Perception of Pressure on Foot

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ABSTRACT

This study attempted to identify the factors that affect the pressure pain threshold (PPT) on the heel region of the foot. Using dimensional analysis, it was found that probe area (A), indentation speed (V) and their interaction contribute towards PPT. A power form of these factors can be used to model PPT with an exponent of 0.63.

Keywords: Perception, Power Law, Foot, Pressure Pain Threshold, Dimensional Analysis, Modeling.

INTRODUCTION

Human interaction with different types of equipment always involves various types of forces. When the force per unit area commonly known as pressure is excessive, people will experience pain or discomfort (Gonzalez et al., 1999). In this respect, the pressures acting on feet have received considerable attention due to constant contact of the foot with some type of footwear or directly with ground. The pressure acting on the foot when wearing footwear can result in foot deformities, ulcers, corns, callous, bunions, if the normal or shear forces are excessive or repetitive (Dunn et al., 2004). The pressure distribution on the foot can vary with a person's body weight, type of the activity (walking, running, jumping, and so on) performed (Soames, 1985; Rodgers, 1988) and the type of footwear (Yung-Hui and Wei-Hsien, 2005; Stewart et al., 2007) as well. Researchers are still searching for the optimum distribution and the best means to support load acting on any body part so that potential pain and discomfort are minimized (Goonetilleke, 2001).

Hence, it is no surprise that there is a growing trend to investigate the effects of pressure on the foot. Most research has focused on ways to reduce peak plantar pressure either by introducing differing insole materials (O'Leary et al.,2008; Hinz et al.,2008) or by varying the insole shapes (Yung-Hui and Wei-Hsien, 2005; Stewart et al., 2007). However, little is known as to why some designs are more comfortable or less uncomfortable than others. In this study, we explore potential factors that may influence pressure sensations.

The pressure pain threshold (PPT) (Fischer, 1987) has been found to be a reliable measure to quantify pressure sensations. PPT has been found to reduce with increases in stimulus size (Greenspan et al., 1991; Goonetilleke and Eng, 1994; Greenspan et al., 1997; Defrin et al., 2006; Xiong, 2008) and the number of indentations (Fransson-Hall and Kilbom, 1993; Defrin et al., 2008). Furthermore, PPT increases with increasing rate of change of the stimulus (Defrin et al., 2006; Xiong, 2008). However, the theoretical basis for these changes has not been well documented.

Dimensional analysis is a well-known technique to obtain the explicit functional relationship among variables (Barenblatt, 1987). It can be applied in psychophysics as well (Marinov, 2004; Marinov, 2005). Thus, we attempted to derive a preliminary model for pressure perception based on dimensional analysis and test the validity of the model using perception data.

METHODOLOGY

PARTICIPANTS

Twenty-four participants (12 males and 12 females), from the Hong Kong University of Science and Technology, with informed consent were recruited for the study. The descriptive statistics of the participants are given in the Table 1. All the subjects were selected based on their ability to make reasonable judgments of magnitude estimation and none of them had any visible foot abnormalities or foot illnesses.

Table 1 Descriptive statistics of participants. Standard deviations are in parenthesis.

	Mean (SD)				
	Age (yrs)	Weight (kg)	Height (cm)	Foot breath (cm)	Foot length (cm)
Male	23.67 (2.15)	68.03 (7.06)	172.93 (3.97)	9.71 (0.49)	25.17 (0.90)
Female	22.50 (2.55)	53.55 (9.25)	160.06 (5.07)	8.66 (1.45)	23.15 (0.82)
Total	23.14 (2.36)	61.45 (10.83)	167.08 (7.89)	9.23 (1.14)	24.25 (1.33)

EXPERIMENT PROCEDURE

The experimental design was 4 (size of probes) x 2 (indentation speeds) full factorial design with 2 repeated measurements. Cylindrical rods made of aluminum having a silicon-tip were fabricated for the test. The probe areas were 0.25 cm^2, 0.5 cm^2, 1 cm^2 and 2 cm^2 and the two indentation speeds were 1 mm/s and 2 mm/s. PPT and Pressure Discomfort Threshold (PDT) at the heel center of plantar foot were determined using the Automatic Tissue Tester (ATT) designed and developed by us. The ATT can control the probe indentation and records the force and displacement profile of the probe (Xiong, 2008). The results of PDT are not discussed here.

