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The Influence of Walking Speed and Heel Height on Peak Plantar Pressure in the Forefoot of Healthy Adults: A Pilot Study

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Abstract

Background: The body of empirical research is suggestive of the fact that faster walking speed and increasing heel height can both give rise to elevated plantar pressures. However, there is little evidence of the interaction between walking speed and heel height on changes in plantar pressure. Therefore, the aim of this study was to investigate whether the effect of heel height on plantar pressure is the same for different walking speeds

Methodology: Eighteen healthy adults, between the ages of 18 and 35 were assessed for changes in peak plantar pressure at walking speeds of 0.5 mph, 0.8 mph, 1.4 mph and 2.4 mph on a treadmill, wearing heels of 2 cm, 3 cm, 6 cm and 9 cm. Both the speed of walking and heels were randomly assigned to each participant. Peak plantar pressure values were determined in the forefoot region using the F-scan system which made use of in-shoe insoles. Data were analysed using two-way ANOVA.

Results: Increasing heel height and walking speed resulted in significantly higher peak plantar pressure in the forefoot. Post-hoc analysis also confirmed the findings of two-way ANOVA of significant increase in peak plantar pressure with increments in heel height and walking speed. The two-way ANOVA illustrated significantly higher peak plantar pressures in both the forefeet due to interaction of walking speed and increasing heel heights.

Conclusion: This study suggests that an interaction of walking speed and footwear design on distribution of plantar pressure exists. Therefore it is necessary to standardize walking speed and shoe design in future studies evaluating plantar pressures.

Keywords: Plantar pressure; Walking speed; Heeled shoes; Pressure distribution; Forefoot

Introduction

Fashionable footwear designs are now becoming increasingly complex and incorporating high heels; some designs include heels up to 10 cm or more [1]. Footwear purchase is dictated by fashion and not a sense of comfort [2]. It has been reported that 49% of American women own high heeled shoes, of which 71% reported foot pain [3]. High heeled shoes have come under much speculation as one of the causative factors for forefoot pain and discomfort. Literature relating to effects of high heels offer conflicting findings.

Dawson et al. [4] reported foot problems such as great toe deformity, foot pain, cross fingers and arthritis affecting the feet in 83% of women using high heeled shoes. A study in Netherlands found that 60% of women and 30% of men suffered similar foot problems directly related to shoes [5]. However, a recent study reported that wearing high heels did not cause deformities in women, but pain and callosities [6]. A recent review identified that musculoskeletal problems including hallux valgus, pain and first-party injury were associated with high heeled shoes [7].

The biomechanical effects of high heel shoes ranging from 2 cm up to 10 cm have been studied by various researchers in the past [1,8-12]. In terms of measurement, the peak plantar pressure is defined as the highest pressure value recorded by each sensor over the entire period of the stance phase [13]. Elevated peak plantar pressures are of significant concern due to risk of tissue injury, foot discomfort, a source of pain, foot ulceration and arthritic changes in the foot [14]. It has been reported that high heeled shoes directly affect biomechanics of gait, including the peak plantar pressure distribution. There is an increase in peak plantar pressure under the forefoot as a result of realignment of body segment such that center of pressure shifts further anteriorly and medially [9,10,15-17]. Speksnijder and colleagues report an increase of 30% in peak plantar pressure under the forefoot region in women wearing high heels [11].

Similarly, other studies reported increase in forefoot peak pressures with increase in heel height [18,19]. Walking speed is another important variable that influences plantar pressure. Studies have reported that an increase in walking speed results in higher plantar pressures [20-22]. This has been supported by the evidence that suggests that there are higher vertical ground reaction forces with faster walking speeds [23] as force is directly proportional to pressure (Pressure=Force × Area^{-1}). Warren and colleagues, using a sample of

19 men, reported that pressures increased by 91% to 289% when the walking speed changed from 0.045 and 1.79 m/s and concluded that a linear relationship exists between speeds and peak plantar pressure in heel, medial forefoot and toes [21]. Similarly, other studies have established a positive correlation between walking speed and peak plantar pressure in various regions of foot [22,24]. It is evident from the literature that speed can influence plantar pressures. Despite this, many researchers who investigated the effects of heel height on plantar pressure haven't considered the effect of potentially confounding variable such as speed.

