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Do the Mechanical Properties of Midsole Affect Body Shock and Stabilization for Lower Extremity During Running?

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Objective: The purpose of this study is to examine the relation between the mechanical properties of midsole and stabilization strategies for lower extremity during running.

Background: Since stabilization strategies for a human body are to be adjusted according to the mechanical properties of the shoes, such properties of shoes that a runner wears need to be taken into consideration.

Method: Mechanical characteristics regarding the midsole cushioning properties (thickness [mm], dwell time [ms], peak acceleration [g], and energy return [%]) of each shoe were investigated by means of an impact tester. Twelve-male participated in the biomechanical experiment. They wore 12 different shoes and ran on the treadmill. To examine the relation between the mechanical properties of midsole and biomechanical variables during running, Pearson's correlation coefficient was referenced.

Results: It turned out that the shoe thickness, dwell time, and peak acceleration were in correlation with one another. During running, the initial maximum vertical ground reaction force (GRF), the Initial peak time of vertical GRF, the loading rate, the cross timing of the braking and propulsion were in correlation with mechanical properties of midsole. The inversion-eversion angle of the ankle joint at the moment of toe off was in correlation with the thickness. The internal rotation-external rotation angle of the knee joint at heel contact was in correlation with the dwell time.

Conclusion: While the thickness and dwell time of midsole play positive roles in reducing shock on a human body, there is a significant possibility that they affect the stabilization of the joint of the lower extremity negatively.

Application: Midsole thickness and dwell time may reduce the impact on the lower extremity.

Keywords: Thickness, Peak acceleration, Dwell time, Energy return, Shoe cushioning

1. Introduction

A human body perceives and recognizes environmental changes, learning from a course of activity and adjusting motions accordingly (Shumway-Cook and Woollacott, 2012). In order to move efficiently during running without being exposed to risk factors, the physical intelligence that helps stabilize the joints of the lower extremity needs to be developed (Cook et al., 1990; Taunton et al., 2003; Yen et al., 2015). In addition to that, one significant environmental factor is the shoes to be worn, and a human body is affected by various mechanical properties of shoes (Lam et al., 2019; Lam et al., 2017; Morio et al., 2009). Previous research shows that even if the mechanical properties of shoes change as its hardness deteriorates, a human body adjusts its motions and changes running patterns in order to cope with external loads in the same manner (Kong et al., 2009). It is also reported, however, that such pattern changes cause significant contribution to lower extremity injuries (Cook et al., 1990; Taunton et al., 2003).

It turns out that depending on the hardness differences of the midsole, there is a difference between soft and hard shoes during running in terms of load applied to the joint of the lower extremity, ankle joint range of motion, plantar pressure, ground reaction force (GRF), and loading rate (Agresta et al., 2018; Baltich et al., 2015; Kulmala et al., 2018; Lam et al., 2019; Lam et al., 2017; Meardon et al., 2018; Nigg et al., 1987). Such difference may be explained as a relative strategy to adjust the extent of the shock or the stability of the lower extremity (De Clercq et al., 1994). Therefore, such mechanical properties of shoes must be considered, along with other relevant factors in running, since different strategies of stabilizing movement for a human body are applied depending on the mechanical properties of the shoes.

Shoes are designed to reduce the external shock applied repeatedly to the human body and protect the feet from it. In recognition of the purposes of shoes, many previous studies have quantified and reported shocks applied to a human body during running, as well as hardness which is a cushion-related mechanical property (Lam et al., 2019; Lam et al., 2017; Meardon et al., 2018; Morio et al., 2009; Nigg et al., 1987), peak acceleration (Kurz and Stergiou, 2004), heel thickness, stiffness, and bending stiffness (Agresta et al., 2018). However, there can be differences among studies since the applied criteria of mechanical properties are varied.

