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Thilina W. Weerasinghe
Hong Kong University of Science and Technology

Ravindra S. Goonetilleke
Hong Kong University of Science and Technology

Uwe Reischl
Boise State University

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Thilina W. Weerasinghe
Human Performance Laboratory
Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong

Ravindra S. Goonetilleke*
Human Performance Laboratory
Hong Kong University of Science and Technology
Clear Water Bay, Hong Kong
ravindra@ust.hk

Uwe Reischl
Boise State University
Boise, Idaho

Abstract

The objective was to develop a methodology to assess Pressure Discomfort Thresholds (PDT), Pressure Pain Thresholds (PPT), and tissue stiffness on the plantar surface of the foot. Ten male and ten female participants volunteered for the study. Foot landmarks were used to create a standardized grid-type template of 95 points. For each test point, PPT and PDT values were obtained, and stiffness was calculated for each of the twenty participants. Cluster analyses were performed to determine the regions of similarity for the three dependent variables, PPT, PDT and stiffness. Moran's-I-index was used to determine the spatial auto correlations. The use of k-means clustering showed five distinct clusters while the three dependent variables showed strong correlations to each other. Morisita's similarity index was used to check the similarity of the grid among all participants. Both male and female participants showed a Morisita's index greater than 0.7 confirming the reliability of the foot template.

Practitioner Summary: Pressure Discomfort thresholds (PPT), Pressure pain thresholds (PPT) and tissue stiffness were evaluated at 95 points on the plantar surface of the foot. The PPT and related PDT map are useful to design the footbeds of shoes. Based on the data collected, five distinct clusters of locations were identified.

Keywords: algometry, discomfort, insoles, pressure pain threshold, tissue stiffness.

1. Introduction

Minimizing pain and discomfort is an important user requirement for many products that people use. Unfortunately, the strategy to enhance sensation or diminish discomfort is yet unclear. For example, Floyd and Roberts (1985) suggested concentrating the load on the bony areas while others have proposed a more uniform force distribution over the contact area to reduce discomfort (Sanders and McCormick, 1987). This dilemma of whether to distribute or concentrate may be resolved, for shoes and other accessories, by understanding the pain pressure threshold (PPT) on the corresponding body part (Brennum et al., 1989). The pain pressure threshold is described as the minimum pressure that induces pain (Fischer, 1987). The importance of PPT has been recognized in recent times (Huang et al., 2015; Makhsous, et al., 2012; Rathleff, et al., 2013). However, pressure discomfort threshold (PDT) is more suitable as a design criteria in product design (Goonetilleke, 2001).

During activities such as running, standing or walking, force is transmitted through the plantar surface rather than the dorsal surface of the foot, and hence the sensations on the plantar surface play a large role in pain and discomfort (Moreira et al., 2016; Price et al., 2013). Researchers have evaluated various objective and subjective properties on the plantar surface of the foot (Aerts and De Clercq, 1993; Cavanagh et al., 1984; Challis et al., 2008; Gonzalez et al., 1999; Hurn et al., 2014; Kinoshita et al., 1992; Rodrigo et al., 2013; Xiong et al., 2010). Unfortunately, there is no way to compare the results of these studies except at the common anatomical landmarks that the researchers have used. This is due to the inability to locate and match the similar points across the various studies. The anatomical landmarks for the plantar foot are quite limited. Some of them, especially in the hind-foot, are not easy to locate due to the thickness of the soft tissue.

PPT has been evaluated at selected locations by some researchers (Gonzalez et al., 1999; Goonetilleke and Eng, 1994), and is known to be higher in the bony area as compared to those with soft tissue (Kosek et al., 1999). Given that the foot is a very complex structure, it is not possible to interpolate or extrapolate the known PPT information to points other than those that have been tested by researchers. Data are limited due to the time it takes to test points and also due to the inability to align and register the points across participants so that consistent data can be obtained. This study is primarily aimed at overcoming the latter limitation.

Researchers have used various axis systems including heel center to second toe tip, "symmetrical" axis (equidistant to the edges), and so on in anthropometric studies (Kouchi,2003). These axis systems serve its purpose in anthropometry, but differ from person to person and hence the measurement consistency is suspect especially in relation to bones and soft tissue regions (Ma and Luximon, 2014). Herein a template has been developed to resolve the above issue by using anatomical landmarks. The method can be applied across many participants to make comparisons. In the experiment reported here, the template was used and its validity checked for PPT and PDT so that areas with similar sensations could be identified on the plantar foot.

2. Methodology

2.1 Landmarking and Template Generation

Several attempts were made to generate an appropriate template. However, some of them failed as they were not able to produce consistent patterns for PDT and PPT. These inconsistencies were judged based on the anatomy of the foot. For example, the soft tissue of one participant ended up being a bony area for another and so on. What is reported here is a grid-type template that showed consistent results across many participants.

In general, it is difficult to locate the anatomical landmarks on a plantar surface. Therefore, an instrument, similar to a mechanical divider, was developed to "map" the points on the dorsum side to the plantar surface. This device included two spirit levels to ensure that the instrument was straight and not tilted to one side. The 1st metatarsal head, 2nd metatarsal head, 5th metatarsal head and metaphysis of the 5th metatarsal bone (Fig. 1) were identified by palpation and marked on the foot dorsum surface while the participant stood on a plate with small holes. The instrument was used to project the dorsum side landmark to the plantar surface. These points on the plantar surface were then marked with a pen.

A finding that aided the grid development was related to the linear measurements A, B, and C (Fig. 1b). A pilot study with three participants showed that the ratio of B/A was about 6 and the C/A ratio was about 7. Drawing a line from the5th MPJ to metaphysis of the 5th metatarsal ensured that the line was along the 5th metatarsal bone. Taking this line as a reference and by dividing it into seven equal parts (corresponding to the ratio C/A) and dividing the 1st MPJ to 5th MPJ line into six equal parts (corresponding to B/A), a grid was drawn on the plantar-foot surface. The pilot participants had 17 grid lines along the foot length and 7 grid lines along the foot width. After developing the grid, the PPT at each grid point was evaluated with a 0.5 cm^2 probe at an indentation speed of 1 mm/s.

The PPT data of these three pilot subjects showed that the maximum PPT of each widthwise grid line until the 8th grid line, was on the 5th MPJ to metaphysis of the 5th metatarsal line (6th lengthwise gridline). The maximum PPT of most of the widthwise grid lines after the 8th gridline was on the 3rd lengthwise grid line (Fig. 2). Given the uniformity of the PPT pattern, an experiment was performed to collect data with more participants.

