

Article

The Effect of Different Midsole Cushioning Types on Impact Forces and Joint Stiffness in Heel-Toe Runners

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Abstract

(1) Background: The midsole hardness (i.e., cushioning) of running shoes has received significant attention as a crucial element influencing both performance and injury prevention. This research aimed to examine how variations in midsole hardness affect the biomechanical responses of the lower extremities during running. (2) Methods: Twenty-five male recreational runners in their 20 s with no history of musculoskeletal injuries (age: 23.3 ± 4.24 years) were recruited. Custom-made shoes with four different midsole hardness levels (Asker-C 70, 60, 50, and 40) were used, and the mechanical properties of the midsoles were analyzed. Participants ran on an instrumented treadmill at speeds of 2.3 m/s and 3.3 m/s. Ground reaction forces and motion data were collected during the trials. A one-way repeated-measures ANOVA was conducted to compare groups. (3) Results: In the running trials, a decrease in midsole hardness increased the impact peak (IP) while loading rate (LR) decreased significantly ($p < 0.05$). In addition, runners wearing shoes with greater cushioning exhibited higher ankle joint stiffness than those wearing harder shoes ($p < 0.05$). (4) Conclusions: Adjusting joint stiffness appears to be a key strategy employed by runners in response to softer or cushioned running environments (i.e., shoe and surface), ultimately contributing to greater dynamic stability during movement.

Keywords: running; midsole; surface; cushioning; joint stiffness; impact peak; loading rate; injury; mechanical test; adaptation



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1. Introduction

Walking and running are two of the most fundamental movements humans perform for the purpose of moving. At the transition from the flight phase to the stance phase, the feet collide with the surface, and the resulting impact is transmitted to the body [1]. During running, repeated high-impact activities have been reported to increase injury risk in the musculoskeletal system, including soft tissues, knee arthritis, and stress fractures [2–5]. Previous research has divided the factors affecting biomechanical variables during running, such as body movements and impact, into internal and external ones. The internal factors include body weight, leg length, and height, while the external factors include slope, bottom surface, and shoes [6]. Most of all, biomechanics research on footwear focuses on minimizing injury and improving running mechanics [7–11].

Shoes can have their structures modified to control function, and their midsoles can be adapted to different shapes and materials, and their hardness adjusted to alter cushioning. In particular, extensive research has been conducted on running shoe cushioning because it controls forces on the body and provides rebound elasticity during landing in running [12–15]. However, it has been commonly assumed that altering midsole cushioning does not necessarily reduce impact peak, but recent findings call this into question [14,16].

A previous study has found that running in hard midsole shoes produced no kinematic changes in the ankles or knees at initial contact but decreased ankle dorsiflexion and knee flexion during stance [17]. However, these previous studies examined only the kinematic variable of joint angle and kinetic variables, such as maximum force and loading rate, independently.

A human body can adapt to any impact by adjusting posture consciously to the surface conditions (i.e., cushioning) during landing [16,18–21]. That is, when an impact force is applied to the body, the force can be controlled by the bending of the joints more or less [22]. After the feet touch the surface, the body's center of mass (CoM) decreases as the ankle, knee, and hip joints move, indicating energy absorption and compression of the spring [23]. Therefore, research on impact force during running needs to examine the interrelationships with kinematic factors, such as joint angles, leg length, and vertical body posture.

Body stiffness can be used as a variable representing the whole body's elasticity, acting like a spring in response to load during human movement. The impact force is quantified during various motions, such as walking and running, and is applied along the body's length or at an angle, which naturally changes [24]. Therefore, although the whole body receives the same impact, body stiffness can vary with changes in its length or angle [22,25]. Biomechanic research has frequently used the variable of stiffness, which can be obtained in this way, as encompassing all intrinsic components, such as muscles, tendons, ligaments, cartilage, and bones [12,14,16,23,24]. Many of the previous studies have used vertical, leg, and joint stiffness [23,24]. Vertical stiffness is a variable based on the displacement of the CoM and the maximum force and can be used when the positions of the feet and the CoM are on a vertical line during landing [24]. Furthermore, leg stiffness varies with leg length and maximum force and can be used when the feet land aslant during walking or running [25]. Previous studies demonstrate that joint stiffness of lower extremity joints, such as the ankle, knee, and hip, can be more specific to express fluctuations in body movement under dynamic loads than other stiffnesses [22]. This body stiffness can be interpreted in various ways from the perspective of performance and injury prevention. Some degree of stiffness should be secured to improve movement performance. However, a high level of stiffness may increase the risk of musculoskeletal injury, whereas a low level of stiffness may increase the risk of injury to cartilage and soft tissues [26].

A previous study has emphasized that a detailed investigation of body stiffness and biomechanical differences associated with variations in midsole properties requires prior characterization of the intrinsic physical properties of footwear through mechanical testing [14]. Mechanical tests were conducted to characterize the properties of four different shoe designs [27]. By doing so, they examined variations in joint stiffness during landing from a vertical jump as a function of shoe physical properties. In addition, contact time and leg joint stiffness during running, as well as the mechanical properties of shoes across variations in midsole materials, were investigated [13]. It is therefore necessary to conduct a study on the physical properties of a substantial running shoe.

Research is needed to investigate, according to variations in the midsole hardness of shoes, their kinetic and kinematic variations and the relations among them. This study aimed to present the mechanical properties of shoes, variations in the hardness of running shoes, and the biomechanical responses of the body to variations in midsole cushioning during running.

2. Materials and Methods

2.1. Participants

The participants in this study were those without orthopedic abnormalities who had neither musculoskeletal injury nor experience of surgery within the last six months.

Twenty-five male participants in their twenties who were heel-toe recreational runners led by the right foot and wore 270 mm running shoes (age: 23.3 ± 4.24 , height: 174.9 ± 4.07 cm, weight: 75.5 ± 7.44 kg) were designated as subjects. Before the experiment, the participants were informed of its purpose and procedure and wrote to provide informed consent (Project Control Number: 1263-202005-HR-031-01, Approval Number: 20200518-034, Research Approval Date: 19 May 2020).

