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Abstract

Objective To investigate the effects of different running speeds on lower limb kinematics, kinetic characteristics, and plantar pressure distribution in male athletes.

Methods Fifteen physical education students from a university' s sports institute were selected and divided into three groups based on treadmill speed settings: 7 km/h (low-speed group), 11 km/h (normal-speed group), and 14 km/h (high-speed group). The Footscan insole system, Vicon motion capture system, and Bertec three-dimensional force-measuring treadmill were used to accurately measure lower limb kinematic parameters (spatiotemporal parameters, joint angles), lower limb kinetic parameters (ground reaction force, peak joint flexion-extension torque, peak power, work), and plantar pressure indicators (peak pressure, pressure loading rate, peak pressure intensity, pressure intensity loading rate) for each group, and the results were compared and analyzed.

Results The high-speed group exhibited significantly shortened gait cycles, reduced contact time, and increased stride length and frequency compared to the normal-speed and low-speed groups ($P<0.05$). The maximum knee flexion angle increased with running speed, while the ankle dorsiflexion angle at initial contact showed a trend of first decreasing then increasing with speed ($P<0.05$). With increasing running speed, the impact peak, propulsive peak, average loading rate, maximum loading rate, and maximum propulsive force of ground reaction force all showed significant increasing trends ($P<0.05$), whereas no significant differences were observed in knee joint peak torque or knee joint peak power ($P>0.05$). Additionally, significant differences were found among the three groups in peak pressure and pressure loading rate in the medial forefoot and heel regions ($P<0.05$), which increased with speed. The normal-speed group showed significantly different peak plantar pressure intensity compared to the low-speed group ($P<0.05$). No significant differences were observed among the three groups in pressure intensity loading rate in the lateral forefoot and midfoot regions ($P>0.05$).

Conclusion Increasing running speed has significant effects on plantar pressure distribution and lower limb biomechanical parameters in male athletes. Therefore, running speed should be reasonably adjusted according to individual conditions and training goals to optimize running efficiency and reduce the risk of sports injuries.

Full Text

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Effects of Running Speed on Lower-Limb Kinematics, Kinetics, and Plantar Pressure Distribution in Male Athletes

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Abstract: Objective To investigate the effects of different running speeds on lower-limb kinematic and kinetic characteristics and plantar pressure distribution in male athletes. **Methods** Fifteen physical education majors from a university were selected. Using treadmill speed settings, they were evenly divided into a 7 km/h group (low-speed group), an 11 km/h group (normal-speed group), and a 14 km/h group (high-speed group). The Footscan insole system, Vicon motion-capture system, and Bertec three-dimensional force-measuring treadmill were used to accurately measure lower-limb kinematic parameters (spatiotemporal parameters and joint angles), lower-limb kinetic parameters (ground reaction force, peak joint flexion–extension moment, peak power, and work), and plantar pressure indices (peak pressure, pressure loading rate, peak pressure intensity, and pressure-intensity loading rate) for each group of athletes; the results were then compared and analyzed. **Results** Compared with the normal-speed and low-speed groups, the high-speed group had a significantly shorter gait cycle and contact time, and significantly greater step length and step frequency; all comparisons showed significant differences ($P < 0.05$). The maximum knee flexion angle increased with increasing running speed, while the ankle dorsiflexion angle at contact first decreased and then increased as speed increased ($P < 0.05$). With increasing running speed, the impact peak, propulsive peak, average loading rate, maximum loading rate, and maximum propulsive force of the ground reaction force all showed significant increasing trends ($P < 0.05$), whereas the differences in peak knee-joint moment and peak knee-joint power were not significant ($P > 0.05$). In addition, among the three groups of athletes, peak pressure and pressure loading rate in the forefoot middle region and heel region showed significant differences ($P < 0.05$) and increased with increasing speed. The normal-speed group and low-speed group differed significantly in peak plantar pressure intensity ($P < 0.05$). Among the three groups, the pressure-intensity loading rate in the lateral forefoot region and midfoot region showed no significant differences ($P > 0.05$). **Conclusion** Increasing running speed has a significant effect on plantar pressure distribution and lower-limb biomechanical parameters in male athletes. Therefore, in running training, speed should be reasonably adjusted according to individual conditions and training goals in order to optimize running efficiency and reduce the risk of sports injury.

Keywords: running speed; athletes; plantar pressure; kinematics; kinetics

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Research on the influence of running speed on the lower extremity dynamics, kinematic characteristics and plantar pressure distribution of male athletes

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Abstract: Objective To explore the influence of different running speeds on the kinematic and kinetic characteristics of the lower limbs and the distribution of plantar pressure in male athletes. **Methods** Fifteen students majoring in physical education from the School of Physical Education of a certain university were selected. With the aid of treadmill speed settings, they were evenly divided into a 7 km/h group (low-speed group), an 11 km/h group (normal-speed group), and a 14 km/h group (fast-speed group). The Footscan insole system, Vicon motion-capture system, and Bertec three-dimensional force-measuring treadmill platform were used, respectively, to accurately measure lower-limb kinematic parameters (spatiotemporal parameters, joint angles), lower-limb kinetic parameters (ground reaction force, peak flexion and extension joint torque, peak power, work), and plantar-pressure indicators (peak pressure, pressure loading rate) in each group of athletes; the results were then compared and analyzed. **Results** Compared with the normal-speed group and the low-speed group, the fast-speed group showed a significantly shortened gait cycle, significantly reduced contact time, and significantly increased stride length and stride frequency ($P < 0.05$). The maximum knee flexion angle increased as running speed increased, and the dorsiflexion angle at the instant of ankle contact first decreased and then increased as running speed increased ($P < 0.05$). As running speed increased, the impact peak, push-off peak, average loading rate, maximum loading rate, and maximum propulsive force of the ground reaction force all showed a significant increasing trend ($P < 0.05$). However, there were no significant differences in peak knee torque or peak knee power ($P > 0.05$). Meanwhile, among the three groups of athletes, significant differences ($P < 0.05$) were found in peak pressure and pressure loading rate in the middle forefoot region and heel region, both of which increased as speed increased. There was a significant difference in peak plantar pressure between the normal-speed group and the low-speed group ($P < 0.05$). There were no significant differences in the pressure loading rates of the anterolateral and midfoot regions among the three groups of athletes ($P > 0.05$). **Conclusion** Increased running speed has significant effects on plantar-pressure distribution and lower-limb biomechanical parameters in male athletes. Therefore, in running training, speed should be adjusted reasonably according to individual conditions and training objectives so as to optimize running efficiency and reduce the risk of sports-induced injury.

Key words: running speed; athlete; plantar pressure; kinematics; dynamics

Running, as one of the most basic forms of human movement, not only plays an important role in daily life but also occupies a pivotal position in competitive sports. With the rapid development of modern sports science, in-depth research on the performance of the foot and lower-limb movements during running has become an important direction for improving athletic performance and preventing sports injuries[^1]. As a key variable in the running process, running speed has a significant influence on athletes' plantar-pressure distribution, lower-limb joint loading, and overall movement efficiency[^2-3]. Therefore, systematically investigating the dynamic relationships among running speed, plantar pressure, and lower-limb biomechanical parameters is of great value for optimizing athletes' technical movements, formulating individualized training programs, and reducing the risk of sports injury.

