

## Effects of Running Shoe Sole Thickness Gradient

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### Abstract

**Objective** To compare the effects of running shoes with different sole thicknesses on lower-limb biomechanical parameters during running. **Methods** Thirty male university students majoring in physical education were recruited as participants. Biomechanical indices, including lower-limb muscle activity (integrated EMG), lower-limb kinematics (joint angles, angular velocities, and range of motion), and lower-limb kinetics (ground reaction forces, joint moments, and joint power), were compared across running conditions with shoe sole thicknesses of 36, 39, and 42 mm (increased by 3–6 mm). **Results** With increasing sole thickness, the integrated EMG values of major lower-limb muscle groups exhibited a “U-shaped” trend, with the lowest integrated EMG observed at a 3 mm increase in sole thickness (39 mm), and the differences were significant ( $P < 0.05$ ). The first peak of the vertical ground reaction force gradually decreased, while the time to the first peak and the first peak loading rate gradually increased, with significant differences ( $P < 0.05$ ). Knee joint moments and knee valgus moment impulse gradually decreased, whereas the effect on hip joint moments was not significant ( $P > 0.05$ ). There was no interaction effect on the range of motion of lower-limb joints at take-off and landing; however, ankle inversion-eversion range of motion was minimal when sole thickness was increased by 6 mm. **Conclusion** Appropriately increasing shoe sole thickness (e.g., by 3 mm) can effectively reduce joint impact and enhance running stability, whereas excessively thick soles (e.g., increased by 6 mm) may impair movement efficiency.

### Full Text

## Influence of Gradient Differences in Running Shoe Sole Thickness on Lower Limb Biomechanical Parameters

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## Abstract

**Objective:** To compare the effects of different shoe sole thicknesses on lower limb biomechanical parameters during running.

**Method:** Thirty male college students majoring in sports were recruited as subjects. The study systematically analyzed changes in biomechanical indicators including lower limb muscle activity (integrated electromyography, iEMG), kinematics (joint angles, angular velocities, and range of motion), and kinetics (ground reaction force, joint torque, and power) across shoe sole thicknesses of 36 mm, 39 mm, and 42 mm.

**Results:** As sole thickness increased, the iEMG values of major lower limb muscle groups exhibited a “U-shaped” trend, reaching minimum values at 39 mm sole thickness ( $P < 0.05$ ). The first peak of vertical ground reaction force gradually decreased, while the time to first peak and first peak loading rate gradually increased ( $P < 0.05$ ). Knee joint torque and knee abduction angle impulse gradually decreased ( $P < 0.05$ ), while hip joint torque showed no significant effect ( $P > 0.05$ ). At toe-off and ground contact moments, lower limb joint range of motion showed no interaction effects with sole thickness, though ankle inversion/eversion range of motion was smallest with 42 mm soles.

**Conclusion:** Appropriately increasing sole thickness (e.g., by 3 mm) can effectively reduce joint impact and improve running stability, but excessively thick soles (e.g., increased by 6 mm) may compromise movement efficiency.

**Keywords:** sole thickness; running; biomechanics; lower limb joints; kinematics; dynamics

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## 1. Introduction

Running is a high-intensity dynamic activity that demands efficient energy conversion and excellent impact absorption capacity from the lower limbs. During running, lower limb biomechanical characteristics not only affect running efficiency but are also closely related to injury risk. Athletic footwear serves as indispensable equipment for runners, and its design profoundly influences overall performance and health status. Shoe sole thickness, as a key factor directly affecting foot-ground interaction, relates closely to running comfort, energy expenditure, and injury risk.

Differences in sole thickness can provide varying degrees of cushioning against ground impact, thereby influencing running efficiency and lower limb injury risk. Previous research has provided valuable insights, but most studies have focused on static effects of sole thickness on biomechanical characteristics, while the dynamic process and specific mechanisms of how sole thickness influences lower limb biomechanics during running require further investigation.

This study employs high-precision biomechanical measurement techniques and advanced data analysis methods to conduct a series of running experiments with athletes wearing shoes of different sole thicknesses. The research aims to systematically quantify the effects of varying running shoe sole thickness on lower limb biomechanical characteristics, including joint angles, muscle activity intensity, and ground reaction forces, during running. The findings will provide a theoretical basis for scientific shoe selection, enhance running experience, and promote athletic health.