To Summarize, speed and shoe heel height themselves have an effect on plantar pressure distribution [11,18-21,24], but there is limited evidence with regards to the interaction between speed and heel height on changes in peak plantar pressure. Therefore, the aim of this study is to investigate whether the effect of heel height on plantar pressure is the same for different walking speeds.

Methods

Ethics

Ethical approval was granted from the Queen Margaret University, Edinburgh Research Ethics Committee.

Participants

Eighteen healthy adults (10 females and 8 males), aged 18-35 years, were recruited using a convenient sampling technique. Participants with history of foot pain, foot deformities, diabetes, peripheral neuropathy were excluded from this study. The average age, weight and height of the participants were 25 ± 2.7 years, 60.3 ± 1 0.9 kg and 166.5 ± 9.0 cm, respectively.

Materials and instrumentation

All participants were provided appropriately fitted generic shoes from the same manufacturer and standard design. Custom made heels from ethyl vinyl acetate were fitted on the shoes. These heels were grinded at an angle so to obtain a functional toe spring angle; to mimic high heeled shoes available in the market.

Additionally, the sole of the shoes was semi-flexible which helped in maintaining the toe spring angle while walking. The heights of the heels were as follows: 2 cm (neutral), 3 cm (low), 6 cm (medium) and 9 cm (high). These increments were added externally on to the shoes (Figure 1).

Figure 1: Heels made from ethyl vinyl acetate 9 cm (right) and 3 cm (left), respectively.

The plantar pressure was measured using F-scan system (Tekscan Inc. South Boston, MA, USA). This system consists of 960 sensors per insole which accounts for spatial resolution of 3.9 sensors/cm^2. The sampling frequency was setup to 120 Hz which was deemed appropriate for this study.

The selected frequency is higher than required to average walking speed recommended by the manufacturer. A treadmill (Tunturi® 40) with an operating speed of 0.5 to 12.5 mph was used to regulate walking speed.

Procedure

The shoes were fitted with the F-scan insoles. Participants did not wear socks and shoe laces for all participants were tied by the examiner. This was done to standardize the procedure as different socks and tightness of shoe lacing are known to influence plantar pressure [25,26]. Prior to testing all participants walked on the treadmill wearing shoes of the particular heel height assigned randomly at a self-selected speed and zero inclination for 5 minutes. This was done to familiarize the participants to the various heel heights, treadmill and for conditioning sensors.

The insoles were then calibrated according to the manufacturer's guidelines. All testing was carried out in a single session lasting 40-50 minutes. For each participant the walking speeds of 0.5 mph, 0.8 mph, 1.4 mph and 2.4 mph on the treadmill and heel heights 2 cm, 3 cm, 6 cm and 9 cm were both, randomly assigned. Computer generated randomization was used for the order of walking speed and heel height. For each respective speed and heel height a recording of 3 trials was made by the F-scan system.

Each trial consisted of a mid-gait approach. In this approach recording was initiated after a number of steps had been taken.

Additionally, a delay recording was setup for 5 seconds, to help the record the data after a few steps. The distance walked on the selected speed and heel height was approximately 12 steps for each foot (6 gait cycles). The recording was generated throughout the 6 gait cycles and the middle 3 steps were used to extrapolate peak plantar pressure measurements generated during the entire stance phase. The 3 selected recordings were then averaged for each foot.

Data processing and analysis

Peak plantar pressure (KPa) was measured in the forefoot region. The forefoot was considered the metatarsal heads and toes [27]. For the analysis, a mask encompassing the forefoot region was defined in the F-scan software version 6.30. Peak plantar pressure values and its distribution were extracted from this mask (forefoot region).

A Shapiro-Wilks test was carried out and data was normally distributed (p>0.05) hence a two-way Analysis of Variance (repeated measures) was carried out. This was followed by post-hoc pair wise comparisons using paired t-tests with applied Bonferroni corrections, to compare between different heel heights and walking speeds and overall interaction between walking speeds and heel heights.

The interaction between walking speed and heel height was further explored through an interaction graph. Post hoc simple effects statistical analysis was not carried out to evaluate interaction between heel height and walking speed owing to the small sample size.

