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Designing for Comfort: A Footwear Application

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Custom products are becoming the trend, possibly, as a result of the vast number of selections available when buying products. It has become an impossible task to select the right product that will have the right appeal and the right fit even though fit itself is somewhat nebulous. So it appears that customized products may be able to furnish the necessary "comfort" that one may require. But, how does a manufacturer make a product more comfortable not knowing the standards for comfort or even discomfort? In this paper, we present some directions based on sensation and pain to achieve the desirable fit between people's feet and footwear.

1. INTRODUCTION

It is well known that product compatibility is necessary for a person to experience comfort and satisfaction during use. However, compatibility is not so well known for all types of interaction between people and equipment (Karwowski, 2000). With the growth of online marketing and customisation, more consumers have increased their ability to fulfil their own product needs. Footwear purchases have primarily been governed by (Clarks, 1976):

- Appearance and fashion
- Comfort and fit
- Performance and Durability
- Price

Significant variations exist among different populations when considering these factors. For example, women may place more weight on fashion than fit, and may be prepared to pay a high price for their shoes. Men on the other hand, may not be as concerned on appearance, but will in general pay an appropriate price to get the comfort they require. When buying footwear for children, parents may be prepared to pay a high price for fit and comfort, thereby giving protection to the development of the child's feet (Clarks, 1976). Variations do exist among different cultures too.

Comfort is a very complex and multi-faceted entity (Goonetilleke, 1999). Many factors such as size, shape, flexibility, style (oxford, pump, boot, etc.), weight, inside shoe climate (temperature, humidity), materials, tread, cushioning are all known to affect footwear comfort (http://www.nh.ultranet.com/~dd1822a/facts.html). In order for a shoe to fit a person's foot, the fitting ought to be more than just length and width. Proper fit means achieving the right fit in terms of heel width, heel-to-ball length, top-line fit, toe box space, and so on. In other words, proper fit requires a good understanding of the total 3-D shape.

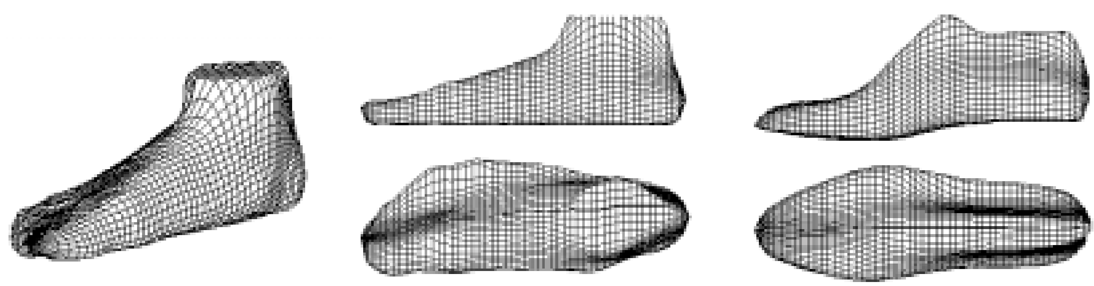
In an age where custom products are becoming the trend, it becomes necessary to consider all these aspects so that footwear are "compatible" with the people who use them. Kolarik (1995) stated, “the customer will judge his or her shoe fit by wearing the shoes, but at the factory we must use “substitute” characteristics like length, width, and so on, to design, develop and produce our product”. How can such a process be adopted for customized footwear unless the manufacturer is willing to go through several iterations to achieve a satisfactory product?

2. FOOTWEAR COMPATIBILITY

The aim of this paper is to illustrate some theories and ways to think of footwear comfort. Figure 1 shows 3-D scans of a foot and a last generated using the Yeti™ (from Vorum in Vancouver, Canada) foot scanner. It is clear that when we buy or fit footwear, we are generally trying to fit an irregular shaped object into a more regularly shaped shoe. On the flip side, if we attempt to replicate the foot shape in a shoe, that will pose other problems as the foot undergoes deformation due to temperature, impact, blood "pooling" and so on. For a shoe to be comfortable, it ought to give the right feel and at the same time not cause any discomfort or pain. Hence the foot should be supported (that is, the movement degrees of freedom reduced) at locations where such deformations are not significantly large. The contours on the foot and shoe will determine the exact positioning of the foot inside a shoe. The relative position can have many different possibilities depending on the shoe design. Some such possibilities are:

1. Posterior of foot matching with backseam tack (Figure 2a)
2. Height or waist girth compatibility at mid foot (Figure 2b)
3. Forward restrictions at the shoe tongue (instep point). (Figure 2c)
4. 2-D Curvature restrictions (top view of Figure 1b and 1c) or heel-cup restrictions

In the 2-D problem, Goonetilleke et al (2000) showed that the dimensional error between the unconstrained foot and shoe seems to indicate the quality of fit. In that study, differences were evident when matching was done in the heel area. Each foot-shoe combination may behave differently and it is important to know the optimal locations to constrain the foot.



(a) 3-D Foot image (b) Foot image (side and top view) (c) Last image (side and top view)

Figure 1. Scanned images of a foot and a last. The apparent mismatch in shape and size between the "irregular" foot and the regular-shaped last can be seen from (b) and (c).

(a) (b) (c)

Figure 2. Possibilities for "positioning" a foot inside the shoe. (a) Matching backseam (b) Matching midfoot height (c) Tongue restriction on forward movement

In the 3-dimensional foot location problem, after the foot is located relative to the shoe, the dimensional differences will indicate areas with high pressure (that is, foot overhangs) and those that have little or no pressure. Alternatively, if we assume that we know the stiffness of the human skin at various locations on the foot, we can find the force or the pressure in areas wherever there is a mismatch between foot and shoe. Most discomfort results from such compression on the foot.

