Journal of Mechanics in Medicine and Biology
Vol. 10, No. 4 (2010) 667–674

DOI: 10.1142/S0219519410003630

BIOMECHANICAL EFFECTS OF FOAM INSERTS ON FOREFOOT LOAD DURING THE HIGH-HEELED GAIT: A PILOT STUDY

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Received 25 January 2010
Revised 30 March 2010
Accepted 31 March 2010

This pilot study analyzed the loading on the medial forefoot (MF) region during walking in high-heel shoes. Eight healthy female volunteers have participated in this study with the heel height varied from 0 cm (flat), 4.5 cm (low), and 8.5 cm (high). The results showed that the load on MF increased with the heel height and the magnitude of the load could be effectively reduced by using foam inserts. Comparative studies of foams with different hardness and thicknesses showed that thicker soft foams had a significant advantage over thiner hard foams ($P < 0.05$) in reducing the peak pressures. An optimum condition with a thick soft insert could reduce MF pressure by 26%, impact force by 27%, and force time integral by 20% when compared to the condition without insert.

Keywords: High-heel shoes; foam insert; insole measurements; pressure distribution.

1. Introduction

Wearing high-heel shoe is a common daily practice for elegant and professional women. However, women's walking pattern could be altered significantly by raising the heel height. Previous studies have demonstrated that walking in high-heel shoes could affect the lower-extremity joint function,[1] raise the peak pressure in the forefoot,[2] and increase the peak pressure of the medias foot region.[3] In addition, it could

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also increase the metabolic cost of gait and result in accelerated muscle fatigue,[4] and elevated inner stress level of metatarsal bones.[5] Despite concerns regarding their adverse effects on human musculoskeletal system, the high-heel shoes remain one of the most popular footwear choices for fashionable females.

High loading force could be successfully reduced through optimizing characteristics of insole such as the shape,[6] the thickness,[7] and material properties.[8] For example, Goske *et al.*[7] reported that insole thickness was an important variable in designing footwear to reduce peak plantar pressure. A reduction up to 12.1% was achieved when the insole thickness was increased from 6.3 to 12.7 mm. Cheung and Zheng[8] also reported the positive effect of using soft insole material for plantar pressure relief with a 25% improvement of the pressure contribution achieved by varying the insole stiffness. Alternatively, it was reported that soft insole plugs, allowing increased compression in the area of high pressure, could be used to relieve the load on target focal areas.[9,10] Previous studies showed that increase of the heel height could increase the maximum peak pressure under the metatarsal heads of the forefoot.[11,12] In most of these works, the medial forefoot (MF) has been identified to be the most sensitive area with the change of the heel height.[13–15] The work by McBride *et al.*[16] implied that wearing high-heel shoes allowed a greater proportion of the total force to act directly on the first metatarsal bone than walking barefoot causing many injuries related to first metatarsal bone. In addition, wearing high-heel shoes also made the trunk to lean more, which may increase joint moment of lower limb during walking.[17] Therefore, it is important to investigate the cushioning and protection function of the forefoot and develop technologies to reduce the forefoot loading in high-heeled gait.

The purpose of this study was to determine the effect of heel height and the use of foam inserts in targeted MF region on the foot force/pressure distribution during normal walking. The influence of some key design attributes of the foam insert was analyzed in details and the method to effectively enhance the protective function of high-heel shoes were discussed.

2. Methods

Eight healthy female subjects have participated in the biomechanical tests and data collection. The average age of the subjects was 22 years (range 19–24 years), the average weight was 51 kg (range 46–55 kg), and the average height was 163 cm (range 160–166 cm). Clinical check of each subject confirmed that there were no structural abnormalities of the feet or the legs, plantar calluses, or skin lesions. A brief health questionnaire has also been completed by volunteers to ensure that there is no recent history of injury. All participants have worn high heels regularly for more than two years. The high-heel shoes used in this study were commercially available items with similar construction and sole materials. Fabric-based soft shoes were used to simulate the bare foot condition (Fig. 1). The main difference among

Fig. 1. Shoes with three different heel heights used in this study. From left to right: a flat (0 cm), a low (4.5 cm), and a high heel (8.5 cm).

these shoes was the height of the heel designated as: flat (bare foot), low (4.5 cm), and high heel (8.5 cm).