It is reported that the hardness of midsole affects shock dispersion regardless of the length of use (Lam et al., 2019). Nonetheless, most previous studies focus on the hardness of midsole while there has been little research on the different ways that a human body copes with the variations of shoes' mechanical properties in relation to shock absorption. Further, as previous studies examine ankle joints only, it is necessary to analyze how such properties affect knee joints where injuries during running occur most frequently (Taunton et al., 2003). Accordingly, the aim of this study is to examine the relation between the mechanical properties of midsole and stabilization strategies for lower extremity during running.

2. Methods

2.1 Participants

Twelve recreational rear-foot-strike runners (age: 22.0±3.3yrs, height: 177.2±4.1cm, weight: 74.3±9.6kg, footwear size: 270mm) volunteered for this study. They answered specific questions regarding their training pace and past injury history. All the runners were fully informed of the procedures and possible risks of the experiment, and they gave their written agreement to participate in this study.

2.2 Procedures

Twelve pairs of shoes of different structures were procured from 8 different brands (Figure 1; FILA, Nike, Asics, Adidas, Under Armour, Mizuno, K2, Black Yark). The size for all the samples was 270mm. First of all, mechanical characteristics, specifically midsole cushioning properties, were measured (Figure 2) and then the biomechanical running experiment followed. The experiment was completed within 3 days so that the midsole properties would not be affected with temperature and humidity under control (temperature: 23.3˚, humidity: 32.0%).

Figure 1. Shoe condition (8 Brands)

As for the mechanical characteristics, midsole cushioning properties were measured with all the uppers removed to obtain pure midsole characteristic and by means of an impact tester (CompITS v5.0, Exeter Research, Inc., USA). With the sampling ratio set to 3,000Hz, the thickness [mm], peak acceleration [g], dwell time [ms], and energy return [%] were measured. Thickness was measured using a caliper. To quantify the other variables, the missile (weight: 8.5kg, diameter: 45mm) was dropped 50mm above the heel and around the spot 12% from the heel to the toe (Figure 2; Determan et al., 2009).

Dwell time means as the total time that the missile head is in contact with the sample during impact and rebound. In this study, dwell time is defined as shock absorption that absorbs external impact forces (Exeter Research, 2019). The peak acceleration during impact expressed in gravitational force. Energy Return is explained as a percentage of impact energy returned to the missile as it rebounds after striking the sample material.

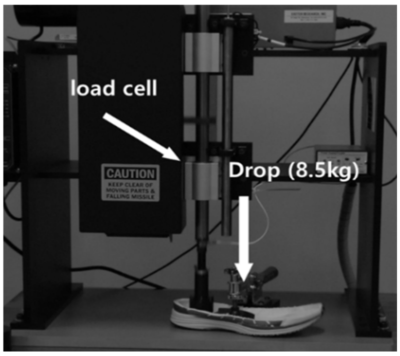

Figure 2. Mechanical drop test

To analyze motions in the running experiment, 8 infrared cameras (Miqus 3, Qualysis, Sweden; sampling rate: 120Hz) and a treadmill (Instrumented Treadmill, Bertec, USA; sampling rate: 1,200Hz) were used. To model the body segments, 19 reflective markers (right leg: 1; thigh: 4, shank: 4, knee joint: 2, ankle joint: 2, shoe: 7; Qualysis, Sweden) were attached on the subject (Figure 3). After warming up, every subject was given one of the 12 pairs of shoes in a random-selected order and was asked to run on the treadmill at 3.5m/s (Gil et al., 2018; Ueda et al., 2016). Data of 60 strides were collected during 2 minutes of running. Subjects were then given a time of rest for 5 minutes. While data was collected, the Qualisys Track Manager (Qualysis, Sweden) was utilized for every pair of shoes.

Figure 3. Marker set and biomechanical running test

2.3 Data processing

As for the mechanical (cushioning) properties of midsole, the automatic algorithm used in CompITS v5.0 software was utilized to derive results.