2.2. Material Properties of Running Shoes

For this study, four identical pairs of running shoes (SKY RUNNER, FILA Holdings, Seoul, Republic of Korea) were manufactured to assess thickness, weight, and size, except for hardness (cushioning). An impact test (Exeter Research, Brentwood, NH, USA; ASTM F1614-99) [28] was performed to examine the differences in the mechanical properties of the midsoles of running shoes. In this test, an 8.5 kg mass attached to a piston was dropped onto a midsole (Figure 1). The falling mass was adjustable, and the head of a falling body, including a motor-driven system for lifting the falling body, is 45 mm in diameter with a round edge. An accelerometer was used to measure acceleration (g) and, consequently, estimate midsole dwell time, energy return, and displacement (Table 1).

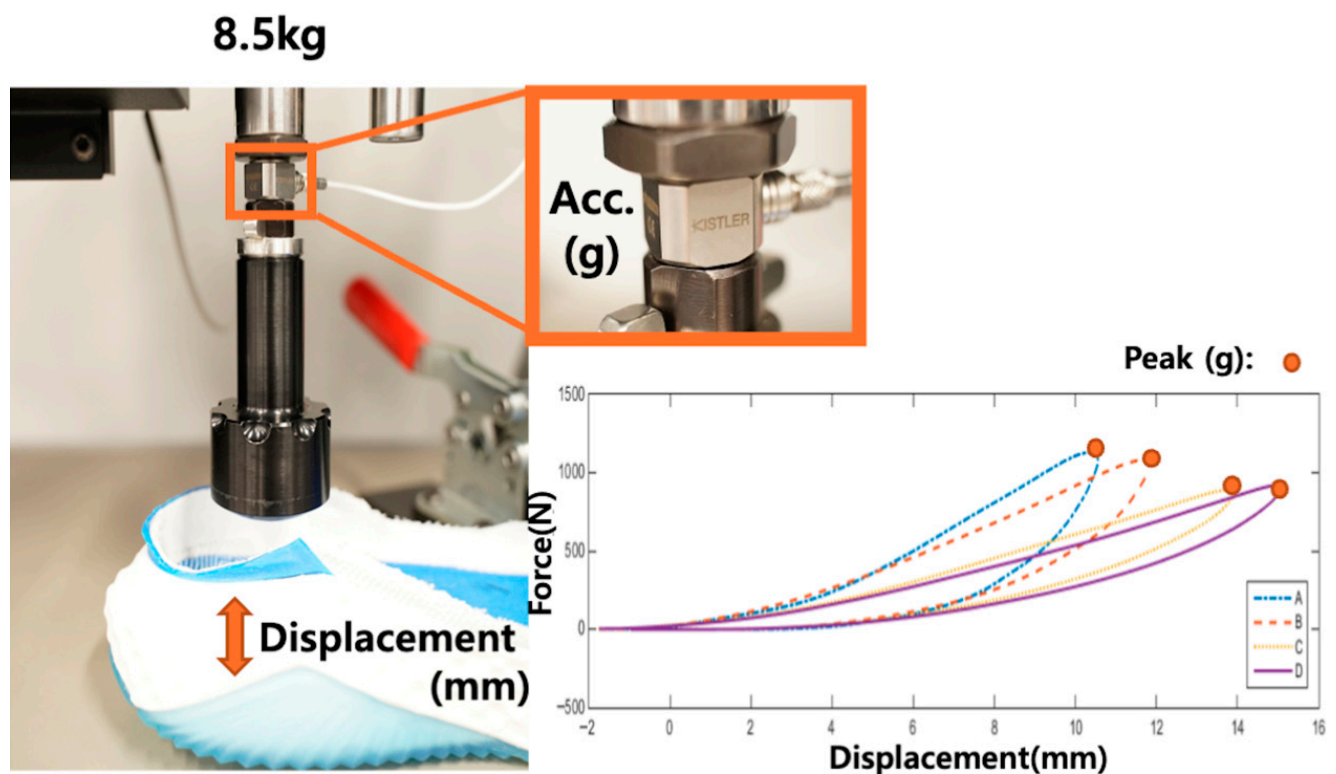


Figure 1. Mechanical tests were performed using an impactor on shoe models manufactured at different hardness levels (Shoe A: Asker-C 70, Shoe B: Asker-C 60, Shoe C: Asker-C 50, Shoe D: Asker-C 40). An 8.5 kg weight was attached to the piston.

Table 1. Variations in Mechanical Properties due to Cushioning.

Variables	Mean $\pm$ SD				F (p)	Post Hoc	Effect Size ($\eta_p^{2.7}$)	Statistical Power
	Shoe-A	Shoe-B	Shoe-C	Shoe-D				
Force (N)	1214.89 $\pm$ 25.97	1109.73 $\pm$ 7.51	971.41 $\pm$ 5.87	909.1 $\pm$ 5.55	296.25 (0.001)	A > B > C > D	0.98	1
Dwell Time (ms)	33.93 $\pm$ 1.92	37.12 $\pm$ 2.43	43.26 $\pm$ 1.29	45.4 $\pm$ 0.59	179.59 (0.001)	D > C > B > A	0.97	1
E Ret (%)	46.75 $\pm$ 1.32	56.01 $\pm$ 0.56	63.46 $\pm$ 0.42	65.69 $\pm$ 0.28	411.93 (0.001)	D > C > B > A	0.99	1
Displacement (mm)	10.35 $\pm$ 0.93	11.84 $\pm$ 1.1	14.43 $\pm$ 0.56	15.14 $\pm$ 0.28	164.61 (0.001)	D > C > B > A	0.97	1

E Ret = Energy Return.

2.3. Experimental Protocol of Biomechanical Test

To measure running in the subjects, 12 infrared cameras (Qualisys, Gothenburg, Sweden) were installed around a treadmill with an embedded force plate (Bertec, Columbus, OH, USA). They completed a pre-experimental consent form and performed movements with a full understanding of the experimental procedure. Then, four types of running shoes, whose properties were analyzed using mechanical tests, were randomly assigned for running trials. The subjects ran on the treadmill at speeds of 2.3 m/s (8.3 km/h) and 3.3 m/s (11.9 km/h) [16,29] for 1 min, and the five steps were analyzed. They had sufficient rest after transitioning from running shoes and performed the next running session.

