THE COMFORT-DISCOMFORT PHASE CHANGE

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CONSUMER PRODUCT DESIGN

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1. Introduction

Pressure at the human interface is generally considered to be an important parameter in comfort evaluation. However, the ideal pressure distribution between the human body and any surface of a given application has yet to be defined. A hard-core materials perspective to loading would be to distribute the force over an area as large as possible to minimize stress concentration. However, products such as a bed of nails or a bed of springs, “health sandals”, steering wheel covers with semi-spherical protrusions are very popular in some cultures. So, why is it that people tend to like products with localized force? Researchers have pointed out that poor biomechanics may turn comfort into discomfort. Why does such a transition take place over time? The objective of this article is to explain why some design strategies work for human-product interfaces and why some others "slip" from their desirable state or change phase.

2. Interface Pressure

Pressure at the human-product interface is unavoidable, and it has received considerable attention over the years because it can cause injury, pain, and discomfort. Pressure is defined as follows:

$$\textbf{Pressure}\ \text{(Pascal)} = \textbf{Force /Area}\quad \text{(Newton/m}^2\text{)} \tag{2.1}$$

Alternatively, stress has a similar formulation and is generally in the form of compression, tension or shear:

$$\textbf{Stress}\ \text{(Pascal)} = \textbf{Force /Area}\ \text{(Newton/m}^2\text{)} \tag{2.2}$$

Interface pressure can play an important role in the development of products and devices such as seat cushions (figure 1), shoe insoles, handles, and beds. An understanding of the pressure patterns that are appropriate for the human body (that is, the patterns that reduce discomfort or improve what is called comfort) can make product design and usage very satisfying and fulfilling. One primary problem related to this aspect stems from the fact that the word *comfort* has many definitions. For example, comfort has been defined as the lack of discomfort. More recently, it has been associated with feelings of *relaxation* and well-being (Zhang, Helander and Drury, 1996). A good example is the use of a beanbag. Generally, a sense of comfort is associated with a beanbag comprising macrospheres of rigifoam or the like. Are beanbags really comfortable because of their pressure distribution or are they comfortable because we use them in environments where we are already in a relaxed state?

[Insert figure 1 about here]

As shown in figure 1, the pressure pattern between the two supporting surfaces is somewhat different. Researchers have shown that this pressure pattern is related to the level of comfort and discomfort (Lueder and Noro, 1992). Generally, discomfort may be quantified using a combination of the following:

1. Peak pressure
2. Pressure gradients and
3. Contact area

It is quite unfortunate that the most appropriate pressure pattern for each individual or individual-product interface is still unknown. If it were known, product design for the human body would be so much easier. Part of the problem stems from the fact that contact area has been neglected in the past.

In general, forces can be supported in two ways:

1. Distribute “Uniformly” or
2. Concentrate (i.e., load the “stronger” parts of the structure) to reduce “breakage”.

Which one of the two strategies is best to maximize comfort or even minimize discomfort on the human body and why? Could it be that both strategies are applicable depending on the loading scenario? The most common and sometimes naive approach is to distribute force, as much as possible, to achieve the uniform condition. However, some consumer products and existing research suggest a concentrated strategy. For example, Krouskop et al. (1985) has shown that mattresses with a uniform pressure distribution make people restless thereby opposing the distributed theory of force. In addition, products such as a bed of nails or a bed of springs, “health sandals”, shoe insoles or steering wheel covers with semi-spherical protrusions, 'massage' mats made of wooden slats and cane chairs are very popular in some cultures. All such devices induce localized force, rather than “distributed” force, supposedly creating desired sensations. Active cushions, which operate on the basis of periodic pressure relief in the form of a pressure wave, are also popular among paraplegic individuals. In some sense, these active cushions may be viewed as units that impose 'concentrated' loading of a certain level with reduced duration of exposure. In other words, they create a concentrated strategy of short duration. Hence it appears that concentrated force also has certain advantages and possibly a sensation of comfort or relaxation. If uniform pressure is the ideal pressure distribution for optimal comfort, interface design should be relatively easy, especially since pneumatic or hydrostatic balloons or bladders can be used to give this “constant” or uniform pressure at the interface. What could be affecting the pressure-comfort or pressure-discomfort relationship?

3. Physical Sensation

Discomfort or pain originates when special nerve endings, called nociceptors, detect an unpleasant stimulus. There are millions of nociceptors in the skin, bones, joints, muscles, and internal organs. These nociceptors use nerve impulses to relay pain messages to networks of nearby nerve cells (peripheral nervous system). Each cell-to-cell relay is almost instantaneous and is facilitated by neurotransmitters. Messages then travel along nerve pathways to the spinal cord and brain (central nervous system). Scientists believe that pain signals must reach a *threshold* before they are relayed. *Gate control theory* explains how specialized nerve cells in the spinal cord act as gates that open to allow messages to pass, depending on the intensity and nature of the pain signal.