For analysis, running motions were classified into 3 events (heel strike, midstance, toe off) and 4 phases (braking, propulsion, stance, swing). The event of midstance was defined as the transition timing of the pre-post impulse $\int_{t1}^{t2} \mathrm{Fdt}$ (Schilling et al., 2008) variable during a single stance where the deceleration phase was Fy and the propulsion phase was Fy-1. Matlab2019b (The Mathworks, Inc., USA) was utilized to calculate the vertical GRF, loading rate, impulse, cross time of deceleration and acceleration, and ankle/knee joint angle. To calculate the joint angle, the Joint Coordination System (JCS) of Cardan/Euler principle was utilized on the basis of the marker coordinate (Figure 4). The ankle joint is defined as follows: Dorsi Flexion (+), Plantar Flexion (−), Inversion (+), Eversion (−), Adduction (+), Abduction (−). The knee joint is defined as follows: Flexion (+), Extension (−), Adduction (+), Abduction (−), Internal Rotation (+), External Rotation (−).

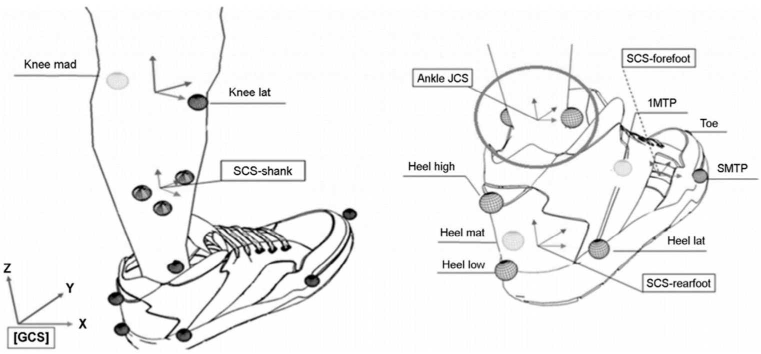

Figure 4. Joint coordination system (Gil et al., 2018)

2.4 Statistics

In order to analyze the relation between the mechanical characteristics (cushioning properties) of midsole and bio-mechanical variables observed during running, Pearson's correlation coefficient was utilized. Matlab2009b software was used for analysis, and the significant level was set to α = .05.

3. Results

This study aims to examine the effects of the mechanical characteristics of midsole on shock impact variables and kinetic movements of ankle and knee joints during running. To this end, the correlation coefficient between the two following items were calculated: 1) mechanical measurements of midsole thickness, dwell time, peak acceleration, and energy return (Table 1) 2) biomechanical impact variables, ankle joint angle, and knee joint angle.

Table 1. Mechanical properties of 12 shoes (M ± SD)

	Thickness	Dwell time	Peak acceleration	Energy return
Shoe1	26.40±0.00	47.80±0.18	10.08±0.06	59.08±0.69
Shoe2	35.00±0.00	46.67±0.24	10.52±0.09	53.14±0.43
Shoe3	33.70±0.00	51.40±0.15	10.04±0.02	67.53±0.25
Shoe4	37.90±0.00	56.26±0.15	10.02±0.06	51.16±0.29
Shoe5	43.00±0.00	58.93±0.15	8.75±0.04	58.74±0.20
Shoe6	39.40±0.00	62.26±0.15	9.62±0.07	43.06±0.32
Shoe7	30.60±0.00	57.67±0.00	11.89±0.11	52.87±0.59
Shoe8	35.60±0.00	58.67±0.00	8.91±0.08	57.05±0.73
Shoe9	40.10±0.00	54.27±0.28	9.98±0.08	57.62±0.59
Shoe10	33.40±0.00	55.74±0.15	9.93±0.09	62.46±0.40
Shoe11	21.20±0.00	43.53±0.19	15.43±0.26	52.41±0.58
Shoe12	25.00±0.00	36.87±0.18	14.04±0.09	54.11±0.32

M: mean, SD: standard deviation

The correlation coefficient among the mechanical characteristics of shoes is shown in (Table 2). There was a positive correlation between the thickness and dwell time (r=.703, p=.011) while there was a negative correlation between the thickness and peak acceleration (r=-.780, p=.003). It also turned out that there was a negative correlation between the dwell time and peak acceleration (r=-.742, p=.006).