2.4. Data Processing for Kinematic and Kinetic Variables

The force plate (2500 Hz) used to estimate the kinetic variables during running on the treadmill had analog voltage values in a total of six channels, which were converted into digital values through an A/D converter and output as three digital values (F_x , F_y , F_z , unit: N) within a QTM-analyzing program. F_x (right-left), F_y (anterior-posterior), and F_z (top-bottom) reflect values of different directions and show the degree of force in each direction. The kinematic variables measured by an infrared camera (250 Hz) were recorded using a local coordinate system relative to the global coordinate system. An L-shaped frame was installed on the +y axis in the direction of progression at the starting point in the analysis interval, and a calibration wand was used to set an analysis scope. Eighty-one reflective markers were attached to the surface of segments and joint points after wearing tights. A Butterworth 2nd-order low-pass filter was used to smooth the data collected from the force plate, reducing noise. The cutoff frequency was set to an accumulated rate of 99.9% in the Power Spectral Density (PSD). Kinetic data were normalized to body weight (i.e., N/kg and Nm/kg) for comparison. The analysis began after the heel of the subject's right foot touched the ground and reached 10 N. Among the data of one-minute recording, the 5-step was analyzed. Here, the time point of impact peak (IP) was set as Event 1, and the time to the maximum impact force (Maximum force) was set as Event 2.

2.5. Biomechanical Variables

2.5.1. Running Spatiotemporal Variables

Variations in running parameters were analyzed according to running shoe cushioning. The time from initial heel contact to toe off on the ground was estimated as the contact time; on this basis, running parameters were calculated.

2.5.2. Kinematic Variables of Running

Three-dimensional position data obtained via the reflective marker using an infrared camera were used as kinematic data. The position data were used to estimate the maximum and minimum angles and the range of motion of the hip, knee, and ankle joints through Cardan's three-dimensional angle estimation [30]. Variation between the point of heel-toe landing and the interval of the maximum ground reaction force was used as a variable for the displacement of CoM and leg length. The hip and knee joint angles had flexion set in the + direction, and the ankle joints had dorsi-flexion set in the + direction. Data were analyzed in the sagittal plane.

2.5.3. Kinetic Variables of Running

The initial impact force, occurring within 10 to 50 ms after heel-toe landing, was defined as the impact peak (IP). IP was then divided by time to estimate a slope, representing the loading rate (LR) at which impact is transferred to the human body [31]. In the ground

reaction force, the second maximum impact force was defined as the maximum force. The moments used in the kinetic analysis were estimated as inverse dynamics [32]. The hip and knee joints had the extension-flexion moment set in the + direction, and the ankle joints had the plantarflexion moment set in the + direction.

2.5.4. Vertical, Leg, and Joint Stiffness

The concept of stiffness originated in Hooke's Law, which describes the degree of deformation an object undergoes under a given force [24]. In biomechanics, body stiffness, as expressed by a mass-spring model, represents the body's elasticity, as muscles and tendons lengthen to store and release energy at toe-off during landing in running [33]. The mass-spring model defines the maximum force required to initiate motion as F , the displacement as X , and the stiffness constant as K [22]. Therefore, body stiffness was estimated from kinematic variations in CoM, leg length from the initial contact to the time of the maximum ground reaction force [16]. Here, leg length in estimating leg stiffness was set as the displacement between the greater trochanter and the lateral malleolus, and variation in displacement was used as leg length. Joint stiffness was calculated as the slope of the change in joint moment relative to the angular change during the stance phase (Figure 2).

$$K_{Joint} = \Delta M_{Joint} / \Delta \theta_{Joint} \quad (1)$$

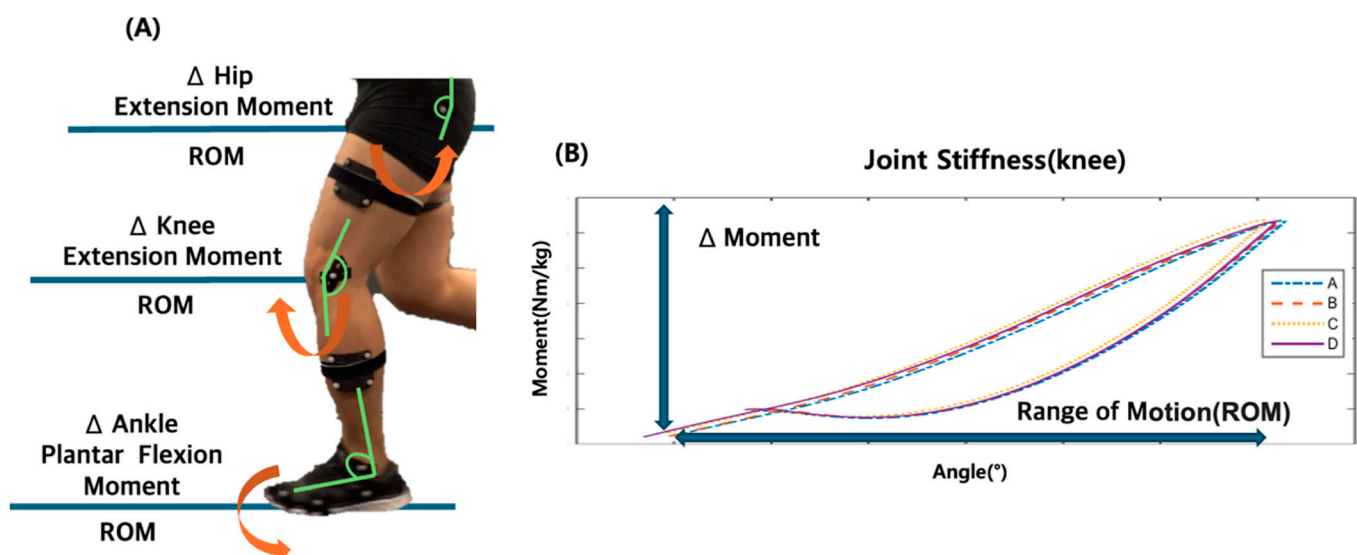


Figure 2. (A) Estimation of joint stiffness and (B) A time-series graph for joint stiffness during running.

2.6. Statistics

This study aimed to examine the effect of midsole hardness on the human body during running. The 5-step was analyzed from a one-minute running record. For statistical analysis, an SPSS program (Version 24.0; IBM Corp., Buffalo Grove, IL, USA) was used with one-way repeated measures (ANOVA). The Bonferroni post hoc test was used for η_p^2 , along with the effect size and statistical power. The significance level was set at 0.05 ($\alpha = 0.05$).

3. Results

3.1. Running Parameters

Table 2 shows the results of the running parameters, indicating no differences in any of the contact times (heel touching the ground), stride length, stride width, or stride time.

Table 2. Running Parameters of Four Running Shoes with Different Cushioning Types.