Insert Figures 1, 2, and 3 about here

2.2 Procedure

2.2.1 Participants

A total of twenty students participated in the study. The mean age of the ten males was 24.2 years (SD= 4.39 years) and the mean age of the ten females was 23 years (SD= 2.4 years). Various foot measurements were recorded (Fig. 3). The male participants had a mean foot length of 259.6 mm (SD = 13.8 mm) and the mean foot length of the females was 234.2 mm (SD = 10.2 mm). All participants were free of foot deformities and did not have any skin diseases. The experiment was approved by the institutional research ethics committee.

2.2.2 Equipment

Pressure algometers are generally used for measuring PPT and PDT. However, these offer very little control in terms of the speed and orientation of application. Hence, the Automatic Tissue Tester (ATT) (Rodrigo et al., 2013; Xiong et al., 2010) was used at an indentation speed of 1 mm/s with a 0.5 cm^2 cylindrical, rounded-edge probe. The grid spacing on the template was about 1 cm and the 0.5 cm^2 (or 7.9 mm diameter) probe avoided any interaction between testing points due to their distance from each other. A speed of 1 mm/s was used so that the results could be compared to other studies such as Xiong et al., (2010) and Rodrigo et al., (2013). The participants were requested to indicate the PDT and PPT by pressing the appropriate button on the hand-held control panel. The indentor retracted as soon as the PPT button was pressed. Labview software was used to record the force and displacement values over the duration of testing.

All viable intersection points on the 95-grid were tested. The sequence of testing was determined by a Microsoft Excel Visual Basic for Applications (VBA) program which ensured that neighboring points were not selected during a 5 min time period to minimize any residual effects as a result of indentation. Each point was tested only once to:

1. Minimize fatigue: the experimental time was around 3 hours for one trial on the 95 points, and hence, a second trial would double the time.
2. Prevent any adaptation to the pressure stimulus with multiple trials at same site.

Each participant was given a 10 min rest after testing 30 points. Each participant stood on the ATT platform with equal load on each foot. To ensure equal loading on both feet, the F-scan pressure sensor from TEKSCAN (Boston, MA) was placed under the participant's left foot to monitor the force as it was not tested. The participant was asked to adjust and maintain half body weight on each foot during any one trial.

2.2.3 Data Analysis

For the proposed grid to be usable, its applicability should be checked across participants. Hence the similarity of each variable, across all participants, was determined using Morisita's index of difficulty (Morisita, 1959) as it is known to be one of the most robust similarity indices (Krebs, 1999). This index is independent of sample size and diversity (Wolda, 1981).

$$C_\lambda = \frac{2\Sigma X_{ij} X_{ik}}{(\lambda_1 + \lambda_2) N_j N_k}$$

$C\lambda$= Morisita's index of similarity between subject j and k (0 - no similarity 1- completely similar)

X_{ij}, X_{ik} = Value of the variable in i point in participant j and participant k

$N_j = \Sigma X_{ij}$ = Summation of the variable in all i points in participant j

$N_k = \Sigma X_{ik}$ = Summation of the variable in all i points in participant k

$$\lambda_1 = \frac{\Sigma[X_{ij}(X_{ij} - 1)]}{N_j(N_j - 1)} \qquad \lambda_1 = \frac{\Sigma[X_{ik}(X_{ik} - 1)]}{N_k(N_k - 1)}$$

Spatial autocorrelations, the correlations among nearby locations, of PDT and PPT were checked with Moran's-I index (Moran, 1950; Odland, 1988). It was calculated as follows:

$$I = \frac{N}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2}$$

The weighting matrix (w_{ij}) was determined from the inverse distance of each pair of points. The I values range from -1 (perfect dispersion) to +1 (perfect correlation) with zero indicating a random spatial pattern. Moran's-I was calculated for each variable and each participant and the variable with a higher Moran's-I was selected for the cluster analysis using K means (Wagstaf, 2001) so that the areas having similar sensations of discomfort and pain can be identified.

The correlations reported in subsequent sections are Pearson Correlation coefficients.

3. Results

3.1 Foot Measurements

A correlation analysis was performed on the foot measurements (Fig. 1). Measurement A and the distance between 1st MPJ to 5th MPJ (B) had a Pearson correlation of 0.872 ($p < 0.05$). Measurement A and the distance between 5th MPJ to metaphysis of 5th metatarsal had a correlation of 0.886 ($p < 0.05$). Ratio of B/A was about 6 for each subject (mean = 6.06, SD = 0.21). The ratio C/A was approximately 7 for each subject (mean = 6.82, SD = 0.23).

3.2 PPT and PDT

PDT and PPT showed high Morisita's similarity index values (> 0.80). Males showed high correlations between PPT and PDT (Pearson correlation coefficient = 0.91; $p < 0.01$) (Fig. 4). The average PPT values for both male and female participants are shown in Table 1. Surprisingly, females did not have a significant correlation between PPT and PDT (Pearson correlation coefficient = 0.071; $p > 0.4$). Fisher's least significant difference (LSD) *post-hoc* test (Widyanti et al., 2015) showed that both minimum and maximum PPT and PDT had significantly higher values in males when compared to the female participants ($p < 0.01$).

The mean, maximum, and minimum values with their corresponding locations are quite useful for design especially as it is unlikely to be the same location for every participant. Furthermore, it helps to see if there are "favored" areas in terms of loading. The mean value of the maximum PPT across all males was 2331.4 kPa (range: 1710.2 - 3042.7 kPa). The locations of the maximum PPT were at (14,3), (15,3), (13,4), (12,3), (13,3), (14,2), (14,3), (13,3), (14,3),(14,2)]. The mean value of the minimum PPT across all males was 382.6 kPa (range: 186.2 - 549.1 kPa) at (10,1), (9,6), (16,3), (15,5), (10,1), (15,5), (9,6), (16,2), (10,1). The mean values of the maximum and minimum PPT of females were 1434.9 kPa (range: 936.5 - 2122.3 kPa) at (12,2), (14,3), (14,2), (13,3), (12,3), (12,3), (13,4), (13,3), (13,4), (12,3) and 189.1 kPa (range: 82.2 - 281.9 kPa) at (7,1), (10,1), (6,1), (10,1), (4,2), (3,3), (10,1), (9,1), (16,2), (16,2). Similarly, the means of the maximum and minimum PDT of males were 1659.2 kPa (range: 664 - 2547 kPa) at (14,3), (15,3), (13,4), (13,2), (14,3), (13,3), (15,3), (13,3), (13,3), (14,3) and 232.0 kPa (range: 41.0 - 477.7 kPa) at (11,1), (4,0), (6,3), (15,5), (11,1), (5,2), (3,1), (7,1), (7,1), (10,1), respectively. The means of maximum and minimum PDT of females were 938.8 kPa (range: 371.8 - 1461.1 kPa) at (13,5), (1,6), (13,5), (13,5), (13,5), (12,5), (13,5), (12,5), (14,5) and 97.1 kPa (range: 28.2 - 195.8 kPa) at (6,3), (6,5), (6,3), (7,6), (4,3), (6,2), (8,3), (4,4), (6,5), (6,3), respectively.