## 2. Methods

### 2.1 Subjects

This experiment recruited 30 male college students majoring in sports from Chengdu Sport University. All subjects were in good physical condition and athletic ability. The study obtained ethics committee approval (No. TY202303230002). Before the experiment, each subject was informed of the research purpose and requirements, and signed informed consent forms.

#### **Inclusion Criteria:**

- Normal foot morphology
- Body Mass Index (BMI) between 18.5-23.9
- No history of lower limb injuries
- Voluntary participation with informed consent
- No limb injuries at the time of testing
- Shoe size 40-44 EUR
- Rearfoot strike pattern confirmed through gait analysis ( $>15^\circ$ )

#### **Exclusion Criteria:**

- Any underlying diseases (e.g., cardiovascular or nervous system diseases)
- Impaired liver or kidney function
- Inability to effectively cooperate with the experiment
- Mid-experiment withdrawal
- Incomplete data
- Wearing foot orthotics or having local skin damage or other dermatological conditions

### 2.2 Test Footwear

This study selected three models from the Saucony Endorphin series (Speed 3, Pro 3, and Shift 3) as test shoes. All three models feature identical PWRRUN supercritical foamed midsoles and unified last designs, with only midsole thickness varying progressively. Heel thicknesses were  $(36\pm 0.5)mm$ ,  $(39\pm 0.5)mm$ , and  $(42\pm 0.5)mm$  respectively. All outsoles used XT-900 wear-resistant rubber with measured masses of 225 g and 285 g. Through verification, the three shoes showed no significant differences in outsole friction coefficient ( $<10\%$ ), effectively controlling non-research variables

Figure 1

Figure 1: Figure 1

to enable precise analysis of the independent effects of sole thickness on lower limb biomechanics. The test groups were designated as medium-thick (36 mm), thick (39 mm), and extra-thick (42 mm) conditions

### 2.3 Test Protocol

The test runway length was set at 16 m, with a three-dimensional force platform (Kistler 9260AA6, 60 cm × 50 cm) positioned in the middle. Collection frequency was set at 1000 Hz. A Motion Analysis Raptor-4 infrared high-speed motion capture system was used with a sampling frequency of 200 Hz. Data were collected using Vicon Nexus software.

A wireless surface EMG telemetry system (DELSYS Trigno) was placed on the right leg's biceps femoris, rectus femoris, and tibialis anterior. EMG signals were processed with 20-500 Hz bandpass filtering and full-wave rectification. Continuous stable gait cycles were selected and time-normalized (0-100%). Integrated EMG (iEMG) was calculated as a percentage of maximum voluntary contraction.

Before testing, subjects underwent gait analysis using pressure-distribution insoles (Novel Pedar) to screen for rearfoot strike patterns. Subjects wore the same socks and tight shorts for all conditions. The target running speed was 3.3 m/s. After completing tests with each shoe condition, subjects rested for 30 minutes. Three valid trials were collected per condition and averaged. The order of shoe testing was randomized.

### 2.4 Test Metrics

**Muscle Activity:** iEMG values were used to measure overall muscle activation during the entire contraction process.

**Kinematic Indicators:**

- Joint angles and angular velocities at toe-off (first frame when GRF < 50 N) and ground contact (first frame when GRF > 50 N) moments
- Range of Motion (ROM): The movement amplitude achievable within maximum active or passive joint motion range, used to evaluate joint flexibility and functional status

**Kinetic Indicators:**

- Vertical ground reaction force: first peak force, time to first peak, buffer time, and first peak loading rate
- Joint torque: Reflects rotational moments produced by muscles or external

forces on joints

- Power: Quantifies energy absorption and transmission efficiency of lower limb joints during running (negative power indicates energy absorption, positive power indicates energy generation)

## 2.5 Statistical Methods

All data were expressed as mean  $\pm$  standard deviation (Mean  $\pm$  SD). Independent samples t-tests and paired samples t-tests were used for between-group and within-group comparisons respectively. Statistical significance was set at  $p < 0.05$ , while  $p < 0.01$  indicated highly significant differences. To eliminate potential errors from subjects' height or body mass, subsequent analyses used normalized ground reaction forces (BW), normalized joint torques (BW  $\cdot$  BH), and normalized joint powers (W/kg). Experimental data were input into Excel for statistical analysis using multi-factor analysis of variance (ANOVA) to examine interaction effects between sole thickness and joint locations.