Variables	Speed	Mean $\pm$ SD				F (p)	Post Hoc	Effect Size (η_p^2)	Statistical Power
		Shoe A	Shoe B	Shoe C	Shoe D				
Contact Time (s)	2.3 m/s	0.30 $\pm$ 0.01	0.30 $\pm$ 0.01	0.30 $\pm$ 0.01	0.30 $\pm$ 0.01	0.944 (0.424)		0.038	0.248
	3.3 m/s	0.24 $\pm$ 0.01	0.24 $\pm$ 0.01	0.24 $\pm$ 0.01	0.24 $\pm$ 0.01	0.711 (0.548)		0.029	0.194
Step Length (cm)	2.3 m/s	86.69 $\pm$ 4.33	86.60 $\pm$ 4.7	86.15 $\pm$ 3.79	86.39 $\pm$ 4.25	0.426 (0.735)		0.017	0.131
	3.3 m/s	118.99 $\pm$ 6.27	119.38 $\pm$ 6.94	119.58 $\pm$ 6.04	119.33 $\pm$ 6.41	0.231 (0.894)		0.010	0.092
Stride Time (s)	2.3 m/s	0.75 $\pm$ 0.03	0.75 $\pm$ 0.04	0.74 $\pm$ 0.03	0.75 $\pm$ 0.03	0.426 (0.735)		0.017	0.131
	3.3 m/s	0.72 $\pm$ 0.03	0.72 $\pm$ 0.04	0.72 $\pm$ 0.03	0.72 $\pm$ 0.03	0.231 (0.874)		0.010	0.092
Stride Length (cm)	2.3 m/s	173.38 $\pm$ 8.67	173.21 $\pm$ 9.41	172.31 $\pm$ 7.58	172.78 $\pm$ 8.50	0.426 (0.735)		0.017	0.131
	3.3 m/s	237.98 $\pm$ 12.55	238.76 $\pm$ 13.89	239.16 $\pm$ 12.08	238.67 $\pm$ 12.82	0.231 (0.874)		0.010	0.092

3.2. Kinematics of Running Biomechanics

Table 3 shows the kinematic results for a human body with running shoe cushioning; as midsole cushioning increased, no significant differences were observed in CoM displacement and leg-length variation. In contrast, the maximum ankle angle (2.3 m/s: $F = 35.283$, $p = 0.001$; 3.3 m/s: $F = 36.18$, $p = 0.001$) and the range of motion for ankles (2.3 m/s: $F = 13.170$, $p = 0.001$; 3.3 m/s: $F = 8.587$, $p = 0.001$) differed significantly. The post hoc test found that ankle range of motion was low in shoes with soft cushioning (Shoe D) at 3.3 m/s. It also found that the maximum ankle angle was larger for Shoe A than for Shoes C or D at 2.3 m/s, and smaller for Shoe D than for Shoes B or C ($F = 36.18$, $p = 0.001$) at 3.3 m/s. The minimum knee angle was smallest for the softest shoes during 3.3 m/s running.

Table 3. Kinematic Variables of Four Different Running Shoe Cushioning Types.

Variables	Speed	Mean $\pm$ SD				F (p)	Post Hoc	Effect Size (η_p^2)	Statistical Power
		Shoe A	Shoe B	Shoe C	Shoe D				
Leg-Length (cm)	2.3 m/s	16.96 $\pm$ 1.44	17.10 $\pm$ 1.74	17.22 $\pm$ 2.09	17.49 $\pm$ 1.68	0.64 (0.592)		0.026	0.178
	3.3 m/s	16.96 $\pm$ 1.44	17.10 $\pm$ 1.74	17.22 $\pm$ 2.09	17.49 $\pm$ 1.68	1.302 (0.281)		0.032	0.176
Displacement of COM (cm)	2.3 m/s	6.74 $\pm$ 0.66	6.74 $\pm$ 0.79	6.76 $\pm$ 0.75	6.88 $\pm$ 0.77	0.976 (0.409)		0.039	0.256
	3.3 m/s	6.36 $\pm$ 0.70	6.35 $\pm$ 0.71	6.40 $\pm$ 0.74	6.54 $\pm$ 0.75	2.32 (0.083)	-	0.088	0.562
Max Hip Flex. (°)	2.3 m/s	28.41 $\pm$ 5.31	28.27 $\pm$ 5.80	27.92 $\pm$ 5.57	27.99 $\pm$ 5.31	0.629 (0.599)		0.026	0.175
	3.3 m/s	32.85 $\pm$ 5.56	33.13 $\pm$ 5.77	32.19 $\pm$ 5.83	32.38 $\pm$ 5.12	2.061 (0.113)		0.083	0.532
Min Hip Flex. (°)	2.3 m/s	24.70 $\pm$ 5.86	24.03 $\pm$ 5.86	24.13 $\pm$ 5.76	23.98 $\pm$ 5.28	3.018 (0.035)	A > D	0.112	0.688
	3.3 m/s	26.94 $\pm$ 6.09	26.99 $\pm$ 5.68	26.27 $\pm$ 6.10	26.15 $\pm$ 5.61	1.637 (0.188)		0.064	0.412
ROM Hip Joint (°)	2.3 m/s	3.74 $\pm$ 1.30	4.17 $\pm$ 1.75	3.78 $\pm$ 1.47	3.99 $\pm$ 1.49	2.43 (0.072)		0.092	0.583
	3.3 m/s	5.74 $\pm$ 2.42	5.98 $\pm$ 2.37	5.74 $\pm$ 2.16	6.24 $\pm$ 2.21	0.606 (0.613)		0.025	0.170
Max Knee Flex. (°)	2.3 m/s	38.94 $\pm$ 3.57	38.90 $\pm$ 4.01	38.53 $\pm$ 3.65	38.37 $\pm$ 4.01	1.281 (0.288)		0.051	0.328
	3.3 m/s	41.27 $\pm$ 4.16	41.18 $\pm$ 4.08	40.65 $\pm$ 4.59	40.88 $\pm$ 3.94	1.430 (0.241)		0.052	0.336
Min Knee Flex. (°)	2.3 m/s	8.86 $\pm$ 4.68	8.94 $\pm$ 4.54	8.34 $\pm$ 4.29	7.82 $\pm$ 4.16	2.296 (0.085)		0.087	0.556
	3.3 m/s	10.03 $\pm$ 3.82	10.00 $\pm$ 4.50	10.04 $\pm$ 4.26	8.63 $\pm$ 4.53	9.089 (0.001)	A, B, C > D	0.275	0.995
ROM Knee Joint (°)	2.3 m/s	30.07 $\pm$ 4.47	29.96 $\pm$ 4.38	30.19 $\pm$ 4.22	30.53 $\pm$ 4.15	0.516 (0.673)		0.021	0.150
	3.3 m/s	31.22 $\pm$ 4.31	31.16 $\pm$ 4.34	30.58 $\pm$ 4.13	32.16 $\pm$ 4.48	4.915 (0.004)	D > A, B, C A > C	0.170	0.895
Max Ankle Dorsiflex (°)	2.3 m/s	22.40 $\pm$ 2.84	22.22 $\pm$ 3.04	21.79 $\pm$ 2.75	20.20 $\pm$ 3.08	35.283 (0.001)	A > C, D B, C > D	0.595	1
	3.3 m/s	23.91 $\pm$ 3.12	23.65 $\pm$ 3.00	23.21 $\pm$ 3.28	21.78 $\pm$ 3.20	36.18 (0.001)	A > C, D B, C > D	0.337	1
Min Ankle Dorsiflex (°)	2.3 m/s	7.05 $\pm$ 2.50	6.82 $\pm$ 2.61	7.48 $\pm$ 2.57	6.30 $\pm$ 2.82	3.516 (0.019)	-	0.128	0.761
	3.3 m/s	5.44 $\pm$ 2.56	5.32 $\pm$ 2.40	5.85 $\pm$ 2.93	4.86 $\pm$ 2.85	2.481 (0.068)	-	0.094	0.593
ROM Ankle Joint (°)	2.3 m/s	15.34 $\pm$ 2.14	15.39 $\pm$ 2.24	14.30 $\pm$ 2.27	13.89 $\pm$ 2.03	13.170 (0.001)	A, B > C, D	0.354	1
	3.3 m/s	18.46 $\pm$ 3.34	18.32 $\pm$ 2.89	17.35 $\pm$ 2.84	16.92 $\pm$ 2.87	8.587 (0.001)	A, B > D	0.264	0.992

