Effects of surface characteristics on the plantar shape of feet and subjects' perceived sensations

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Abstract

Orthotics and other types of shoe inserts are primarily designed to reduce injury and improve comfort. The interaction between the plantar surface of the foot and the load bearing surface contributes to foot and surface deformations and hence to perceived comfort, discomfort or pain. The plantar shapes of 16 participants' feet were captured when standing on three support surfaces that had different cushioning properties in the mid-foot region. Foot shape deformations were quantified using 3D laser scans. A questionnaire was used to evaluate the participant's perceptions of perceived shape and perceived feeling. The results showed that the structure in the mid-foot can change shape, independent of the rear-foot and forefoot regions. Participants were capable of identifying the shape changes with distinct preferences towards certain shapes. The cushioning properties of the mid-foot materials also have a direct influence on perceived feelings. This research has strong implications for the design and material selection of orthotics, insoles and footwear.

Keywords: plantar shape; custom-made orthotics; footwear; cushioning; foot shape; perception

1. Introduction

Consumers today are concerned with footwear fit and comfort (Alcántara et al., 2005; Au and Goonetilleke, 2007; Gao et al., 2008) as poorly fitting shoes can result in many different types of foot problems (Cavanagh, 1980; Cheskin, 1987; Clarks, 1976; Gard and Berggård, 2006; Holscher and Hu, 1976; Marr and Quine, 1993; Rajput and Abboud, 2007; Rossi, 1988) and leg fatigue, which may increase the risk of slips and falls (Hignett and Masud, 2006; Pline et al., 2006). Even though numerous studies have reported anthropometric data (e.g., Bertrand et al., 2006; Witana et al., 2006), very few have investigated the shapes of different body parts in relation to fit and comfort (Lee and Hong, 2007). When a body part

such as the buttocks or feet of a person are supported by objects such as chairs and shoes, the interface shapes and the material properties (Goonetilleke, 1999; Wang et al., 2006)) and deformation characteristics (Kuijt-Evers et al., 2007) play important roles in the comfort or discomfort experienced by the sitter (Smith et al., 2006) or shoe wearer.

In-depth understanding of changes in the foot shape when the foot interacts with surfaces having varied deformation characteristics is required in designing shoes, so that the compatibility or the proper match between foot and shoe in every region can be well understood (Au and Goonetilleke, 2007; Gould, 1991; Rossi, 1983; Steele, 1981). Witana et al. (2004) used 2D outlines of lasts and feet to predict the perceived feelings of fit in the forefoot and mid-foot regions. The general findings were that the tolerances between a shoe and a foot were different in the mid-foot and forefoot regions in order for a shoe not to be tight and not to be loose. Very few studies have attempted to determine the shape of the plantar surface of the foot even though contact or the lack of contact between a foot and shoe will alter the force distribution along the plantar surface, especially in the mid-foot region (Alemány et al., 2003). The firmness, anthropometric features and pressure distributions (Na et al., 2005, DeVocht et al., 2006) are all factors known to contribute towards comfort (Lee and Park, 2006).

The foot is primarily supported by the plantar surface and therefore the interaction between the plantar surface of the foot and the surface on which the person stands (for example, the inside of a shoe, a floor mat, etc.) would determine the deformations of not only the plantar surface but also of the dorsal surface, the whole body's posture, and the overall comfort/discomfort/fatigue (Cham and Redfern, 2001; Hansen et al., 1998; Kelaher et al., 2000; King, 2002). Hence determining the shape of the plantar surface is as important, if not more important, than determining the shape of the dorsal surface of the foot.

High plantar pressures have been linked to foot pain and discomfort (Gardner et al., 1988; Godfrey et al., 1967; Hodge et al., 1999; Silvino et al., 1980). Many researchers have

performed studies to compare the effectiveness of reducing plantar pressure with different materials (Leber and Evanski, 1986) and shoe inserts (Chiu and Wang, 2007; Lee and Hong, 2005; Tsung et al, 2004). Schwellnus et al. (1990) reported that neoprene insoles can significantly reduce the incidence of tibial stress syndrome through better shock absorption. Some studies have found that neoprene insoles reduce transmitted forces better than viscoelastic insoles (Brodsky et al., 1988). Cook et al. (1985) attributed the increase in risk of stress fractures to a loss of mechanical support or the shock-absorbing properties of the midsole of footwear. Material properties no doubt contribute to altering pressures. But, the shape of the surface plays an important role as well. Plantar fasciitis, which is an inflammation of the plantar fascia (Kwong et al., 1988), is a common injury experienced by many runners (Brody, 1980; Middleton and Kolodin, 1992). Bolgla and Malone (2004) have reported that both high-arched as well as low-arched feet may be prone to plantar fasciitis. Even though the causes of fasciitis are not really well understood, clinicians have found that fasciitis is more frequent in rigid cavus feet (Lutter, 1981; Newell, 1977). It is somewhat puzzling that no one has attributed the cause of plantar fasciitis to a combination of shoe shape and the cushioning properties of the shoe even though a person suffering from plantar fasciitis or heel pain can very quickly sense a mismatch between these two variables by just putting on shoes because the footbed design of certain shoes results in instantaneous pain or discomfort. Recommendations to relieve heel pain include using a different size shoe (Healthlink, 2006), changing the heel wedge angle, increasing the heel height (Reiley, 1995), cutting out relief areas (Schepsis et al., 1991), wearing a shoe with a rigid shank and using hard or soft custom orthotics and so on. All such recommendations allude to the fact that the shape of the plantar surface and the deformations (or “cushioning”) of both the shoe and foot are extremely important to improve compatibility and reduce any incidence of foot injury. Fasciitis is primarily experienced at the end of the heel bone or the calcaneous and hence the shape and the deformation of the mid-foot can be considered to be quite important to

minimize excessive stress on the fascia. Lastmakers have given predefined shapes for that portion of the shoe (called the shank) that supports the mid-foot. The shank shapes vary primarily with heel height (Adrian, 1991; Rossi and Tennant, 2000) but, surprisingly, appear to be the same with differing levels of cushioning. No controlled studies have been performed to determine the shape of the plantar surface of the foot under full-load conditions for a given heel height and forefoot posture. Moreover, subjective preferences for varying shank shapes in shoes are also unknown. We therefore tested the following three hypotheses in this study:

1. H_0 : The plantar mid-foot shape does not differ with differing support surfaces
 H_1 : The plantar mid-foot shape differs with differing support surfaces
2. H_0 : The participant cannot perceive differences in mid-foot shapes
 H_1 : The participant can perceive differences in mid-foot shapes
3. H_0 : Material properties of a supporting surface, especially in the mid-foot region, are not related to perceived feelings.
 H_1 : Material properties of a supporting surface, especially in the mid-foot region, are related to perceived feelings.

Psychophysical (Gescheider, 1985) approaches are quite common in many different domains (e.g., Choi and Fredericks, 2007; Li et al., 2007) and hence psychophysical techniques coupled with mechanical testing were used for the subjective as well as objective evaluations of the above hypotheses.

2. Methods

2.1. Participants

The participants in this study were sixteen Hong Kong Chinese males between the ages of 20 to 35 years. Foot shape variations exist between genders. Men have longer and wider feet compared to women when the foot length and width are normalized with respect to stature (Wunderlich and Cavanagh, 2000; Ashizawa et al., 1997; Xiong and Goonetilleke, 2007). Researchers such as Dyck et al. (1987a, b), Adams et al. (1989), and Lin et al. (2005) have all shown changes in light touch, pinprick, deep pressure, vibration, and even temperature perception during aging as well as in some disease conditions. These confounding effects were eliminated in this study by limiting our choice of participants to young males of Asian origin.

Descriptive statistics of the participants are given in Table 1. None of the participants had any foot illnesses or foot abnormalities. Each of the participants was paid HK\$100 at the end of the experiment for their time.

[Insert Table 1 about here]

2.2. Equipment

2.2.1. Foot Support Surface

The heel height was fixed at 20 mm to simulate men's dress shoes and the heel seat was 45 mm in length and "rigid", to determine the shape of the mid-foot independent of heel deformation. The heel wedge angle and toe spring angle were set to zero. The foot support surface (Goonetilleke and Witana, 2006) was made of three different materials and was designed such that the mid-foot was allowed to deform even without deformation in the heel and forefoot regions. The surface on which a participant stood had a cantilever effect as the heel end was fixed while the other end was free to move in an anterior-posterior direction. Stiffness or softness has been related to comfort while the energy loss or rebound has been

related to performance and possibly feeling. Hence, three different surfaces were selected that could capture potential relationships among the physical properties of stiffness and energy loss as well. The physical properties of the three plates that were chosen are given in Table 2. SS25 and SS60 had a similar Young's modulus (E) whereas the polyurethane (PU) surface had a different Young's modulus. However, the flexural rigidity (Gere and Timoshenko, 1990), which characterizes the bending stiffness of a plate, was of the same order of magnitude for both SS25 and PU (Table 2).

[Insert Table 2 about here]

2.3. Procedure

Voluntary consent was obtained from each participant and all procedures were in conformance with the guidelines set forth by the committee on research practices at the Hong Kong University of Science and Technology.

2.3.1. System set-up

The three support surfaces were adjusted and digitized using a FARO Arm 3D Digitizer (Model B08/ REV 12) to ensure that the required heel height was 20 ± 0.5 mm and that the toe spring angle and wedge angle were 0 ± 0.5 degrees prior to testing. The adjustment and digitization process was repeated until the values were within the above specifications for every participant.

2.3.2. Material testing

Material testing is not new and many methods exist for measuring material properties (Fredrick, 1984; Goonetilleke, 1999; Nigg and Kerr, 1983). The tensile strength and the Young's Modulus of the surface materials were obtained using a MTS Sintech 10/D Universal Test Machine (Table 2). In addition, a displacement-controlled (30 mm/min)

compression test, with a 10 mm diameter semi-sphere probe and maximum force of 50N, was performed at 58 locations on each standing surface from the heel starting position to 285 mm in front of it at 5mm intervals along the centerline. Forces and displacements were obtained and recorded at 100 Hz. Figure 1 shows a sample plot of the force-displacement curves for the three surfaces in the mid-foot region, which was 100 mm in front of the heel edge.

[Insert Figure 1 about here]

2.3.3. Screening test

The ability of each participant to give a valid subjective rating for a physical variable was evaluated using line length estimation (Kee and Karwowski, 2001) based on the well-known free modulus method (Gescheider, 1985) of psychophysics. All participants passed this screening test.

2.3.4. Measurements

Each of the participant's feet was cleaned with warm water (25 ± 1 °C) using a foot bubble roller massager (Evertop model ET-4085) and dried. Foot length and arch length on both left and right feet were measured along the foot-axis that joins the pternion (the posterior point of the heel) and the tip of the second toe. The distance along the foot from the pternion to the point at which the rearfoot touches the ground was also measured along the same axis and is henceforth referred to as distance, "D". This distance was used to align the participant's feet on the foot supports.

Each participant's stride width and step length (Sarrafian, 1993) was measured when walking in their own low-heel shoes at their preferred walking speed. Nine such measurements were obtained (3 trials * 3 readings per trial) for stride width and step length and the median value of each participant was used in the experiment to simulate the loading pattern on the foot as well as the posture during gait.