Running is a cyclical movement, and its core biomechanical features are reflected in the phase of contact between the foot and the ground[^4]. As the direct interface between the human body and the ground, the sole bears instantaneous impact forces and sustained pressure during running; its pressure distribution directly affects the load balance of the foot and even the entire lower limb[^5-6]. Existing studies have shown that as running speed increases, the peak plantar pressure shifts toward the forefoot, while the pressure in the arch region increases significantly; this change may lead to fatigue of the soft tissues of the foot and concentration of skeletal stress[^7]. WILLEMS et al.[^8], through force-platform experiments, found that during long-distance running the loads on the forefoot, midfoot, and medial heel increased, whereas the load on the lateral toe decreased; moreover, during the forefoot push-off phase, lateral pressure distribution became greater, which may increase the risk of stress fractures of the metatarsals. Lower-limb biomechanical parameters can further reveal the influence of speed changes on the overall kinetic chain of the lower limb. During high-speed running, the knee flexion angle increases to enhance shock-absorbing capacity, and the ankle plantarflexion angle increases to improve propulsion efficiency; however, these adaptive adjustments may be accompanied by excessive loading of joint cartilage and ligaments[^9]. LIEBERMAN et al.[^{10}] pointed out that the vertical component of ground reaction force–

component peaks were linearly positively correlated with running speed, whereas increases in horizontal shear force may exacerbate wear of the hip joint. In addition, the output characteristics of joint power change significantly as speed increases, which has a dual effect on energy metabolic efficiency and the accumulation of muscle fatigue[11]. However, although numerous studies have examined the effects of speed differences on plantar pressure and lower-limb biomechanics, most of these studies have focused on changes at a single speed or within a speed range[12]. The integrated mechanisms by which different speed differences affect plantar pressure and lower-limb biomechanics remain insufficiently investigated.

Therefore, this study takes male athletes as the research participants. By simulating running processes at different speeds through treadmill training, and using diversified high-precision equipment, key parameters such as lower-limb joint trajectories and plantar pressure during running are captured in real time. Through a multi-speed gradient experimental design, the study aims to systematically reveal the specific influence mechanisms of running speed on lower-limb kinematics, kinetic characteristics, and plantar pressure distribution in male athletes, thereby providing a scientific theoretical basis for athletic training.

1 Materials and Methods

1.1 Participants

This study selected 15 students from the School of Physical Education of a certain university as experimental participants. The students were 20–23 years old, with heights of 171.5–180.5 cm, body masses of 63.5–70.5 kg, and body mass indices (BMI) of 22–25. The inclusion criteria were: male athletes with at least 3 years of professional running training experience, no major sports injuries in the past year, and good physical functional status. They came from

Fig. 1 Shoes used for testing

Figure 1: Fig. 1 Shoes used for testing

Fig. 2 Foot pressure measurement system

Figure 2: Fig. 2 Foot pressure measurement system

different running specialties, including sprinting, middle-distance running, and long-distance running, so as to ensure that the study results could broadly cover the biomechanical response characteristics of athletes with different specialty requirements to changes in running speed. This study was approved by the Ethics Committee (approval No.: TY202303230002). Before participating in the test, all participants were required to read and sign an informed-consent form. The basic information of the selected participants is shown in Table 1.

Table 1 Basic information of the subjects

Tab. 1 Basic information of the subjects

Number of participants	Sex	Age/years	Height/cm	Body mass/kg	Body mass index/(kg · m^{-2})
15	Male	22.41 ± 2.16	175.22 ± 4.08	66.50 ± 8.46	23.65 ± 4.18

1.2 Testing Equipment

Testing shoes: all athletes were uniformly provided with ASICS Gel-Kayano 29 professional running shoes. As shown in Fig. 1, this shoe uses FlyteFoam midsole technology, which can effectively reduce the impact force borne by the sole during running; the upper uses a breathable engineered mesh material while conforming to the contour of the foot, reducing slippage during exercise; the outsole is made of AHAR + rubber, providing both wear resistance and good grip, thereby minimizing interference from shoe factors on the test results.

Fig. 1 Shoes used for testing

Plantar pressure measurement system[13] (Fig. 2): the Footscan insole system of RSscan, Belgium (model: v9 scientific) was used. It contains 325 capacitive pressure sensors, with a sensor distribution density of 4 sensels/cm^2 and a sampling frequency of 500 Hz, enabling high-precision, real-time capture of pressure changes in each plantar region of the athlete. This device was used to monitor indicators such as peak pressure, pressure loading rate, peak pressure intensity, and pressure-intensity loading rate.

Fig. 2 Foot pressure measurement system

Fig. 4 Test site of 3D force measuring table

Figure 3: Fig. 4 Test site of 3D force measuring table

Motion-capture system[14] (Fig. 3): the motion-capture system of Vicon, United Kingdom (model: Vicon Bonita), consisting of 8 Vicon T40S high-speed cameras, was used. The cameras were arranged around the treadmill, with a camera resolution of 4 MP and a frame rate up to 200 frames/s. Combined with professional Vicon Nexus 2.0 three-dimensional motion reconstruction software, the reflective marker points on the lower-limb skeleton of the athlete were accurately tracked, and the lower-limb skeletal model was reconstructed in real time. Thus, spatiotemporal parameters, joint angles, and other kinematic indicators of the lower-limb joints during running were measured precisely[15]. The paste positions of the Mark reflective marker points are as follows.

(a) Frontal view (b) 3D model

Fig. 3 Diagram of Mark reflection spot paste position and modeling

Three-dimensional force-measuring treadmill[^{16}] (Fig. 4): a three-dimensional force-measuring treadmill (model: FIT) from Bertec, USA, was used. The treadmill uses 16-bit digital acquisition and calibration technology; the sampling frequency is 1,000 Hz, the load range is 0–5,000 N in the vertical direction and 0–2,500 N in the horizontal direction, and the speed range is 0–24 km/h in both forward and reverse directions. The treadmill is also equipped with an adjustable-slope function; in this study, the slope was set to 0°. The treadmill collected in real time the three-dimensional force data exerted on it while the athletes were running.

图 4 三维测力跑台的测试现场

Fig. 4 Test site of 3D force measuring table

1.3 Test procedure

Before the formal test, the athletes performed a sufficient warm-up, including routine components such as slow jogging and dynamic stretching, lasting approximately 10 min. At the same time, they jogged on the treadmill for 5 min to ensure that their physiological functions reached a suitable exercise state.

The athletes performed running tests on the treadmill at different speeds: low speed (7 km/h), medium speed (11 km/h), and high speed (14 km/h). At each running speed, they ran continuously for 5 min; between speed changes, they rested for 5 min to ensure recovery of physical strength, avoid the accumulation of fatigue interfering with subsequent tests, and, at each speed transition, were given clear verbal prompts to ensure a smooth transition to the target speed.

