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Effects of shoe inserts and heel height on foot pressure, impact force, and perceived comfort during walking

Lee Yung-Hui*, Hong Wei-Hsien

Department of Industrial Management, National Taiwan University of Science and Technology, No. 43, Kee-Lung Road, Sec IV, Taipei, Taiwan, 106 ROC

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Abstract

Studying the impact of high-heeled shoes on kinetic changes and perceived discomfort provides a basis to advance the design and minimize the adverse effects on the human musculoskeletal system. Previous studies demonstrated the effects of inserts on kinetics and perceived comfort in flat or running shoes. No study attempted to investigate the effectiveness of inserts in high heel shoes. The purpose of this study was to determine whether increasing heel height and the use of shoe inserts change foot pressure distribution, impact force, and perceived comfort during walking. Ten healthy females volunteered for the study. The heel heights were 1.0 cm (flat), 5.1 cm (low), and 7.6 cm (high). The heel height effects were examined across five shoe-insert conditions of shoe only; heel cup, arch support, metatarsal pad, and total contact insert (TCI). The results indicated that increasing heel height increases impact force ($p<0.01$), medial forefoot pressure ($p<0.01$), and perceived discomfort ($p<0.01$) during walking. A heel cup insert for high-heeled shoes effectively reduced the heel pressure and impact force ($p<0.01$), an arch support insert reduced the medial forefoot pressure, and both improved footwear comfort ($p<0.01$). In particular, a TCI reduced heel pressure by 25% and medial forefoot pressure by 24%, attenuate the impact force by 33.2%, and offered higher perceived comfort when compared to the non-insert condition.

Keywords: High-heeled shoes; Insert; Impact force; Pressure distribution

1. Introduction

Surveys of shoe choice have shown that 37–69% of women wear high-heeled shoes on a daily basis (The Gallup Organization, 1986; Frey et al., 1993). Wearing high-heeled shoes modifies gait kinematics and kinetics (Esenyel et al., 2003; Snow et al., 1992; Mandato and Nester, 1999; Voloshin and Loy, 1994; Kerrigan et al., 1998). Previous studies have demonstrated that walking in high-heeled shoes alters lower-extremity joint function (Esenyel et al., 2003), raises the peak pressure in the forefoot (Snow et al., 1992; Mandato and Nester, 1999), and shifts peak pressures from the third, fourth and fifth metatarsal heads to the first and second (Soames and Clark, 1985; Snow et al., 1992; Eisenhardt et al., 1996). In addition, wearing high-heeled shoes for walking generates a force spike at the initial ground contact (i.e., impact force) and the force is then transmitted up to the skeleton as a "shock wave" (Voloshin and Loy, 1994). This shock wave appeared to damage soft tissues, which may result in leg and back-pain complaints (Wosk and Voloshin, 1981; Voloshin and Wosk, 1982) and eventually lead to degenerative joint disorders (Kerrigan et al., 1998). Despite concerns regarding their adverse effects on human musculoskeletal system, employment criteria and/or fashion customs encouraged the continuous use of high-heeled shoes. Studying the impact of high heels on kinetic changes and perceived discomfort provide a basis for designs that minimize adverse effects.

*Corresponding author. Tel.: +886 2737 6339; fax: +886 2737 6344.
E-mail address: yhlee@im.ntust.edu.tw (L. Yung-Hui).

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Engineering efforts to reduce foot loading caused by peak pressure and impact force, and to improve shoe comfort, involved designing shoe inserts with different shapes (Light et al., 1980; Chen et al., 1994; Hodge et al., 1999; Lee et al., 2004). The use of inserts is effective in redistributing the pressure beneath the foot and absorbing energy in terms of reducing impact force. Various inert designs demonstrate different kinetic modification during gait. For example, a heel pad is effective in reducing heel pressure and the magnitude of the heelstrike impact (Light et al., 1980; Jorgensen and Ekstrand, 1988). An arch support was designed to resist depression of the foot arch during weight bearing through skeletal support, thereby decreasing tension in the plantar aponeurosis (Kogler et al., 1996). A metatarsal pad has been found to reduce forefoot pressure and transfer weight bearing to the longitudinal and metatarsal arches (Lee et al., 2004). Finally, a total contact insert (TCI) provided pressure relief in the heel and forefoot regions (Lord and Hosein, 1994; Chen et al., 2003). These studies, however, focused on inserts in flat or running shoes. No study, insofar as we have examined, attempted to identify insert effectiveness in high heels.