Max: Maximum, Min: Minimum, ROM: Range of Motion, Flex.: Flexion, Dorsiflex: Dorsiflexion, COM: Center of Mass.

3.3. Kinetics of Running Biomechanics

The variables affecting the human body from midsole cushioning are as follows (Table 4): As hardness decreased, the impact peak differed between the two speeds. The post hoc test found that it was larger for Shoes C and D than for Shoes A and B in case of 2.3 m/s ($F = 8.44$, $p = 0.001$). The loading rate was lowest for the softest cushion in both speeds (2.3 m/s: $F = 16.78$, $p = 0.001$; 3.3 m/s: $F = 15.48$, $p = 0.010$). There was no difference in the maximum ground reaction force across shoe cushioning types. Greater ankle joint moment was shown for shoes with higher values for Shoe B than for Shoes A and D in both speeds (2.3 m/s: $F = 7.32$, $p = 0.001$; 3.3 m/s: $F = 4.41$, $p = 0.001$).

Table 4. Kinetic Variables of Four Different Running Shoe Cushioning Types.

Variables	Speed	Mean $\pm$ SD				F (p)	Post Hoc	Effect Size (η_p^2)	Statistical Power
		Shoe A	Shoe B	Shoe C	Shoe D				
Impact Peak (N/kg)	2.3 m/s	14.83 $\pm$ 2.22	15.06 $\pm$ 2.26	16.08 $\pm$ 2.38	15.86 $\pm$ 2.13	8.44 (0.001)	C, D > A, B	0.840	1
	3.3 m/s	18.98 $\pm$ 2.86	19.62 $\pm$ 2.91	20.28 $\pm$ 3.09	19.14 $\pm$ 2.31	2.53 (0.009)		0.096	0.456
Loading Rate ((N/kg)/sec)	2.3 m/s	364.41 $\pm$ 55.13	354.03 $\pm$ 66.23	329.05 $\pm$ 61.63	306.03 $\pm$ 42.82	16.78 (0.001)	A, B > C, D C > D	0.402	1
	3.3 m/s	535.92 $\pm$ 90.77	505.98 $\pm$ 94.29	497.63 $\pm$ 96.47	436.1 $\pm$ 72.61	15.48 (0.010)		0.392	1
Max Vertical Force (N/kg)	2.3 m/s	23.11 $\pm$ 1.76	23.23 $\pm$ 1.18	23.58 $\pm$ 1.87	23.47 $\pm$ 1.31	2.164 (0.100)		0.083	0.529
	3.3 m/s	26.20 $\pm$ 1.73	26.16 $\pm$ 1.99	26.59 $\pm$ 2.12	26.29 $\pm$ 1.73	0.972 (0.411)		0.040	0.220
Δ Hip Extension Moment (Nm/kg)	2.3 m/s	1.01 $\pm$ 0.28	1.01 $\pm$ 0.27	1.02 $\pm$ 0.29	0.99 $\pm$ 0.28	0.500 (0.684)		0.180	0.469
	3.3 m/s	0.94 $\pm$ 0.25	0.96 $\pm$ 0.29	0.99 $\pm$ 0.32	0.93 $\pm$ 0.28	1.952 (0.129)		0.750	0.484
Δ Knee Extension Moment (Nm/kg)	2.3 m/s	2.33 $\pm$ 0.29	2.34 $\pm$ 0.31	2.34 $\pm$ 0.31	2.33 $\pm$ 0.32	0.035 (0.991)		0.001	0.056
	3.3 m/s	2.70 $\pm$ 0.39	2.70 $\pm$ 0.37	2.73 $\pm$ 0.42	2.68 $\pm$ 0.39	0.622 (0.603)		0.026	0.180
Δ Ankle Plantar Flexion Moment (Nm/kg)	2.3 m/s	1.98 $\pm$ 0.26	2.08 $\pm$ 0.32	2.02 $\pm$ 0.29	1.96 $\pm$ 0.31	7.32 (0.001)	B > A, D	0.234	0.980
	3.3 m/s	2.47 $\pm$ 0.32	2.55 $\pm$ 0.36	2.48 $\pm$ 0.39	2.44 $\pm$ 0.34	4.41 (0.001)		0.090	0.897

3.4. Body-Stiffness During Running

Body stiffness by running shoe cushioning is as follows (Table 5) (Figure 3): Knee stiffness lowered in the softest midsole ($F = 4.479$, $p = 0.006$). The Post Hoc test found that knee stiffness was lowest for Shoe D than Shoes A, B, C. In addition, the result showed that the softer midsoles are related to the higher ankle stiffness in both speeds (2.3 m/s: $F = 5.268$, $p = 0.002$; 3.3 m/s: $F = 2.78$, $p = 0.047$). The Post Hoc test found that ankle stiffness was higher for Shoes C and D than for Shoe A in both speeds (Figure 4).