Insert Figure 4 about here

3.3 Stiffness

Stiffness, a measure of the force required for a unit deflection has been used to characterize various materials (Goonetilleke, 1999). The secondary stiffness (highest gradient in the Force versus Deflection curve) corresponding to the stiffness of the hard tissue (Rodrigo et al., 2013) was calculated by maximizing the R-squared value of the linear fit at the higher force values (Fig. 5). The reason for using the higher force values was that both PDT and PPT were on the secondary part of the force-deflection curve rather than on the lower gradient representing the lower stiffness of the softer tissue (Rodrigo et al., 2013). The mean secondary stiffness values are shown in Table 2. The LSD *post-hoc* test showed that males had a higher stiffness when compared to the female participants ($p < 0.01$). Stiffness is strongly correlated with PPT for both males and females (Pearson correlation coefficient, $R = 0.89$ ($p < 0.001$) for males; $R=0.86$ ($p < 0.001$) for females). The stiffness - PDT correlation was 0.86 ($p < 0.001$) for males, but it was not that high for females ($R= 0.56$; $p < 0.001$). The Stiffness versus PPT and PDT relationships are shown in Fig. 6 and Fig.7.

Insert Figures 5, 6 and 7 about here

Moran's-I was calculated for the variables using the ArcGIS software (Esri Inc., Redlands, CA). PPT and PDT had positive Moran's-I values for both males and females. PPT had an average Moran's I index of 0.485 (SD=0.11) in males and 0.477 (SD= 0.13) in females. PDT had an average Moran's-I index of 0.601 (SD =0.08) in males and 0.747 (SD= 0.12) in females. Stiffness had a Moran's-I index of 0.479 (SD= 0.1) in males and 0.608 (SD= 0.07) in females.

The cluster maps of PPT, PDT and stiffness are shown in Fig. 8.

Insert Figure 8 about here
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4. Discussion

A foot-grid was developed with reference to four skeletal points that could be identified by palpation. The points were projected onto the plantar-foot surface using an especially designed instrument. Spatial correlations and similarity across participants are important aspects to compare the differing properties measured at the grid points. Morisita's similarity index has been used to check the similarity in other studies (Armstrong, 2006). This index has been shown to be independent of sample size and diversity. Hence it was used in this study. Morisita's similarity index had relatively high values (> 0.8) among both males and females. Thus, the grid is a good way to standardize testing in future studies. One male and one female had wide feet. Their ratio between the 1st MPJ to 5th MPJ distance (B) and perpendicular distance of 2nd MPJ to 1st MPJ and 5th MPJ line (A) was about seven. Therefore, the data of these two subjects were not used in the analysis reported here. A different template may be required for those with extra-wide feet. The important finding to note is that these measurements are ideal to classify normal as well as wide feet.

Soames (1985) has reported differences in feet and gait of both males and females. The data in this experiment shows that males have a significantly higher PPT and PDT value when compared to females. These differences are in agreement with prior studies such as Racine et al. (2012), Riley et al. (1997) and Lautenbacher et al. (2004). Expectancy may be a possible cause for such a difference (Fillingim, 2000). In other words, females express pain while males hold-back emotions of pain. However, it should be noted that the cultural background of the subject population tested, and their willingness to express pain may dictate the presence or absence of a difference between genders.

The maximum PPT of males was about 2000 kPa. However, previous studies reported a PPT of about 1100 kPa at the heel of young Chinese adults (Rodrigo et al., 2013; Xiong et al., 2010). Again, such a difference may be a reflection of the higher thresholds in the population tested. In the current study seven out of ten participants were South Asians who may have a higher PPT possibly due to extensive barefoot walking. The mean values, at each point, of Chinese participants and South Asian participants showed a significant difference in a paired t-test with South Asians having higher PPT values. Another possible reason for the higher PPT in this study over the previous studies could be due to sensory adaptation. Here, 95 points were tested and over time, the participants are likely to adapt to the discomfort and pain they perceive. Sensory adaptation, where a higher threshold for pain is experienced in the presence of a constant stimuli during the course of the experiment has not been well studied (Adrian, 1928; Peck et al., 2008).

The design criteria for a shoe or accessory should be below the discomfort threshold. Knowing the PDT/PPT ratio and the PPT allows PDT to be calculated easily. Rodrigo et al. (2013) reported a ratio of 41-49% for just three points on the plantar surface of the foot. In this study the PDT/PPT ratio in males was 60.8% (Range 42.3%

- 86.4%), and that in females was 58.5%. (Range 15% - 99.4%). PPT values and the PDT/PPT ratios for both male and female participants for each point are in table 1. The variation of PDT/PPT on the plantar surface was relatively large in females.

Insert Table 1 about here

As expected the Moran's-I index was relatively high for PPT, PDT and stiffness indicating that the data exhibit distinct clusters. K means clustering together with the within- cluster sum of squared elbow method was used to determine the optimum number of clusters (Tibshirani et al., 2001; Edward and Sforza, 1965). The elbow method suggests that the apparent turning point of the curve of the sum of the squared Euclidean distance against the number of clusters is the optimum number of clusters. The analysis was carried out separately for males and females. Five clusters appear to be the optimum for PPT, PDT and stiffness in both males and females (Figure 8). The clusters are quite useful. Even though we evaluated the thresholds at 95 points, the clustering indicates that testing five points can reveal the behavior of the plantar foot surface due to similarities across locations. Thus, the points chosen by Rodrigo et al., (2013) and Xiong et al., (2010) are justified.

The strong correlation between stiffness and PPT has been reported previously (Rodrigo et al. 2013). This relationship is seen in this study as well indicating that the stiffer regions tend to have higher pressure thresholds and thus are able to withstand higher loads.

