Pressure Perception on The Foot of Young Healthy Adults: Measuring Reliability and Foot Sensitivity

Shuping XIONG[1] and Ravindra S. GOONETILLEKE[2]
[1]Department of Industrial Engineering and Management, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, P.R.China
[2]Human Performance Laboratory, Department of Industrial Engineering and Logistics Management, Hong Kong University of Science and Technology, Hong Kong

Objective: Even though pressure on feet is generally unavoidable and undue pressure on some regions have been widely accepted as the major source of foot discomfort, pain and problems, there is little understanding of related human perceptions. The purpose of this study is two-folded: (1) to evaluate the reliability of a developed indentation apparatus for measuring pressure thresholds of discomfort and pain; (2) to determine the pressure sensitivity map on foot. ***Method:*** The pressure discomfort threshold (PDT) and pressure pain threshold (PPT) of 13 representative test locations distributed on the right feet of 20 healthy subjects (10 males and 10 females) were measured twice through a developed indentation apparatus. ***Results:*** Measurement reliability tests (intra-class correlation, ICC) on both PDT and PPT demonstrate that the participants are not only capable of judging the pain threshold, but also reliably differentiate discomfort from pain. PDT is highly correlated to PPT and PDT accounts for slightly less than half of the PPT. Pressure sensitivity of the foot varies across the test locations of the foot and a typical sensitivity pattern has been found: except for the medial plantar arch and foot center, which have less contact with the ground and bears less load, all tested locations on the foot sole have higher PDT and PPT than those on the foot dorsum. ***Conclusions:*** The developed indentation apparatus can be used for measuring pressure thresholds with reasonable levels of reliability. The pressure sensitivity map on foot and quantitative data of PDT, PPT can help footwear designers distinguish sensitive foot locations under pressure and then design tissue-compliant footwear products for improved footwear comfort.

INTRODUCTION

Pressure mapping between foot and footwear is a common technique to determine hot spots under the foot so that they can be relieved to prevent injury and improve comfort. However, not knowing the thresholds of discomfort and pain hampers the clinician from designing comfortable orthotics or insoles. The human foot alters itself in various ways to cope with the pressure from external loading to keep its integrity (Hawes and Sovak, 1994). The pressure on the foot changes and is dependent on the activity and can vary from a sensation of touch to discomfort to pain (Engen, 1971). While the sensation of touch provides the necessary sensory feedback for balance and locomotion, discomfort and pain from pressure warn the human body of potentially damaging situations

(Xiong et al., 2008). The pressure on feet is generally unavoidable and undue pressure in some regions has been widely accepted as the major source of foot discomfort, pain and problems (Goonetilleke, 1998). Thus, understanding pressure perception especially pressure thresholds is important to design footwear and other accessories for improved foot health and comfort (Dohi et al., 2003). The objectives of the present study were:

1) To evaluate the reliability of a developed indentation apparatus for measuring pressure thresholds of discomfort and pain;
2) To determine the pressure sensitivity map on foot in terms of pressure thresholds.

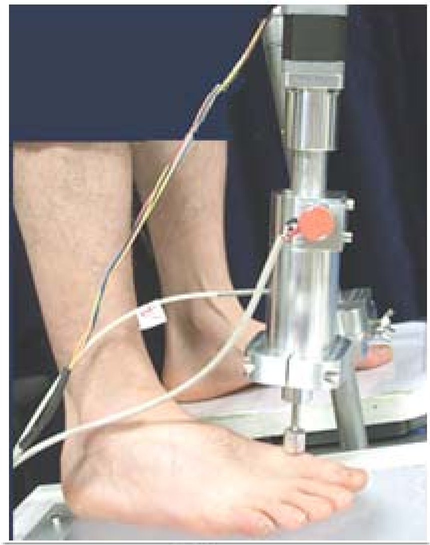
METHODS

Participants

The participants were twenty (ten males and ten females) university students between the ages of 20 and 24 years. Those with any form of foot problems and those who were unable to perform magnitude estimation were not chosen to be participants (Witana et al., 2009). Participation was voluntary and the experiment was approved by the university research ethics committee.

Experimental Apparatus

An indentation apparatus (IA), with precise control on indentation speed while measuring pressure thresholds and the mechanical properties of foot tissue in-vivo (Figure 1a) was developed and used to measure the pressure perception. The IA consists of a replaceable indentation probe, a stepper motor, a load cell and a potentiometer, a personal computer with a Labview program. The stepper motor controls the indentation speed, the load cell and the potentiometer record the reactive force and the tissue deformation (displacement) respectively. Calibration results indicated good accuracy. More details can be found in Xiong (2008).



(a)

(b)

Figure 1. Experimental set-up for testing locations on (a) foot dorsum and (b) plantar surface of foot.

