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RESEARCH PAPER

Regional plantar foot pressure distributions on high-heeled shoes-shank curve effects

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Abstract Forefoot pain is common in high-heeled shoe wearers due to the high pressure caused by the center of body mass moving forward and the increased arch height with heel elevation. Sufficient arch support could reduce the high pressure over forefoot. However, too much arch support could lead to abnormal foot alignment and pain over midfoot. Little information is reported on the relationship among plantar arch height, shank curve design and plantar pressure. This study aimed at quantifying the plantar arch height changes at different heel heights and investigating the effect of shank curve on plantar pressure distribution. The plantar arch height increased to (7.6±1.3) mm at heel height of 75 mm. The Chinese standard suggests the depth of last should be 8.5 mm for heel height of 75 mm. When a shank curve with higher depth of last (11 mm) was used, the peak pressure over forefoot further decreased in midstance phase, which might ease the forefoot problems, while the peak pressure over midfoot increased but not exceeded the discomfort pressure thresholds. To achieve a more ideal pressure distribution in high-heeled shoes, a higher than expected depth of last would be suggested that would not cause discomfort over midfoot.

Keywords High-heeled shoes · Shank curve · Plantar arch height · Plantar pressure · Foot biomechanics

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1 Introduction

Females prefer to wear high-heeled shoes for better apperarance. However, long-term wearers of high-heeled shoes are vulnerable to forefoot problems such as forefoot pain, hallux valgus [1–3], metatarsalgia and calluses [2,4]. These forefoot problems were associated with the plantar loading redistribution caused by the alteration of foot alignment in high-heeled shoes. Firstly, plantarflexion of the ankle joint increases which leads to a forward movement of the center of mass when wearing high-heeled shoes [5,6]. These alterations cause high pressure over the medial forefoot [7–10]. Secondly, dorsiflexion of the hallux raises the medial longitudinal arch due to the windlass mechanism [11,12]. The arch rise decreases the peak pressure and the contact area over midfoot [10,13–16], also resulting in the high pressure over forefoot and hindfoot. Redistribution of pressure is an important consideration in high-heeled shoe design [9,17].

Shank of the shoe is a critical structure of plantar support over the midfoot. The shank material is hard for the purpose of bearing the body weight and keeping the shoe bottom shape during walking. The shank design accounted for about 14% of fitting problems in footwear for both men and women [18]. Good-designed high-heeled shoes should have a proper shank curve to provide sufficient support over the raised medial longitudinal arch [19]. Previous studies evaluated the insole configurations for redistribution of plantar pressure and researchers found that orthoses with higher medial arch profiles reduced the peak pressure over the heel or the medial forefoot regions [20,21]. However, these studies focused on flat shoes and there exists no sufficient information which could be applied to high-heeled shoes. In high-heeled shoes, Lee and Hong [9] found that the contact area enlargement over the midfoot produced by cushioning arch pad could improve the foot comfort, but their focus was not on quantifying the area of the arch support. Arch support should not put excessive loads over the midfoot as this can cause pain. Witana et al. [22] evaluated the effects of footbed shape on comfort and suggested that a comfortable footbed would not cause a peak pressure higher than 100 kPa when standing. However, this study was limited to a static standing condition. There is a lack of information on the effect of shank curve design of high-heeled shoes on the distribution of plantar pressure during walking.

The Chinese standard measures the depth of last to quantify the shank curve for high-heeled shoes. The depth of last is the distance from the waist of the last *G* to the line jointing the edge of heel *H* and the ball tread *J* (Fig. 1a), which should be 8.5 mm for the heel height of 75 mm in Chinese standard [23]. In the market, different companies follow different standards to design the shank curve for high-heeled shoes or healthcare products such as arch pad. It is unclear what kind of shank curve is better for altered arch shape wearing different shoes. The changes in plantar arch height at different heel heights provide critical information for the shank curve design. Although it has been suggested that elevated heel height would increase the height of the longitudinal arch, the magnitude of the arch rise has not been well documented.

The purpose of this study was to investigate how the plantar arch shape changes with increasing heel height and how shank curve designs of high-heeled shoes affect the plantar pressure distribution during walking. Attempt was also made to identify if the changes in plantar pressure over midfoot area would produce discomfort based on the discomfort pressure threshold (100 kPa). Results from this study would provide design suggestions to shoe manufacturers on redistributing mechanical stresses in high-heeled shoes and benefit foot health.