The purpose of this study was to determine whether increasing heel height and the use of various types of shoe inserts would result in changes in foot pressure distribution, impact force, and perceived comfort during walking. The types of shoe inserts used in the current study included heel cup, arch support, metatarsal pad, and TCI.

2. Methods

2.1. Participants and materials

Ten healthy females volunteered for this study. The average age of the subjects was 23 years (range 20–28), average weight was 50 kg (range 47–53), and average height was 160 cm (range 156–162). None of the subjects had suffered an injury to the lower extremity during the preceding year. Four subjects had worn high-heeled shoes two-to-five times per week for at least 1 year. The other six had relatively limited experience. Written consent was obtained from each subject before commencement of the experiment.

The shoes used in this study were commercially available items and were selected based on the similarity of construction such as foot contact points, supports, and pump style. The main difference among these shoes was the height of the heel: a flat (1.0 cm), a low (5.1 cm) and a high heel (7.6 cm) (Fig. 1). The mediolateral by anteroposterior dimensions of the heel of the shoes were as follows: 2.8×3.0 cm and 2.4×2.6 cm (low and high heel, respectively). Each participant received five insert conditions: (1) shoe only; (2) heel cup; (3) arch support; (4) metatarsal pad; and, (5) TCI (Fig. 2).

The inserts were custom fabricated for each individual. The fabricating steps were: (1) negative impression of foot using Hydrogum alginate (Zhermack, SPA, Italy) set while the subject was wearing the high-heeled shoes in seating posture; (2) producing a positive cast of the feet by pouring plaster into the high-heeled shoes;

Fig. 1. The shoes of three different heel heights were used in this study. From left to right: a flat (1.0 cm), a low (5.1 cm) and a high heel (7.6 cm).

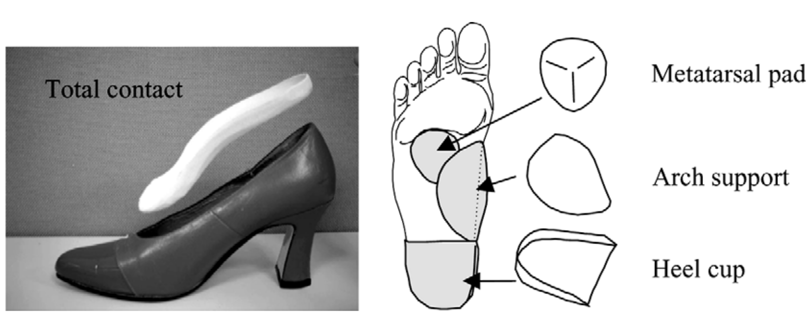

Fig. 2. The custom-made inserts and their support positions.

and, (3) making semi-rigid inserts from Multiform molded materials (AliMed Inc., Dedham, MA) that were contoured from the individual positive casts. Multiform is a thermoformable cross-linked polyethylene foam. The density of multiform provides good support as well as cushioning (Lamb, 1991). To prevent a tight feeling in the toe box, the TCI was designed to terminate at the distal border of the metatarsal heads (see Fig. 2). To avoid slipping around the inside of the shoe, the inserts were adjusted to appropriate position and then attached inside the shoe while being worn.

2.2. Apparatus

Pressure distributions were measured using the Pedar in-shoe pressure measurement system (Novel GmbH, Munich, Germany) (Fig. 3). The Pedar system consists of A/D conversion electronics housed in a small unit attached to the subject's waist. Leads to each 99-sensor insole (sample rate 50 Hz) were connected to A/D conversion electronics linked to a computer. The pressure-measuring insole has a linear response to applied loads of 0–50 N/cm^2 with minimal error, and no interference to normal gait characteristics has been demonstrated (McPoil et al., 1995). A description of the Pedar system and components have been previously reported (McPoil et al., 1995; Barnett et al., 2001). For measuring impact force external to the shoe, two AMTI force plates (Model OR6-5-1000; Advanced Biomechanical Technology, Newton, MA) were installed on the walkway (960 Hz sampling rate). The Novel player software (Novel GmbH, Munich, Germany) synchronized foot-pressure data with video and force-plates. The player is made for effortless synchronized playback, presentation or analysis of complex dynamic events.