2.3.5. Experimental Design

In this experiment, the independent variable was the type of foot support surface at the three levels corresponding to SS25, SS60 and PU. The dependent variables were the shape of the plantar surface of the foot, perceived shape rating and perceived feeling rating when standing on the three surfaces. The experiment was a within-subject design with 16 participants. Each participant stood on and evaluated each surface twice but the standing surfaces on left and right feet were different. The combinations for left-right feet were SS25-SS60, SS60-PU, PU-SS25, SS25-PU, PU-SS60, and SS60-SS25 with a random order among these combinations. The surfaces were covered with a black leather sheet in order to make them look the same. The number of surfaces that were tested was not disclosed and hence the participants were unaware that there were only three different units. The right foot shape was obtained from castings when the subject was standing on each of the three surfaces in addition to the shape of the right foot when standing on a flat surface. A counter-balanced Latin square design was used when casting the four conditions.

2.3.6. Questionnaire

A questionnaire was used to obtain the Perceived Shape (PS) and Perceived Feeling (PF) ratings (Table 3). The PS questionnaire (in a static posture) was aimed at checking if participants could differentiate between the mid-foot shapes of the foot support surfaces and also to check their preferences for each shape. Similarly, the PF questionnaire (in a dynamic posture) was used to evaluate the cushioning (Goonetilleke, 1999) of the support surfaces. Participants were first asked to respond to the PS questionnaire without moving their feet (that is, in a static posture). Thereafter, their perceived feel was assessed from a simulated dynamic posture with the subjects allowed to move their feet as in “on-the-spot walking” while standing on the support surfaces. The participant’s left and right feet were on two different

surfaces at any one time when responding to the two questionnaires. The participants were requested to respond to the questionnaires based on their perceptions.

The free modulus magnitude estimation method (Gescheider, 1985) was used to elicit the participants' ratings.

[Insert Table 3 and Figure 2 about here]

2.3.7. Foot Landmarking

Eleven anatomical locations were identified on the right foot and 6 mm diameter self-adhesive stickers were placed at these locations. Five of the landmarks (landmarks 6 to 10 in Figure 2) were on top of the metatarsal-phalangeal joints (MPJ), one each at the sides of the first and fifth MPJ (landmarks 11 and 5 in Figure 2), one each on the medial and lateral malleolus (landmarks 3 and 4 in Figure 2), and one each on the medial and lateral sides of the calcaneus, 30 mm away from the pternion and 15 mm from the plantar surface of the foot (landmarks 2 and 1 in Figure 2). Landmarks 1, 2 and 9 were used to align the 3D scan data to evaluate the differences among the foot shapes.

2.3.8. Foot impression castings

The foot supports were made of opaque materials and hence the plantar foot shape could not be obtained when the participant was standing on each surface. Thus, foot impression castings were made for each person when standing on each of the three surfaces and one casting was made when the participant was standing on a flat surface (i.e., a total of four). Details on the foot castings taken on the flat surface are not reported in this paper.

Each participant's right foot was aligned on the standing surface such that the foot axis and standing surface's centerline overlapped each other. In addition, the foot was positioned on the standing surface's centerline by coinciding the distance, D, mark (previously marked on the foot) with the heel seat starting position. The standing posture was similar to the initial

stage of the stance phase in human walking with the weight bearing foot (right foot) on the supporting surface and the left foot simulating toe off with it being located behind on a platform that was 15 cm ($\pm$ 1mm) higher than the right foot heel at a distance equal to the median step length and at a lateral distance corresponding to the stride width (refer to section 2.3.4, *Measurements*). The participant was asked to maintain 90% of his body weight on the weight bearing right foot during the foot casting process by looking at the display screen of the Bertec Force plate (Model 4060-10). In order to maintain a stable standing posture, a backpack with a weight of 5 kg was worn by each participant while being suspended with a force of 5 kg using two ropes which were fixed to a lockable pulley system. In addition, a horizontal bar at waist height was also provided for stability. Medio-lateral movement of the tibia was controlled, as it can change the shape of the foot, with two pointers touching the anterior and lateral part of the right knee. The Fscan Pressure assessment system was used to capture the plantar pressure when standing on each of the surfaces. The center of pressure information was used to monitor the posture throughout the casting process.

Once the foot was located and the participant was stable on the support surface, the surface was enclosed and converted to a molding box. The castings were made using Jeltrate® Fast Set Dustless Alginate Impression Material (Caulk Dentsply, 2006) and Plaster of Paris ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$). When the plaster was semi-hard, a steel bolt was inserted into the casting such that the hardened casting could be scanned in the same orientation as that when it was made.

2.3.9. *Scanning*

The foot castings were maintained under Standard Laboratory Conditions for 12 ($\pm$ 0.5) hours prior to the 3D laser scanning. The 11 landmarks were located and marked on each casting. The axis through the pternion and the tip of the second toe of the casting was aligned with the YETI (Vorum Research Corporation, 2000) scanner centerline. A special jig was

fabricated so that the heel height of the casting was held 20 cm above the surface of the scanner while the forefoot of the casting rested on the scanner platform. This was done to generate a first-cut alignment that was approximately the same as the foot when located on the support surface. The 3D point cloud data and the location of the landmarks obtained from the laser scanner were processed thereafter to obtain the foot shape.