The F-scan pressure sensors (Hsiao et al. 2002, Wettenschwiler et al., 2015) were used during the test to balance the load between the left and right feet. At that time, the standing pressure patterns were collected as well. The barefoot standing pressure patterns have a close resemblance to PPT (Fig. 9); higher pressures correspond to higher thresholds and vice versa. This implies that footwear designs based on barefoot pressure maps may help minimize discomfort and pain if they can be accommodated with the footbed design. Of course, the loading areas have to be accounted if the foot is not fully touching the support surface.

Insert Figure 9 about here
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5. Limitations

The complete plantar-surface, excluding the toes, was tested only with a 0.5 cm^2 probe at a speed of 1 mm/s. Even though the patterns may be similar, more data for different indentation areas and differing speeds may be useful for substantial generalization. In addition, it may be appropriate to also check the toe areas.

6. Conclusions

A template of 95 points was used to determine PPT, PDT and stiffness data. The efficacy of the template was tested with twenty volunteer participants. Morisita's similarity index was used to check the similarity of the grid among these participants. Both males and females showed a Morisita's index greater than 0.8, confirming the reliability of the grid. The plantar surface has regions with similar sensations as shown by the clusters. The PPT map and its closely related PDT map can now be used to design and develop footbeds for insoles and shoes so that the higher PPT areas can bear higher loads and vice versa.

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List of Tables

Table 1a: PPT (kPa) of the male participants at grid intersection points. PDT/PPT ratio is in brackets. The maximum and minimum values are shown in bold.

6	5	4	3	2	1	0	Grid Point
1079.5 [0.65]	1276.6 [0.78]	1188.9 [0.68]	1396.8 [0.66]	1189.1 [0.69]	1169.6 [0.58]	1180.9 [0.68]	**0**
1471.63 [0.64]	1207.8 [0.61]	1306.7 [0.71]	1229.2 [0.65]	1203.5 [0.62]	1139.9 [0.62]	1228.8 [0.72]	**1**
1386.1 [0.66]	1178.3 [0.55]	1059.4 [0.59]	1073.1 [0.63]	1076.0 [0.53]	1081.9 [0.61]	1022.2 [0.67]	**2**
1540.1 [0.53]	1206.1 [0.62]	1093.4 [0.52]	1046.6 [0.59]	966.8 [0.56]	1138.4 [0.62]	906.6 [0.54]	**3**
1537.1 [0.52]	1398.2 [0.56]	1190.4 [0.65]	1118.1 [0.50]	975.3 [0.56]	1164.6 [0.53]	949.1 [0.57]	**4**
1683.6 [0.58]	1312.7 [0.62]	1046.2 [0.50]	1020.1 [0.60]	1025.8 [0.51]	999.9 [0.61]		**5**
1632.9 [0.57]	1280.1 [0.58]	1255.9 [0.69]	957.3 [0.53]	1070.9 [0.53]	1016.7 [0.51]		**6**
1688.9 [0.59]	1330.8 [0.56]	1187.5 [0.53]	1307.9 [0.61]	1052.7 [0.53]	815.8 [**0.42**]		**7**
1524.5 [0.53]	1333.1 [0.58]	1277.1 [0.54]	1092.9 [0.54]	1219.6 [0.5]	973.2 [0.52]		**8**
797.0 [0.71]	1312.5 [0.61]	1283.1 [0.60]	1427 [0.58]	1070.0 [0.56]	**714.39** [0.61]		**9**
	1338.4 [0.55]	1409.4 [0.62]	1477.9 [0.50]	1268.3 [0.64]	784.0 [0.58]		**10**
	1362.9 [0.58]	1436.8 [0.65]	1792.7 [0.57]	1463.5 [0.66]	720.4 [0.65]		**11**
	1488.1 [0.59]	1542.3 [0.64]	1889.4 [0.58]	1572.8 [0.66]	826.4 [0.65]		**12**
	1536.8 [0.69]	1748.5 [0.62]	2034.7 [0.65]	1629.3 [0.68]			**13**
	1223.7 [0.71]	1667.4 [0.63]	**2124.0** [0.62]	1729.5 [0.72]			**14**
	1101.4 [**0.86**]	1528.2 [0.64]	1804.4 [0.65]	1487.7 [0.64]			**15**
		1055.0 [0.70]	1048.7 [0.64]	734.8 [0.78]			**16**

Table 1b: PPT (kPa) of female participants at the grid intersection points. The PDT/PPT ratio is in brackets. The maximum and minimum values are shown in bold.

6	5	4	3	2	1	0	Grid Point
634.2 [0.67]	739.8 [0.79]	660.0 [0.86]	729.3 [0.86]	659.7 [0.80]	628.2 [0.52]	570.3 [0.58]	**0**
794.9 [0.69]	719.4 [0.83	792.1 [0.98]	703.6 [0.73]	667.5 [0.89]	590.0 [0.88]	671.7 [0.65]	**1**
818.9 [0.80]	611.3 [0.60]	615.6 [0.60]	607.0 [0.66]	556.9 [0.77]	619.7 [0.97]	500.7 [0.96]	**2**
811.3 [0.94]	531.6 [0.63]	519.4 [0.59]	409.3 [0.45]	487.7 [0.58]	424.6 [0.47]	359.1 [0.38]	**3**
747.2 [0.78]	542.2 [0.33]	542.9 [0.28]	473.2 [0.26]	413.5 [0.22]	412.0 [0.25]	343.0 [0.26]	**4**
769.0 [0.96]	566.2 [0.62]	478.6 [0.68]	429.1 [0.37]	482.9 [0.39]	388.6 [0.30]		**5**
768.8 [0.41]	582.6 [0.42]	615.2 [0.42]	563.9 [0.54]	507.4 [0.50]	332.2 [0.35]		**6**
727.1 [0.59]	689.3 [0.77]	600.8 [0.33]	544.3 [0.29]	480.3 [0.22]	344.9 **[0.15]**		**7**
613.8 [0.54]	621.7 [0.69]	681.1 [0.62]	596.7 [0.65]	531.0 [0.47]	454.2 [0.32]		**8**
547.8 [0.31]	620.5 [0.40]	674.8 [0.46]	702.9 [0.53]	555.6 [0.43]	**326.3** [0.27]		**9**
	748.7 [0.57]	762.8 [0.81]	826.9 [0.56]	660.5 [0.40]	358.9 [0.19]		**10**
	679.5 [0.73]	826.8 [0.98]	1004.8 [0.73]	769.1 [0.68]	420.3 [0.36]		**11**
	796.4 [0.64]	999.7 [0.87]	**1184.7** [0.70]	970.5 [0.88]	559.5 [0.54]		**12**
	831.1 [0.59]	1050.2 [0.70]	1172.0 [0.72]	896.2 [0.71]			**13**
	809.0 [0.57]	878.0 [0.64]	1004.6 [0.88]	1007.3 **[0.99]**			**14**
	620.9 [0.48]	849.2 [0.66]	907.9 [0.72]	841.5 [0.60]			**15**
		506.8 [0.47]	484.8 [0.48]	361.2 [0.3]			**16**