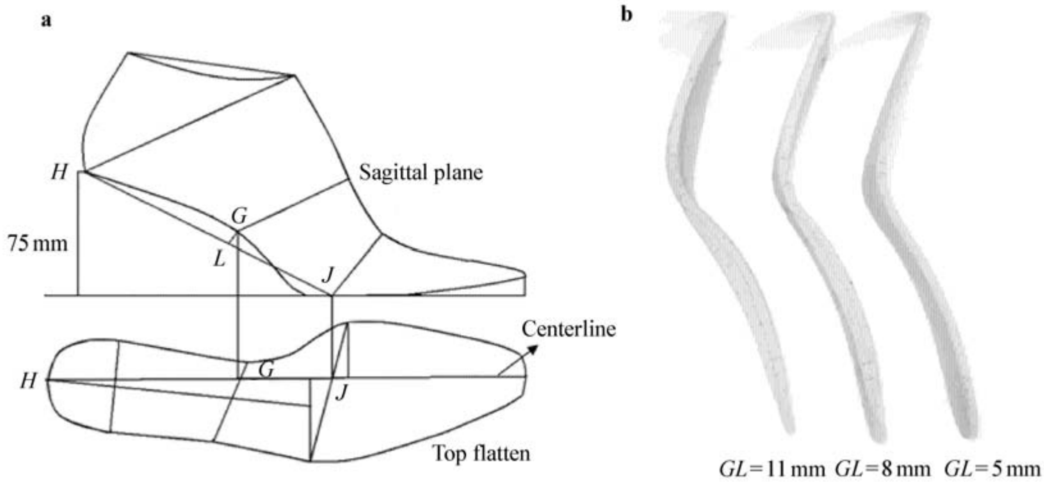

Fig. 1 **a** Definition of shank curve; **b** Inserts with different shank curve shapes

2 Materials and methods

2.1 Materials and subjects

The shoes with 75 mm heel height used in this study were European size of 37. Inserts with depth of last (*GL*) of 11 mm, 8 mm and 5 mm were attached inside the shoes to simulate different shank curves (Fig. 1b). The insole material has hardness of 60 degrees (Shore *A*).

Twelve female subjects voluntarily participated in this study. They had the experience of wearing high-heeled shoes and can fit comfortably into the selected high-heeled shoes. The subjects did not have high or low arch, hallux valgus, hammer digits, plantar calluses, limb-length discrepancy or any ankle/knee/hip problems. Their average age was 24 years old (range 20–28 years), average body mass was 53 kg (range 45–62 kg) and average body height was 159 cm (range 154–165 cm). Every subject was asked to sign a consent form before the experiments and this study was approved by The Hong Kong Polytechnic University Research Ethics Committee.

2.2 Foot shape measurement

Infoot 3D foot scanner (I-Ware Laboratory, Osaka, Japan) was used to collect the 3D foot shape data at 0 mm, 50 mm and 75 mm heel height levels. For all three conditions, the subjects stood with their feet positioned shoulder width apart and even with each other. To study the high-heeled conditions, the subjects stepped on the heels with 50 mm and 75 mm heights, respectively, as shown in Fig. 2. Arch curves were extracted from the sagittal plane passing the plantar centerline of each right foot and the plantar arch height was defined in Fig. 3.

Fig. 2 Feet stepping on the heels with 50 mm and 75 mm heights, respectively

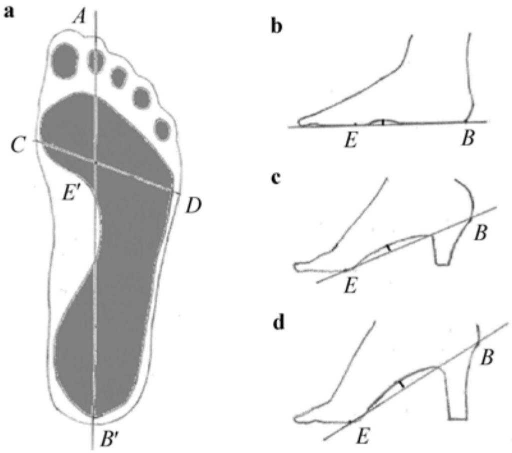

Fig. 3 **a** The projection of the foot plantar surface on the horizontal plane, where *AB*′ is the plantar centerline defined as a line passing the heel center *B*′ and the second metatarsal head, *CD* is the line connecting the first and fifth metatarsal heads, *E*′ is the tread point which lies alternately on lines of *CD* and *AB*′. The outlines of footbed curves (right) are extracted from the sagittal plane passing the plantar centerline *AB*′, where *E* and *B* is the projection of *E*′ and *B*′, respectively, on the foot. The plantar arch height is defined by the distance from the highest point of the arch curve to the line of *BE*. Outlines of footbed curves at **b** 0 mm; **c** 50 mm; **d** 75 mm heel heights