2.4. Data Processing

2.4.1. Scan data alignment

The X-, Y-, and Z-axes were along the length, width and height directions of the foot, respectively. All the laser-scanned feet were software aligned to a datum for higher precision in the determination of differences as mentioned below:

- Step 1: Determine the foot axis on the XY plane as the line joining the mid-point of the two calcaneal landmarks (1 and 2) and landmark 9 on the second MPJ.
- Step 2: Calculate the angle in the XY plane between the foot axis determined in step 1 and the X axis and rotate all points around the Z-axis such that the foot axis is parallel to the X-axis. Translate the scan data such that the pternion corresponds to X=0 and Y=0, and to be Z=0 at X=(Distance-D) and Y=0.
- Step 3: Calculate the angle between the flat plantar foot heel and the XY plane in the YZ plane and rotate all points around the X-axis with the center of rotation at (0, 0, 0).
- Step 4: Project the foot scan point cloud data to the XZ plane and calculate the present heel height of the foot casting and rotate it around the Y-axis with the center of rotation as (Distance-D, 0, 0) so that the heel height is 20 mm.
- Step 5: Repeat Step 2 to Step 4 until the calculated angle in Step 3 falls within $\pm 0.0001^\circ$ degree and the heel height calculated in Step 4 is $20 \text{ mm} \pm 0.5 \text{ }\mu\text{m}$.

2.4.2. 2D mid-foot profile determination

The transformed data points were projected onto the XZ plane to obtain the 2D outline points in contact with the support surface. The curve that joins these points is referred to as the 2D shank profile. Since the participants' foot lengths were not the same, all feet were normalized with respect to the foot-surface "contact" length. This length was defined as (foot length – distance D – 5% of foot length corresponding to distance that is not in contact with the surface in the toe area). Lengths were calculated as the Euclidean distance between two neighboring points.

2.4.3. Material property determination

The Flexural Rigidity (EI) (Gere and Timoshenko, 1990) that characterizes the resistance to bending was computed from the Young's Modulus (E) and the second moment of area (I) (Table 2) by:

$$\text{Flexural Rigidity (EI)} = \text{Young's Modulus (E)} \times \text{Second moment of area (I)} \quad (1)$$

$$\text{Second moment of area (I)} = \frac{b \times d^3}{12}, \quad (2)$$

where b is the width and d is the depth of the rectangular cross-section.

The compression test data were used to determine the rebound resilience (Bassi, 1978) and the percentage of energy loss (Andreasson and Peterson, 1986) as follows:

$$\text{Rebound resilience (R)} = \frac{\text{Energy returned}}{\text{Energy applied}} \quad (3)$$

$$\text{Percentage Energy loss} = \frac{\text{Energy applied} - \text{Energy returned}}{\text{Energy applied}} \times 100 \quad (4)$$

$$\text{Percentage Energy loss} = (1 - R) \times 100$$

(5)

Since R and the percentage of energy loss are correlated with each other, only the percentage of energy loss is reported here. The stiffness ($k = f/d$) at each location was determined as the gradient of the fitted straight line in 35 to 45 N region of force in the loading portion of the force-displacement curve. Stiffness has received some attention in the past. Brown (1987) suggested the use of the peak force as a measure of the *stiffness* of the material under impact conditions. Andreasson and Peterson (1986) have suggested that running-shoe related injuries occur when the overall spring constant (k) on impact exceeds 100 kN/m (equivalent to 3.2 MPa in the dynamical modulus).

3. Results

The SAS package was used for all statistical analyses. The descriptive statistics of the participants are given in the table 1. The material properties are in table 2.

3.1. Mid-foot deformation

The mean normalized 2D mid-foot profiles of all participants when standing on support surfaces SS60, SS25, and PU are shown in Figure 3. The height or Y-axis values at normalized plantar foot length locations of 20%, 30%, 40%, 50%, 60%, 70%, and 80% were determined through interpolation. The calculated Y-values were subjected to a two-way ANOVA (surface type and location) and a simple-effects test to analyze the deformation of the plantar surface in the sagittal view. The ANOVA showed that all the main effects and interactions were significant at the 0.05 level (Table 4a). The simple-effect test revealed significant interactions between the support surface type and the locations of 30%, 40%, 50%,

60%, and 70% (Table 4b). Further tests on interaction effects showed that plantar surface deformation on the SS60 and PU support surfaces were significantly different at all locations from 30% to 70%. The results were similar between the SS25 and SS60 support surfaces as well (Table 4c). However, the plantar foot deformation of the support surfaces of SS25 and PU showed significant differences at only the 30% location (Table 4c). In summary, the deformation of the plantar surface on the SS60 support surface showed significant differences in the mid-foot region when compared with the other two surfaces.

[Insert Table 4 about here]

3.2. Perceived mid-foot shapes

The presence of any outliers in the Perceived Shape (PS) and Perceived Feeling (PF) questionnaire ratings were checked using the Mahalanobis distance calculated between trials. Participant 8 was identified as an outlier in the PF questionnaire ratings ($\leq \chi^2_2(0.005)$) and was hence eliminated from all the PS and PF questionnaire analyses. Data collected from the PS questionnaire section (a) revealed that more than 73.33% of participants perceived that the shapes when standing on SS25 and PU were different to that of SS60. At the same time, 46.67% of participants perceived that the shapes on the surfaces SS25 and PU were not similar, and 36.67% perceived the two surface shapes to be similar, while 16.67 % were not sure whether or not they were similar (Figure 4). These results were subjected to a one-sample proportions hypothesis test, which showed that the surface shape comparisons between SS60 and SS25 and those between SS60 and PU were significantly “Not Similar” (Table 5). The percentages of response for “Not Sure” was significantly lower than one-third of the total responses in all the cases (Table 5).

[Insert Figure 4 and Table 5 about here]

Each participant's shape preference ratings (PS Questionnaire b & c) were normalized using his own maximum and minimum ratings. An Analysis of Variance (ANOVA) and *post-hoc* Student–Newman-Keuls (SNK) test was performed on the normalized PS ratings (Table 6). The ANOVA results showed statistically significant variations among the support surfaces (p value $<.0001$) and the side of the foot followed a trend ($p = 0.0578$). The SNK test showed significantly different shape preferences between SS60 and the other two surfaces, SS25 and PU (Table 6).