Results

Two-way ANOVA for repeated measures indicated a statistically significant effect of heel height on peak pressure for left (F(1,17)=66.9, p<0.001) and right (F(1,17)=97.9, p<0.001) forefoot. Post hoc comparisons showed that peak pressure in the both feet was significantly different between every heel height. Table 1 shows pairwise comparison of individual levels of heel height on peak plantar pressure.

		Left Forefoot			Right Forefoot		
Heel (I)	Heel (J)	Mean Difference (I-J)	Std. Error	p	Mean Difference (I-J)	Std. Error	p
2 cm	3 cm	-104.8	21.7	0.001*	-51.2	13.7	0.009*
2 cm	6 cm	-126.5	18.5	<0.001*	-93.6	12.8	<0.001*
2 cm	9 cm	-318.6	36.3	<0.001*	-286.2	21.2	<0.001*
3 cm	6 cm	-21.8	7.2	0.046*	-42.4	12.0	0.014*
3 cm	9 cm	-213.8	21.1	<0.001*	-235.1	25.7	<0.001*
6 cm	9 cm	-192.1	23.2	<0.001*	-192.7	17.8	<0.001*
*Statistically significant at P<0.05							

Table 1: Depicts pairwise comparison of individual levels of heel height on the measures of peak plantar pressure (KPa).

ANOVA also showed a significant effect of walking speed on peak pressure in the left (F(1,17)=238.9, p<0.001) and right (F(1,17)=383.3, p<0.001) forefoot. Post hoc comparisons demonstrated significantly higher peak plantar pressure for every increase in walking speed. Table 2 illustrates pairwise comparison of individual levels of walking speed on peak plantar pressure. Figure 2 Illustrates peak plantar pressure across the left (a) and right (b) forefoot with increasing heel height and walking speed.

The main effect for two-way ANOVA illustrated a significant interaction between heel height and walking speed for left (F(1,17)=28.3, p<0.0005) and right (F(1,17)=39.8, p<0.0005) forefoot, respectively.

The interaction graph (Figure 3) shows changes in peak plantar pressure with respect to increase in heel height and walking speed. At 2 cm of heel height, the plantar pressures were consistently lower at all speeds when compared to the other heel heights. For heel heights of 3 cm and 6 cm, the peak pressures were similar for all speeds except 1.4 mph which showed a slightly higher peak pressure for 6 cm heel in comparison to 3 cm heel. The most prominent trend in these graphs was the plantar pressure was substantially increased with 9 cm heel height while walking at 1.4 mph and 2.4 mph which may have clinical implications.

		Left Forefoot			Right Forefoot		
Speed (I)	Speed (J)	Mean Difference (I-J)	Std. Error	p	Mean Difference (I-J)	Std. Error	p
0.5 mph	0.8 mph	-78.1	8.7	<0.001*	-51.2	13.6	0.009*
0.5 mph	1.4 mph	-209.3	14.4	<0.001*	-93.6	12.8	<0.001*
0.5 mph	2.4 mph	-282.5	12.8	<0.001*	-286.2	21.2	<0.001*
0.8 mph	1.4 mph	-131.2	10.7	<0.001*	-42.4	11.9	0.014*
0.8 mph	2.4 mph	-204.5	13.2	<0.001*	-235.05	12.7	<0.001*
1.4 mph	2.4 mph	-73.2	9.1	<0.001*	-192.7	17.76	<0.001*
*Statistically significant at P<0.05							

Table 2: Illustrates pairwise comparisons of individual levels of walking speed on peak plantar pressure (KPa).