4. Spatial Summation Theory

The *spatial summation theory* (SST) states that simultaneous stimulation of many sensory receptors is required to arouse stimulation (Hardy and Oppel, 1937). In simple terms, it means that the larger the area stimulated, the greater the sensory response experienced. For example, the sensation induced by a hand would generally be greater than that induced by a finger alone. The spatial summation theory has important implications for force distribution. Consider the case of a pleasant sensation gradually moving towards discomfort when the applied pressure is increased. At the limit, when sensations tend toward the so-called discomfort experience, a force distributed over a large area may induce greater discomfort than the same force over a small area. Thus, the extension of the spatial summation theory may be used to explain the discomfort experience as well. In this article, the validity of the SST extension is shown using maximum pressure tolerance (MPT). In addition, I would use an example of footwear to show why "comfort" changes phase to discomfort in the long-term.

Researchers have shown that the skin blood flow changes are influenced by three factors: the ratios of bone depth, the ratios of indentor diameter to bone diameter, and percentage compression of the tissue overlying the bone. “Indentor” or loading area is a factor neglected by many and its effect on discomfort can explain perceived sensations of interface designs having concentrated loading.

5. Maximum Pressure Tolerance

Goonetilleke and Eng (1994) showed that the maximum pressure tolerance (MPT = applied force/probe area) is strongly related to the probe or indentor size or the contact area of the stimulus. The mean MPT with a probe of 5 mm diameter (831 kPa) was 3.3 times that with a probe of 13 mm diameter (249 kPa). The results for two locations on the dorsum (top) side of the foot are shown in figure 2.

[Insert figure 2 about here]

The measurement procedure is described in Goonetilleke and Eng (1994). There were no statistically significant ($p < 0.05$) differences between locations or between genders. In general, it was found that the values of pressure tolerance with the two probes were related by the following equation:

$$MPT_{5\ mm\ diameter} = 3.3 * MPT_{13\ mm\ diameter} \qquad (4.1)$$

It is logical to look at the maximum *force* (or maximum force tolerance, MFT = MPT* Area) that can be supported rather than the pressure. The force relation between the two indentors would be as follows:

$$MFT_{5\ mm\ diameter} = 3.3 * (5/13)^2 * MFT_{13\ mm\ diameter} \qquad (4.2)$$

or

$$MFT_{5\ mm\ diameter} = 0.5 * MFT_{13\ mm\ diameter} \qquad (4.3)$$

In other words, at the maximum tolerable value, the force that a probe with a 5 mm diameter can exert is half of what a probe with a 13 mm diameter can exert. This suggests that even though the MPT is lower with a 13 mm diameter probe, the force that the 13 mm probe can support at the tolerable threshold is twice the force that can be supported by a 5 mm probe. This is a surprising result when the MPT is compared to a 'dead' material. For any material other than the human tissue, the equivalent “MPT” at breaking point (or breaking strength) should be independent of area since it is *constant* for a given ('dead') material.

If the maximum force is such that even though only half of the force can be supported with a 5 mm probe, the probe area results in 3.3 times the tolerance of the 13 mm probe area, then it implies a counter-intuitive suggestion for loading on the human body. Consider the force supported at the tolerance level (249 kPa) of the 13 mm probe. The maximum force corresponding to the MPT with the 13 mm probe (249 kPa) is 33 Newtons and the corresponding area of support is 132.7 mm^2. The area of the 5 mm probe is 19.6 mm^2 (that is 6.8 times smaller). If six (for convenience, rather than 6.8) load bearing areas of 5 mm diameter are chosen to carry the load corresponding to the MPT of the 13 mm probe, the load on each 5 mm probe will be 5.5 Newtons or a pressure value of 281 kPa (will be 249 kPa if 6.8 was used instead of 6), which is far below the MPT with one 5 mm probe. In other words, the load, which may have caused someone to indicate that it is the maximum tolerable force over an area of 132.7 mm^2, could now be shared among a number of smaller areas (localized) without experiencing any such maximum tolerable value. The advantage of smaller areas to support loads is clear when the loads are high.