Table 5. Vertical, Leg, and Joint Stiffness of Four Different Running Shoe Cushioning Types.

Variables	Speed	Mean $\pm$ SD				F (p)	Post Hoc	Effect Size (η_p^2)	Statistical Power
		Shoe A	Shoe B	Shoe C	Shoe D				
V_Stiffness ((N/kg)/cm)	2.3 m/s	3.47 $\pm$ 0.37	3.49 $\pm$ 0.42	3.52 $\pm$ 0.35	3.45 $\pm$ 0.39	0.681 (0.567)	-	0.028	0.187
	3.3 m/s	4.19 $\pm$ 0.40	4.16 $\pm$ 0.44	4.20 $\pm$ 0.50	4.06 $\pm$ 0.42	2.625 (0.057)		0.099	0.622
L_Stiffness ((N/kg)/cm)	2.3 m/s	1.59 $\pm$ 0.21	1.59 $\pm$ 0.24	1.63 $\pm$ 0.23	1.60 $\pm$ 0.23	1.211 (0.312)		0.048	0.312
	3.3 m/s	1.56 $\pm$ 0.17	1.55 $\pm$ 0.22	1.57 $\pm$ 0.26	1.52 $\pm$ 0.18	1.15 (0.335)		0.046	0.258
Ankle_Stiffness ((Nm/kg)/°)	2.3 m/s	0.13 $\pm$ 0.02	0.14 $\pm$ 0.03	0.15 $\pm$ 0.03	0.15 $\pm$ 0.03	5.268 (0.002)	A < C, D	0.180	0.916
	3.3 m/s	0.14 $\pm$ 0.03	0.14 $\pm$ 0.03	0.15 $\pm$ 0.03	0.15 $\pm$ 0.03	2.78 (0.047)		0.104	0.650
Knee_Stiffness ((Nm/kg)/°)	2.3 m/s	0.09 $\pm$ 0.01	0.09 $\pm$ 0.01	0.089 $\pm$ 0.01	0.089 $\pm$ 0.01	0.834 (0.480)		0.034	0.222
	3.3 m/s	0.10 $\pm$ 0.01	0.10 $\pm$ 0.01	0.10 $\pm$ 0.01	0.09 $\pm$ 0.01	4.479 (0.006)		0.060	0.768
Hip_Stiffness ((Nm/kg)/°)	2.3 m/s	0.47 $\pm$ 0.52	0.41 $\pm$ 0.35	0.43 $\pm$ 0.33	0.37 $\pm$ 0.20	1.751 (0.180)		0.068	0.347
	3.3 m/s	0.29 $\pm$ 0.31	0.29 $\pm$ 0.20	0.26 $\pm$ 0.20	0.22 $\pm$ 0.13	1.15 (0.320)		0.460	0.238

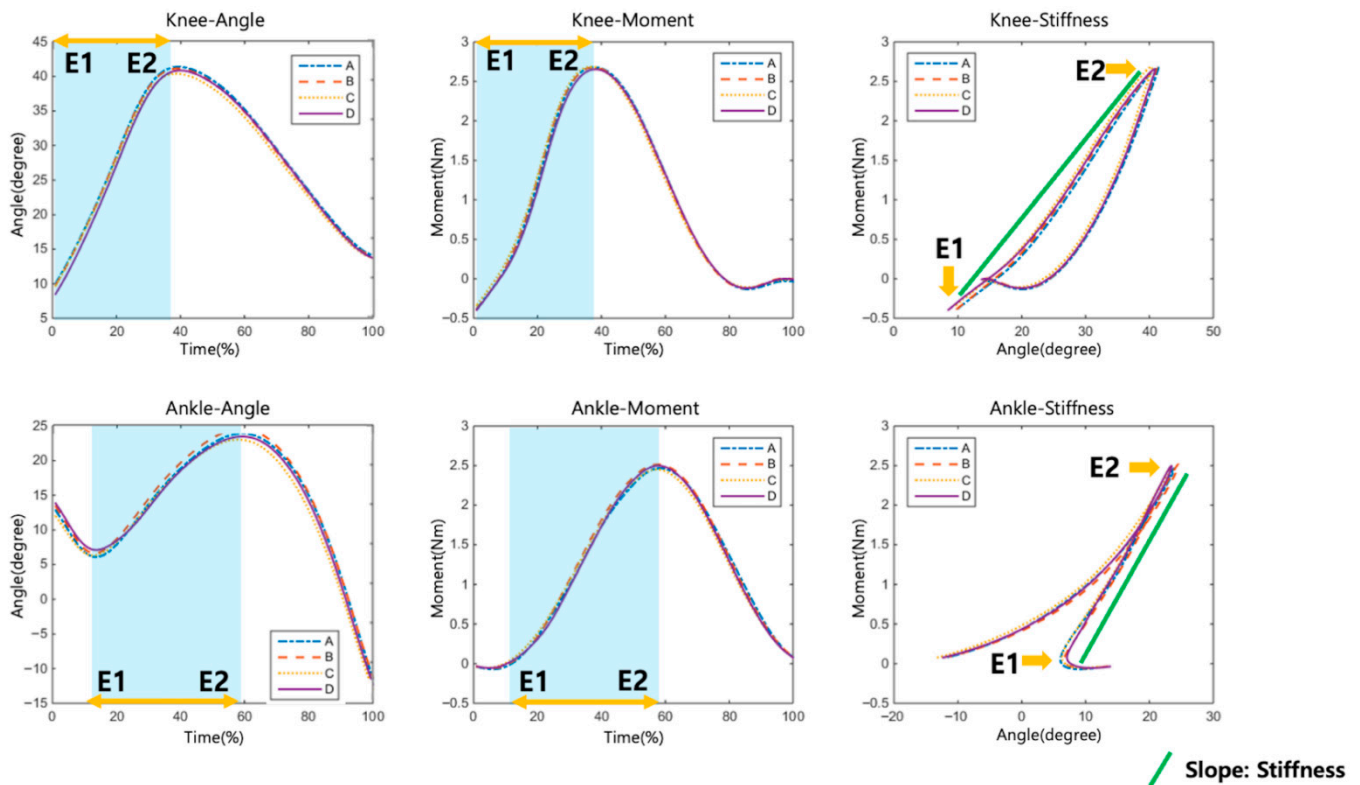


Figure 3. Time-series graph for knee and ankle angle, moment, and stiffness by running shoe cushioning for running (3.3 m/s).