During the testing process, the researchers monitored the operating status of the equipment throughout, checked the quality of data acquisition in real time,

Fig. 5 Distribution of plantar region

Figure 4: Fig. 5 Distribution of plantar region

and ensured that the pressure insole was closely fitted to the athlete' s sole, with no abnormal conditions such as displacement or wrinkles, thereby ensuring the completeness and accuracy of the data.

1.4 Test indicators

In this experiment, the plantar regions were divided according to the anatomical structure of the human sole into the forefoot region, midfoot region, and heel region, abbreviated as M1, M2, and M3, respectively[^{17}]. Among them, the forefoot region was divided into the medial forefoot region (i.e., the hallux region, T1), the central forefoot region (i.e., the second and third toe regions, T2), and the lateral forefoot region (i.e., the fourth and fifth toe regions, T3). The specific distribution is shown in Fig. 5.

图 5 足底区域分布

Fig. 5 Distribution of plantar region

1.4.1 Lower-limb kinematic parameters Spatiotemporal parameters[^{18}]: Athletes wearing reflective marker points ran on the treadmill at preset speeds. The cameras of the Vicon Bonita system synchronously collected the three-dimensional spatial coordinate data of the reflective markers, and the collected data were processed using the accompanying data-analysis software. Results such as gait cycle, stride length, step frequency, and contact time were calculated, and were used to evaluate the loading condition of the lower limbs during the support phase and the effectiveness of the cushioning mechanism.

Joint angles[^{19}]: Based on the collected three-dimensional spatial coordinate data of the reflective markers, professional kinematic algorithms were used to calculate the angular changes of the knee joint (flexion and extension angles) and ankle joint (dorsiflexion and plantarflexion angles) during running.

1.4.2 Lower-limb kinetic parameters Ground reaction force: The FIT three-dimensional force-measuring treadmill collected, in real time, the ground reaction force data generated during athletes' running, including forces in three directions: vertical, anterior–posterior, and left–right. By analyzing the collected force–time curves, parameters such as the peak ground reaction force and action time were obtained.

Knee- and ankle-joint moments, joint power, and joint work[^{20}]: The athletes performed running tests on the FIT three-dimensional force-measuring treadmill at preset speeds. The treadmill collected in real time the three-dimensional force data exerted on it during running. Combined with the joint-angle data obtained from the Vicon motion-capture system, the accompanying data acquisition and analysis system was used to calculate the knee- and ankle-joint moments, joint power, and joint work.

1.4.3 Plantar pressure parameters Peak pressure: The athletes wore their daily training running shoes with built-in Footscan insole insoles and performed running tests at different speeds on the Bertec three-dimensional force-measuring treadmill. During running, the insole system collected plantar pressure data in real time and transmitted them to the Footscan v9 software on the computer. Based on the sensor data, the software automatically identified and recorded the maximum pressure values occurring in each plantar region throughout the running process.

Pressure load rate[^{21}]: While recording the peak pressure in each region, Footscan v9 software also calculated the total pressure borne by the entire plantar surface.

value. Formula for calculating pressure load rate: (peak pressure in a given region / total peak pressure of the entire sole) × 100%.

Peak pressure: The Footscan insole system accurately recorded the pressure values in each plantar region and, combined with the area data for each region preset in the system, calculated the peak pressure in each plantar region. Formula for calculating peak pressure: peak pressure in a given region / area of that region.

Peak-pressure load rate: Based on the peak pressure values for each region calculated by Footscan v9 software, the total peak pressure of the entire sole was further calculated. Formula for calculating peak-pressure load rate: (peak pressure in a given region / total peak pressure of the entire sole) × 100%.

1.5 Statistical analysis

Excel 2021 and SPSS 26.0 were used to perform statistical and variance analyses on the data obtained from the tests. One-way analysis of variance was used to analyze differences in lower-limb kinematic parameters, lower-limb kinetic parameters, and plantar pressure indicators among male athletes at different running speeds. The measured data are expressed as mean ± standard deviation ($\bar{x} \pm s$). Independent-samples T tests and paired-samples T tests were used to compare intergroup and intragroup test data, respectively. When $P < 0.05$, the difference was considered significant; when $P < 0.01$, the difference was considered highly significant; otherwise, the difference was not significant.

2 Research results

2.1 Lower-limb kinematic parameters

2.1.1 Comparison of spatio-temporal parameters As shown by the test results in Table 2, with increasing running speed, the step cycle of the participants showed a decreasing trend, and the step cycle of the fast-speed group was significantly shorter than that of both the low-speed group and the normal-speed group ($P < 0.05$). The degree of shortening of the step cycle in the normal-speed group compared with the low-speed group was small and not significantly different ($P > 0.05$). The lower-limb ground-contact time during running in the three groups of participants showed a decreasing trend with increasing running speed, and both the normal-speed group and the fast-speed group were significantly different from the low-speed group ($P < 0.05$). The ground-contact time of the fast-speed group was shortened by approximately 0.09 s compared with the low-speed group. The step length of the three groups of participants showed an increasing trend with increasing speed, and the fast-speed group was very significantly different from the low-speed group ($P < 0.01$), with an increase of approximately 1.06 m. The step frequency of the three groups of participants showed an increasing trend with increasing running speed, and both the normal-speed group and the fast-speed group were significantly different from the low-speed group ($P < 0.05$).

Table 2 Comparison of spatio-temporal parameters at different running speeds ($\bar{x} \pm s$)

Item	Low-speed group	Normal-speed group	Fast-speed group
Step cycle / s	0.72 ± 0.06	0.70 ± 0.02	$0.66 \pm 0.03^{b*}$
Contact time / s	0.32 ± 0.16	$0.27 \pm 0.12^{a*}$	$0.23 \pm 0.11^{b*}$
Step length / m	1.42 ± 0.58	$2.16 \pm 0.43^{a*}$	$2.48 \pm 0.14^{b**}$
Step frequency / (steps · min^{-1})	84.77 ± 4.21	$87.32 \pm 5.15^{a*}$	$91.24 \pm 3.08^{b*}$

Note: ^{a} indicates that the normal-speed group differs from the other two groups; ^{b} indicates that the fast-speed group differs from the other two groups; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, a highly significant difference.

2.1.2 Comparison of joint angles From the test results for the knee- and ankle-joint angles during the touchdown phase shown in Table 3, it can be seen that the minimum knee-joint flexion angle of the three groups of participants increased with speed, showing a trend of first increasing and then decreasing, but the difference was not significant ($P > 0.05$). The maximum knee-joint flexion angle increased with increasing speed, and the fast-speed group was significantly different from the low-speed group ($P < 0.05$), with an increase of approximately 5.39°, whereas the low-speed group and the normal-speed group were not significantly different ($P > 0.05$). The knee-joint flexion angle at touchdown increased with running speed, but the difference was not significant ($P > 0.05$). The knee-joint flexion angle at take-off increased with speed, showing a trend of first decreasing and then increasing, and both the normal-speed group and the fast-speed group were significantly smaller than the low-speed group ($P < 0.05$). Knee-joint range of motion increased with running speed, showing a trend of first increasing and then decreasing, and both the normal-speed group and the fast-speed group were significantly greater than the low-speed group ($P < 0.05$), with the largest increase in the normal-speed group, approximately 2.91°.