6. The Phase Change

Since the maximum pressure tolerance is dependent on the contact area, it may be concluded that, at high forces, a larger area may cause a higher level of discomfort than a smaller area when stimulated with the same magnitude of pressure. The aforementioned results suggest that localized pressure regions may in fact prove to be less discomforting when compared to "distributed-moderate" pressures. However, we do not know whether distributing force over a larger area increases comfort at low force values even though spatial summation theory indicates that the sensation will be higher. We may thus conclude that perceived sensation and contact area appear to have a relationship similar to that shown in figure 3. The term sensation is used since it is unclear whether comfort can be equated to positive sensations. However, a negative sensation may be viewed as discomfort. The traditional thinking of distributing forces may be successful only in the upper half of figure 3, when forces are very low or below a critical value, F_{crit}. The bottom half of figure 3 will not be seen at very low forces or forces below F_{crit}. Hence the decision to distribute or concentrate forces really depends on the magnitude of the pressure that exceeds a critical or threshold pressure (P_{crit}) for a given surface area.

[Insert figure 3 about here]

7. Examples

The extension of the spatial summation theory, the *discomfort hypothesis,* will now be illustrated using two examples. Some “high-end” commercial footwear have adopted “dynamic fit sleeves” made of an elastic material, which may convince consumers that such footwear conform to the foot resulting in a better “fit” and a uniform pressure, and thereby high sensation. In the short term or at the point of purchase, these shoes are very comfortable. However, with prolonged use, due to foot swelling and foot deformations, shoes using a dynamic fit sleeve can be extremely uncomfortable. So how does the *discomfort hypothesis* explain such a change in sensation? At the point of purchase, the foot covering conforms to the foot giving a stronger sensation as predicted by the spatial summation theory since there are more sensory receptors being stimulated at one time (upper half of figure 3). However, with activity, the foot swells and deforms, and then the pressure induced is greater at each of the receptors. At this point, the wearer is at the other end of the sensory experience. More receptors are stimulated over a greater area, giving the wearer greater discomfort than if he/she wears shoes that do not have dynamic fit sleeves (bottom half of figure 3). In other words, over time, the perceived sensation changes phase (or "slips") from the top half to the bottom half, transforming the "high" intensity pleasant sensations (at time=0), to a "high" intensity unpleasant (or discomfort) experience.

A different type of example is a pilot headset. A conventional headset has cushioned material against the ears. It is generally comfortable in the short term. As the flying time increases, however, such a headset causes a high level of discomfort as a result of a phase change from positive sensations to negative sensations. The discomfort on the ears can be relieved even in the long term with the use of slow recovery (or open cell) foam such as Confor™ foam. With this type of foam, the force acting on the ears is significantly reduced so that even with increases in time, no phase change occurs.

8. Recommendations

Based on the above discussion, the following suggestions are made to designers of human-product interfaces:

i. Identify the threshold force or pressure (F_{crit} or P_{crit}) to delineate between the experience of a positive sensation and discomfort.

ii. If the pressure is below P_{crit}, then it would be best to distribute the forces.

iii. When the pressures are "high" and close to the MPT, the designer needs to consider a more localized or concentrated force (preferably of short duration) to relieve discomfort caused by simultaneous neuron firings over larger areas.

No doubt, it is sometimes impossible to concentrate pressures over small regions if there is a high risk of damage in terms of pressure sores or ulcerations (Webster, 1991), especially for paraplegics who have no sensation or reduced sensation. The ideal pressure profile generally comes from a combination of distribution and concentration, which gives a showroom or point-of-purchase feel with a distributed force but a less discomforting support with concentrated force. Successful examples include mattress overlays and shoe insoles.

References

Goonetilleke, R. S. and Eng, T. J., 1994, Contact area effects on discomfort. *Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting* (pp. 688-690).

Hardy, J. D. and Oppel, T. W., 1937, Studies in temperature sensation. The sensitivity of the body to heat and the spatial summation of the end organ responses. *Journal of Clinical Investigation*, **16**, 533-540.

Lueder, R. and Noro, K., 1992, *Hard facts about soft machines: The ergonomics of seating* (London: Taylor and Francis).

Krouskop, T., Krebs, M., Herskowicz, I., and Graber, S., 1985, Effectiveness of mattress overlays in reducing interface pressure during recumbency. *Journal of Rehabilitation Research and Development*, **22**, 7-10.

Webster, J. G., 1991, *Prevention of Pressure Sores*. (Philadelphia: Adam Hilger).

Zhang, L., Helander, M. G., and Drury, C. G., 1996, Identifying factors of comfort and discomfort in sitting. *Human Factors*, **38**(3), 377-389.

Figure captions

Figure 1. Pressure on buttock during sitting a) Pressure pattern on a laboratory chair b) Pressure pattern on a hard surface (Pressure values are in kPa).

Figure 2. Effect of probe size on the mean value of maximum pressure tolerance.