An in-shoe pressure measurement system (Novel Pedar System, Germany) was employed in this study to measure the ground reaction forces exerted on the force sensors embedded in the insole. The thin pressure-measuring insole with 99 force sensors has a linear response to applied loads ranging from 0 to 50 N/cm^2 with minimal error. All sensors of the insole were individually calibrated before testing, and preliminary tests showed that the accuracy of the testing was not interfered by normal gait characteristics. The subjects were asked to walk in a straight line for about 20 m with each new type of shoes at their own pace before the test. After habituating to the heel height, each participant randomly selected shoes among those with/without soft foam insert in the MF region and walked for a distance of 20 m three times. In order to keep the foam inserts in the same position, the inserts were glued to the insole before the test (Fig. 2). During each walk, data were collected from the two steps in the middle of the walking to avoid potential bias in the starting and ending phases. In order to establish the influence of the foam thickness on high-heeled gait, foams with different thicknesses (5 or 10 mm) and hardness were used in all the studies.

Plastazote® foam materials commonly used in orthopedic footwear were chosen for making the inserts. Two grades of polyethylene foam, Plastazote® soft with a shore hardness of 20 and Plastazote® hard with a shore hardness of 40 were fabricated into the same shape for biomechanical testing. Analysis of the in-shoe pressure data was performed using Novel multi-masks analysis software (Novel Electronics, Inc.). The peak pressure, peak force, and the impulse (force-time-integral) were then used to characterize the load-bearing role of each anatomical area. The maximum force was normalized against the body weight of each individual subject,

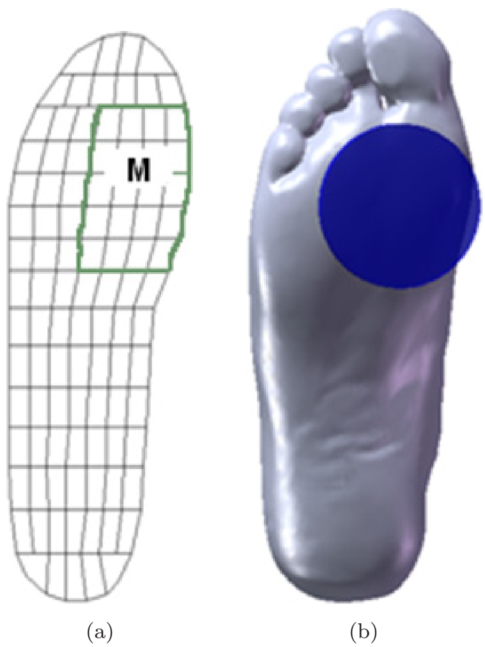

Fig. 2. Illustration of foam insert: (a) Pedar calculating masks for MF region and (b) foam insert position which glue to the insole of Pedar measurement before shoe wearing.

and the value is reported in units of body weight (BW). Statistical data analysis was conducted with a statistical software package SPSS (version 13.0). Analysis of variance (ANOVA) was employed to study the effects of heel height, and Turkey's HSD test was used for post hoc comparison with the level of statistical significance set at the 5% level.

3. Results

The comparison of peak plantar pressure distributions between conditions with/without using the 10-mm soft inserts for shoes of different heel height was shown in Fig. 3. It was clearly illustrated that the soft foam insert could reduce the peak pressure of the targeted area of MF. Meanwhile, pressure distribution in other foot regions was less significant, the pressure distribution pattern and magnitude for the shoe with foam insert were comparable to conditions without foam inserts.