## 3. Results

### 3.1 Lower Limb Muscle Activity Analysis

When subjects ran in 39 mm sole thickness shoes, the normalized iEMG value of the biceps femoris was lowest. The 42 mm condition showed significantly higher biceps femoris iEMG values compared to both 36 mm and 39 mm conditions ( $P < 0.05$ ), indicating that extra-thick soles increased muscle activation demands. As sole thickness increased, iEMG values of major lower limb muscle groups showed a "U-shaped" trend, with the lowest activation at 39 mm thickness .

**TABLE:2** iEMG values of lower extremity muscles during running in shoes of different thicknesses ( $\mu V \cdot s$ )

Muscle	36 mm	39 mm	42 mm
Biceps Femoris	23.18 $\pm$ 10.62	21.36 $\pm$ 12.15	28.81 $\pm$ 13.90
<i>Rectus Femoris</i>	24.13 $\pm$ 8.64	26.45 $\pm$ 9.33	31.04 $\pm$ 10.12

Note:  $P < 0.05$  indicates significant difference;  $P < 0.01$  indicates highly significant difference.

### 3.2 Lower Limb Kinematic Parameters

**At Toe-off:** As sole thickness increased, foot toe-off angle first increased then decreased. The 42 mm condition showed significantly smaller ankle toe-off angular velocity compared to 36 mm (286.15 $\pm$ 11.26 $^\circ/s$  vs. 361.43 $\pm$ 57.22 $^\circ/s$ ,  $P < 0.01$ ). Knee joint toe-off angle was significantly different between 42 mm and 36 mm conditions ( $P < 0.05$ ). No significant interaction effects were found between sole thickness and hip joint toe-off angle or angular velocity ( $P > 0.05$ ) .

**TABLE:3** Changes in angles and angular velocities of lower limb joints at toe-off moment

Parameter	36 mm	39 mm	42 mm
Foot toe-off angle (°)	5.02±1.16	5.78±1.75	4.83±1.31
Ankle toe-off angle (°)	16.88±4.05	15.13±3.95	13.85±5.02
Ankle toe-off angular velocity (°·s <sup>-1</sup> )	361.43±57.22	352.16±66.32	333.42±52.37
Knee toe-off angle (°)	112.49±8.85	258.61±10.22	236.53±12.16
Hip toe-off angle (°)	2.21±0.78	1.96±0.43	2.07±0.37
Hip toe-off angular velocity (°·s <sup>-1</sup> )	109.33±9.64	103.58±9.07	103.58±9.07

**At Ground Contact:** No significant interaction effects were found between sole thickness and foot contact angle, ankle contact angle, knee contact angle, or hip contact angle (P > 0.05). The 39 mm condition showed maximum ankle contact angular velocity (211.36±31.12°·s<sup>-1</sup>), significantly higher than 36 mm (186.74±28.56°·s<sup>-1</sup>), P < 0.05).

**TABLE:4** Changes in angles and angular velocities of lower limb joints at ground contact moment

Parameter	36 mm	39 mm	42 mm
Foot contact angle (°)	-5.28±1.21	5.12±1.11	5.09±1.36
Ankle contact angle (°)	4.38±0.98	4.41±1.02	4.47±0.84
Ankle contact angular velocity (°·s <sup>-1</sup> )	186.74±28.56	211.36±31.12	206.18±4.41
Knee contact angle (°)	22.47±4.12	21.65±3.38	20.11±3.46
Hip contact angle (°)	38.65±6.72	39.01±6.72	39.01±6.72
Hip contact angular velocity (°·s <sup>-1</sup> )	25.38±4.24	26.75±3.37	29.88±5.21

**Joint Range of Motion:** No interaction effects were found between sole thickness and ankle flexion ROM, knee flexion ROM, knee inversion/eversion ROM, hip flexion ROM, hip adduction/abduction ROM, or hip internal/external rotation ROM (P > 0.05). However, ankle inversion/eversion ROM was smallest in the 42 mm condition (14.12±2.75°), significantly smaller than 36 mm (17.33±4.02°), P < 0.05).