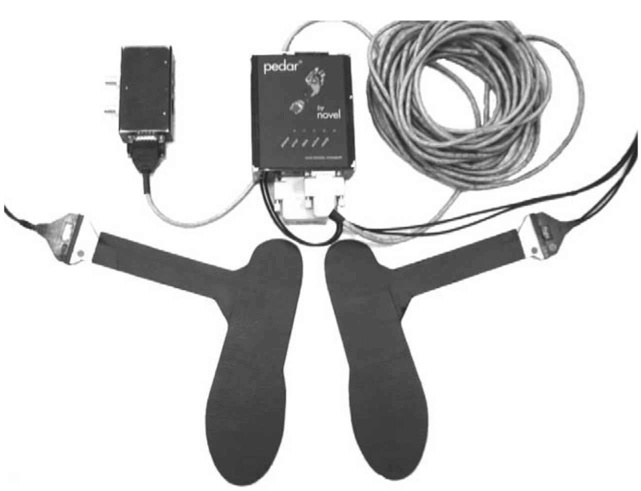

Fig. 3. The Pedar in-shoe pressure measurement system.

2.3. Comfort measurement

The visual analogue scale (VAS) developed by Münermann et al. (2002) was a reliable measure to assess footwear comfort. The VAS was used to rate the footwear comfort for each experimental condition in this study. Comfort was rated by a ruler that consisted of a 100 mm VAS with the left end of the scale labeled 'not comfortable at all' (0 comfort point) and the right end labeled 'the most comfortable condition imaginable' (10 comfort points). To perceive uniform comfortable experiences, we required participants to comfortably fit into the size and advised them not to take the effects of shoe cosmetics and styles into comfort rating.

2.4. Procedures

In the study, all participants walked on a treadmill for warm up and walked on a level walkway for data collection. Firstly, each participant walked on a treadmill for 5 min at 130 cm/s to become habituated to each heel height and walking speed. The speed of 130 cm/s was used because walking speed may influence plantar pressure and ground reaction force (Schwartz et al., 1964; Murray et al., 1970). The comfortable speeds reported in previous studies about high heels ranged from 122 to 140 cm/s (Opila-Correia, 1990; Snow and Williams, 1994; Esenyel et al., 2003).

A split plot design was used in the study. Firstly, a heel height was randomly assigned to the participant. For the same heel height, the order of inserts was then randomly selected. To prevent fatigue, each participant took a 5-min rest in between. Data of three successful trials were collected. The gait initiation and termination phases were recorded and only the middle gait cycle was used for analysis to each trial. A total of 450 trials (10 subjects $\times$ 3 heel heights $\times$ 5 insert conditions $\times$ 3 trials) were obtained for data analysis.

2.5. Data analysis

Novel Multimasks analysis software (Novel Electronics, Inc.) was used to calculate the peak plantar pressure, at the region of highest pressure during gait cycle, for the six foot regions: heel, midfoot, lateral and medial forefoot, toes, and hallux (big toe). The region was defined based on a percentage of the width and the length of foot (Fig. 4A). A LabView (National Instruments, Austin, TX, US)-based program using a low-pass filter with a cut-off frequency of 400 Hz (Gillespie and Dickey, 2003) was written to analyze ground reaction force. Impact force obtained from ground reaction force was a force spike superimposed on the upslope of the initial ground-reaction peak occurring right after the heelstrike (Whittle, 1999) (Fig. 4B). Impact force was normalized to body weight (%BW). As described by