The correlation coefficient between the biomechanical impact variables and mechanical characteristics of shoes is shown in (Table 3). There was a negative correlation between the initial maximum vertical GRF during running and the peak acceleration of midsole (r=-.756, p=.004). The onset time showed a positive correlation with midsole thickness (r=.898, p=.000), a positive correlation with the dwell time (r=.738, p=.006), and a negative correlation with the peak acceleration of midsole (r=-.836, p=.001). The loading rate showed a negative correlation with the thickness of midsole (r=-.903, p=.000), a negative correlation with the dwell time of midsole (r=-.769, p=.003), and a positive correlation with the peak acceleration of midsole (r=.823, p=.001). The cross timing of braking and propulsion was in positive correlation with the thickness of midsole (r=.770, p=.003).

Third, the correlation coefficient of ankle joint movements and mechanical characteristics of midsole is presented in (Table 4). The inversion-eversion angle of the ankle joint at toe-off was in positive correlation with the thickness of midsole (r=.620, p=.032).

Table 2. Pearson's correlation coefficient between the mechanical properties of midsole

	Thickness	Dwell time	Peak acceleration	Energy return
Thickness	r=1.000 (p=.000)	r=.703 (p=.011)*	r=-.780 (p=.003)**	r=-.227 (p=.478)
Dwell time		r=1.000 (p=.000)	r=-.742 (p=.006)**	r=-.107 (p=.741)
Peak acceleration			r=1.000 (p=.000)	r=-.226 (p=.480)
Energy return				r=1.000 (p=.000)

*p<.05, **p<.01

Table 3. Pearson's correlation coefficient for the mechanical properties of midsole and impact variables of running

	Thickness	Dwell time	Peak acceleration	Energy return
Initial peak of vertical GRF	r=.550 (p=.064)	r=.565 (p=.056)	r=-.756 (p=.004)**	r=.360 (p=.251)
Initial peak time of vertical GRF	r=.898 (p=.000)***	r=.738 (p=.006)*	r=-.836 (p=.001)***	r=.060 (p=.854)
Loading rate	r=-.903 (p=.000)***	r=-.769 (p=.003)*	r=.823 (p=.001)***	r=.047 (p=.885)
Breaking impulse	r=.565 (p=056)	r=.145 (p=.652)	r=-.214 (p=.503)	r=-.147 (p=.649)
Propulsion impulse	r=.211 (p=.509)	r=.220 (p=.493)	r=.101 (p=.756)	r=-.450 (p=.142)
Breaking & propulsion cross time	r=.770 (p=.003)*	r=.505 (p=.094)	r=-.511 (p=.090)	r=-.229 (p=.475)

GRF: ground reaction force, *p<.05, **p<.01, ***p<.001

Table 4. Pearson's correlation coefficient for mechanical properties of midsole and ankle joint angle of running