Each subject was asked to stand on a plexi-glass platform. The control unit that the subject held had two buttons to indicate PDT and PPT. The right foot of the participant was aligned so that the centre of heel coincided with the center of probe (Figure 1). When performing the test, subjects were asked to keep equal weight on both feet and to press the PDT and PPT buttons in the hand-held unit as soon as they felt discomfort and thereafter pain. Prior to the actual test, subjects were given an opportunity to familiarize themselves with the controls and the test procedure.

ANALYSIS AND RESULTS

SPSS statistical software was used for the data analysis. Intra-class correlation (ICC) (Shrout and Fleiss, 1979) type (2,1) was used to check the test-retest reliabilities. The intra-class correlations ($p < 0.001$) were 0.959 and 0.966 for the 1 mm/s and 2 mm/s indentation speeds, respectively. Effect of probe area (A) and indentation speed (V) on PPT were statistically tested using a repeated measures ANOVA (Huck and McLean, 1975; Gorden, 1992). The effect of A, V and their interaction was statistically significant ($p < 0.05$). However, gender and all other interactions were not significant. Hence the male and female data were pooled in all subsequent analyses.

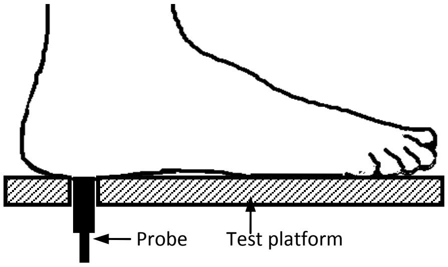

FIGURE 1 Schematic of experiment set-up.

The PPT decreases with increasing probe area and indentation speed (Figure 2).

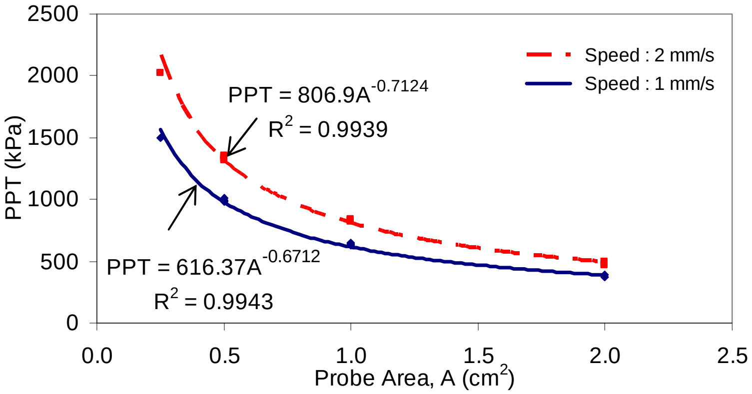

FIGURE 2 PPT variation with probe area and indentation speed.

MODEL OF PPT

Dimensional analysis is based on a comparison of the measurement units of the variables. The probe characteristics can be represented using probe area (A), indentation speed (V) and indentation time (t). Similarly, the tissue characteristics can be represented with tissue deformation (d) and Young's modulus of tissue (E). Since $d=V.t$, only two of these three variables need to be considered in the problem description.

Hence, PPT = f(A, V, t, E) and Table 3 shows the dimensions of these variables.

Table 3 Variables and their corresponding dimensions

Variable	PPT	A	V	t	E
Dimension	$ML^{-1}T^{-2}$	L^2	LT^{-1}	T	$ML^{-1}T^{-2}$
Units	$Pa=Nm^{-2}$	m^2	ms^{-1}	s	Nm^{-2}

According to the Buckingham Π-theorem (Buckingham, 1914), any relationship between n dimensional variables and constants can be reduced to a relation between (n-r) dimensionless variables, where r is the number of independent dimensions. In this study, n=5 and r=3 corresponding to mass (M), length (L), and time (T). Thus, (n-r) = 2 and two dimensionless groups, Π_1 and Π_2, can be formed as follows:

$$\Pi_1 = \frac{PPT}{E} \text{ and } \Pi_2 = \frac{(V.t)^2}{A} \ ;$$

$$\text{where } \Pi_1 = \left[\frac{PPT.}{E}\right] = \frac{ML^{-1}T^{-2}}{ML^{-1}T^{-2}} = [1] \text{ and } \Pi_2 = \left[\frac{(V.t)^2}{A}\right] = \frac{\left(LT^{-1}T\right)^2}{L^2} = [1] \ ;$$

$$\text{Hence, } \Pi_1 = f(\Pi_2)\text{, or } \frac{PPT}{E} = f\left(\frac{(V.t)^2}{A}\right) ;$$

$$\text{Thus } PPT = E.f\left(\frac{(V.t)^2}{A}\right) \quad or \quad PPT = E.f\left(\frac{d^2}{A}\right).$$