Table 3 Comparison of joint angles in touchdown stage at different running speeds ($\bar{x} \pm s$, °)

Item	Low-speed group	Normal-speed group	Fast-speed group
Minimum knee-joint flexion angle	14.68 ± 5.31	13.55 ± 4.33	15.21 ± 3.65
Maximum knee-joint flexion angle	35.83 ± 4.68	37.43 ± 7.24	$41.22 \pm 6.61^{b*}$
Knee-joint flexion angle at touchdown	15.84 ± 3.18	16.12 ± 6.16	17.45 ± 2.28
Knee-joint flexion angle at take-off	27.14 ± 6.52	$19.45 \pm 5.33^{a*}$	$21.36 \pm 4.29^{b*}$
Knee-joint range of motion	21.76 ± 5.34	$24.67 \pm 3.75^{a*}$	$24.08 \pm 4.13^{b*}$
Minimum ankle-joint dorsiflexion angle	-17.43 ± 3.26	-20.64 ± 3.61	-21.32 ± 4.33
Maximum ankle-joint plantarflexion angle	16.03 ± 5.16	16.45 ± 3.21	16.27 ± 2.88

Item	Low-speed group	Normal-speed group	Fast-speed group
Ankle-joint dorsiflexion angle at touchdown	3.03 ± 1.88	2.86 ± 1.13	$3.62 \pm 2.04^{b*}$
Ankle-joint plantarflexion angle at take-off	-18.32 ± 2.14	-21.26 ± 4.57	-21.69 ± 5.22
Ankle-joint range of motion	32.83 ± 7.58	35.75 ± 4.06	36.24 ± 5.34

Note: ^{a} indicates that the normal-speed group differs from the other two groups; ^{b} indicates that the fast-speed group differs from the other two groups; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, a highly significant difference.

ankle joint minimum dorsiflexion angle, ankle joint maximum plantarflexion angle, ankle joint plantarflexion angle at toe-off, and ankle joint range of motion all changed with increasing running speed, but the differences were not significant ($P > 0.05$). The ankle dorsiflexion angle at foot contact first decreased and then increased as running speed increased; moreover, compared with the low-speed and normal-speed groups, the high-speed group showed significant increases, with increments of approximately 0.59° and 0.76°, respectively.

2.2 Lower-limb kinetic parameters

2.2.1 Ground reaction force

From the test results of the ground reaction force indexes at different running speeds shown in Table 4, it can be seen that, with increasing running speed, the impact peak, propulsive peak, average loading rate, maximum loading rate, and maximum propulsive force of the ground reaction force of the subjects' lower limbs all showed a significant increasing trend ($P < 0.05$). The time to impact peak and the time to propulsive peak showed a gradual decreasing trend with increasing running speed. The time to impact peak in the high-speed group differed extremely significantly from that in the low-speed group ($P < 0.01$), with a decrease of approximately 9.48 ms; however, there was no significant difference in the time to propulsive peak among the three groups of subjects ($P > 0.05$). The maximum braking force increased with running speed, but there was no significant difference between groups ($P > 0.05$).

Table 4 Comparison of ground reaction force indexes at different running speeds ($\bar{x} \pm s$)

Tab. 4 Comparison of ground reaction force indexes at different running speeds ($\bar{x} \pm s$)

Item	Low-speed group	Normal-speed group	High-speed group
Impact peak / $(N \cdot BW^{-1})$	1.78 ± 5.31	$1.83 \pm 4.33^{a*}$	$1.86 \pm 3.65^{b*}$
Time to impact peak / ms	39.33 ± 7.66	$35.43 \pm 6.21^{a*}$	$29.85 \pm 6.02^{b**}$
Propulsive peak / $(N \cdot BW^{-1})$	2.43 ± 0.32	$2.57 \pm 0.24^{a*}$	$2.60 \pm 0.16^{b*}$
Time to propulsive peak / ms	99.44 ± 18.36	98.25 ± 16.08	97.13 ± 13.01
Average loading rate / $(N \cdot s^{-1})$	82.56 ± 8.75	$87.78 \pm 11.23^{a*}$	$92.54 \pm 14.65^{b*}$
Maximum loading rate / $(N \cdot s^{-1})$	90.08 ± 21.32	$96.33 \pm 19.56^{a*}$	$101.76 \pm 24.33^{b*}$
Maximum propulsive force / $(kN \cdot BW^{-1})$	0.26 ± 0.05	$0.29 \pm 0.05^{a*}$	$0.31 \pm 0.04^{b*}$
Maximum braking force / $(kN \cdot BW^{-1})$	-0.35 ± 0.02	-0.37 ± 0.03	-0.38 ± 0.02

Note: ^{a} indicates that the normal-speed group differs from the other two groups; ^{b} indicates that the high-speed group differs from the other two groups; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, an extremely significant difference.

2.2.2 Joint flexion-extension peak torque, peak power, and work

From the test results of ankle- and knee-joint flexion-extension peak torque, peak power, and work at different running speeds shown in Table 5, it can be seen that, with increasing running speed, the ankle-joint peak torque, ankle-joint peak power in the toe-off plantarflexion phase and landing cushioning phase, and ankle-joint work in the toe-off plantarflexion phase and landing cushioning phase of the three groups of subjects all showed a significant increasing trend ($P < 0.05$). Among them, the ankle-joint peak power in the toe-off plantarflexion phase in the high-speed group and normal-speed group was extremely significantly higher than that in the low-speed group ($P < 0.01$), with increases of 9.09 and 5.21 W/kg, respectively. The ankle-joint peak power in the landing cushioning phase in the high-speed group differed extremely significantly from that in the low-speed group ($P < 0.01$), and differed significantly from that in the normal-speed group ($P < 0.05$). The ankle-joint work in the toe-off plantarflexion phase in the normal-speed group increased compared with that in the low-speed group, but the difference was not significant ($P > 0.05$). With increasing running speed, the knee-joint peak torque, knee-joint peak power in the toe-off plantarflexion phase and landing cushioning phase, and knee-joint work in the toe-off plantarflexion phase and landing cushioning phase of the three groups of subjects all showed a gradually increasing trend, but the differences were not significant ($P > 0.05$). Knee-joint work in the toe-off plantarflexion phase and landing cushioning phase first increased and then decreased with increasing speed, but the differences were not significant ($P > 0.05$).