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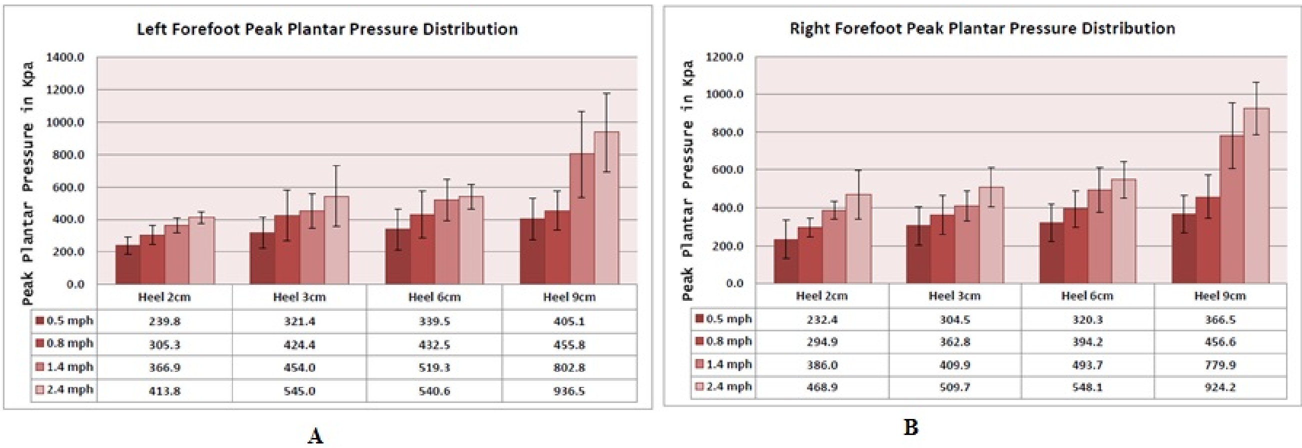

Figure 2: Illustrates peak plantar pressure across the left (a) and right (b) forefoot with increasing heel height and walking speed.

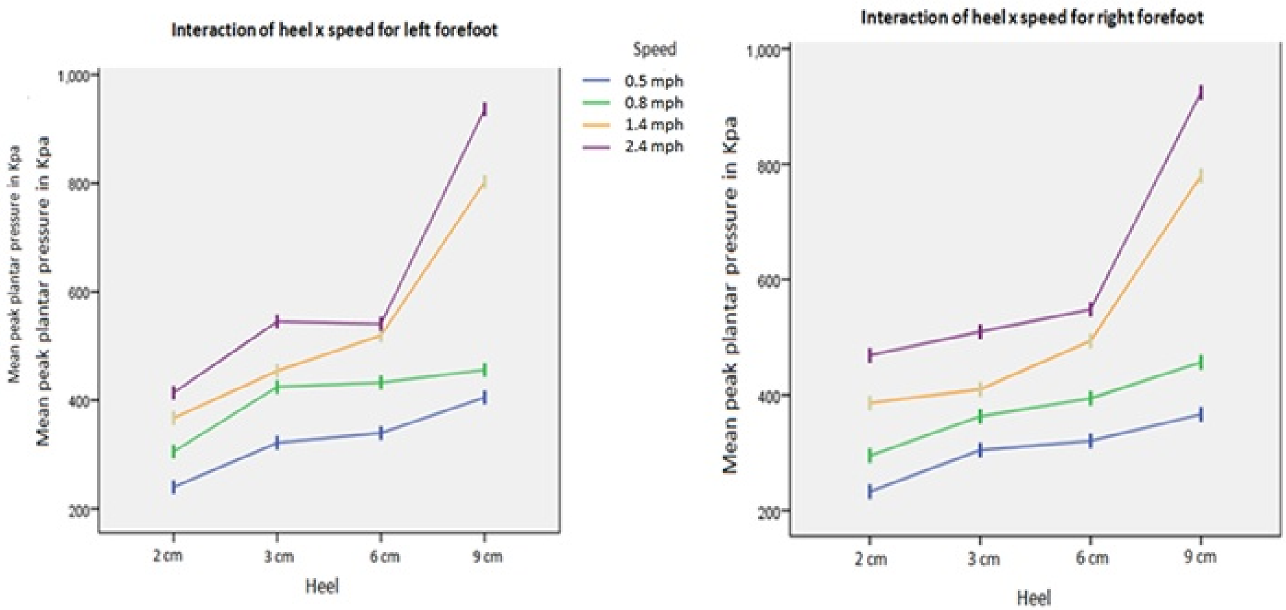

Figure 3: Graph showing interaction between walking speeds and heel heights for peak plantar pressures in both left and right feet.