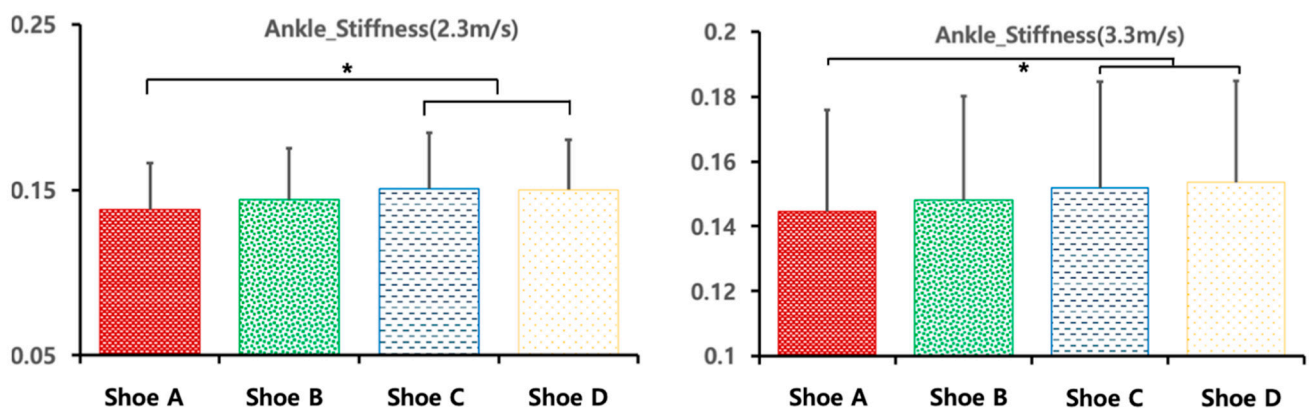


Figure 4. Bar graph for ankle stiffness among Running Shoe Cushioning Types (Left: 2.3 m/s, Right: 3.3 m/s). * indicates a statistically significant difference ($p < 0.05$).

4. Discussion

Humans experience a wide range of impacts on their bodies during running. It is reported that repeated high-impact activities increase the risk of musculoskeletal injuries, including soft-tissue injuries, knee arthritis, and stress fractures [2–5]. Thus, running shoe midsole cushioning is a frequently addressed topic because it relates to impact as a risk factor during landing and to exercise performance [34]. In particular, it was reported that variations in the kinetic and kinematic parameters, including impact force to the human body induced by midsole cushioning, were due to differences in the mechanical properties of running shoes [14]. Therefore, the purpose of this study was to investigate the effect of running shoe midsole cushioning on kinetic and kinematic responses of the human body during running.

4.1. The Effect of Running Shoe Cushioning on Running Parameters and Body Stiffness

First, there was no difference in running variables across midsole cushioning conditions. In addition, no differences were found in maximum force or CoM displacement across different cushioning levels in shoes during running. Previous research reported that individuals might try to maintain a constant load by adjusting their running pattern in response to external surface conditions [35,36]. As surface condition (i.e., cushioning) varies, the level of stability fluctuates; the human body can adapt to these fluctuations by adjusting movements and controlling impact [18–21]. The load on the human body, especially at the joints, is influenced by the mass of body segments and running kinematics [15,37]. Based on these results, although changes in surface condition caused instability, adaptations in body movements demonstrated no difference in running variables, including maximum force and CoM displacement.

A study found that subjects with high-hardness shoes were not affected by the maximum force [36]. The effects of three shoe hardness levels (Asker-C 46, 51, 55) on the human body were examined, revealing no significant differences in maximum force or COM displacement, consistent with the results of this study [38]. Body stiffness can be calculated as the maximum force divided by the CoM displacement during the stance phase of running [23]. The study states that variations in midsole hardness at the whole-body level may not have sufficient impact to alter the overall impact magnitude, because humans tend to maintain whole-body stiffness in response to changing external loads, and it also demonstrates how humans adapt to changing midsole cushioning by adjusting their body stiffness to reduce overall impact. The impact on the body can depend on the sole material or footwear type; here, body stiffness indicates whether an individual has landed rigidly or softly, based on the force transmitted to the body and the resulting movements. As for leg stiffness, a mass-spring model captures the shortening and lengthening associated with the flexion and extension of lower-body joints through the energy conservation and release process [33]. Therefore, it has been suggested that leg or joint stiffness, as modeled by the mass-spring model, is a more specific variable that reflects energy storage and release during the stretch–shorten cycle (SSC) [39].

Kinematic differences between soft and hard midsoles were examined, revealing that rigid midsoles resulted in lower leg stiffness than soft midsoles, while both conditions reached the same maximum force, an indicator of leg stiffness due to compensatory strategy in joint angles, angular velocities, and muscle activity during landing [15]. In addition, surface stiffness variation can cause leg stiffness variation to maintain a constant combined stiffness between the runner and the surface; this concept of leg stiffness is not an adaptation of a specific joint but reflects whole-body responses [40]. Therefore, variations in joint angles and moments at each joint can lead to joint stiffness, thereby contributing to lower extremity stiffness [41,42]. It is therefore necessary to investigate the landing mechanism by examining joint stiffness.

4.2. Impact Force of Running According to Running Shoe Cushioning Types

This study found that as midsole cushioning increased, the impact peak increased significantly. A heel-toe landing causes rapid deceleration of the lower extremities, resulting in an impact peak associated with shock [1,31]. The shock from a sudden slowdown is transmitted to the body, increasing the risk of injury and overuse. Kinetic variables during running with hard shoes were investigated, revealing significant differences in impact peak [13]. Although soft midsoles are generally expected to reduce the impact peak transmitted to the body, recent research has reported that softer midsoles increase this force. Lower midsole hardness in running shoes has been found to increase the impact peak, consistent with the results of this experiment [13,16,38]. In other words, a too

highly cushioned midsole may instead transfer greater impact to the body, contributing to overuse and soft-tissue injuries. The impact peak is correlated with tibial impact shock [43]. Furthermore, a frequency analysis of impact shock indicates high-frequency components resulting from the rapid movement of the lower extremities. In contrast, low-frequency components indicate the passive movement of soft tissues in the legs [44–46]. Therefore, it is further required to use an accelerometer to assess shock magnitude in frequency analysis to understand the mechanics of different types of joint injuries.

