, 2019.

[5] Y. Ma, " Influence of Midfoot Running Shoe Bending Stiffness on Iomechanical and Subjective Characteristics during Running," Chinese Master's Theses Full-text Database, 2015.

[6] Y. Chen, " Effects of Different Stiffness Insoles on Lower Limb Biomechanical Characteristics during Long-time Running," Chinese Master's Theses Full-text Database, 2020.

[7] D. Sun, Y. Song, J. Quan, S. Li, and D. Gu, " Effect of Running Shoes Bending Stiffness Alteration on Lower Extremity Biomechanical Performance and Running Economy," China Sport Science and Technology, vol. 58, no. 07, 68-75, 2022.

[8] W. Hoogkamer, S. Kipp, and R. Kram, "The biomechanics of competitive male runners in three marathon racing shoes: a randomized crossover study," *Sports Medicine,* vol. 49, 133-143, 2019.

[9] E. Day and M. Hahn, "Optimal footwear longitudinal bending stiffness to improve running economy is speed dependent," Footwear Science, vol. 12, no. 1, 3-13, 2020.

[10] P. R. Cavanagh and M. A. Lafortune, "Ground reaction forces in distance running," Journal of biomechanics, vol. 13, no. 5, 397-406, 1980.

[11] H. Chen, E. Shao, D. Sun, R. Xuan, J. S. Baker, and Y. Gu, "Effects of footwear with different longitudinal bending stiffness on biomechanical characteristics and muscular mechanics of lower limbs in adolescent runners," Frontiers in Physiology, vol. 13, 907016, 2022.

[12] L.-A. M. Furlong and A. J. Harrison, "Differences in plantarflexor function during a stretch-shortening cycle task due to limb preference," Laterality: Asymmetries of Body, Brain and Cognition, vol. 20, no. 2, 128-140, 2015.

[13] L. Xiang, Q. Mei, A. Wang, V. Shim, J. Fernandez, and Y. Gu, "Evaluating function in the hallux valgus foot following a 12-week minimalist footwear intervention: A pilot computational analysis," Journal of Biomechanics, vol. 132, 110941, 2022.

[14] J. A. Ortega, L. A. Healey, W. Swinnen, and W. Hoogkamer, "Energetics and biomechanics of running footwear with increased longitudinal bending stiffness: a narrative review," Sports Medicine, vol. 51, no. 5, 873-894, 2021.

[15] S. Willwacher, M. König, B. Braunstein, J.-P. Goldmann, and G.-P. Brüggemann, "The gearing function of running shoe longitudinal bending stiffness," Gait & posture, vol. 40, no. 3, 386-390, 2014.

[16] P. Tabor, A. Mastalerz, D. Iwańska, and O. Grabowska, "Asymmetry indices in female runners as predictors of running velocity," Polish Journal of Sport and Tourism, vol. 26, no. 3, 3-8, 2019.