In comparing to the data for the walking condition without foam insert, ANOVA results indicated a significant effect from the soft foams used on the peak pressure, maximal force, and force-time-integral of the MF with different heel heights. Typical data for the case of 10-mm foam insert were shown in Fig. 4. The peak pressure value under barefoot condition ($P = 0.085$) with foams seemed not to be significantly different from that when no soft foam insert was used. Peak pressure value of

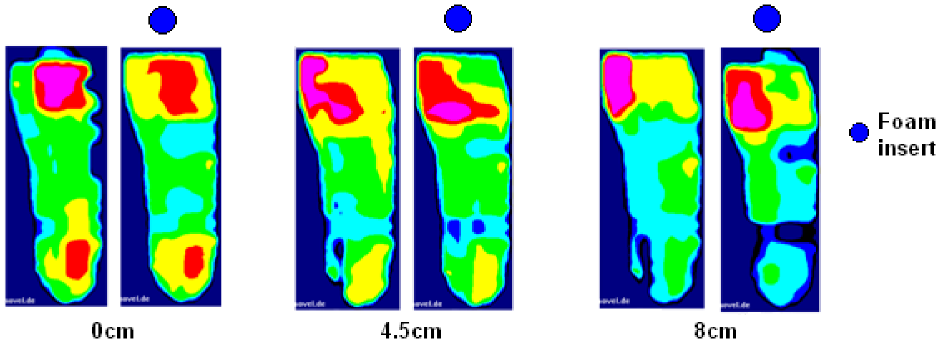

Fig. 3. Peak pressure distribution with and without 10-mm soft foam insert in the different height shoes.

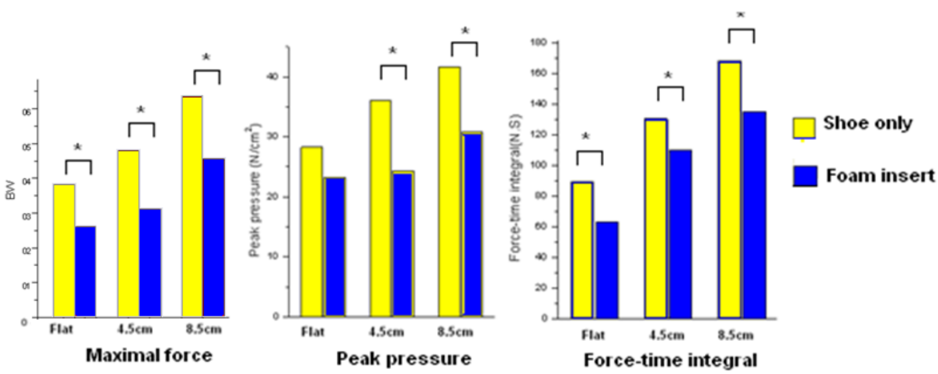

Fig. 4. Comparisons of 10-mm soft foam insert effect under different heel heights (significant change $^*P < 0.05$).

MF of the low-heel shoes was clearly higher than that of the bare foot condition; however, the extent of the pressure differences were reduced when soft foam inserts were used.

The foams insert effect in MF region under high-heel shoes was further analyzed statistically and the values were listed in Table 1. The ANOVA results indicate that

Table 1. Comparisons of different foams insert effect in high-heel height.

	Maximal force (BW)	Peak pressure (N/cm^2)	Force-time-integral (NS)
No insert	0.63 ± 0.09	41.2 ± 7.8	169.8 ± 56.6
10-mm P-soft	0.46 ± 0.05^{a}	30.1 ± 4.6^{a}	135.5 ± 35.8^{a}
5-mm P-soft	0.53 ± 0.06^{a}	32.3 ± 5.5^{a}	144.8 ± 41.5^{a}
10-mm P-hard	0.58 ± 0.08^{b}	33.1 ± 6.9^{a}	157.6 ± 49.3
5-mm P-hard	0.61 ± 0.08^{b}	$36.5 \pm 7.1^{a,b}$	160.2 ± 52.3^{b}