[Insert Table 6 about here]

3.3. Perceived feelings of surfaces

Perceived feeling ratings (PF Questionnaire a & b) for each participant were normalized based on his own maximum and minimum ratings. An ANOVA followed by a simple effect test was performed on the normalized PF ratings. The ANOVA and simple effects tests showed significant differences in support surface type, foot region (rear-foot, mid-foot, forefoot and overall) and in the interaction between support surface type and foot regions, and a marginal significance ($p=0.0489$) in the three-way interaction, surface type*side*region (Table 7a). Simple effect tests showed that all the foot regions have significant interactions with the type of support surface (Table 7b). Further analyses showed that the participants' perceived feelings of the three surfaces were significantly different ($p < 0.05$) in the three foot regions (Table 7c).

[Insert Table 7 about here]

3.4. Correlation of material properties with subjective ratings

A correlation analysis was performed to understand the relationship between the PS ratings and the physical properties of tensile strength, Young's modulus, flexural rigidity, rebound resilience, and percentage of energy loss from the surfaces. To generalize the results, the physical property used was that corresponding to each participant's normalized foot length

in the mid-foot region of 20% to 70% foot length at intervals of 5%. The 20% location lies in front of the heel seat and the 70% was the minimum percentage of arch length among all participants (Table 1). The physical properties showed a low correlation (absolute of the Pearson correlation coefficient < 0.666) with PS ratings at all the above plantar locations. Additionally, the linear regression analyses showed a poor relationship ($R^2 < 0.49$) of energy loss percentage and stiffness with the PS ratings.

The PF ratings showed high correlations between overall foot and mid-foot region (correlation coefficient = 0.8804), and overall foot and forefoot region (correlation coefficient = 0.7458) (Table 8). This result suggests that the PF ratings for the overall foot may have been influenced by the perceived feelings of both mid-foot and forefoot regions. The correlations among other regions were lower than 0.7. In the experimental conditions, the rear-foot and the forefoot regions of the three foot support surfaces were designed and fabricated such that they were independent of the physical properties of the mid-foot region. Hence the low correlations of the PF ratings among rear-foot, mid-foot and forefoot regions' is not surprising.

[Insert Table 8 about here]

Correlation analyses were also performed between PF ratings and the measured physical properties of the support surfaces (SS60, SS25 and PU). The Pearson correlation coefficients were calculated between PF ratings (in overall foot and mid-foot region) and the calculated percentage of energy loss values at each participant's normalized plantar foot length locations from 20% to 70% in 5% intervals. The percentage of energy loss showed a significant negative correlation with the overall foot PF ratings (absolute value of the correlation coefficient > 0.8 and p-value $< .0001$) in the 30% to 50% region. Rebound resilience showed a higher positive correlation (correlation coefficient > 0.8 and p-value $< .0001$) as well in the same region. Flexural rigidity also showed a significant positive

correlation (correlation coefficient = 0.8146, p-value = <.0001). The correlations of tensile strength and Young's modulus with PF ratings (overall foot) were low (correlation coefficient = 0.5963 and 0.6460, respectively). Similar to overall foot correlation results, the percentage of energy loss showed a significant but negative correlation with mid-foot PF ratings (absolute value of the correlation coefficient > 0.788 and p-value < .0001) within the 30% to 50% region. Rebound resilience showed a higher positive correlation (correlation coefficient > 0.788 and p-value < .0001) as well within the above region. Flexural rigidity showed a significant positive correlation (correlation coefficient = 0.8219, p-value = <.0001) with PF ratings. The correlations of tensile strength and Young's modulus with mid-foot region PF ratings were low (correlation coefficient = 0.5466 and 0.5994, respectively). Both forefoot and rear-foot regions showed low correlations (absolute value of the correlation coefficient < 0.61) with the measured physical properties at all locations along the length. At the same time, the linear regression analyses showed strong relationships ($R^2 > 0.7$ and p-value = <.0001) between energy loss percentage and stiffness at loading with overall PF ratings in the region 35% to 45% of the plantar foot length (Figure 5). The PF rating of the mid-foot region showed a similar relationship with energy loss percentage and stiffness at loading (Figure 5) with a maximum R^2 value of 0.69 at 40% of the plantar foot length.

[Insert Figure 5 about here]

4. Discussion

4.1. Surface type effects

The results of the plantar shapes when standing on the three surfaces show interesting patterns. The surfaces were chosen such that the stiffness of two surfaces, PU and SS25, were similar and the percentage of energy loss of SS60 and SS25 were similar as these two physical properties have been shown to improve comfort and to reduce impact loads and injuries (Basford and Smith, 1988; Brodsky et al., 1988; Cook et al., 1985; Schwellnus et al.,

1990). The laser scans and the analyses related to the castings clearly showed that mid-foot plantar shapes were significantly different, even though the rear-foot and forefoot were fixed and the same among the three surfaces. This shows that the structure in the mid-foot can change shape independent of the rearfoot and forefoot areas. The normalized mean plantar profiles of the 16 participants showed that the shape when standing on SS60 was significantly different from that when standing on PU and SS25 (Figure 3). The statistical analyses (Table 4) revealed that the significant differences in shapes among the three surfaces were in the region 30% to 70 % of the plantar foot length. Even though the materials of the support surfaces were different, participants were still able to judge similar shapes as can be seen from the similarity of the PS questionnaire results between SS25 and PU (Figure 4 and Table 5). PU and SS25 were somewhat equally split between the “similar” and “not similar” categories whereas the comparisons between SS60 with both SS25 and PU showed a significant bias towards “not similar” and the proportions showed a significant difference as well. In other words, a majority of the 16 participants was able to identify the supporting surface shape of SS60 to be different from SS25 and PU. Thus, it is evident that participants can sense mid-foot shape during static standing even though the heel and forefoot areas are exactly the same. The PS ratings were static ratings obtained when the participant was standing on the support surface. Hence, the PS ratings ought to be a reflection purely of shape. The low correlations of the PS ratings with the physical properties are a clear reflection that the PS ratings are mainly related to shape rather than to the physical properties of the materials. The ANOVA and simple effects tests on the PS as well as PF ratings showed that the type of support surface used has significantly different effects on the mid-foot region (Tables 6 and 7).