	Thickness	Dwell time	Peak acceleration	Energy return
DF(+)/PF(−) at heel contact	r=.073 (p=.821)	r=.238 (p=.457)	r=-.159 (p=.621)	r=.062 (p=.848)
IV(+)/EV(−) at heel contact	r=.329 (p=.296)	r=.216 (p=.500)	r=-.027 (p=.933)	r=-.413 (p=.182)
DF(+)/PF(−) at mid-stance	r=.013 (p=.968)	r=.139 (p=.668)	r=-.069 (p=.831)	r=.492 (p=.104)
IV(+)/EV(−) at mid-stance	r=.311 (p=.326)	r=.054 (p=.867)	r=.041 (p=.900)	r=-.027 (p=.933)
DF(+)/PF(−) at toe off	r=.510 (p=.090)	r=.551 (p=.063)	r=-.461 (p=.131)	r=.148 (p=.646)
IV(+)/EV(−) at toe off	r=.620 (p=.032)*	r=.228 (p=.476)	r=-.217 (p=.498)	r=-.322 (p=.307)
Maximum eversion during stance phase	r=.366 (p=.242)	r=-.058 (p=.858)	r=.045 (p=.889)	r=-.445 (p=.147)
DF/PF ROM during breaking phase	r=.210 (p=.512)	r=.367 (p=.241)	r=-.326 (p=.301)	r=.055 (p=.865)
IV/EV ROM during breaking phase	r=.221 (p=.489)	r=.359 (p=.251)	r=-.254 (p=.425)	r=-.017 (p=.959)
DF/PF ROM during propulsion phase	r=-.067 (p=.837)	r=.053 (p=.870)	r=-.030 (p=.926)	r=.336 (p=.285)
IV/EV ROM during propulsion phase	r=.033 (p=.919)	r=.180 (p=.576)	r=-.083 (p=.798)	r=.251 (p=.431)

DF: dorsiflexion, PF: plantarflexion, IV: inversion, EV: eversion, ROM: range of motion, *p<.05

Fourth, the correlation coefficient of knee joint movements and mechanical characteristics of midsole is presented in (Table 5). The internal rotation-external rotation angle of the knee joint at heel contact was in negative correlation with the dwell time of midsole (r=-.719, p=.008).

Table 5. Pearson's correlation coefficient for mechanical properties of midsole and knee joint angle of running

	Thickness	Dwell time	Peak acceleration	Energy return
F(+)/E(−) at heel contact	r=-.070 (p=.830)	r=-.398 (p=.200)	r=.085 (p=.794)	r=.150 (p=.642)
ADD(+)/ABD(−) at heel contact	r=.381 (p=.222)	r=.272 (p=.392)	r=-.284 (p=.370)	r=-.135 (p=.676)
IR(+)/ER(−) at heel contact	r=-.482 (p=.113)	r=-.719 (p=.008)**	r=.455 (p=.138)	r=-.117 (p=.717)
F(+)/E(−) at toe off	r=.346 (p=.270)	r=.042 (p=.898)	r=-.422 (p=.172)	r=.075 (p=.817)
ADD(+)/ABD(−) at toe off	r=-.134 (p=.677)	r=-.108 (p=.737)	r=.406 (p=.191)	r=-.167 (p=.605)
IR(+)/ER(−) at toe off	r=.152 (p=.637)	r=-.095 (p=.769)	r=-.278 (p=.382)	r=-.002 (p=.994)
Maximum ABD during stance phase	r=.314 (p=.321)	r=.209 (p=.515)	r=-.214 (p=.503)	r=-.146 (p=.650)
Maximum ER during stance phase	r=-.526 (p=.079)	r=-.548 (p=.065)	r=.209 (p=.515)	r=.210 (p=.511)
F/E ROM during stance phase	r=.383 (p=.220)	r=.336 (p=.285)	r=-.080 (p=.805)	r=-.198 (p=.537)
ADD/ABD ROM during stance phase	r=.205 (p=.522)	r=.089 (p=.783)	r=.240 (p=.452)	r=-.322 (p=.307)
IR/ER ROM during stance phase	r=.495 (p=.102)	r=.429 (p=.164)	r=-.124 (p=.701)	r=-.293 (p=.355)

F: flexion, E: extension, ADD: adduction, ABD: abduction, IR: internal rotation, ER: external rotation, ROM: range of motion, ** p<.01

4. Discussion

This study examines the effects of the mechanical characteristics of midsole, such as thickness, dwell time, peak acceleration level, and energy return quotient on the shock variables during running and kinetic movements of the ankle and knee joints.