**TABLE:5** Lower joint ROM at ground contact moment for shoes of different thicknesses (°)

ROM Parameter	36 mm	39 mm	42 mm
Ankle flexion	33.72 $\pm$ 3.12	32.65 $\pm$ 5.33	33.12 $\pm$ 4.78

### 3.3 Ground Reaction Force

As sole thickness increased, buffer time during running increased, while first peak loading rate showed an increasing trend. The first peak force gradually decreased with increasing thickness. The 42 mm condition showed significantly lower first peak force compared to 36 mm (102.21 $\pm$ 18.3BW vs. 88.32 $\pm$ 12.75 BW,  $P < 0.01$ ). However, no significant difference was found in time to first peak force between conditions ( $P > 0.05$ ).

**TABLE:6** Ground reaction force indices for running shoes of different thicknesses

Parameter	36 mm	39 mm	42 mm
First peak force (BW)	88.32 $\pm$ 12.75	97.33 $\pm$ 11.5	102.21 $\pm$ 18.3
$\hat{s}^{-1}$	33.83 $\pm$ 2.74	33.92 $\pm$ 3.16	33.98 $\pm$ 3.74

### 3.4 Lower Limb Joint Torque

As sole thickness increased, knee maximum extension torque, maximum abduction torque, and internal rotation torque all showed decreasing trends. The 42 mm condition showed significantly lower knee maximum extension torque compared to 36 mm (0.21 $\pm$ 0.027BW · H vs. 0.25 $\pm$ 0.012BW · H,  $P < 0.05$ ). Knee abduction angle impulse also decreased significantly with increasing sole thickness ( $P < 0.05$ ). Ankle maximum plantar flexion torque decreased with sole thickness (0.121 $\pm$ 0.011BW · H at 42mm vs. 0.136 $\pm$ 0.014 BW · H at 36 mm,  $P < 0.05$ ). Hip joint torque was not significantly affected by sole thickness changes ( $P > 0.05$ ).

**TABLE:7** Joint torque indices for running shoes of different thicknesses

Torque Parameter	36 mm	39 mm	42 mm
Knee max extension (BW · H)	0.25±0.012	0.23±0.018	0.21±0.027
<i>Kneemaxabduction</i> (BW·H)	0.04±0.006	0.03±0.004	0.03±0.011
<i>Kneemaxinternalrotation</i> (BW·H)	0.045±0.004	0.041±0.009	0.030±0.002
<i>Kneeabductionimpulse</i> (BW·H)	0.0012±0.0001	0.0009±0.0001	0.0007±0.0001
<i>Anklemaxplantarflexion</i> (BW·H)	0.136±0.014	0.127±0.018	0.121±0.011
<i>Anklemaxeversion</i> (BW·H)	0.021±0.003	0.017±0.001	0.023±0.003
<i>Anklemaxexternalrotation</i> (BW·H)	0.0024±0.0003	0.0017±0.0005	0.0021±0.0003
<i>Hipmaxextension</i> (BW·H)	0.163±0.018	0.159±0.021	0.155±0.016
<i>Hipmaxflexion</i> (BW·H)	0.122±0.011	0.116±0.014	0.112±0.016

### 3.5 Lower Limb Joint Power

When subjects ran in 42 mm sole thickness shoes, knee maximum negative power decreased by 0.92 W/kg compared to 36 mm ( $P < 0.01$ ). Ankle maximum positive power also decreased with increasing sole thickness ( $11.26 \pm 2.78 \text{ W/kg}$  at 42 mm vs.  $13.12 \pm 4.22 \text{ W/kg}$  at 36 mm,  $P < 0.05$ ). No significant interaction effects were found between sole thickness and hip maximum positive or negative power ( $P > 0.05$ ).

**TABLE:8** Joint power for running shoes of different thicknesses ( $\text{W} \cdot \text{kg}^{-1}$ )

Power Parameter	36 mm	39 mm	42 mm
Knee max positive	4.37±1.08	4.28±1.17	4.44±1.43
<i>Kneemaxnegative</i>	6.82±1.62	—	—
<i>Anklemaxpositive</i>	7.11±1.54	—	—
<i>Anklemaxnegative</i>	7.74±2.13	13.12±4.22	11.37±2.78
<i>Anklemaxplantarflexion</i>	8.55±2.36	—	—
<i>Anklemaxeversion</i>	9.12±1.33	—	—
<i>Anklemaxexternalrotation</i>	9.48±2.77	4.99±1.76	5.01±1.54
<i>Hipmaxpositive</i>	4.20±2.06	—	—
<i>Hipmaxnegative</i>	4.15±1.96	—	—
<i>Hipmaxplantarflexion</i>	4.18±2.01	—	—