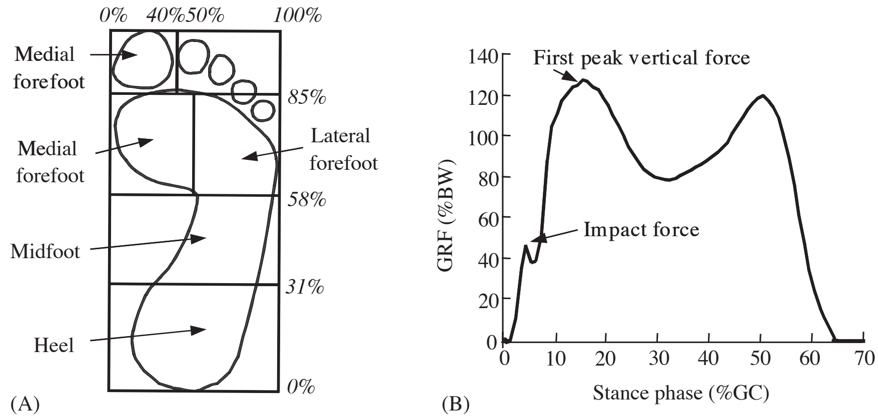

Fig. 4. (A) Definition of the six plantar-surface regions; (B) vertical ground reaction force.

Kadaba et al. (1989), a statistical assessment of the between-trial repeatability was performed by using the coefficient of multiple correlations for each motion pattern per participant for each condition. Repeatability was high between trials for each participant, the three trials that showed the highest repeatability were chosen for averaging. All subsequent analyses were derived from these averaged data sets.

Analysis of variance (ANOVA) was employed to study the effects of heel height and shoe insert. Tukey's HSD test was used for post hoc comparison. To test for relationships between comfort rating and pressure and impact-force variables, Pearson's correlation coefficients were calculated. An alpha level of 0.01 was used for all tests of statistical significance to minimize the experiment-wise error rate.

3. Results

The assumption of homogeneity is examined and not violated. Fig. 5 illustrates the comparisons of peak pressures in different foot regions and Table 1 lists the comparisons of impact forces for each test condition. ANOVA results indicated a significant heel height effect on peak pressure of the medial forefoot ($F_{(2,18)} = 42.6$; $p<0.01$), the heel ($F_{(2,18)} = 51.2$; $p<0.01$), and the midfoot ($F_{(2,18)} = 16.3$; $p<0.01$) regions, and impact force ($F_{(2,18)} = 64.4$; $p<0.01$). Post hoc comparisons using Tukey's HSD test showed a significantly higher peak pressure in the medial forefoot region during high-heeled walking. On the contrary, peak pressure in the heel and the midfoot regions decreased as the heel height was increased. The impact force in high heel was significantly higher than in low heel and flat shoes.

ANOVA results also indicated a significant insert effect on peak pressure of the medial forefoot ($F_{(4,36)} = 25.6$; $p<0.01$), the heel ($F_{(4,36)} = 24.8$; $p<0.01$), and the midfoot ($F_{(4,36)} = 12.6$; $p<0.01$) regions, and impact force ($F_{(4,36)} = 8.6$; $p<0.01$). Post hoc comparisons showed that peak pressure in the heel region was significantly reduced with the use of heel cup and TCI than that with the use of metatarsal pad and shoe only in all heights. In the midfoot region, the peak pressure was increased with the use of arch support, metatarsal pad, and TCI compared to the use of the heel cup and shoe only. In medial forefoot region, the peak pressure was decreased with the use of arch support and TCI compared to the use of shoe only, and peak pressure with the use of TCI was also significantly lower than that with the use of metatarsal pad in low and high heel (Fig. 5). The impact force was effectively attenuated with the use of heel cup and TCI compared to the use of shoe only in all heights. Impact force with a use of TCI was also significantly lower than that with a use of metatarsal pad in high heel (Table 1).

Fig. 6 illustrates the comparisons of comfort ratings for each test condition. ANOVA results indicated a significant heel height ($F_{(2,18)} = 46.8$; $p<0.01$) and insert ($F_{(4,36)} = 30.4$; $p<0.01$) effects for the comfort rating. Post hoc comparisons showed that comfort rating was significantly decreased with an increase of heel height. The comfort rating with the use of TCI was higher than that with the use of metatarsal pad and shoe only in all heights, and the rating with the use of heel cup and arch support were higher than that of the shoes only in low and high heel.

Table 2 lists the coefficients of correlation between measures of biomechanical variables and comfort rating. The comfort ratings were significantly correlated ($p<0.01$) with peak pressure in medial forefoot (−0.601), in the midfoot (0.356), and impact force (−0.369).