4.2. Participant preferences

Not only are people capable of judging the mid-foot shapes, but they have different preferences for different shapes as well even in a static state such as standing. This could be

why a person suffering from plantar fasciitis is able to judge the shape mismatch in a shoe much quicker than a person without any injury as the shape mismatch between foot and a surface will cause uneven tensile forces on the tender plantar fascia thereby exacerbating the pain or discomfort. The ANOVA and SNK on the perceived shape ratings (Table 6) showed that the plantar shape of SS60 as having the highest preference and the shape on PU as having the lowest preference among all 16 participants. The potential reason for the differences may be related to plantar pressure (Alemány et al., 2003) as high plantar pressures are related to discomfort (Godfrey et al., 1967; Hodge et al., 1999). Figures 6 and 7 show the plantar pressure distribution of two participants when standing on the three surfaces. The significant characteristic of the pressures appears to be the smooth distribution of pressure from the heel to mid-foot on the SS60 surface when compared to SS25 and PU, which have very low load and low pressures in the mid-foot region. This observation points to the fact that the distribution of load into the mid-foot area helps improve perceived feelings by alleviating the loads in both heel and forefoot areas. This is consistent with Lee and Hong's (2005) results where the use of a TCI (Total Contact Insert) increased the peak pressure in the mid-foot region by 120 % and thereby increased the overall comfort rating by 261.5% when compared to a non-shoe insert condition of 7.6 cm high-heeled shoes.

[Insert Figure 6 and 7 about here]

4.3. Effect of material properties on subjective ratings

The physical property of the surface material will determine deformation under loading. Since a plate was used as the surface supporting the foot, the deformation in this case is bending-related deformation, which is characterized by the flexural rigidity property or EI. The SS25 and PU materials had very similar values for EI and hence the deformation under loading was similar even though the percentage of energy loss associated with the loading was different. Thus, the shape-related ratings should and were similar between the

SS25 and PU surfaces. Even though the PS ratings showed no significant relationship with the physical properties of the surfaces, the PF ratings exhibited strong relationships. The PF rating was given when the participant was allowed to move on the surface and hence those ratings should be related to physical properties. The PF ratings were highly correlated with the percentage of energy loss (negative), flexural rigidity (positive) and rebound resilience (positive). The results also showed that the percentage of energy loss and stiffness at loading in the 35% to 45% foot length region have the highest correlations with the PF ratings (Figure 5). In other words, the perceived feelings can be influenced by using a suitable material within this region. Goonetilleke (1999) showed that during standing, walking, and running, the “energy loss” property in materials used in the foot-shoe-floor interface is not important to rear-foot cushioning. This may possibly be due to the fact that when the heel hits the ground, the heel has to come off the ground, which will be aided by having good material rebound but, at the same time, the energy of impact has to be dissipated as well, which requires a high energy loss material. This requires a compromising solution and it could possibly be the reason that rebound or energy loss was not significant for the heel area for walking/running. On the contrary, the mid-foot and forefoot areas are more involved in the “take-off” phase and thus rebound would be helpful and thus explain why the two materials with higher rebound resilience, higher flexural rigidity and lower percentage of energy loss were perceived to feel better.

4.4. Importance of mid-foot shape

Our results show that even when the heel and forefoot are fixed, footwear or other appliances should have the right shape and deformation in the mid-foot area so that the required pressure profiles can be obtained. Otherwise, the mid-foot area of the foot will be raised off the surface or will experience too much compression. This can result in a lack of a smooth transition from heel strike to toe-off when walking or running. The lack of

compatibility may strain the plantar fascia as well resulting in plantar fasciitis (Cole et al., 2005; Riddle et al., 2003; Singh et al., 1997). Cushioning properties of foot supporting materials have a direct influence not only on the shape but also on the perceived feelings. The participant can sense the variations in the mid-foot shape even without moving the heel and forefoot. The mid-foot shapes may further change with changes in heel height (Alemány et al., 2003) and thus careful consideration of the mid-foot region is essential to prevent injuries and improve comfort. Overall, it may be said that perceived feelings depend on the mid-foot shape as well as the cushioning properties of the mid-foot.

4.5. Temperature effects

A question that can be posed is whether the responses would be the same if the feet were cold. The free nerve endings are the receptors that are sensitive to thermal stimuli (Levine and Shefner, 1990). Hence, the changes in thermal sensations may influence the touch sensation. Skin cooling causes a reduction in tactile sensitivity (Gescheider et al., 1997, Provins and Morton, 1960) and alters the sensory thresholds to pressure and vibration stimuli (Pitkow et al., 1981). Stevens et al. (1977) reported that pressure sensation is severely limited when the temperature drops below 10 °C. However, Kuklane et al. (2001) reported that, on average, when the ambient temperature varied between +5 and -11 °C, the lowest mean foot and toe skin temperatures were 24.1 ± 2.6 °C and 16.0 ± 1.4 °C when workers wore socks and boots. The toe temperatures were on average 7.3 °C colder than foot temperatures. Extremities are known to be cooler than the rest of the body (Jeong and Tokura, 1993; Purvis and Tunstall, 2004). Hall et al (2004) found that the temperature on the sole of the foot increased by 6-9 °F after walking and there were no differences in temperatures on the sole of the foot when different types of materials were used as insoles. Purvis and Tunstall (2004) also reported similar findings when they observed that the sock type had no effect on thermal and physiological responses during exercise. Based on previous research, it may be stated that

cold temperature effects would be significant on the toes but not on the mid-foot part of the sole of foot. Hence our conclusions may still be valid even when the ambient temperatures are low.