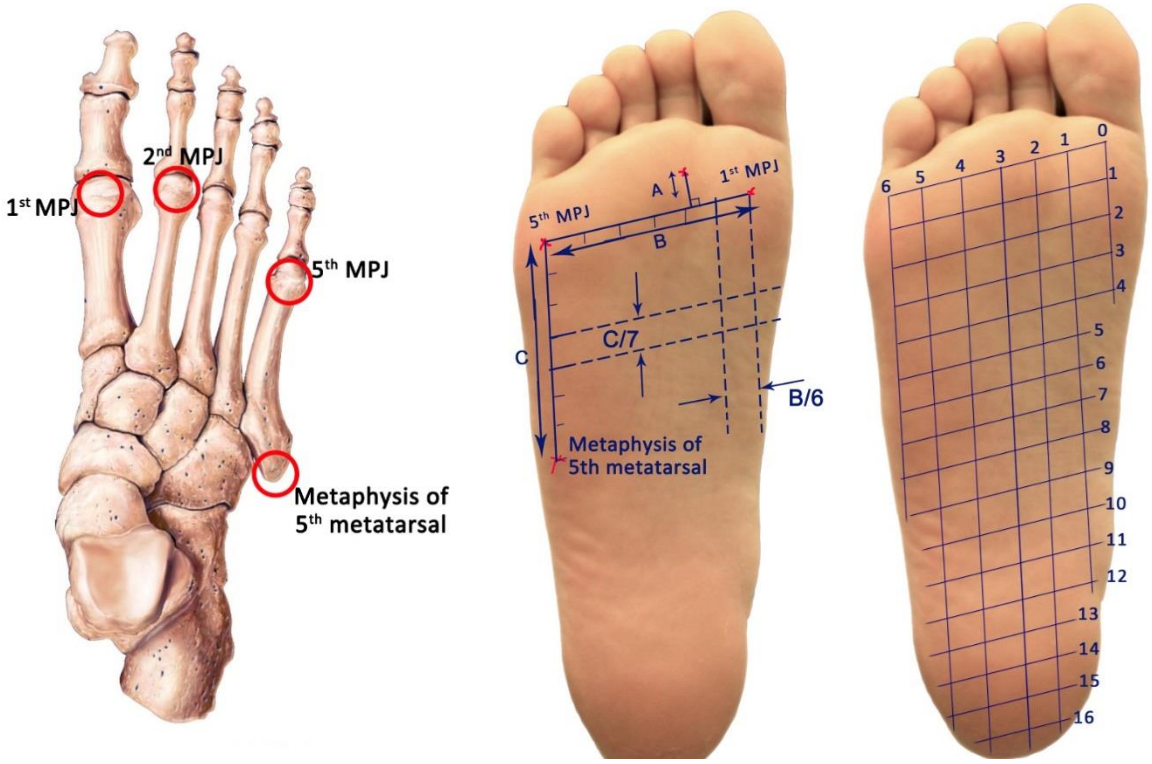
Table 2a: Secondary stiffness (K) kN/m of males at the grid intersection points. All in units of kN/mm

6	5	4	3	2	1	0	Grid Point
6.35	9.02	11.07	10.08	10.12	9.21	11.24	**0**
11.79	10.57	9.80	9.32	10.11	10.89	8.44	**1**
9.25	8.19	8.28	7.27	7.26	7.53	7.09	**2**
9.54	8.64	7.29	7.13	6.29	7.31	5.49	**3**
10.35	9.51	7.92	7.13	6.85	7.30	5.98	**4**
11.29	8.48	7.16	7.53	7.17	6.35		**5**
10.87	9.33	8.75	6.81	7.43	6.47		**6**
11.29	8.78	8.19	8.95	7.06	5.30		**7**
8.48	9.05	8.69	7.96	8.11	6.01		**8**
4.06	8.73	8.32	8.91	7.36	4.49		**9**
	7.32	9.56	9.48	8.47	4.22		**10**
	8.17	9.98	11.81	10.05	4.11		**11**
	9.38	11.71	15.69	11.31	4.89		**12**
	8.51	15.35	20.15	15.25			**13**
	6.48	13.75	21.42	16.36			**14**
	7.03	9.88	12.69	10.59			**15**
		5.54	7.14	4.15			**16**

Table 2b: Secondary stiffness (K) of females at the grid intersection points. All in units of kN/mm

6	5	4	3	2	1	0	Grid Point
5.20	6.66	8.64	7.89	7.52	6.50	6.84	**0**
8.20	6.91	7.21	7.47	7.77	7.23	7.08	**1**
7.32	5.41	5.70	5.75	5.49	5.05	5.65	**2**
6.72	5.40	4.33	4.01	4.32	4.25	3.44	**3**
7.39	5.70	5.18	4.68	3.95	3.88	2.96	**4**
8.02	5.75	4.51	4.75	4.37	3.42		**5**
8.07	6.20	6.57	4.62	4.68	3.48		**6**
6.53	7.39	5.90	5.65	4.99	3.46		**7**
5.27	5.97	7.08	5.52	6.03	4.34		**8**
4.97	5.60	6.70	6.27	5.40	2.64		**9**
	6.72	7.87	7.06	7.04	3.00		**10**
	6.28	7.51	10.02	7.56	3.54		**11**
	8.04	11.29	14.05	9.89	4.48		**12**
	9.04	13.24	15.85	12.11			**13**
	7.54	10.80	18.87	10.77			**14**
	6.23	8.62	9.39	6.96			**15**
		5.03	4.96	3.26			**16**

Figures



(a) (b) (c)

Fig. 1: Illustration of how to generate test grid (a) Foot landmarks used in referencing plantar grid parameters. (b) Projected landmarks and the dimensional measurements, A, B, and C. (c) test grid generated by drawing lines parallel to the 1stmPj-5th MPJ line and the 5th MPJ-metaphysis of 5th metatarsal lines.