Table 5 Comparison of joint flexion-extension peak torque, peak power, and work at different running speeds ($\bar{x} \pm s$)

Tab. 5 Comparison of peak joint flexion and extension torque, peak power and work done at different running speeds ($\bar{x} \pm s$)

Item	Low-speed group	Normal-speed group	High-speed group
Ankle-joint peak torque / ($Nm \cdot kg^{-1}$)	-1.78 ± 0.24	$-2.46 \pm 0.38^{a*}$	$-2.79 \pm 0.62^{b*}$
Ankle-joint peak power in toe-off plantarflexion phase / ($W \cdot kg^{-1}$)	7.12 ± 1.65	$12.33 \pm 4.23^{a**}$	$16.21 \pm 5.22^{b**}$
Ankle-joint peak power in landing cushioning phase / ($W \cdot kg^{-1}$)	-2.96 ± 1.02	$-3.67 \pm 1.16^{a*}$	$-5.08 \pm 1.77^{b**}$
Ankle-joint work in toe-off plantarflexion phase / ($J \cdot kg^{-1}$)	0.88 ± 0.22	1.01 ± 0.41	$1.18 \pm 0.32^{b*}$

Item	Low-speed group	Normal-speed group	High-speed group
Ankle-joint work in landing cushioning phase / $(\mathrm{J} \cdot \mathrm{kg}^{-1})$	-0.13 ± 0.04	$-0.21 \pm 0.08^{a*}$	$-0.27 \pm 0.06^{b*}$
Knee-joint peak torque / $(\mathrm{Nm} \cdot \mathrm{kg}^{-1})$	2.98 ± 0.63	3.21 ± 0.54	3.36 ± 0.38
Knee-joint peak power in toe-off plantarflexion phase / $(\mathrm{W} \cdot \mathrm{kg}^{-1})$	5.42 ± 1.33	5.74 ± 2.21	5.86 ± 2.62
Knee-joint peak power in landing cushioning phase / $(\mathrm{W} \cdot \mathrm{kg}^{-1})$	-11.88 ± 2.37	-12.89 ± 2.44	-14.01 ± 2.46
Knee-joint work in toe-off plantarflexion phase / $(\mathrm{J} \cdot \mathrm{kg}^{-1})$	0.30 ± 0.05	0.33 ± 0.06	0.31 ± 0.08
Knee-joint work in landing cushioning phase / $(\mathrm{J} \cdot \mathrm{kg}^{-1})$	-0.62 ± 0.18	-0.70 ± 0.11	-0.67 ± 0.24

Note: ^{a} indicates that the normal-speed group differs from the other two groups; ^{b} indicates that the high-speed group differs from the other two groups; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, an extremely significant difference.

2.3 Plantar Pressure

2.3.1 Comparison of Peak Pressure in Plantar Regions

As can be seen from the results measured in Table 6, there was no significant difference between the left and right feet at different speeds ($P > 0.05$), and different running speeds had different effects on the peak pressure in each plantar region. Among them, the peak pressures in the forefoot middle region and heel region differed significantly among different running speeds ($P < 0.05$), and gradually increased with increasing running speed; the peak pressures in the forefoot middle region, forefoot lateral region, and midfoot region showed no significant differences among different running speeds ($P > 0.05$). The forefoot medial region had the smallest peak pressure among all regions, and the peak pressure tended to first increase and then decrease with increasing running speed; under normal-speed running, the peak pressure in the forefoot medial region was the largest, but the difference was not significant ($P > 0.05$). The peak pressure in the forefoot lateral region tended to first decrease and then increase with increasing running speed, but the difference was not significant ($P > 0.05$). The peak pressure in the midfoot region was similar during normal-speed and fast running, and differed significantly from that during low-speed running ($P < 0.05$).

Table 6 Comparison of peak pressure in plantar region at different running speeds ($\bar{x} \pm s$, N)

Tab. 6 Comparison of peak pressure in plantar region at different running speeds ($\bar{x} \pm s$, N)

Region	Low-speed group Left foot	Low-speed group Right foot	Normal-speed group Left foot	Normal-speed group Right foot	Fast-speed group Left foot	Fast-speed group Right foot	P
T1	55.67 ± 15.33	53.76 ± 11.52	78.57 ± 25.41^{a**}	77.94 ± 32.22^{a**}	61.56 ± 22.48^{c}	58.75 ± 30.84	0.176
T2	287.83± 45.16	286.32± 62.07	322.34± 35.06^{a*}	320.35± 34.13^{a*}	388.21± 58.61^{b**}	383.12± 48.07^{b**}	0.038
T3	160.38± 41.24	159.75± 32.35	148.78± 45.05^{a*}	145.02± 52.66^{a*}	155.57± 32.05	152.37± 28.61	0.318
M2	164.38± 21.36^{c}	161.72± 32.08	182.68± 15.02^{a*}	185.83± 20.54^{a*}	183.89± 23.21^{b*}	184.01± 20.31^{b*}	0.258
M3	186.52± 25.32	183.49± 31.37	229.16± 33.48^{a*}	231.85± 28.86^{a*}	336.88± 52.42^{b**}	339.36± 43.12^{b**}	0.041

Note: ^{a} indicates a difference between the normal-speed group and the other two groups; ^{b} indicates a difference between the fast-speed group and the other two groups; ^{c} indicates a difference between the left and right feet within the group; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, a highly significant difference.

2.3.2 Comparison of Plantar Pressure Load Rate

As can be seen from the results measured in Table 7, the pressure load rates in the heel region and the forefoot middle region increased progressively with increasing running speed, and the comparisons among the three groups showed significant differences ($P < 0.05$); moreover, the increase in the heel region was larger, with the left and right feet in the fast-speed group increasing by 2.86 and 2.82 N/ms, respectively, compared with the low-speed group. At the three running speeds, the pressure load rates in the midfoot region, forefoot lateral region, and forefoot medial region of the participants showed no significant differences ($P < 0.05$); among them, the forefoot medial region showed a trend of first increasing and then decreasing with increasing speed, with a significant difference in the comparison ($P < 0.05$), and reached its highest value under the normal-speed condition, being 1.37 ± 0.15 N/ms for the left foot and 1.52 ± 0.66 N/ms for the right foot; the pressure load rate in the forefoot lateral region increased with increasing speed, but the difference was not significant ($P > 0.05$); the pressure load rate in the midfoot region tended to stabilize with increasing speed.