Experimental Procedure

The experiment was performed in two sessions. In the first, the pressure thresholds were determined and in the second session, perceived sensations were elicited. The experiment was conducted in a quiet, temperature-controlled (22^0C) room. The brief details of the testing procedure were as follows:

(1) Manually measure foot dimensions;
(2) Mark the thirteen test locations (P1-3: under the 1^{st}, 3^{rd}, 5^{th} metatarsal head; P4: intersection point between line P1P6 and line P3P5; P5: medial plantar arch point; P6: lateral plantar arch point; P7: center of the heel. P8: top of the 1^{st} metatarsal head; P9: midway of 5^{th} MPJ head and lateral side of 5^{th} MPJ; P10: forefoot dorsal point; P11: top instep point; P12: lateral instep

point; P13: the foot-lower leg intersection point) on the right foot;

(3) Administer a few practice trials on locations that were not of interest to familiarize subjects with the testing procedures so that the participant could differentiate discomfort from pain;
(4) Determine the pressure thresholds (PDT & PPT) of the seven points (P1-7) on the plantar surface of the foot. In order to check the test-retest reliabilities of PDT and PPT, each threshold was repeated twice with a ~45 s interval to minimize the subject's fatigue and sensitization or adaptation to recurrent pressure stimulus (Johansson et al. 1999; Chesterton et al. 2003);
(5) Have the participant estimate the sensation magnitude when the pressure on the foot corresponded to 20%, 40%, 60%, and 80% of PPT given that PPT was the reference set to a magnitude of 100. The order of presentation of the pressure stimulus was randomized;
(6) After the above testing, the participant was given a "rest" day;
(7) Determine the pressure thresholds and tissue properties on the six points (P8-13) of the dorsal surface of the foot;
(8) Repeat step (5) above for the six points on the dorsal surface of the foot.

The experimental set-up is shown in Figure 1. During the test, an aluminum indentation probe with chamfered edge (cross-sectional area of 1.0 cm^2, diameter=11.3mm) was used to compress the foot at the indentation speed of 2.0mm/s when the participant stood with half of body weight on each foot. The subject was given a control unit with two push-buttons to indicate discomfort and pain. If and when the pain button was activated, the indention probe was withdrawn from the foot to ensure subject safety. After the data has been recorded, the discomfort (PDT) and pain (PPT) pressure thresholds (= force/stimulus area) can be determined when the subject presses the "discomfort" and "pain" buttons respectively during the loading phase.

Data analysis

Only the data from the first session of the experiment was reported and analyzed here. The intra-class correlation (ICC) type (2, 1) (Shrout and Fleiss, 1979) was used to check the test-retest reliabilities of pressure thresholds (PDT and PPT) at each test point. Afterwards, a one-way (test location) repeated measures analysis of variance (ANOVA) was performed to evaluate the effects of location differences on pressure thresholds. P values less than 0.05 were considered statistically significant.

RESULTS AND DISCUSSION

Test-retest Reliability of Pressure Thresholds (PDT and PPT)

All 13 test locations have reasonable test-retest reliability (Table 1). All intra-class correlations (ICC) are larger than 0.8 on PPT and acceptable (most ICC≥0.70, with a few 0.5 < ICC < 0.70) on PDT since it is generally accepted that an acceptable ICC value is within the range of (0.5~0.75) (Ma et al. 2006). PDT has relatively lower reliability than PPT, probably because pain is a specific sensation while discomfort includes various physical sensations such as pressure, pain, fatigue, tension etc (Neumann, 2001). Nevertheless, the reliability of both PDT and PPT demonstrate that not only were participants capable of judging the pain threshold, but were also able to reliably differentiate the discomfort from the sensation of pain.

Foot Sensitivity in Terms of Pressure Thresholds

The PDT and PPT are highly correlated (Pearson correlation coefficient R has a mean of 0.84 with SD of 0.04, range: 0.78-0.92) at each test location. The PDT/PPT ratios are quite consistent and within the range of 0.41 to 0.43 for the male group and 0.45 to 0.49 for the female group. Johansson et al. (1999) measured PDT and PPT of the hand and reported the PDT/PPT ratio to be 0.38 on the finger and 0.40 on the palm. The PDT/PPT ratios in this study are slightly higher than the values for the hand, and it is to be expected as there is generally a higher level of load bearing on the foot.

Table 1. Test-retest reliability ICC (values less than 0.70 is shown in bold) of pressure threshold measurements (PDT, PPT) on the 13 test locations with a cylindrical indentation probe of 1.0cm^2 at indentation speed of 2.0mm/s

Test locations		ICC(2,1)†	
		Pressure discomfort threshold (PDT)	Pressure pain threshold (PPT)
Plantar surface	P1	0.73	0.95
	P2	0.86	0.87
	P3	0.74	0.92
	P4	0.70	0.96
	P5	0.87	0.97
	P6	0.80	0.93
	P7	0.85	0.92
Dorsal surface	P8	**0.60**	0.94
	P9	0.84	0.96
	P10	**0.54**	0.88
	P11	0.96	0.97
	P12	0.95	0.97
	P13	0.73	0.95

†ICC (2, 1) was calculated from two trials of 20 participants

Significant inter-location differences (P<0.001) exist on both PDT and PPT. Two clear patterns exist on foot pressure sensitivity in terms of PPT (Table 2): (1) all test locations on the plantar surface of the foot except for P5 (medial plantar arch) and P4 (foot center) have higher PPT than those on the dorsal surface of the foot; (2) on the plantar surface, the PPT ranks from highest to lowest as follows: P7(heel center), the three locations P1 (under 1st metatarsal head), P2 (under 3rd metatarsal head), P3 (under 5th metatarsal head), then P6 (lateral plantar arch) and lastly P4 (center) and P5 (medial plantar arch). It is interesting to note that Dohi et al. (2003) also reported a similar pattern in terms of foot tactile detection thresholds (TDT), even though the TDT is much lower and cannot be directly compared with PPT.