## 4. Discussion

### 4.1 Effects of Different Sole Thicknesses on Lower Limb Muscle Activity

When subjects ran in shoes with different sole thicknesses, the iEMG values recruited from the biceps femoris, rectus femoris, and tibialis anterior showed an overall U-shaped trend with increasing sole thickness. At 39 mm sole thickness, iEMG values were typically at their lowest level, indicating that moderate

cushioning and energy return characteristics optimized lower limb mechanical transmission efficiency and reduced muscle demand for impact absorption. At 36 mm, thin soles lacked sufficient buffering capacity, causing impact forces to transmit directly to lower limb joints and resulting in muscle compensation. At 42 mm, although thicker soles provided better cushioning, the elongated mechanical transmission path increased knee and hip flexion, requiring greater muscle recruitment to maintain balance and propel the body forward, particularly increasing biceps femoris activation.

#### **4.2 Effects of Different Sole Thicknesses on Lower Limb Kinetic Parameters**

As sole thickness increased from 36 mm to 42 mm, the first peak of ground reaction force gradually decreased while buffer time increased, though time to first peak showed no significant change. This indicates that appropriately increasing sole thickness can effectively prolong foot-ground contact time, providing more cushioning space and time. Impact forces are dispersed and absorbed by the sole over a longer duration, allowing the foot to transition more slowly during ground contact and thereby reducing impact on joints and bones during running.

The loading rate first peak was greatest at 42 mm sole thickness, indicating that while thicker soles provide faster response to impact, the increased loading rate also raises the rate of force application to joints and soft tissues, potentially introducing risks. Knee joint torque and knee abduction angle impulse during running showed decreasing trends with increasing sole thickness, as thicker soles absorb and dissipate more impact force, reducing ground impact on the knee and decreasing torque transmission. The decreased knee abduction angle impulse indicates that increased sole thickness not only reduces impact forces but also better controls foot motion trajectory. Thicker soles provide better support and stability, effectively reducing foot eversion or inversion movements and further decreasing abnormal knee forces during running, thereby lowering injury risk.

Ankle joint torque decreased with increasing sole thickness because the same impact-dissipating effect that reduces knee loading also reduces ankle torque. For the hip joint, impact forces transmitted upward through the leg are largely dispersed and weakened during transmission, so sole thickness changes do not significantly affect hip joint torque in most cases.

#### **4.3 Effects of Different Sole Thicknesses on Lower Limb Kinematic Parameters**

This study included only rearfoot strike runners. Results showed that increasing shoe sole thickness led to increased foot toe-off angle during running, while knee toe-off angle decreased. Hip joint toe-off angle showed no interaction effect with sole thickness. Previous research has also indicated that increased sole thickness and height stretch the plantar fascia, increasing stretch reflex force that helps the foot lift off more quickly, thereby increasing toe-off angle. Knee and hip

toe-off angles are determined by thigh and lower leg muscle contraction and extension, which are not directly affected by sole thickness changes.

From the perspective of joint range of motion at ground contact, no interaction effects were found between sole thickness and most joint ROM parameters. However, ankle inversion/eversion ROM was smallest at 42 mm sole thickness. During running, the ankle requires certain inversion/eversion mobility to adapt to different terrains and gait changes. Thick soles increase the distance between foot and ground, reducing runners' perception of ground conditions and limiting ankle flexibility. This reduces muscle working efficiency and extensibility while increasing muscle force in specific directions, leading to stiffness with prolonged single-direction loading.

## 5. Conclusion

Sole thickness significantly affects runners' lower limb muscle activity and joint loading. Thin soles (36 mm) lack sufficient cushioning, leading to muscle compensation and relatively high joint impact loads. Moderate thickness increase (39 mm) can significantly reduce lower limb muscle activation and decrease joint impact loads, representing an optimal sole thickness for runners. However, excessive thickness (42 mm) increases muscle activation requirements, reduces ankle mobility and flexibility, and affects movement efficiency.

**Limitations:** This study only included rearfoot strike runners and male subjects, limiting generalizability to female populations and other strike patterns.

**Future Directions:** Future research should expand sample diversity to explore mechanisms of sole thickness effects on different genders, foot strike patterns, and running experience levels. This will promote theoretical development and practical applications in running science.

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Figure 2

Figure 2: Figure 2

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## Figures

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