Table 7 Comparison of pressure load rate in plantar region at different running speeds ($\bar{x} \pm s$, $N \cdot ms^{-1}$)

Tab. 7 Comparison of pressure load rate in plantar region at different running speeds ($\bar{x} \pm s$, $N \cdot ms^{-1}$)

Region	Low-speed group Left foot	Low-speed group Right foot	Normal-speed group Left foot	Normal-speed group Right foot	Fast-speed group Left foot	Fast-speed group Right foot	P
T1	0.74 ± 0.03	0.72 ± 8.01	$1.37 \pm 0.15^{ac*}$	$1.52 \pm 0.66^{a*}$	0.98 ± 0.22	0.92 ± 0.16	0.527
T2	3.73 ± 0.79	3.68 ± 0.56	$4.62 \pm 0.68^{a*}$	$4.35 \pm 0.51^{a*}$	$5.54 \pm 0.26^{bc**}$	$5.18 \pm 0.42^{b**}$	0.038
T3	1.83 ± 0.62	1.78 ± 0.33	2.03 ± 0.17	1.96 ± 0.27	2.14 ± 0.29	2.22 ± 0.31	0.551
M2	2.18 ± 0.32	2.02 ± 0.45	$2.81 \pm 0.52^{a*}$	$2.78 \pm 0.47^{a*}$	$2.75 \pm 0.33^{b*}$	$2.80 \pm 0.14^{b*}$	0.316
M3	2.28 ± 0.12	2.21 ± 0.21	$3.89 \pm 0.53^{a*}$	$3.82 \pm 0.46^{a*}$	$5.14 \pm 0.64^{b**}$	$5.03 \pm 0.71^{b**}$	0.042

Note: ^{a} indicates a difference between the normal-speed group and the other two groups; ^{b} indicates a difference between the fast-speed group and the other two groups; ^{c} indicates a difference between the left and right feet within the group; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, a highly significant difference.

2.3.3 Peak Plantar Pressure–Time Integral

As can be seen from the results measured in Table 8, the peak pressure–time integrals in the forefoot medial region, forefoot middle region, forefoot lateral region, midfoot region, and heel region under the three running speeds all showed significant differences in comparison ($P < 0.05$). Among them, the peak pressure–time integrals in the forefoot medial region, forefoot middle region, midfoot region, and heel region all showed an increasing trend with increasing running speed, with significant differences ($P < 0.05$); the normal-speed group showed significant differences compared with the low-speed group ($P < 0.05$), and the high-speed group showed highly significant differences compared with the low-speed group.

differences ($P < 0.01$), and the increase was greatest in the anterior–middle foot region, reaching 23.93 and 24.4 N/cm^2 for the left and right feet, respectively. The peak pressure in the anterior–lateral foot region showed a decreasing trend as running speed increased, with decreases of 7.6 and 7.92 N/cm^2 for the left and right feet, respectively.

Table 8 Comparison of peak pressure in plantar zones at different running speeds ($\bar{x} \pm s$, N·cm^{-2})

Tab. 8 Comparison of peak pressure in plantar zone at different running speeds ($\bar{x} \pm s$, N·cm^{-2})

Zone	Low-speed group Left foot	Low-speed group Right foot	Normal-speed group Left foot	Normal-speed group Right foot	Fast-speed group Left foot	Fast-speed group Right foot	P
T1	29.27 ± 6.64	28.32 ± 7.02	35.65 ± 5.86^{a*}	33.76 ± 5.82^{a*}	41.17 ± 9.86^{b**}	40.28 ± 9.02^{b**}	0.029
T2	24.34 ± 3.16	23.22 ± 3.02	28.08 ± 4.65^{a*}	28.12 ± 2.64^{a*}	48.25 ± 5.14^{b**}	47.62 ± 4.02^{b**}	0.037
T3	15.23 ± 2.27	15.14 ± 2.71	11.67 ± 1.77^{a*}	10.51 ± 1.86^{a*}	7.63 ± 1.02^{b**}	7.22 ± 1.53^{b**}	0.041
M2	5.56 ± 0.83^{c}	5.23 ± 0.47	17.82 ± 2.11^{a*}	16.79 ± 0.88^{a*}	19.08 ± 2.13^{b**}	19.12 ± 2.64^{b**}	0.042
M3	8.16 ± 1.26	8.01 ± 0.83	17.65 ± 3.36^{a*}	18.11 ± 2.08^{a*}	23.36 ± 3.42^{bc**}	22.24 ± 2.78^{b**}	0.033

Note: ^{a} indicates that the normal-speed group differed from the other two groups; ^{b} indicates that the fast-speed group differed from the other two groups; ^{c} indicates that within the group, the left foot differed from the right foot; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, a highly significant difference.

2.3.4 Plantar pressure load rate

As shown in Table 9, the pressure load rates in the anterior-medial foot region, anterior-middle foot region, and heel region under the three step speeds all showed significant differences ($P < 0.05$); the anterior-lateral foot region and midfoot region showed no significant differences ($P > 0.05$). Among them, the pressure load rates in the anterior-medial foot region, anterior-middle foot region, and heel region all increased as step speed increased, and the differences were significant ($P < 0.05$); the pressure load rate in the anterior-lateral foot region first increased and then decreased as step speed increased, with no significant difference ($P > 0.05$); the pressure load rate in the midfoot region first decreased and then increased as step speed increased, with no significant difference ($P > 0.05$).

Table 9 Comparison of plantar pressure load rate at different running speeds ($\bar{x} \pm s$, $N \cdot cm^{-2} \cdot ms^{-1}$)

Tab. 9 Comparison of plantar pressure load rate at different running speeds ($\bar{x} \pm s$, $N \cdot cm^{-2} \cdot ms^{-1}$)

Zone	Low-speed group Left foot	Low-speed group Right foot	Normal-speed group Left foot	Normal-speed group Right foot	Fast-speed group Left foot	Fast-speed group Right foot	P
T1	0.68 ± 0.11	0.65 ± 0.24	$0.96 \pm 0.42^{a*}$	$0.93 \pm 0.27^{a*}$	$1.12 \pm 0.66^{b*}$	$1.14 \pm 0.58^{b*}$	0.032
T2	0.58 ± 0.24	0.52 ± 0.31	$0.73 \pm 0.16^{a*}$	$0.71 \pm 0.23^{a*}$	$0.95 \pm 0.46^{b*}$	$0.95 \pm 0.69^{b*}$	0.016
T3	0.22 ± 0.05	0.23 ± 0.04	0.38 ± 0.07	0.36 ± 0.06	0.18 ± 0.02	0.17 ± 0.04	0.218
M2	0.26 ± 0.08	0.28 ± 0.06	0.19 ± 0.11	0.20 ± 0.09	0.24 ± 0.05	0.22 ± 0.08	0.45
M3	0.28 ± 0.02	0.26 ± 0.06	$0.65 \pm 0.04^{a*}$	$0.65 \pm 0.03^{a*}$	$0.74 \pm 0.04^{b*}$	$0.73 \pm 0.06^{b*}$	0.028

Note: ^{a} indicates that the normal-speed group differed from the other two groups; ^{b} indicates that the fast-speed group differed from the other two groups; ^{c} indicates that within the group, the left foot differed from the right foot; * indicates $P < 0.05$, a significant difference; ** indicates $P < 0.01$, a highly significant difference.