2.3 Plantar pressure measurement

Plantar pressure distribution was measured using Tekscan in-shoe pressure measurement system (Tekscan Co., Boston, USA). The inserts with different shank curves were randomly assigned to the subjects. For each test, the subject was first asked to walk along a 10 m walkway as normally as possible for a few minutes to familiarize the shoes with different inserts. After a short rest, the subject was asked to walk at a self-selected constant comfortable cadence. Data were recorded at a frequency of 100 Hz for 10 s. Repeated measurements were conducted for each test until three successful trials completed. To prevent fatigue, the subject took a 5-min rest between two tests. A total of 108 trials (12 subjects × 3 shank curves × 3 trials) were obtained for data analysis.

The plantar foot was divided into five regions, namely toe region, medial forefoot, lateral forefoot, midfoot and rearfoot. The regions were defined based on a percentage of the width and the length of foot as shown in Fig. 4. For each region, the parameters, namely peak pressure (PP), pressure-time integrals (PTI), and peak contact area (PA) were calculated from stable steps of each walking trial. Repeated measures analysis of variance with one within subject factors (the depth of last) was performed on these variables.

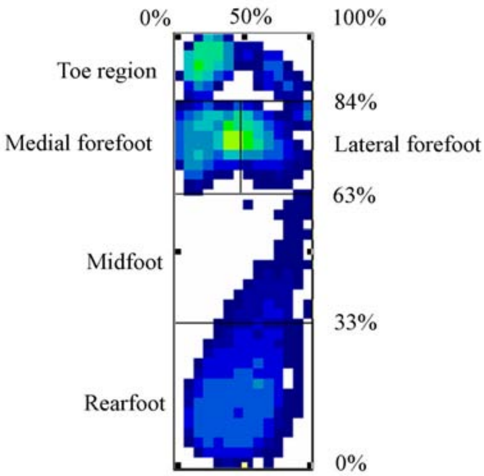

Fig. 4 Definition of the five plantar surface regions by percent mask

3 Results

The plantar arch height increased significantly with heel height elevation ($p < 0.01$, Fig. 5). Compared to the 0 mm heel-height condition ((2.6 ± 1.3) mm), the plantar arch height increased by 135% ((6.2 ± 1.4) mm) for 50 mm heel height and increased by 189% ((7.6 ± 1.3) mm) for 75 mm heel height, respectively.

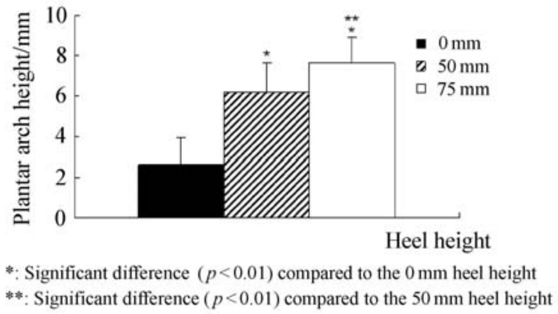

Fig. 5 Plantar arch heights at 0 mm, 50 mm and 75 mm heel height levels

In general, the plantar pressure was redistributed when the depth of last increased (Figs. 6 and 7). It is obvious that the contact area in the midfoot region was enlarged with the increased depth of last (Fig. 6).