With regard to the correlation among the mechanical characteristics of midsole, it turned out that the thickness showed a positive correlation with the dwell time and a negative correlation with the peak acceleration. There was a negative correlation between the dwell time and peak acceleration. The thicker the midsole was, the better the performance of the shock absorption was. The thickness showed a negative correlation with peak acceleration. As demonstrated by the previous study that measured shock applied to a human body during walking and running by means of an accelerometer (Lafortune, 1991; Norris et al., 2014), the thicker the midsole was, the lower the peak acceleration was, according to the mechanical measurements of midsole. Meanwhile, the shock absorption performance proved to be outstanding.

As for the correlation between the mechanical characteristics of midsole and ankle joint movements, it turned out that as the midsole was thick and showed excellent shock absorbing performance, the initial peak time of vertical GRF increased, the loading rate decreased, and the breaking and propulsion cross time increased accordingly. In contrast, as the peak acceleration of midsole increased, the initial peak time of vertical GRF decreased while the loading rate increased accordingly. Previous studies (Lam et al., 2017; Lam et al., 2019) observed impact variables in relation to changes in midsole hardness and examined feelings of wearing shoes. It was also reported that the loading rate was relatively low in low-hardness shoes with excellent cushioning performance compared to that in high-hardness shoes (Meardon et al., 2018). Among the mechanical properties of midsole examined in this study, it was thought that the shock absorbing function was the same variable with the scale that indicated cushioning and hardness in previous studies. In a comprehensive view of findings, it was assumed that the thickness of midsole determined cushioning and shock absorbing performance and was a key factor for reducing impact on a human body that was running.

Third, at the moment that a foot was off the ground, the dorsiflexion of the ankle joint tended to be better with the inversion rate, which was significant when the midsole was thick and they absorbed shock properly. This was likely due to the fact that the dorsiflexion movement of an ankle joint was affected positively at the moment the foot was off the ground, if the midsole was thick, which was in line with the previous study that worn-out shoes being used for a long time showed a relatively low maximum rate. Dorsiflexion angle was measured at the moment the foot was off the ground (Kong et al., 2009). In the initial support phase where shock was absorbed during running, eversion movements of ankle joints were observed while in the propulsion step of the support phase, whereas inversion movements were observed, according to one previous study (Nicola and Jewison, 2012). Likewise, in this study, inversion was more significant when midsole was thick in the propulsion step where the feet were off the ground, which indicated a positive role that midsole thickness played. While the shoe hardness and duration of wearing affected one's GRF and comfort, in relation to shock, the kinetic factors of ankle joints were not modified, according to one previous study (Lam et al., 2019). Likewise, in this study, it was deemed that the mechanical characteristics of midsole such as thickness, dwell time, and acceleration played a positive role in reducing shock applied to a human body, and that they were irrelevant to the stability of ankle joints.

Fourth, as the shock-absorbing performance of midsole was excellent, the external rotation angle of knee joints was wider upon the feet's contact with the ground. In contrast, the maximum external rotation angle of knee joints in the support phase was relatively small since the midsole was thick and they showed excellent shock-absorbing performance. The two findings above were in contrast with each other. It was therefore difficult to clarify the reason because it was reported that, in general, the damage mechanism of the anterior cruciate ligament of knee joints is related to the increase in abduction and external rotation of knee joints upon landing (Hewett et al., 2005). In other words, it was evident that the shock-absorbing performance was an indicator of the risk of knee joint injuries upon landing after running. In the support phase, however, the stability of knee joint was a positive indicator. Thus, it was necessary to examine such characteristics as bending stiffness and torsion moment, in addition to the mechanical characteristics of the target shoes used in this study (Flores et al., 2019).

5. Conclusion

In summary, while the midsole thickness and dwell time of midsole play positive roles in reducing shock on a human body, there is a significant possibility that they could affect the stabilization of the joint of the lower extremity negatively. Future studies, therefore, need to evaluate various mechanical characteristics of shoes that may affect the stabilization of the joints of the lower extremity negatively in running motion, as well as the relevance among such factors.

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