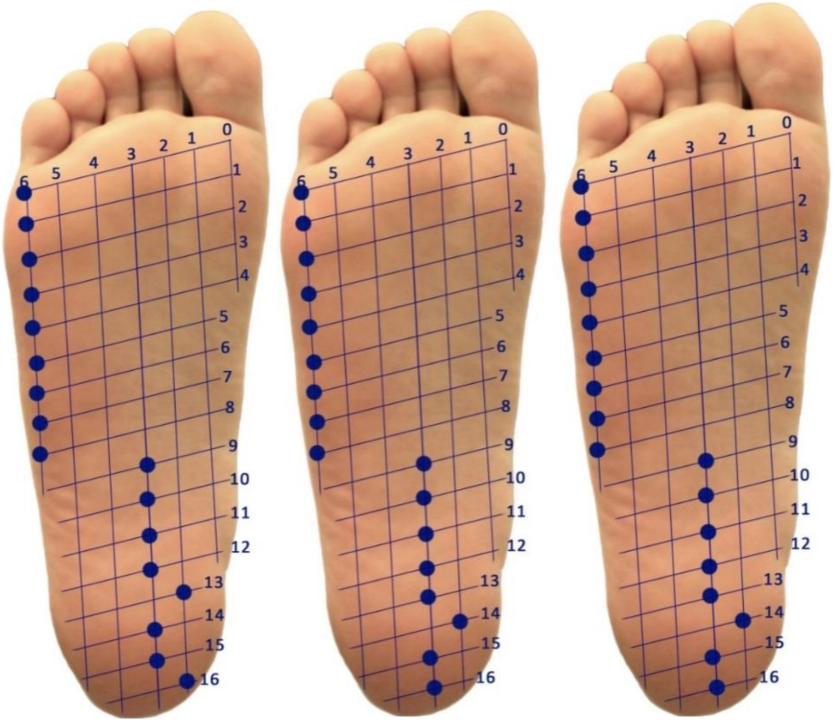


Fig. 2: Maximum PPT measured on each widthwise grid line of three participants in pilot study.