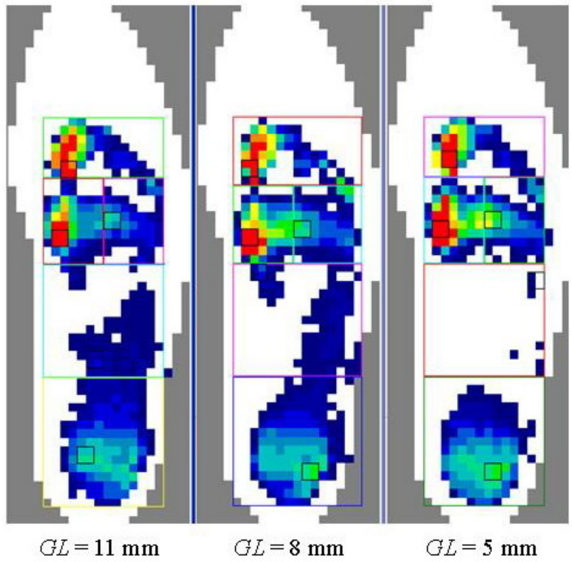

Fig. 6 Accumulative peak pressure patterns under three shank curves for one subject

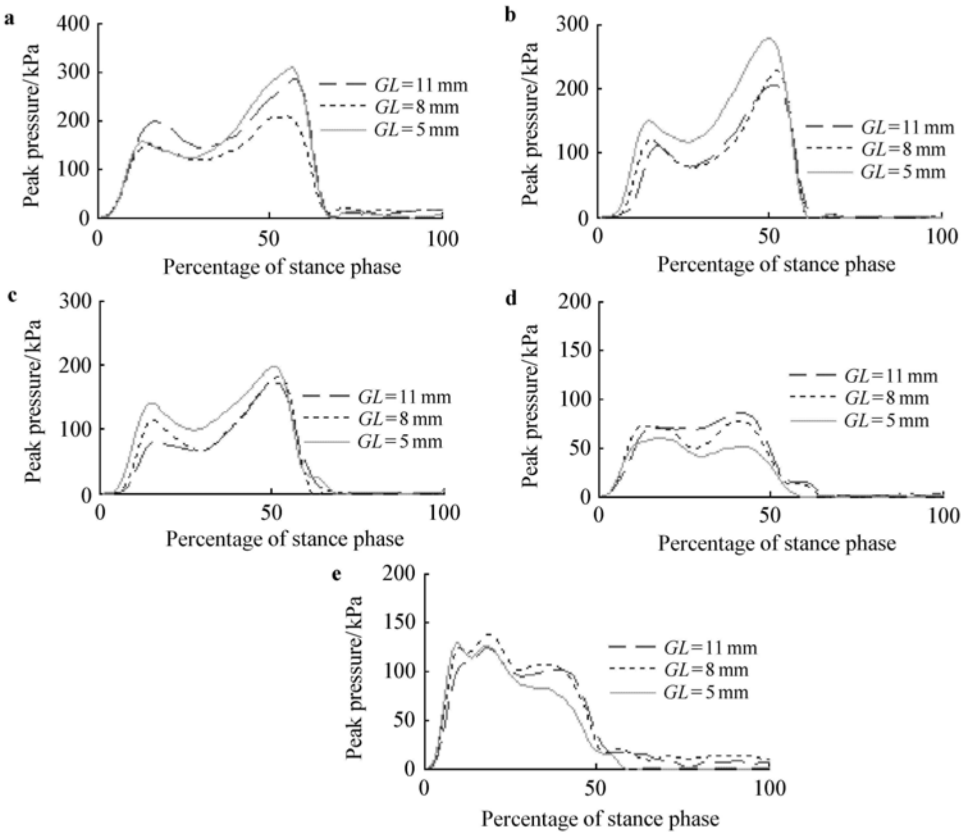

Fig. 7 Peak pressure curves in five foot regions for three shank curves from one subject. **a** Toe region; **b** Medial forefoot; **c** Lateral forefoot; **d** Midfoot; **e** Rearfoot

When the depth of last increased from 5 mm to 11 mm, the maximum peak pressure over the midfoot region increased significantly ($F_{(2,22)} = 9.061$, $p < 0.05$) but still lower than the discomfort pressure thresholds (100 kPa), while the maximum peak pressure decreased significantly in the medial forefoot ($F_{(2,22)} = 4.351$, $p < 0.05$) and lateral forefoot regions ($F_{(2,22)} = 6.811$, $p < 0.05$) as the depth of last increased during the midstance phase (Fig. 8). However, during the push-off phase, the peaks in medial forefoot had no significant difference. Over the toe region, the peaks in either midstance or push-off phase were not significantly different (Fig. 8).