4. Discussion

The results supported our hypotheses that increasing heel height would change pressure distribution under the plantar surface and increased impact force and perceived discomfort during walking. All inserts were

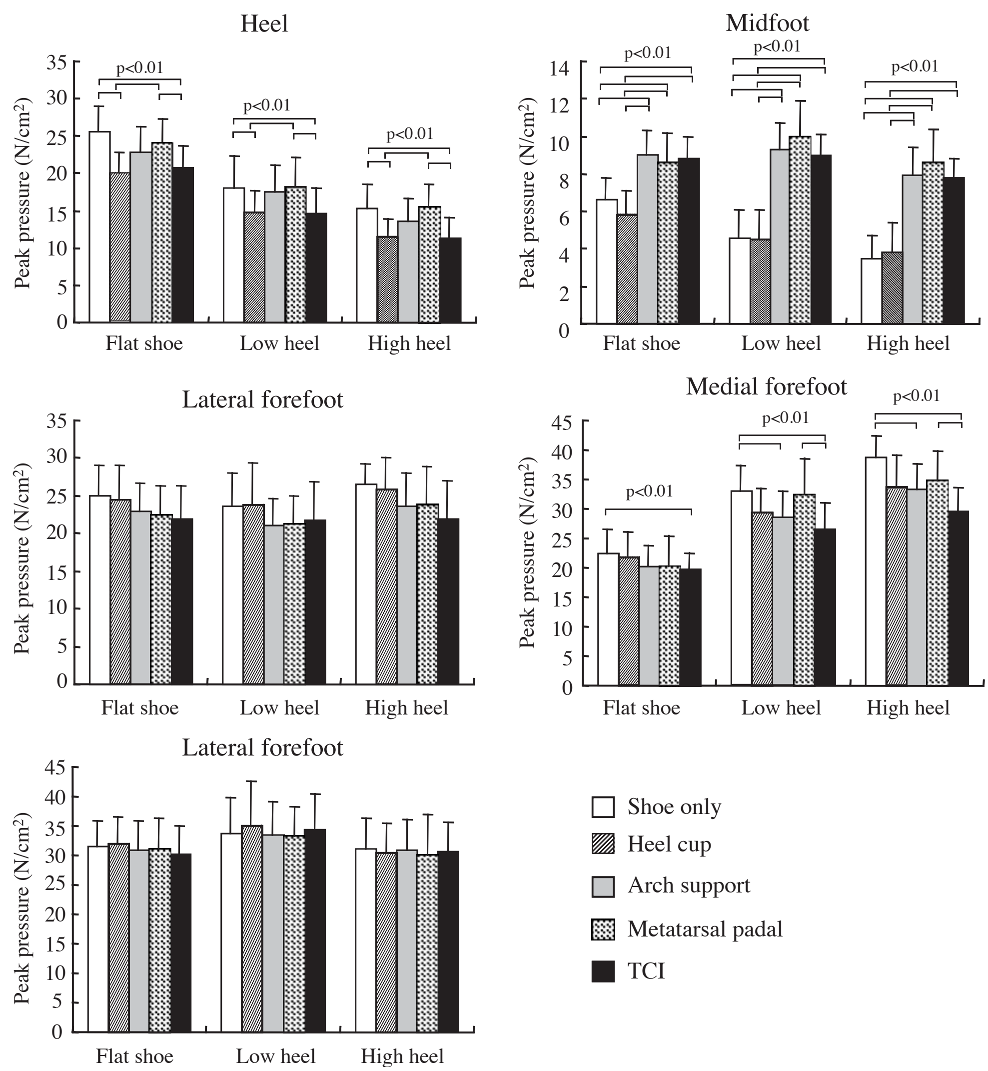

Fig. 5. Comparisons of peak pressures in different foot regions for each test condition.

Table 1
Comparisons of impact forces for each test condition (units: % BW)

Insert conditions	Flat shoe	Low heel	High heel
Shoes only	45.6 (15.3)	47.5 (16.0)	60.5 (17.2)
Heel cup	35.6 (13.6)[a]	35.2 (16.3)[a]	48.6 (11.7)[a]
Arch support	40.8 (7.8)	41.6 (8.2)	51.5 (10.0)
Metatarsal pad	42.5 (12.0)	42.6 (11.4)	54.8 (14.2)[b]
TCI	33.4 (15.2)[a]	35.8 (16.3)[a]	40.6 (13.0)[a]

Data are presented as mean (SD); TCI, total contact insert.
[a]Significant difference in a insert condition compared to shoe only condition, $p<0.01$.
[b]Significant difference between TCI and metatarsal pad, $p<0.01$.

effective in altering pressure distribution. Both heel cup and TCI effectively attenuated impact force. All inserts except for the metatarsal pad were effective in reducing subjects' perceived discomfort.