3. PAIN AND DISCOMFORT

It is known that discomfort precedes pain. Similar to comfort, pain also means many different things (Liebeskind and Paul, 1977). The National Science Foundation Research Briefing on Pain and Pain Management stated "Pain has attributes of a sensation, yet its usual capacity to make us uncomfortable or to suffer distinguishes it from other sensations" (Perl, 1985). Pain has been defined as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" (Merskey, 1986). Pain in general is accepted to be a specific sensation, the intensity of which is proportional to the extent of potential tissue damage (Melzack, 1986). However, pain need not always be linked to tissue damage as it may persist even after tissues have healed.

4. THE EXPERIENCE

Differences in opinion on comfort may be as a result of the inappropriate use of stimulus metrics. The sensation of touch involves energy and this energy may be expressed in terms of pressure or in terms of the work accomplished (force * indentation depth). Researchers use pressure and pressure gradients for comfort evaluations when past research (Kenshalo, 1978) has shown that variations in pressure and pressure gradients have failed to account for variations in touch sensations. Touch thresholds seem to be related to stiffness (gm/mm) for small forces acting through small contact areas. However, von Frey and Kiesow (1899) have shown that this relationship does not hold for large forces acting over large areas. Table 1 shows how the sensitivity changes at different body sites. Harrington and Merzenich (1970) and Mountcastle, (1974) have shown that work (force *indentation depth) is a better metric for touch sensations than either pressure or stiffness. Skin indentation depends on the elastic properties of skin, which in turn are related to age, gender, site of stimulation, and underlying tissue (Dick, 1951; Franke, 1951; Jones, 1960). Thus, differences in sensation between gender (Table 2), age groups and even race ((Johansson et al.,1999; Woodrow et al., 1972) are easily understood if we adopt the metric of work.

When force is held constant, a monotonic relationship exists between the estimates of touch magnitude and indentation depth (Harrington and Merzenich, 1970; Jones, 1960; Mountcastle, 1974). i.e.,

(Magnitude estimate of touch sensation) = constant*(displacement in μm) ……………(1)

Table 1. Sensitivity at different body sites (from Weinstein, 1968)

Body Site	Touch Sensitivity (mg)	Two-point limen (mm)	Point-localization error (mm)
Little finger	5.7	4.5	2.0
Ring Finger	7.9	4.0	1.6
Middle finger	6.8	2.5	1.7
Index Finger	11.4	3.0	1.4
Thumb	9.0	3.5	1.8
Palm	20.1	11.5	7.1
Sole	35.9	22.5	7.5
Hallux	36.7	12.0	2.1

When dynamic components (e.g., velocity, acceleration and so on) are present however, the effects on touch sensations become more complex. For example, indentations of 1.5-2.0 mm may not produce a touch sensation if the rate of indentation is below 0.05 mm/sec (Eijkman, 1959). Nafe and Wagoner (1941a, b) have shown that indentations of about 2.5 mm are necessary to maintain a perceptible touch sensation if the velocity is 0.003 mm/sec.

Table 2. Discomfort and pain thresholds for the hand (Johansson et al.,1999).

Site	Discomfort threshold (kPa)	Pain threshold (kPa)		
		Men	Women	Mean
Finger	188	560	433	496
Palm	200	576	413	494
Thenar	100	505	391	447

Discomfort and pain thresholds of mechanical forces have been studied quite extensively using the pressure algometer. Data for the hand are shown in Table 2. Interestingly, we can see some important relationships for product design. The female/male pain threshold for finger, palm and thenar are 0.77, 0.72, and 0.77. Fransson-Hall and Kilbom (1993) reported a female/male ratio of 0.67. Our studies have shown the female/male pain tolerance to vary in the range 0.68 to 0.80 depending on the site probed. These ratios are shown in Table 3. Most interestingly, if a new measure such as (pressure * length stimulated) is used, it appears to be somewhat consistent across studies and locations as shown in Table 3. The rationale for such a measure is a coupling between the work metric mentioned earlier and a membrane like skin that undergoes deformation. We have also seen that the acceptable in-shoe pressures are approximately in the range of 0.2-0.4 of pressure tolerance. Thus, if pain tolerance is known, one may design a product such that the interface pressures are less than approximately 20% of the pain tolerance. The differences between men and women can also be designed-in through the ratios mentioned above. Alternatively, the designer may start with the approximate values for the new measure (Table 3) that we have proposed, and calculate the pressures to have no discomfort knowing the "length" over which the forces apply. The ultimate aim is to be able to design to minimize discomfort rather than evaluate discomfort as an afterthought.

Table 3. A comparison of two studies (MPJ = metatarsophlangeal joint; MT= metatarsal)

Study	Discomfort/Pain	Female/Male	New Measure (kN/m)	
			Male	Female
Johansson et al., (1999) for pain threshold				
Finger	0.38	0.77	6.3	4.9
Palm	0.40	0.72	6.5	4.7
Thenar	0.22	0.77	5.7	4.4
Goonetilleke and Eng (1994) for pain tolerance				
Toe Nail 1		0.68	5.3	3.6
MPJ5		0.79	4.1	3.2
MPJ23		0.69	5.2	3.6
MT1		0.70	4.5	3.2

5. CONCLUSIONS

Even though custom footwear are made, the comfort and fit may not be optimal for different activities and differently shaped feet. In this paper, we have presented means to quantify mismatches that may cause discomfort as a result of skin compression. Using what is known in the sensation and pain literature, we have shown that useful measures can be developed to better understand comfort and discomfort and also their underlying mechanisms in an effort to design the interface between feet and footwear optimally.

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