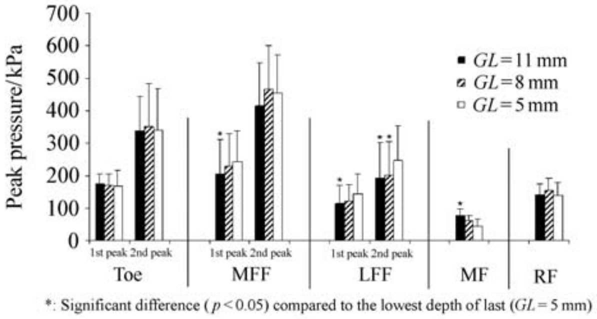

Fig. 8 Comparison of regional peak pressures among different shank curves. MFF: medial forefoot; LFF: lateral forefoot; MF: midfoot; RF: rearfoot

The pressure-time integrals can provide an understanding of the total amount of pressure that has applied over time during the whole stance phase. The results (Fig. 9) exhibited similar patterns to the peak pressure. Compared to the lowest depth of last ($GL = 5$ mm), the higher ones generated smaller PTI in the medial forefoot and lateral forefoot regions (reduced by 13% and 6%, respectively, in medial site, $F_{(2,22)} = 8.696$, $p < 0.05$; reduced by 19% and 17%, respectively, in lateral site, $F_{(2,22)} = 10.254$, $p < 0.05$), but larger PTI in the midfoot region (increase by 92% and 32%, respectively, $F_{(2,22)} = 5.917$, $p < 0.05$).

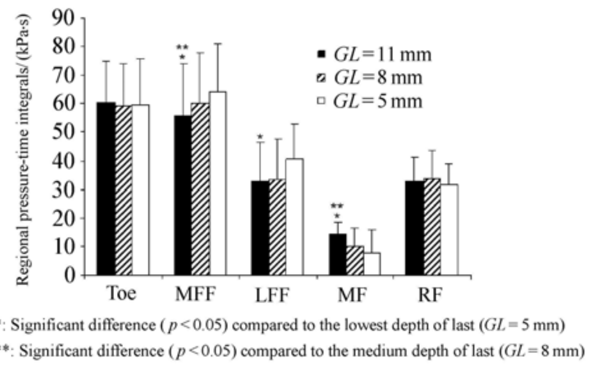

Fig. 9 Comparison of regional pressure-time integrals among different shank curves. MFF: medial forefoot; LFF: lateral forefoot; MF: midfoot; RF: rearfoot

As shown in Fig. 10, the peak contact area of the whole foot region increased slightly with the depth of last. The difference was especially accentuated over the midfoot regions. The peak contact areas of higher depths of last ($GL = 11$ mm and 8 mm) were significantly larger than that of lower depth of last ($F_{(2,22)} = 11.447$, $p < 0.05$). Significant differences in peak contact area in the lateral forefoot ($F_{(2,22)}$=5.425, $p < 0.05$) and rearfoot ($F_{(2,22)} = 3.969$, $p < 0.05$) regions among different shank curve designs were also noticed. However, the trends were opposite in the rearfoot region, where the peak contact areas increased with the depth of last.

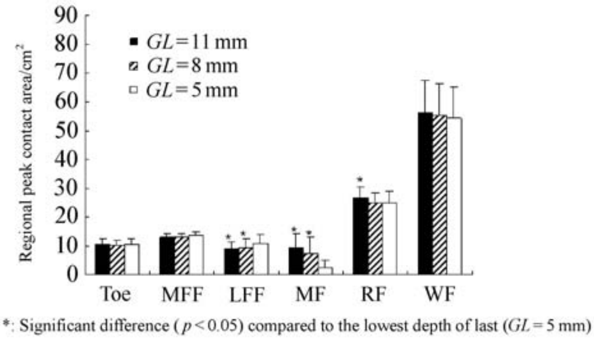

Fig. 10 Comparison of regional peak contact areas among different shank curves. MFF: medial forefoot; LFF: lateral forefoot; MF: midfoot; RF: rearfoot; WF: whole foot

4 Discussion

Shank curve design not only affects fit but also affects the appearance of shoes. In the market, different companies follow different standards to design the shank curve. Both excessively low and high arch support might cause discomfort in either forefoot or midfoot. Shank curve design should seriously take into account the degree of plantar arch height change.