Since E is a constant at any particular location, the plot of PPT vs $(V.t)^2/A$ could reveal the best fitting function (Figure 3). A power law representation of

$\boldsymbol{PPT = c.\left(\frac{(V.t)^{2\beta}}{A^{\beta}}\right)}$, where c ≈1424 Nm^{-2} , and β=0.63 seems to fit the data quite well in the heel (R^2=0.993).

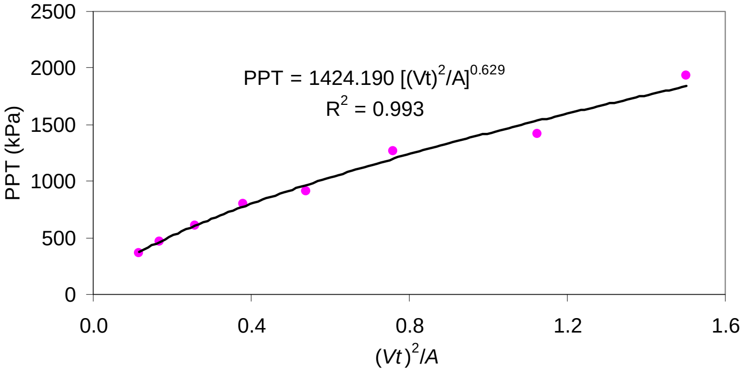

FIGURE 3 Variation of PPT with $(Vt)^2/A$.

The modeling errors were analyzed using the formula, $\boldsymbol{\%\,\text{Error} = \frac{\text{Model Data - Actual Data}}{\text{Actual Data}} \times 100\%}$ and are shown the Figure 4.

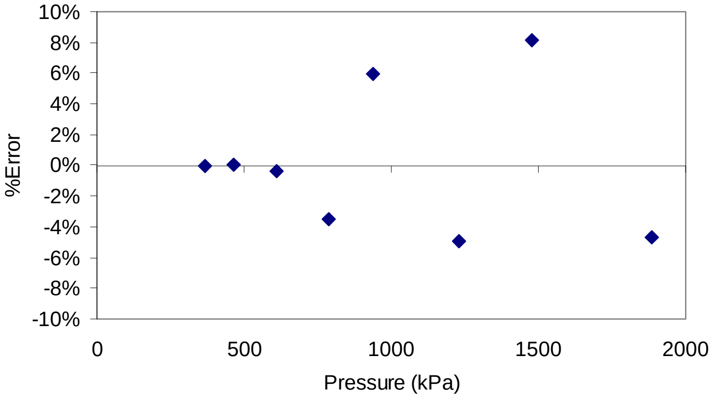

FIGURE 4 Scatter plot of Modeling Error.

DISCUSSION

The aim of this study was to understand the variables related to perceived pressure thresholds. The PPT measurements had very good test-retest reliability (intra class correlation > 0.959) and the variables of probe area, indentation speed and their interaction were found to have a significant ($p < 0.05$) effect on PPT. In general, as found in many previous studies (Greenspan et al., 1997; Goonetilleke and Eng, 1994; and Xiong, 2008.), PPT decreases with increases in area validating the spatial summation theory of pain. It was also seen that PPT increased with increasing indentation speed, consistent with Xiong (2008).

There was no difference in PPT at heel between males and females. Gonzalez et al. (1999) also indicated that there were no gender differences for pressure thresholds on plantar foot even though other studies (Bernnum et al., 1989; Chesterton et al., 2003) have shown differences in gender. The differences among the literature may be related to the site investigated and the tested population.

More importantly, PPT can be mathematically modeled in the form of $PPT = c\left(\frac{(V.t)^{2\beta}}{A^{\beta}}\right)$ or $PPT = c\left(\frac{d^{2\beta}}{A^{\beta}}\right)$. The coefficient '*c*' can characterize the tissue property and the exponent β is possibly a representation of the spatial summation effect of pressure related pain. The model indicates that PPT increases with the speed, *V,* as found in the experiment, and time (t) or indentation depth (*d*).

The scatter plot for modeling error shows that the model has an acceptable fit to the data. Further work is needed to validate the model for other regions of the body.

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