Discussion

Results from the current study demonstrated that increasing heel height and walking speed resulted in higher peak pressures in the forefoot. The pressure in the forefoot increased significantly as the height of the heel increased. High heeled shoe causes the body segment to realign such that the centre of pressure in the foot shifts anteriorly and medially. Higher peak plantar pressure in the forefoot with increasing heel height is caused primarily by increase in Ground Reaction Forces (GRF) due to altered position of the ankle and centre of mass during the gait cycle [16,17]. This is in line with previous studies evaluating peak plantar pressure in heeled shoes [19,23,28,29]. In the current study, post-hoc analysis using Bonferroni's correction indicated all forefoot comparisons as statistically significant even when the increment of heel is as low as 1 cm.

In the current study increase in walking speed elicited increase in peak plantar pressure in the forefoot regions. Similar increases were reported by previous studies evaluating speed and plantar pressure relationship [14,21,22,24,30]. However, most studies have included speeds higher than current the study in their comparisons. The studies which included lower speeds comparable to current study also reported increase in peak plantar pressure in forefoot region with increase in speed [21,22]. Segal and colleagues [22] reported increase in peak plantar pressure in central and medial forefoot regions with initial increase in speed which is comparable to current study, but found that the plantar pressure plateaued at higher speeds. It is evident that increase of walking speed even at lower speeds has a significant effect on peak plantar pressure in the forefoot region.

Two-way ANOVA reported significant interaction of heel height and walking Speed. This suggests that the differences in peak plantar pressures in forefoot with increasing heel height are influenced by changes in walking speed. Heel of 9 cm at all the walking speeds (0.5, 0.8, 1.4 and 2.4 mph) consistently showed the most increment in forefoot plantar pressures when compared to the other heel sizes in both feet. However, it is important to notice that peak plantar pressure at lower walking speeds of 0.5 mph and 0.8 mph with 9 cm heel resulted fairly within the range of highest peak plantar pressure exerted by all heels less than 9 cm. This trend implies for both feet.

The interaction graphs show trends indicating high peak plantar pressure due to interaction of walking speed and heel height at higher speeds while wearing 9 cm heel. Higher peak plantar pressures are associated with increased pain and discomfort in the foot [10,15]. Therefore, there is a need to further evaluate and study such interactions of confounding variables that lead to increased forefoot loading. Increased loading of forefoot, may co-relate to various studies reporting discomfort and pain in the forefoot of individuals using high heel shoes on a regular basis. However, it is important to keep in mind that the interactions were not examined statistically, but they help to understand what drives the interaction. Further evaluation using bigger sample with simple effect analysis may provide further evidence to support this trend.

In this study, the average values of peak plantar pressure recorded at the highest speed at various heel heights are higher than previous studies [21,22] which used standardised heel height shoes and included comparable speeds. The increased plantar pressure associated with interaction of walking speed and high heel shoes may be one of the reasons for this study to report higher mean pressure values. Therefore, collective findings of this study are suggestive of the need for standardization of walking speed and footwear design when assessing plantar pressure distribution in future researches. However, more research is needed to substantially establish these findings.

Overall the results should be interpreted with caution in the light of the various factors affecting peak plantar pressure measurement. As evidence indicate, in this study plantar pressure may have been influenced by structural and function dynamics of foot, footwear design; especially heel design, shoe lacing, foot-sole interface, in shoe displacement and the device measuring the pressure itself [25,31,32]. There are several limitations to the current study. The experience of wearing high heel might be a factor. Several subjects had limited or no experience of using high heels up to 9 cm. In future, a study could compare experienced verses inexperienced high heel uses. In addition, the walking surface in this study was a treadmill it may alter the normal gait pattern. Another important limitation is the small sample size. Therefore, the plantar pressure changes noted may be applicable to the sample only. Better recruitment strategies may be used in the future studies. Further research may be carried out to compare self-selected walking speed with various controlled walking speeds with high heeled shoes. Measuring pressure-time integrals may indicate the amount of time the pressure is applied to different regions of the foot.

Conclusion

Forefoot loading (i.e. peak plantar pressure) in the forefoot region is influenced by confounding variables such as walking speed and heel height of the shoes. This study suggests that an interaction exists between speed and footwear design (height heels) on distribution of plantar pressure. There is a need to further evaluate such interactions that result in higher plantar pressures, as plantar pressures are associated with foot pain and discomfort. There may be a need to standardize walking speed and heel height in future studies evaluating or comparing plantar pressures between subjects.

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