Although researchers inferred that the arch height might increase with the heel height according to the decrease of the peak pressure and the contact area over midfoot [10,14,16], little studies quantify how much the arch height changes as the heel height increases. Results in this study showed that the plantar arch height increased by 189% ((7.6 ± 1.3) mm) for 75 mm heel height compared to that at 0 mm heel height ((2.6 ± 1.3) mm). As human foot is flexible and the plantar soft tissue over midfoot is compressible, an even higher arch support can be indicated.

The results of plantar pressure distribution presented in this study supported that a higher shank curve design could be advantageous. A higher arch support contributed to the redistribution of plantar pressure in high-heeled shoes, because the role of midfoot in dissipating partial compressive stress was enhanced by increasing the contact pressure, contact area and contact time. This would prevent the center of pressure shifting rapidly from heel to forefoot caused by the larger initial ankle plantarflexion in wearing high-heeled shoes [24]. When the depth of last increased to 11 mm, the peak pressure over midfoot reached 77.8 kPa which increased by 72.9% and 27.3% compared to the depth of last of 5 mm and 8 mm, respectively. However, it is still smaller than the discomfort pressure thresholds 100 kPa [22].

The changes over midfoot can further affect the plantar pressure distribution over forefoot region. When the depth of the last increased, the high peak pressure during midstance phase and the pressure-time integrals in both medial and lateral forefoot were released. Reasons for these changes of forefoot plantar pressure are that the increased depth of last provides an extra arch support. The extra arch support could provide a loading on the foot arch to resist the arch-flattening moment during weight bearing [25], which would increase the peak pressure over midfoot but release the higher pressure in forefoot region. Additionally, the extra arch support reduced the heel inclined angle, which would allow the lines of action of the supporting forces under the heel more vertical and these force components would carry more body weight without pressing the foot forward on an inclined surface [19], which can also effectively reduce the forefoot pressure in high-heeled shoes. In the selected high-heeled shoes, the maximum peak plantar pressures occurred over the medial forefoot region, which is consistent with the findings of previous studies [7–10]. The high pressure in forefoot might cause discomfort and put the wearer at a risk of various foot disorders such as hallux valgus, metatarsalgia and calluses. Compared to 5 mm and 8 mm, when the depth of last increased to 11 mm, the peak pressure during midstance phase and the pressure-time integrals in the whole stance phase were smallest. Therefore, properly higher depth of last might be more beneficial to forefoot health without obviously enhancing midfoot discomfort.

Although the peak pressure is reduced during the midstance phase, there is no decrease of the second peak of the plantar pressures in push-off phase over the medial forefoot region, which is consistent with the findings of Guldemond et al. [26]. It suggested that the contact area enlargement over midfoot can not be effective in reducing pressure during push-off because the interaction between footbed and shank curve takes place mainly before push-off phase. Additionally, the narrow toe box might also increase the plantar pressure over the forefoot region. It is suggested that toe box design is another important factor to improve the foot comfort. The effect of toe spring coupled with shank curve designs on the plantar pressure distribution should be investigated in near future. Because the toe box design can affect the plantar pressure distribution, in this study, three pairs of inserts were designed to simulate different shank curves in one pair of testing shoes in order to control the shoe structures such as foot contact points, heel height, toe box and pump style.

A proper shank curve design can be affected by the type of feet. In this study, subjects who did not have flat or high-arch feet have been selected based on the arch index [27]. The relationship between feet type and shank curve designs could be considered in further studies.

This study investigated the effects of shank curves on plantar pressure distribution only at high-heeled shoes of 75 mm heel height, because this level of heel height is commonly used in the market. The shank curve effects in the lower level of heel height may not be so remarkable. However, it is worth in future studies looking into the effects of shank curve designs at different heel heights.

5 Conclusion

It is suggested that in high-heeled shoes, a higher arch support relative to the plantar arch height could be beneficial, as it contributed to a more even distribution of plantar pressure. It enhanced the role of midfoot in ankle rocker by increasing the contact pressure and pressure-time integrals, and further decreased the peak pressure and the pressure-time integrals in both medial and lateral forefoot, with the pressure over midfoot not exceeding the discomfort thresholds. High-heeled shoes with higher depth of last or insoles with arch support might be good choices for wearers of high-heeled shoes to relieve the forefoot high pressure and prevent from forefoot disorders.

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