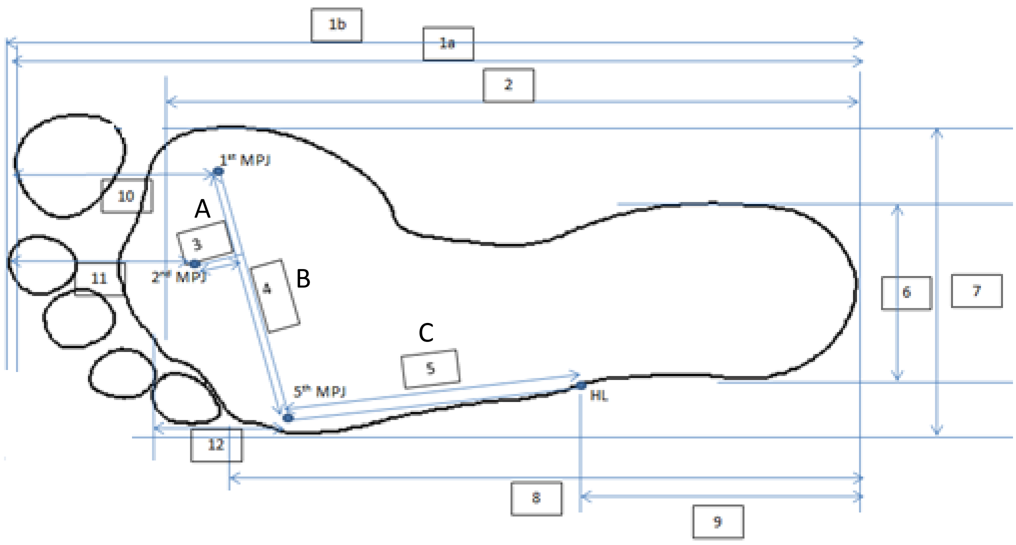


Fig. 3. Illustration of all foot measurements recorded

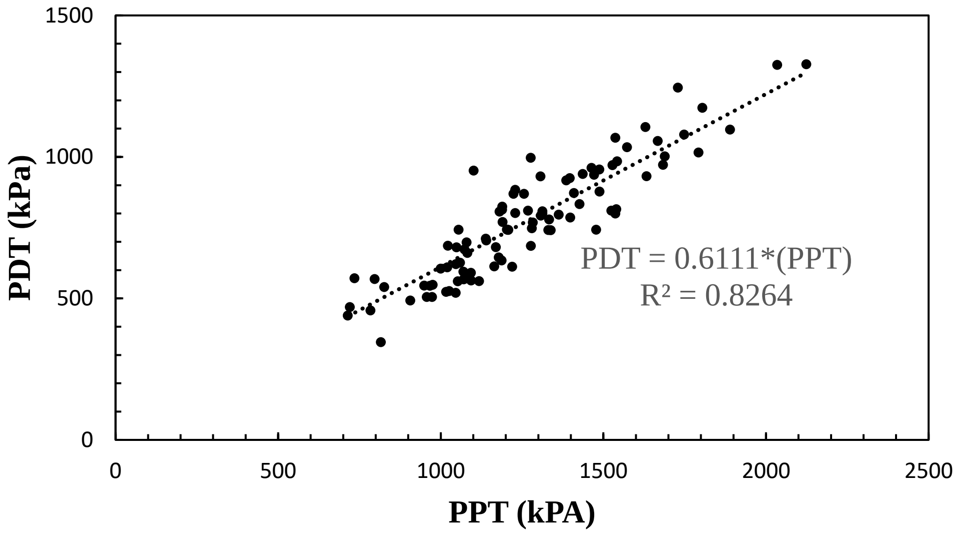


Fig. 4: PPT vs. PDT for the male participants

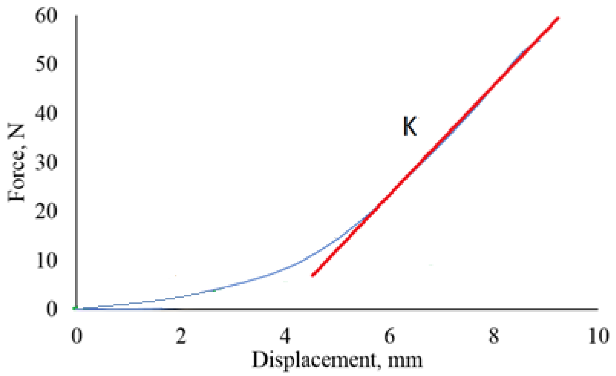
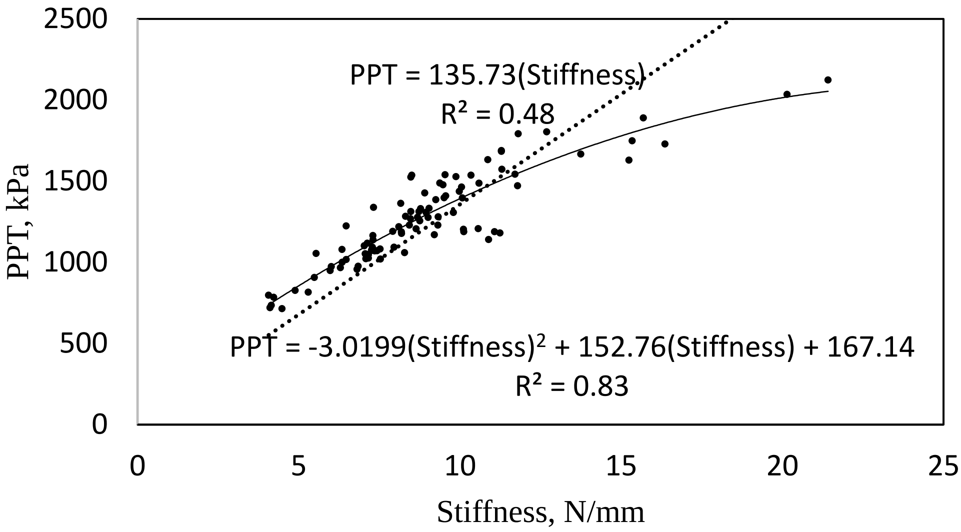
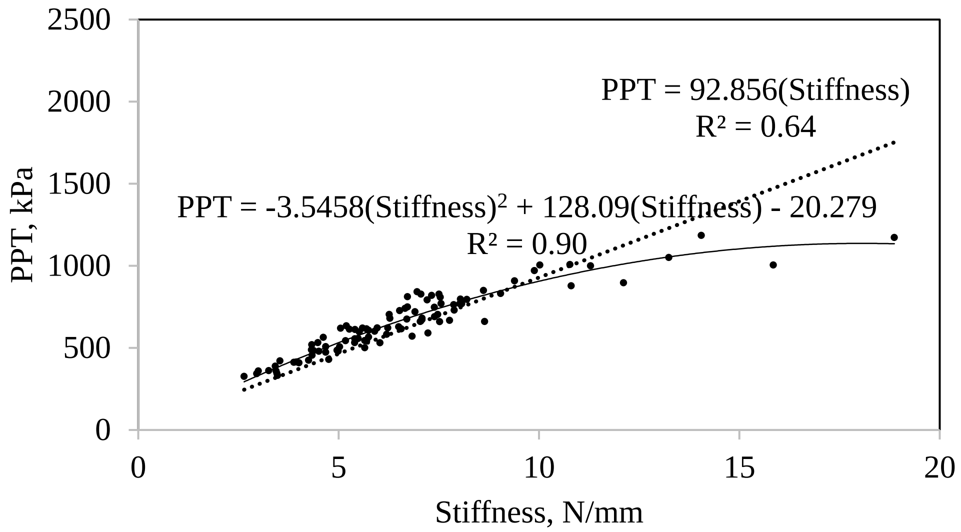


Fig. 5: Illustration on how Stiffness (K) was determined for the hard tissue part of the Force-Deflection (F-D) curve



a)



b)

Fig. 6: PPT vs. Stiffness of (a) Males (b) Females

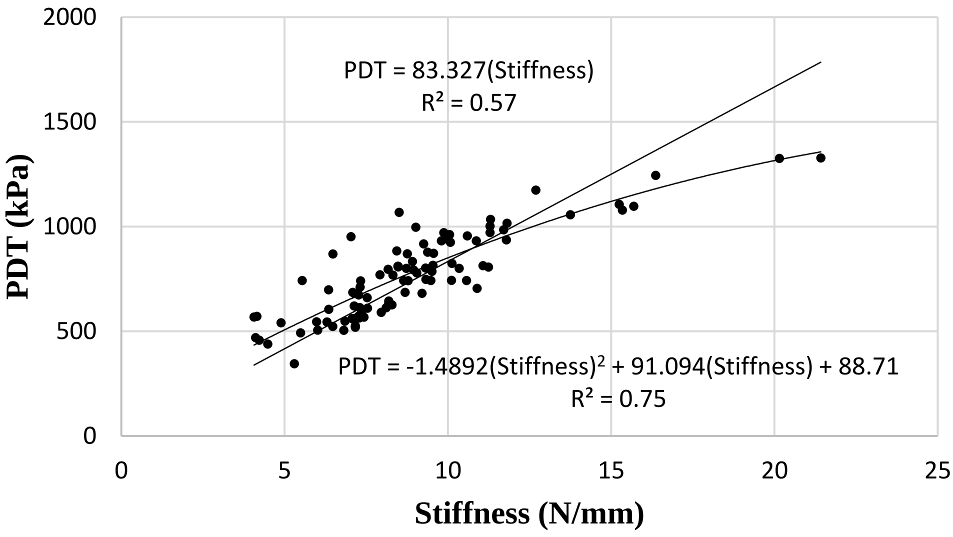


Fig. 7: PDT vs. Stiffness plot for the male participants.