This study found that as midsole hardness decreased, the loading rate decreased. Kinetic variables were analyzed in relation to variations in midsole hardness among 849 adult participants, revealing that lower midsole hardness was associated with lower loading rates, consistent with the results of this study [38]. It is well known that an increase in running speed results in a higher loading rate, as the body load increases accordingly [31]. However, in this study, although softer cushioning increased the initial impact peak and body load, the loading rate decreased because the time to reach the impact peak was longer. It was determined that the reduced loading rate was due to the increased time to impact peak at a low level of hardness [29,47]. According to previous research, the mechanical test showed that midsole hardness increased by 16% after four months of running shoe use. Running in those shoes can also increase injury risk by increasing load, as the impact peak can occur earlier [17]. This suggests that the lower loading rate associated with soft cushioning in shoes may help reduce the risk of joint injuries. Furthermore, simulation research involving two participants demonstrated that running in stiffer shoes increases distal tibial contact forces and ankle dorsiflexion and its angular velocity [48]. The authors also reported that a hard midsole leads to a higher loading rate of the ground reaction force and that this rapid loading can elevate dorsiflexion velocity during early stance. As a result, the plantar flexors may undergo faster lengthening, thereby experiencing greater eccentric loading. These findings further support the notion that midsole mechanical properties can meaningfully influence lower extremity loading patterns.

4.3. The Effect of Running Shoe Cushioning Types on Joint Stiffness

In the present study, increased midsole cushioning was associated with higher ankle joint stiffness and lower knee joint stiffness during running. A previous study indicated that increased midsole cushioning was associated with increased ankle joint stiffness during running [16], which is consistent with our findings. Despite running in highly cushioned shoes, no significant differences were observed in maximum force, vertical and leg stiffness, or center-of-mass displacement. This suggests that runners may regulate their movement by adjusting joint stiffness to maintain consistent overall mechanics. One study using principal component analysis reported that midsole cushioning primarily affects ankle and knee kinematics in the sagittal plane, while exerting comparatively minor effects on hip or frontal-plane knee motions [43]. In agreement with this evidence, our results showed differences in joint stiffness mainly at the ankle and knee rather than at the pelvis. In particular, the observed decrease in knee joint stiffness may reflect a compensatory adjustment in which increased ankle stiffness helps regulate whole-body stiffness, thereby reducing knee stiffness.

Adjustment of joint stiffness during running is a neuromuscular phenomenon achieved through pre-activation of muscles before foot contact and through co-contraction of agonist–antagonist muscle pairs during the stance phase [15]. Joint stiffness can be calculated not only through quasi-stiffness but also using EMG-based approaches. Previous research has suggested that increased muscle pre-activation before landing may stiffen the ankle and, as a result, lead to a higher impact peak even when wearing softer midsoles [49]. The authors further noted that under predictable landing conditions, such as running, this anticipatory

neuromuscular strategy may diminish the mechanical benefits of cushioning [14,38]. The increased impact peak observed in the softer midsole condition in our study may therefore reflect this neuromuscular mechanism.

It is known that joint motion modification may affect the magnitude of the body's impact during running [40]. The study explained that kinematic variations likely alter the impact by adjusting foot inversion, ankle dorsiflexion, and knee flexion. The maximum dorsiflexion angle and velocity were greater in the stiff midsole condition than in the soft midsole condition. Therefore, when the tibia rotates rapidly, the plantar flexor muscles that act to decelerate this motion may produce higher internal forces, which in turn could contribute to increased ankle joint contact forces [48].

The repeated impact may cause overuse injury; in particular, the site where the Achilles tendon is attached to the calcaneus (Sever's disease) and the site where the patellar tendon is attached to the tibial tubercle (Osgood-Schlatter disease) are most common [17]. These pathologies are caused by repeated impacts that generate compressive and tensile forces, as well as by excessive tendon traction on the apophysis [17]. Chronic overloading is not sufficient to cause acute injury; instead, it refers to injury resulting from loads accumulated over time [5]. In this study, a soft midsole reduced ankle dorsiflexion, thereby increasing ankle stiffness. On the other hand, decreased knee stiffness was observed with a soft midsole, while whole-body stability during running was maintained, with no changes in body or leg stiffness.

4.4. Difference Between Mechanical Test and Biomechanical Variables of Running

In this study, mechanical tests were performed on shoes with different levels of cushioning, adjusted by varying hardness (Asker C-70, 60, 50, 40), a factor that affects cushioning in running shoes. The free-fall test with an 8.5 kg weight on the shoes' midsoles at four levels of hardness found that the lower the hardness (i.e., the greater the cushioning), the higher the dwell time, energy return, and displacement, and the lower the force. This is because the lower the hardness level, the longer and deeper the contact between the weight and the midsole. The midsole became softer, less stiff, and more effective in reducing impact. A running experiment was conducted by categorizing running shoe cushioning types from different brands into "good" and "common" levels, with the noted limitation that the mechanical properties of the midsole cushioning were not measured [14]. They indicated that they had difficulty determining which midsole properties affected the human body in the experiment because running shoes varied in materials, thickness, and shape. They contended that a mechanical test should be conducted to quantify the mechanical properties of running shoes with a running experiment [50].

5. Conclusions

This study aimed to determine the effects of midsole hardness on body impact and body stiffness. The results indicate that runners tend to increase distal joint stiffness (specifically at the ankle joint) by 6.7% when using softer midsoles (as seen in shoes C and D at a speed of 3.3 m/s), while also reducing proximal joint stiffness (specifically at the knee joint) by 10.0% in shoe D at the same speed compared to shoe C. This behavior suggests a neuromuscular strategy employed to maintain dynamic stability during running. These findings demonstrate that midsole cushioning influences not only impact-related variables but also the neuromuscular regulation of joint stiffness. This highlights the importance of achieving an appropriate balance between cushioning and support of the shoes to enhance comfort, maintain running efficiency, and potentially reduce fatigue and injury risk. Future research should explore a broader range of cushioning levels and include participants with

diverse characteristics (e.g., sex, age, and running experience) to identify optimal midsole properties that minimize mechanical load while supporting performance.

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