The results showed that increasing heel height shifted pressure from the heel and midfoot regions to the forefoot region, which were consistent with those of previous studies (Corrigan et al., 1993; Morag and Cavanagh, 1999; Mandato and Nester, 1999). Previous studies indicated that women wearing higher heels would have the cavus-type of higher arch (Schwartz and Heath, 1959; McCrory et al., 1997). The higher arch

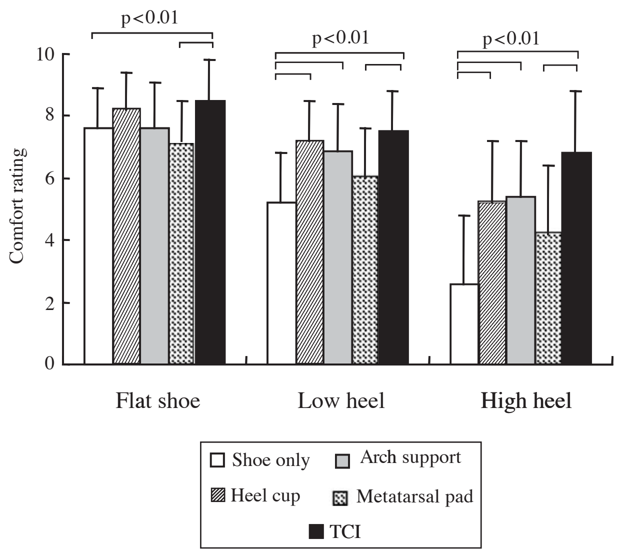

Fig. 6. Comparisons of comfort ratings for each test condition. TCI: total contact insert.

Table 2
Relationships between biomechanical variables and comfort rating

Variables	Correlation coefficient
Peak pressure by regions	
Medial forefoot	−0.601*
Lateral forefoot	−0.192
Midfoot	0.356*
Heel	−0.166
Hallux	−0.105
Impact force	−0.369*

*$p<0.01$.

may cause lower peak pressure in the midfoot, and increase pressure in medial forefoot (Morag and Cavanagh, 1999). The pressure of the heel region was also shifted to the forefoot region (Corrigan et al., 1993; Mandato and Nester, 1999). The alterations of these pressures may lead to the discomfort of the foot and may cause plantar fasciitis (Morag and Cavanagh, 1999).

The findings demonstrated increasing heel height increased impact force at heelstrike. The impact force may produce a shock wave and be transmitted through the musculoskeletal system up to other joints. When wearing high heels, the increased impact force elicited shock wave thus increases the dynamic loads on the human musculoskeletal system (Voloshin and Loy, 1994). In addition, the shock absorption in pronation may be lost because of increased plantar flexion of the ankle joint and supination of the subtalar joint in the initial stance phase (Snow and Williams, 1994). A loss of the natural ability to attenuate the shock waves may increase risk of degenerative joint disorders (Kerrigan et al., 1998) and low back pain (Voloshin and Wosk, 1982; Voloshin and Loy, 1994).

The inserts including the heel cup, arch support, and TCI differentially altered pressure distribution under various regions, and the heel cup and TCI attenuated the magnitude of the impact force the most. In comparison with the non-insert condition, the use of a heel cup reduced the pressure of heel region by 24.3% and reduced the impact force by 18.6% when wearing high heels. The pressure relief depends largely on the elastic properties of the material (Boulton et al., 1984), whereas the attenuation of impact force depends largely on its viscosity (Levitz and Dykyj, 1990). The heel cup insert with viscoelastic properties, thus, effectively reduced pressure of the heel region and also augmented the capability of energy absorption the body already processed in terms of natural heel pad (Jorgensen and Ekstrand, 1988).