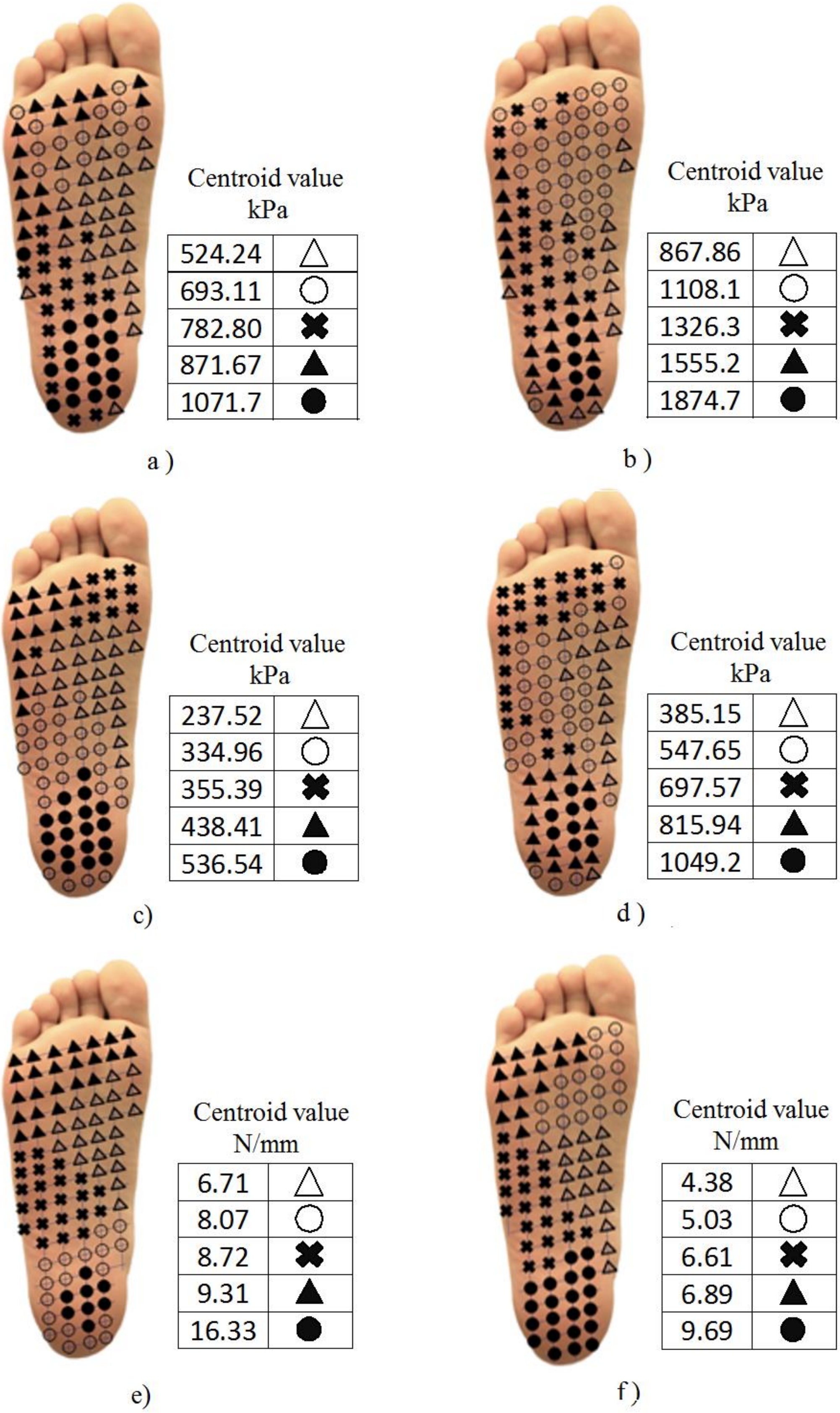
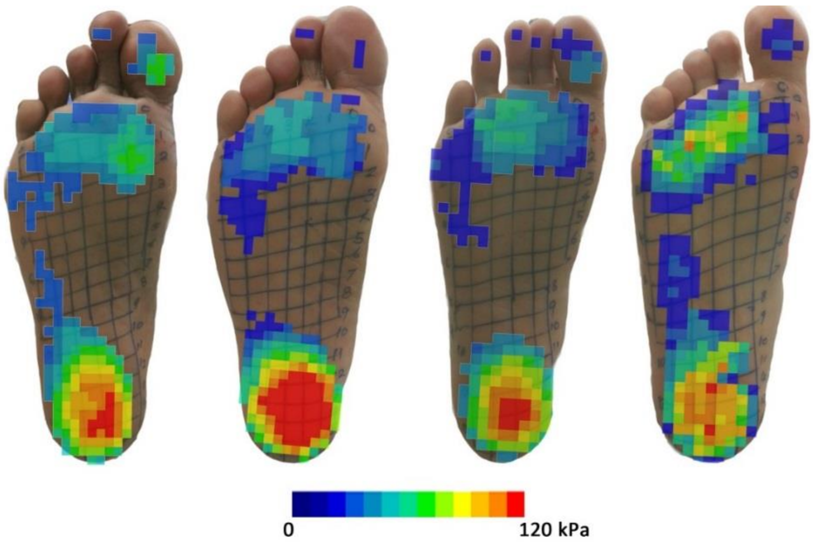
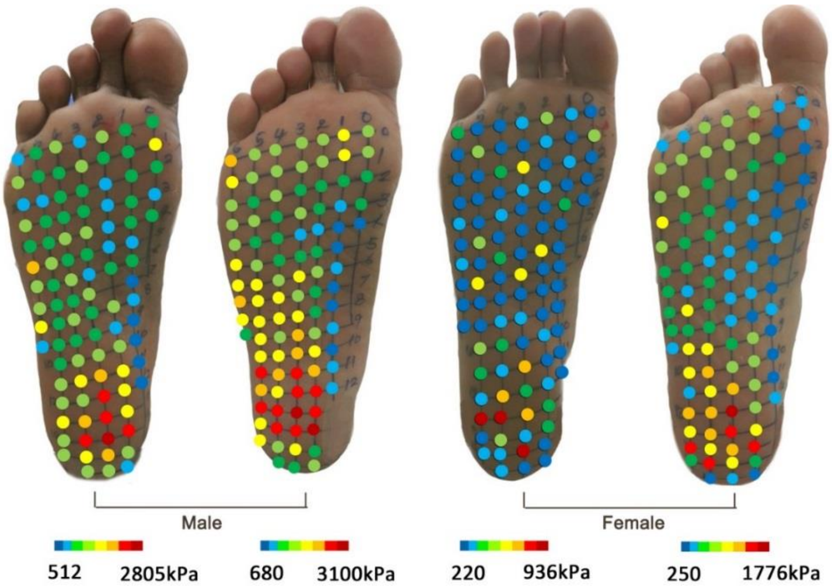


Fig. 8.

a) PDT cluster map for mean male data, b) PPT cluster map for mean male data c) PDT cluster map for mean female data, d) PPT cluster map for mean female data, e) Stiffness cluster map for mean male data, f) Stiffness cluster map for mean female data



a)



b)

Fig. 9: a) Barefoot pressure profile of 4 participants b) The PPT values at each grid point on the same four participants (in Colour)

Fig. 9: a) Barefoot pressure profile of 4 participants b) The PPT values at each grid point on the same four participants

(for B/W printing)