4.6. Whole-body effects

One limitation of this study is that whole-body discomfort was not evaluated even though it is well known that lower back pain is a major problem in many parts of the world (Denis et al., 2006; Gallis, 2006; Gangopadhyay, et al., 2006. Maines and Reiser, 2006). Our assessments were limited to the lower extremities. The effects of floor surfaces on whole-body discomfort have been studied by many (Rys and Konz, 1990; Redfern and Chaffin, 1995; Zhang et al., 1991). Others have evaluated the effects of insoles and foot cushioning devices in reducing back, leg, and foot pain during standing work (Basford and Smith, 1988; Wosk and Voloshin, 1985). Basford and Smith (1988) found that the addition of a visco-elastic insole into a shoe improved comfort while reducing back, leg and foot pain in subjects whose jobs required standing at least 75% of the time. Knowing the ideal mid-foot shape may help alleviate problems related to discomfort and pain when coupled with suitable materials. Another potential limitation is that the study participants were only of Asian origin. Studies in different domains have shown differences between populations. For example, Hu et al. (2007) observed differences in body dimensions between Chinese and Japanese while Ryu et al. (2006) found that the gait characteristics of Koreans are different from those of Westerners. Thus, our findings could be different with different subject pools. Surface roughness is known to affect the tactile sense (Choi and Jun, 2007). Different surface roughnesses could affect the participant responses as well. This is another area for further research.

5. Conclusions

Our results show that the structure in the mid-foot can change shape independent of the rearfoot and forefoot regions. Participants were capable of identifying the shape changes with distinct preferences towards certain shapes. The cushioning properties of the mid-foot materials also have a direct influence on perceived feelings. Therefore, even when the heel and forefoot are fixed, footwear should have the right shape and deformation in the mid-foot area so that the required pressure profiles can be obtained.

Further investigations are needed to check the external validity of the findings in terms of (a) feet of different populations, genders, and ages (b) a wider range of activities such as walking, running, jumping and (c) at different foot temperatures.

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Table 1: Descriptive Statistics of the Participants (N=16)

	Mean	Max.	Min.	SD				
Age (years)	25.44	35	20	3.46				
Weight (kg)	64.11	82.4	46.5	9.50				
Height (cm)	169.6	185.3	159.3	6.10				
	Right Foot				Left foot			
	Mean	Max.	Min.	SD	Mean	Max.	Min.	SD
Foot Length (cm)	25.63	27.7	23.6	1.03	25.58	27.7	24.0	1.07
Foot Length (Brannock)	8.22	10.5	6.0	1.21	8.19	10.5	6.0	1.25
Arch Length (cm)	18.69	20.3	17.3	0.70	18.79	20.5	17.6	0.76
Arch Length (Percentage of Foot Length)	72.96	74.42	71.27	0.87	73.47	75.19	71.70	0.98
Distance – D (cm)	1.01	1.4	0.9	0.12	***	***	***	***

Table 2: Physical properties of the three surfaces. Standard deviations are in parentheses

Abbreviation	SS25	SS60	PU
Material	Spring Steel	Spring Steel	Polyurethane
Thickness (mm)	0.25	0.60	3.20
Width (mm)	140.0	140.0	140.0
Tensile Strength (MPa)	1,268 (3.4)	1,200 (7.8)	4 (0.1)
Young's Modulus (GPa)	183 (4.3)	191 (5.8)	0.1 (0.001)
Flexural Rigidity (Nm ²)	0.033 (0.0008)	0.480 (0.0146)	0.038 (0.0003)

Table 3: Questionnaires used in the experiment.

1. Perceived Shape (PS) Questionnaire Instructions

In this part of the experiment we are trying to investigate the perceived shape feelings on various foot support surfaces. For this purpose, you will be presented with several surfaces in a random order. Your task will be to answer each of the following questions by assigning numbers. Assign a number to each surface presented to you. Then assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers that you may use. You may use whole numbers, decimals, or fractions. You have to stand on the surfaces without moving before giving a rating.

PS Questionnaire

- (a) Is the surface shape on which you are standing, the same on the Left & Right foot? (Same / Not same/ Not Sure)
- (b) Do you like the Left side shape on which you are standing? (Yes / No / Neutral)
Give a rating for how much you like the shape.
- (c) Do you like the Right side shape on which you are standing? (Yes / No / Neutral)
Give a rating for how much you like the shape.

High rating represents like it more

2. Perceived Feeling (PF) Questionnaire Instructions

*Your task will be to answer each following questions by assigning numbers. Assign a number to a foot support surface out of two surfaces presented to you. Then assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers that you may use. You may use whole numbers, decimals, or fractions.
You are allowed to move your feet up and down as if walking and lean forward and backward on the surfaces.*

PF Questionnaire

- (a) Do you like the feel on the left foot? (Yes / No / Neutral)
Give a rating.
Do you like the feel on the left rear-foot? (Yes / No / Neutral)
Give a rating.
Do you like the feel on the left mid-foot? (Yes / No / Neutral)
Give a rating.
Do you like the feel on the left forefoot? (Yes / No / Neutral) .
Give a rating.
- (b) Do you like the feel on the right foot? (Yes / No / Neutral)
Give a rating.
Do you like the feel on the right rear-foot? (Yes / No / Neutral)
Give a rating.
Do you like the feel on the right mid-foot? (Yes / No / Neutral)
Give a rating.
Do you like the feel on the right forefoot? (Yes / No / Neutral)
Give a rating.