3 Analysis and Discussion

3.1 Effects of running-speed differences on lower-limb kinematic characteristics in athletes

3.1.1 Changes in and discussion of spatiotemporal parameters Spatiotemporal parameters are used to evaluate the loading condition of the lower limbs during the support phase and the effectiveness of the cushioning mechanism. The results of this study showed that, as running speed increased, the body needed to complete more displacement per unit time, prompting the joints of the lower limbs to move at a faster coordinated frequency in order to achieve more efficient forward progression; therefore, the gait cycle of the fast-speed group was significantly shortened ($P < 0.05$). Because speed increased, in order to reduce the hindrance of ground friction to speed, and at the same time to rapidly switch between the support and swing phases, the lower limbs needed to complete ground-contact actions more quickly, so that the contact time in the normal-speed and fast-speed groups was significantly shorter than that in the low-speed group. At this time, the contraction force and amplitude of the leg muscles increased, and the driving force propelling the body forward became stronger, thereby increasing step length; this was especially more evident in the fast-speed group ($P < 0.05$). In addition, to match the increase in speed, the nervous system regulates muscle contraction frequency, causing the swing speed of the lower limbs to accelerate so as to maintain a higher speed; therefore, step frequency in the normal-speed and fast-speed groups increased significantly compared with the low-speed group ($P < 0.05$).

3.1.2 Changes in and discussion of joint angles For the knee joint, when speed initially begins to increase, in order to better cushion the impact force from the ground, related muscles such as the quadriceps femoris and hamstrings appropriately adjust their degree of contraction, increasing the knee flexion angle to absorb more energy. However, when speed further increases, in order to more efficiently⋯

propel the body forward, the leg must complete the push-off action more rapidly, and the knee-joint flexion angle correspondingly decreases. The maximum knee-joint flexion angle increased with speed, because a larger knee-joint flexion angle can increase the muscle contraction distance, store more elastic potential energy, and release greater energy during push-off, thereby providing the body with stronger propulsive force. This is consistent with the mathematical model results of ZHAO et al.[22], namely, an increase in speed leads to an increase in shank forward-swing amplitude and an anterior shift of the knee-joint phase, while the knee-joint flexion angle at toe-off first decreases and then increases as support time shortens; the normal-speed and fast-speed groups were significantly smaller than the low-speed group. During normal-speed running, in order to achieve a rapid and forceful push-off, the body adjusts the knee-joint angle so that its flexion angle at toe-off decreases; this allows the force of the leg muscles to be used more effectively to propel the body forward. Knee-joint range of motion first increased and then decreased. This is because, in the fast-speed group, although the overall range of motion was still greater than that in the low-speed group, because the speed was too high, the body' s stride pattern and movement rhythm became more compact, causing the knee-joint range of motion to decrease relative to the normal-speed group.

For the ankle joint, the minimum dorsiflexion angle, maximum plantarflexion angle, plantarflexion angle at toe-off, and range of motion all changed with increasing speed, but the differences were not significant ($P > 0.05$). This indicates that, at different speeds, the overall movement pattern of the ankle joint is relatively stable, so as to maintain its basic support and propulsion functions. However, the ankle-joint dorsiflexion angle at initial contact first decreased and then increased, and the fast-speed group was significantly greater than the low-speed and normal-speed groups ($P < 0.05$). At relatively low speeds, a smaller dorsiflexion angle helps the body quickly transition into the support phase. As speed increases, in order to better attenuate ground impact and maintain body balance, the ankle joint requires a larger dorsiflexion angle to adjust the contact mode between the foot and the ground, ensuring the stability of the body during high-speed movement.

3.2 Effects of Differences in Running Speed on Lower-Limb Kinetic Characteristics in Athletes

3.2.1 Changes in and discussion of ground reaction forces

During fast running, in order to propel the body forward at a higher speed and maintain balance, the major muscle groups of the leg, such as the gluteus maximus, quadriceps femoris, and triceps surae, need to contract more powerfully[23]. Taking the push-off phase as an example, the force generated by these muscles during push-off increases substantially, causing the peak push-off force to increase significantly, thereby providing the body with greater forward propulsive force, namely, an increase in maximum propulsive force. Meanwhile, as running speed increases, the inertia of the body increases, and the impact force generated at the instant of contact with the ground also increases accordingly, leading to an increase in the impact peak. Moreover, because speed increases, the contact and force interactions between the foot and the ground within a unit time become more frequent, causing the average loading rate and maximum loading rate also to increase. The impact-peak time gradually decreases as running speed increases. This is because, when running speed increases, in order to achieve faster alternation of steps, the contact time between the foot and the ground correspondingly shortens, and the impact force reaches its peak within a shorter period of time. The maximum braking force increased with running speed, because, as speed increases, the body requires greater braking force during running to buffer and adjust the movement state, so as to avoid injury caused by excessive impact and to ensure running stability.

3.2.2 Changes in and discussion of joint flexion–extension peak moment, peak power, and work

For the ankle joint, as running speed increased, its peak moment, peak power during the toe-off push-off phase and landing buffering phase, and work all increased significantly ($P < 0.05$). During running, the ankle joint is a key site for maintaining body balance, providing propulsive force, and attenuating ground impact. When speed increases, the body' s functional demand on the ankle joint increases substantially. For example, during the toe-off push-off phase, muscles such as the triceps surae must contract more strongly and rapidly in order to propel the body forward quickly and generate greater force. This high-intensity muscle contraction increases the ankle-joint peak moment and thereby raises the peak power during the push-off phase. At the same time, greater force and faster velocity mean that the ankle joint must complete more work within the same amount of time, so work also increases significantly. The significant increases in ankle-joint peak moment and power contrast with the relatively stable contribution of the knee joint; this is consistent with the findings of SCHACHE et al.[24]: the power contribution of the ankle joint during the support phase becomes increasingly stable as speed increases, whereas the proportion of power from the hip joint during the swing phase increases significantly. During the landing buffering phase, in order to effectively attenuate the greater impact brought by fast running, muscles such as the tibialis anterior must likewise contract more forcefully to control ankle-joint movement; this also leads to increases in peak power and work during this phase. The fast-speed and normal-speed groups showed extremely significant differences from the low-speed group in ankle-joint peak power during the toe-off push-off phase ($P < 0.01$), further indicating that, during fast running, the body' s demand for explosive force at the ankle joint rises sharply and the ankle joint must produce greater power output within a short time.

For the knee joint, although knee-joint peak moment and peak power during the toe-off push-off phase and landing buffering phase all showed a gradual increasing trend with increasing running speed, the differences were not significant ($P > 0.05$). As the main weight-bearing and movement joint of the lower limb, the knee joint requires the surrounding quadriceps femoris, hamstrings, and other muscle groups to work coordinatively at different speeds in order to maintain body stability and normal movement[25]. Over a long period of motor adaptation, these muscles have formed a relatively stable working pattern. Even when running speed changes, they can maintain relatively stable overall mechanical output by finely adjusting contraction mode and force, so that changes in peak moment and peak power are not obvious. As for the work done by the knee joint during the toe-off push-off phase and landing buffering phase,

power, showing a trend of first increasing and then decreasing as speed increased, but the differences were likewise not significant ($P > 0.05$). This is because, in the early stage of speed increase, in order to meet the body' s demands for power generation and cushioning, the muscles around the knee joint need to do more work, and therefore the work increases. However, when speed further increases, in order to adapt to a higher exercise intensity, the body fine-tunes the force-generation pattern, allowing the knee joint to reach a new equilibrium state in terms of work. This leads to a slight decrease in work, while the overall value remains within a relatively stable range, ensuring that the knee joint can continue to function effectively at different speeds.