The pressure sensitivity map of the foot should be considered in the interface design (such as shoe insole) when supporting the foot. Delicate locations, such as the plantar medial arch P4 and foot center P5 should not bear high load compared to locations such as P7, P1, P2, and P3, which can withstand relatively higher pressures without giving rise to discomfort or pain. For example, wearing high-heels results in a load shift towards the forefoot areas and well-designed high-heels will attempt to negate this shift by having good footbed designs (Witana et al., 2009). Additionally, the relatively low PPT values on the foot dorsum highlight the importance of the good footwear fit for minimizing discomfort or pain.

Table 2. PPT at the 13 test locations (cylindrical indentation probe of 1.0cm^2, indentation speed of 2.0mm/s)

Test locations		Mean PPT(kPa)	
		Female group(N_1=10)	Male group(N_2=10)
Plantar surface	P1	409.7	487.7
	P2	515.4	457.4
	P3	384.3	519.5
	P4	301.2	342.3
	P5	236.0	228.3
	P6	342.7	484.0
	P7	584.0	612.3
Dorsal surface	P8	326.5	352.2
	P9	235.2	307.0
	P10	255.8	328.8
	P11	327.4	385.9
	P12	309.7	313.8
	P13	236.0	349.7

CONCLUSIONS

The developed indentation apparatus, IA, shows reasonable levels of reliability to measure the pressure thresholds of foot locations. The data show significant location differences in discomfort and pain thresholds around the surface of the foot. The pressure sensitivity map on foot and quantitative data of PDT, PPT can help footwear designers distinguish sensitive foot locations under pressure and then design tissue-compliant footwear products for improved footwear comfort.

The study is not without limitations. The external validity of the results ought to be tested with other populations. More data is needed to map the sensation thresholds of the complete surface of the foot. Aside from magnitude of load, duration of load and shear forces can also contribute to foot discomfort and pain (Goonetilleke, 1998). Further research on other controlled parameters can further advance the understanding of pressure perception and its application to the design of footwear.

ACKOWLEDGMENT

The authors would like to thank the Research Grants Council of Hong Kong for funding this study under grant HKUST 613406.

REFERENCES

Chesterton LS., Barlas P., Foster NE, Baxter GD., Wright CC (2003). Gender differences in pressure pain threshold in healthy humans. *Pain*, **101**:259-266.

Dohi M, Mochimaru M and Kouchi M (2003). The tactile sensitivity and elasticity of the sole of the foot as factors of shoe comfort. *Proceedings of IEA2003,* Seoul, Korea.

Engen T (1971). Psychophysics: II. Scaling methods, in K. Riggs (ed.), Experimental Psychology (London: Methuen), 47-86.

Goonetilleke RS (1998). Designing to minimize discomfort. *Ergonomics in Design*, **6**(3): 12-19.

Hawes MR and Sovak D (1994). Quantitative morphology of the human foot in a north American population. *Ergonomics*, **37**(7): 1213-1226.

Johansson L, Kjellberg A, Kilbom A and Hagg GA (1999). Perception of surface pressure applied on the hand, *Ergonomics*, **42**(10): 1274-1282.

Ma KH., Yam KL., Tsui KW and Yau FT (2006). Internal consistency and test-retest reliability of the Chinese version of the self-report health-related quality of life measure for children and adolescents with epilepsy. *Epilepsy and Behaviour*, **9**: 51-57.

Neumann ES (2001). Measurement of socket discomfort—Part I: Pressure sensation. *Journal of Prosthetics and Orthotics*, **13**(4): 99-110.

Shrout PE and Fleiss JL (1979). Intraclass correlations: use in assessing operator reliability. *Psychological Bulletin*, **86**(2): 420-428.

Witana CP, Goonetilleke RS, Xiong S and Au EYL (2009). Effects of surface characteristics on the plantar shape of feet and subjects' perceived sensations. *Applied Ergonomics*, **40**:267-279.

Xiong S, Goonetilleke RS, Witana CP and Au EYL (2008). Modelling foot height and foot shape related dimensions. *Ergonomics*, **51**(8): 1272-1289.

Xiong S (2008). Pressure perception on the foot and the mechanical properties of foot tissue during constrained standing among Chinese. PhD thesis of Hong Kong University of Science and Technology, Hong Kong.