High rating represents better feel

Table 4: Two-way ANOVA and Simple Effects Tests results of plantar shape on the SS60, SS25 and PU surfaces for all 16 participants

(a) ANOVA					
Source	df	Sum of Squares	Mean Square	F value	p value
Surface type	2	288.2541	144.1271	321.58	<.0001*
Location	6	15831.5274	2638.5879	5887.22	<.0001*
Surface type*Location	12	225.9358	18.8280	42.01	<.0001*
Error	315	141.1796	0.4482		
(b) Least Squares Means test - Surface Type*Location Interaction analyzed by Location					
Location	df	Sum of Squares	Mean Square	F value	p value
20 %	2	1.1743	0.5872	1.31	0.2713
30 %	2	45.9034	22.9517	51.21	<.0001*
40 %	2	176.2484	88.1242	196.62	<.0001*
50 %	2	197.9023	98.9512	220.78	<.0001*
60 %	2	85.2053	42.6027	95.06	<.0001*
70 %	2	7.7361	3.8680	8.63	0.0002*
80 %	2	0.0190	0.0099	0.02	0.9780
(c) Least Squares Means test of Surface type*Location t-test for Ho: LSMean(i)=LSMean(j) ; p > t					
Location	PU vs SS25 p value	PU vs SS60 p value	SS25 vs SS60 p value		
20 %	0.3268	0.1094	0.5336		
30 %	0.0156*	<.0001*	<.0001*		
40 %	0.1329	<.0001*	<.0001*		
50 %	0.4721	<.0001*	<.0001*		
60 %	0.8116	<.0001*	<.0001*		
70 %	0.8899	0.0005*	0.0003*		
80 %	0.9144	0.9180	0.8333		

* Significant at $p < 0.05$

Table 5: Test of Hypothesis for one-sample proportions in shape similarity ratings (PS

Questionnaire – a) H_0 : Mean = $1/3$; H_1 : Mean $\neq 1/3$

	PU vs SS25	PU vs SS60	SS25 vs SS60
	p value	p value	p value
Not Similar (NS)	0.0606	<.0001*	<.0001*
Similar (S)	0.3483	0.0606	0.0606
Not Sure (NSURE)	0.0262*	0.0010*	0.0002*

* Significant at $p < 0.05$

Table 6: ANOVA and post-hoc SNK on Perceived Shape ratings taken from 15 participants (PS Questionnaire – b & c)

(a) ANOVA					
Source	df	Sum of Squares	Mean Square	F value	p
Participants (P)	14	18935.38			
Surface Type (T)	2	77852.63	38926.32	38.80	<.0001*
P * T	28	28091.87	1003.28		
Side (S)	1	4412.41	4412.41	4.27	0.0578
P * S	14	14456.66	1032.62		
T * S	2	493.47	246.74	0.507	0.6074
T * S * P	28	13612.27	486.15		
Total	179	212609.61			

(b) <i>post-hoc</i> Student –Newman-Keuls (SNK)			
Surface Type (T)	SS60	SS25	PU
N	60	60	60
Mean	77.616	39.622	29.232
SNK Grouping

* Significant at $p < 0.05$

Table 7: ANOVA and Simple Effects Tests results on Perceived Feeling ratings taken from 15 participants (PF Questionnaire – a & b).

(a) ANOVA					
Source	df	Sum of Squares	Mean Square	F value	p
Participant (P)	14	68091.92			
Surface Type (T)	2	311036.58	155518.29	106.54	<.0001*
T * P	28	40872.50	1459.73		
Side (S)	1	292.96	292.96	0.40	0.5373
S * P	14	10267.83	733.42		
Region (R)	3	50803.79	16934.60	13.29	<.0001*
R * P	42	53534.11	1274.62		
T * S	2	466.61	233.30	0.40	0.6741
T * S * P	28	16489.42	588.91		
T * R	6	23430.08	3905.01	9.20	<.0001*
T * R * P	84	35645.52	424.35		
S * R	3	472.82	157.61	0.98	0.4113
S * R * P	42	6779.59	161.42		
T * S * R	6	1217.57	202.93	2.22	0.0489*
T * S * R * P	84	7687.61	91.52		
Total	719	702053.06			
(b) Least Squares Means test – Surface Type*Region interaction analyzed by Region					
Region (R)	df	Sum of Squares	Mean Square	F value	p value
Overall	2	117811	58905	138.81	<.0001*
Forefoot	2	40863	20432	48.15	<.0001*
Mid-foot	2	133821	66911	157.68	<.0001*
Rear-foot	2	41972	20986	49.45	<.0001*
(c) Least Squares Means test for significant differences found in (b) above. t-test for Ho: LSMean(i)=LSMean(j) ; $p > t $					
Region (R)	PU vs SS25 p value		PU vs SS60 p value		SS25 vs SS60 p value
Overall	<.0001*		<.0001*		<.0001*
Forefoot	0.0277*		<.0001*		<.0001*
Mid-foot	0.0001*		<.0001*		<.0001*
Rear-foot	0.0401*		<.0001*		<.0001*

* Significant at $p < 0.05$

Table 8: Intercorrelation matrix of PF ratings among regions

Variable	Overall	Forefoot	Mid-foot	Rear-foot
Overall	1.000	0.7458 (<.0001*)	0.8804 (<.0001*)	0.6718 (<.0001*)
Forefoot		1.000	0.6864 (<.0001*)	0.5338 (<.0001*)
Mid-foot			1.000	0.5256 (<.0001*)
Rear-foot				1.000

Note: Values in parentheses are Prob > |r| under $H_0: \rho=0$.

* Significant at $p < 0.05$