In comparison with the non-insert condition, the use of an arch support reduced the peak pressure of medial forefoot region by 15.0% and increased the pressure of midfoot region by 125.6% when wearing high heels. This insert supported the apical bony structure of the foot arch to resist the arch-flattening moment of the foot during weight bearing (Kogler et al., 1996). The effect may result in an increased midfoot pressure and a reduced forefoot pressure (Anthony et al., 2000), thereby, decreasing tension in the plantar aponeurosis (Kogler et al., 1996).

When comparing with the non-insert condition, the use of a TCI effectively reduced peak pressure of the heel region by 25% and pressure of the medial forefoot region by 24%, increased pressure of the midfoot region by 120%, and attenuated impact force by 33.2% when wearing high heels. The TCI was made according to the plantar geometry of participant's foot in conjunction with accommodative arch-support and heel-cup mechanisms. This produced a high degree of conformity between the contact surface of insert and foot contours. The close fit of the cast insert resulted in even spreading of those pressures over the heel, arch, and forefoot regions with no significant local foci. The heel-cup mechanism also attenuated the impact force at heel-strike. The effect of shock absorption depends largely on the extent to which the shoes confine the foot and prevent it from spreading sideway upon impact loading (Jorgensen and Ekstrand, 1988). The TCI was proved to maximize these confining effects.

The use of a metatarsal pad increased pressure of the midfoot region, but did not significantly reduce pressure of the medial forefoot and impact force. The pad was not effective in improving footwear comfort during high-heeled walking. It was possible that the pad was not customized for each participant and it was also not so easy to install in a definite position compared with other inserts. However, the metatarsal pad did not provide either pressure relief or comfort.

Increasing heel height significantly reduced footwear comfort, however, the uses of the inserts were effective in improving footwear comfort. The mean comfort rating in flat shoe was 7.6 and reduced to 2.6 in high heels, indicating that higher heel lift might lead to more discomfort. VAS provided a reliable measure to assess footwear comfort, as indicated in a previous study (Münermann et al., 2002). This was true for high-heeled ambulation, as previous findings indicate that most people can rapidly distinguish between comfortable and uncomfortable footwear (Münermann et al., 2001). The mechanism underlying this perception and the functioning of the feedback control system are not clearly understood. Our comfort ratings were, however, negatively correlated with peak pressure in the medial forefoot ($r = -0.601$) and impact force ($r = -0.369$), but were positively correlated with peak pressure in the midfoot ($r = 0.356$; $p < 0.01$). It appears reasonable to suggest that our participants were able to perceive the extent of the comfort through realization of the changes in pressure distribution and impact force that characterized the different inserts. The study indicated that the uses of some inserts were effective in improving comfort when wearing high-heeled shoes. In comparison with non-insert shoes, the use of a heel cup improved comfort rating from 2.6 to 5.2, an arch support to 5.4, and a TCI more to 6.8. Therefore, the TCI offered superior comfort compared to non-insert condition when wearing high-heeled shoes.

There are several limitations to the current study. First, the experience of wearing high heels might be a confounding factor in response to the experimental conditions. Several subjects had limited experience using high heels. In addition, this study was laboratory-based and the tasks were preformed over a 2-h period. In a realistic work environment, the individual may be standing for much of the work day. An experiment of longer duration may provide better insight into the behavioral and physical adaptations of each individual and reflect the effects found in real work environments. Second, when examining pressures at the foot–shoe interface using an insert as a measuring device, the fact that the presence of the insert itself could influence these parameters must not be neglected. There is no direct way of measuring this. Therefore, the recorded pressure may have small errors which are inevitable. However, participants' perceptions of changes in comfort produced by the insertion of the insole may give some indication of pressure distribution changes.

5. Conclusion

Increasing heel height increases medial forefoot pressure, impact force, and perceived discomfort during walking. A custom-made insert with a heel-cup or an arch-support mechanism for high-heeled shoes would be effective for reductions of heel pressure and impact force or medial forefoot pressure, and for an improvement in footwear comfort. In particular, a TCI, combined with a heel-cup and an arch-support mechanism, could reduce heel pressure by 25% and medial forefoot pressure by 24%, attenuate the impact force by 33.2%, and offer better comfort when compared to not wearing an insert. It is suggested that these inserts may contribute to relieve foot pressure, reduced impact force, and more comfort at work for women wearing high-heeled shoes.

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