3.3 Effects of Running-Speed Differences on Plantar Pressure Distribution

3.3.1 Changes and discussion of plantar peak pressure

Peak pressure is used to reflect the extreme pressure experienced by each region during movement. The results of this study showed that peak pressure in the forefoot middle region and heel region increased with increasing speed, with significant differences ($P < 0.05$). This is because, as speed increases, the leg muscles need to generate greater force to maintain balance and propel the body; muscles such as the triceps surae and tibialis anterior contract more strongly and transmit force through the skeleton to the plantar surface, thereby increasing pressure in these two regions. The peak pressure in the medial forefoot region was the smallest among all plantar regions, and with increasing speed it showed a trend of first increasing and then decreasing. This is because at low speed, body weight mainly acts on the hindfoot, so this region bears little load; at normal speed, an appropriate forward shift of the center of gravity increases its pressure; at high speed, to adapt to the speed, the body changes its force-generation pattern and the center of gravity shifts further forward, so other regions bear more pressure, leading to a reduction in its pressure. This is consistent with the view of Duan Chaoyang et al. [26], who studied plantar pressure distribution during treadmill running at different speeds. The peak pressure in the lateral forefoot region showed a trend of first decreasing and then increasing as running speed increased. This may be because speed changes cause adjustments in body posture and force-generation mode: at normal speed, a change in the lateral force distribution leads to a decrease in pressure in this region; at high speed, to maintain balance and propulsion, pressure increases again. The peak pressure in the midfoot region was similar at normal and high speeds. Because it mainly plays an auxiliary support and cushioning role, the body' s functional demand on it changes little at these two speeds. In contrast, it differed significantly from that at low speed, because at low speed the exercise intensity of the body is small and the pressure requirement for this region is low.

3.3.2 Changes and discussion of plantar pressure load rate

Pressure load rate is used to understand the contribution of different regions to overall pressure. The results of this study showed that, with increasing running speed, the pressure load rate in the heel region and forefoot middle region increased progressively and differed significantly ($P < 0.05$). This is because higher speed causes the heel region to sustain greater impact, and the forefoot middle region must provide stronger push-off force; the larger increase in the heel region may be due to its more prominent cushioning and support demands at high speed. In the midfoot region, lateral forefoot region, and medial forefoot region, the pressure load rate showed no significant differences in most cases ($P > 0.05$). The pressure load rate in the medial forefoot region showed a trend of first increasing and then decreasing with increasing speed. This is because changes in speed cause center-of-gravity transfer: at normal speed, the position of the center of gravity results in the highest pressure load rate in this region; although the pressure load rate in the lateral forefoot region increased with speed, it was not significant, possibly because the pressure in each region was adjusted in coordination. The pressure load rate in the midfoot region gradually became stable with increasing speed, indicating that its role in sharing overall pressure at different speeds was relatively stable. This is consistent with the view of Yu Jiancheng et al. [27], who pointed out that during running, the pressure load in each plantar region changes with changes in external conditions.

3.3.3 Changes and discussion of plantar peak pressure intensity

Peak pressure intensity is used to reflect the actual intensity of pressure borne by each plantar region. The results of this study showed that, with increasing running speed, peak pressure intensity increased in the medial forefoot region, forefoot middle region, midfoot region, and heel region. This was because the increase in speed raised the intensity and frequency of muscle contraction. Zhang Xiuli et al. [28] also pointed out that, to maintain balance and generate propulsive force, the muscles associated with the leg and foot (such as the triceps surae and gastrocnemius) need to contract to a greater extent, transmitting force through the skeleton to the plantar surface and increasing pressure in plantar regions; this provides theoretical support for the results of the present study. At the same time, stronger body vibration and impact, adaptive deformation of plantar soft tissues, and reduced load-bearing area also promote an increase in plantar peak pressure intensity. The forefoot middle region had the largest increase in peak pressure intensity because it plays a key role in push-off during ground contact; during fast running, the high intensity of muscle activity causes pressure to rise sharply, leading to a significant increase in peak pressure intensity. By contrast, peak pressure intensity in the lateral forefoot region decreased. This resulted from the body' s need to maintain balance and efficient propulsion: the center of gravity shifted toward the forefoot middle region and heel region, reducing pressure in the lateral forefoot region. In addition, neuromuscular feedback mechanisms adjusted the muscle contraction pattern and reduced pressure in this region; together with slight changes in foot skeletal structure and joint angles that affected force distribution, peak pressure intensity decreased when the load-bearing area remained unchanged or increased.

3.3.4 Changes and discussion of plantar pressure load intensity

Pressure load intensity is used to reflect the distribution pattern of pressure intensity in different regions. The results of this study showed that, as the main regions bearing running impact, the medial forefoot region, forefoot middle region, and heel region showed a significant increase in pressure load intensity with increasing speed ($P < 0.05$). This was mainly because, as running speed increased, the ground reaction force increased, and these regions played a key role in cushioning and absorbing impact during ground contact. The pressure load intensity in the lateral forefoot region showed a trend of first increasing and then decreasing with increasing speed. This was because, in the early stage of increased running speed, the landing pattern gradually transitioned from whole-foot landing to forefoot landing, causing a temporary increase in pressure in the lateral region; however, as speed further increased, athletes tended to reduce impact on the lateral region by adjusting their gait. The pressure load intensity in the midfoot region showed a trend of first decreasing and then increasing with increasing speed, which was related to adaptive adjustments of plantar soft tissues when running speed changed, including elastic energy storage and release in structures such as the plantar fascia, as well as changes in dynamic stability in the midfoot region.

4 Conclusions

Through treadmill testing, this study systematically analyzed the effects of different speeds on the lower-limb kinematics, kinetics, and plantar pressure distribution of male athletes. The results show that the subjects' lower-limb spatiotemporal parameters and kinetic parameters changed significantly, such as a shortened gait cycle, increased step length and cadence, and significant increases in ground reaction force and ankle-joint power. Moreover, as running speed increased, the peak pressures and pressure-time integrals in key plantar regions increased significantly, especially in the heel region and the anterior-middle forefoot region. These changes suggest that, in running training, speed should be adjusted reasonably according to individual conditions and training goals. For athletes seeking to improve running efficiency, an appropriate increase in speed may help optimize running technique; whereas for athletes at risk of sports injury, speed should be selected cautiously on the basis of ensuring correct technical movement. Future studies may further explore optimization strategies for running technique at different speeds, as well as how training can improve athletes' lower-limb biomechanical characteristics, thereby providing more comprehensive guidance for running training and sports-injury prevention.

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Figure 1

Figure 5: Figure 1

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Figure 3

Figure 6: Figure 3

Figure 5

Figure 7: Figure 5