^{a}Significantly different compared to no insert ($P < 0.05$).
^{b}Significantly different compared to 10-mm P-soft ($P < 0.05$).

soft foam with different thicknesses (5 or 10 mm) had markedly different effects on the peak pressure, maximal force, and force-time-integral. The hard foams have only influenced the peak pressure value. Comparing the correlation between values for the four foam inserts, thicker soft foams demonstrated the most favorable effect with a reduction of the MF peak pressure by 26%, impact force by 27%, and force-time-integral by 20% from the non-insert condition.

4. Discussion

This study showed that the peak pressure, maximal force, and force-time-integral values under MF region increased with increasing heel height, which were consistent with results of the published studies.[2,14,15] With the increase of the forefoot loading, the natural shock absorbers of the human body could not provide sufficient protection, which may inevitably cause excessive fatigue and degenerative joint disorders, and potentially low back pain.[18] Therefore, it is important to establish the effects of various shock-absorbing devices/materials to reduce the risk of injury when wearing high-heel shoes. As shown in the comparative data for different heel heights and insert support conditions, the use of soft foam insert has reduced the peak pressure of MF by 19%, 30%, and 26% from bare foot to high-heel shoes. In all the cases, the foam inserts have significantly attenuated the maximal loading force generated in normal walking, especially with high-heel shoes. Voloshin and Loy[18] had reported similar results using viscoelastic insoles. In the work, it was shown that the peak pressure in MF region under high-heel shoes could increase more than half of stress level for sneakers' condition with sole made of elastic foams.[2] These biomechanical studies suggest that it could be a significant step forward to replace part of the hard sole material in high-heel shoes with some shock-absorbing material. Due to the fact that the sole of high-heel shoes has to be made of hard rubber/plastics to provide the necessary strength and wear resistance, it is not technically practical to replace the whole shoe heel. Hence, it is particularly promising to use soft foam inserts to enhance the cushioning function.

Comparing the effects of the four foam-inserts, the use of thicker soft material showed the most significant influence. It addition, it was found that the effect of the mechanical properties on load attenuation was more profound than the effect of the thickness, which has been the main focus of several published works. The current finding of the positive effect of the inserts' thickness change for peak pressure relief is consistent with the work of Goske *et al.*[7] who reported peak pressure reductions up to 12.1% when the insole thickness was increased from 6.3 to 12.7 mm. This work demonstrated that a further peak pressure reduction up to 10.3% (36.5–33.1 N/cm^2) when increasing the insert thickness from 5 to 10 mm. Lee and Hong[15] have studied the effect of arch support and reported a reduction of the peak pressure of MF region, 15.0% and 24% reduction under the whole foot (metatarsal pad, arch support, and heel cup). Even during walking with flat shoes condition, an average reduction of about 10% on the forefoot peak pressure could be achieved through arch support and contoured insoles.[19] As custom-molded insole could provide a reduction of peak pressure by increasing contact area,[20] the use of foam insert with conforming surface will be further investigated in future studies to improve the cushioning functions. In the biomechanics tests, the subjects were walked under self-selected walking pace in order to maintain a normal gait pattern. This may cause some potential difference in the walking speed. Another limitation of the work is the effect of the foam insert on the balancing behaviors of the subject. Although the foam inserts could effectively reduce the high loading of MF region, the insert foam itself could potentially influence balancing in the forefoot region and contact sequencing which requires further studies.

5. Conclusion

This pilot study demonstrated that MF was the most vulnerable region with increase of the heel height, and the peak pressure of this region can be effectively reduced by using foam inserts. Both the material property and thickness of the insert were proven to be important variables in designing footwear for reduction of the peak plantar pressure. Detailed statistical data analysis showed that thicker soft foams had the most significant effect. This could provide an effective way for loading relief in MF region for high-heel shoes.

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