Figure 3. Hypothetical relationship between perceived sensation and contact area.

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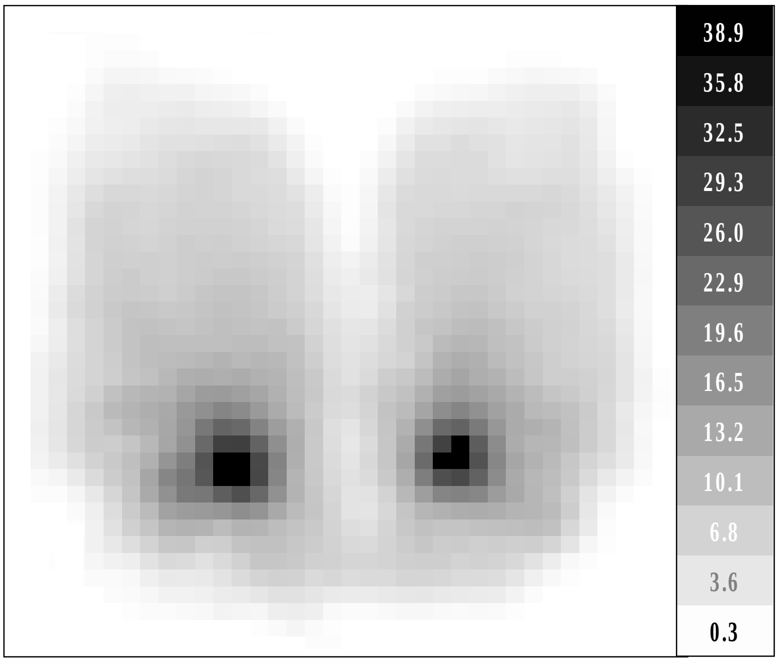
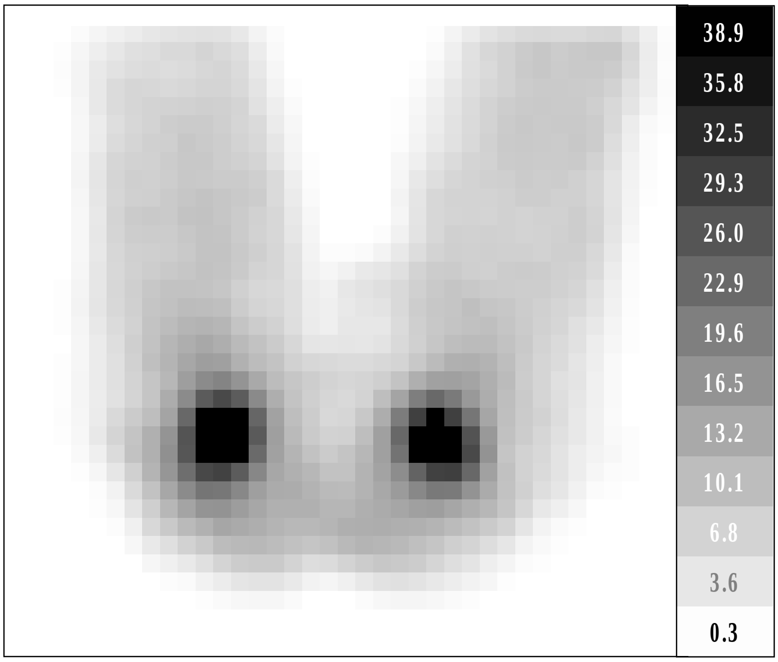


(a)



(b)

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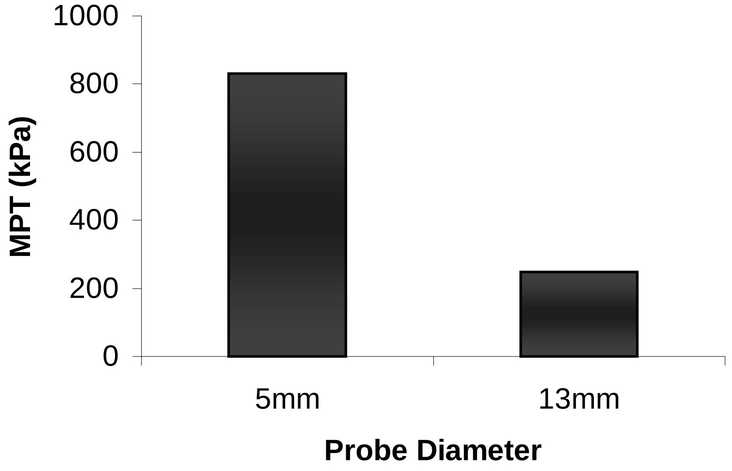

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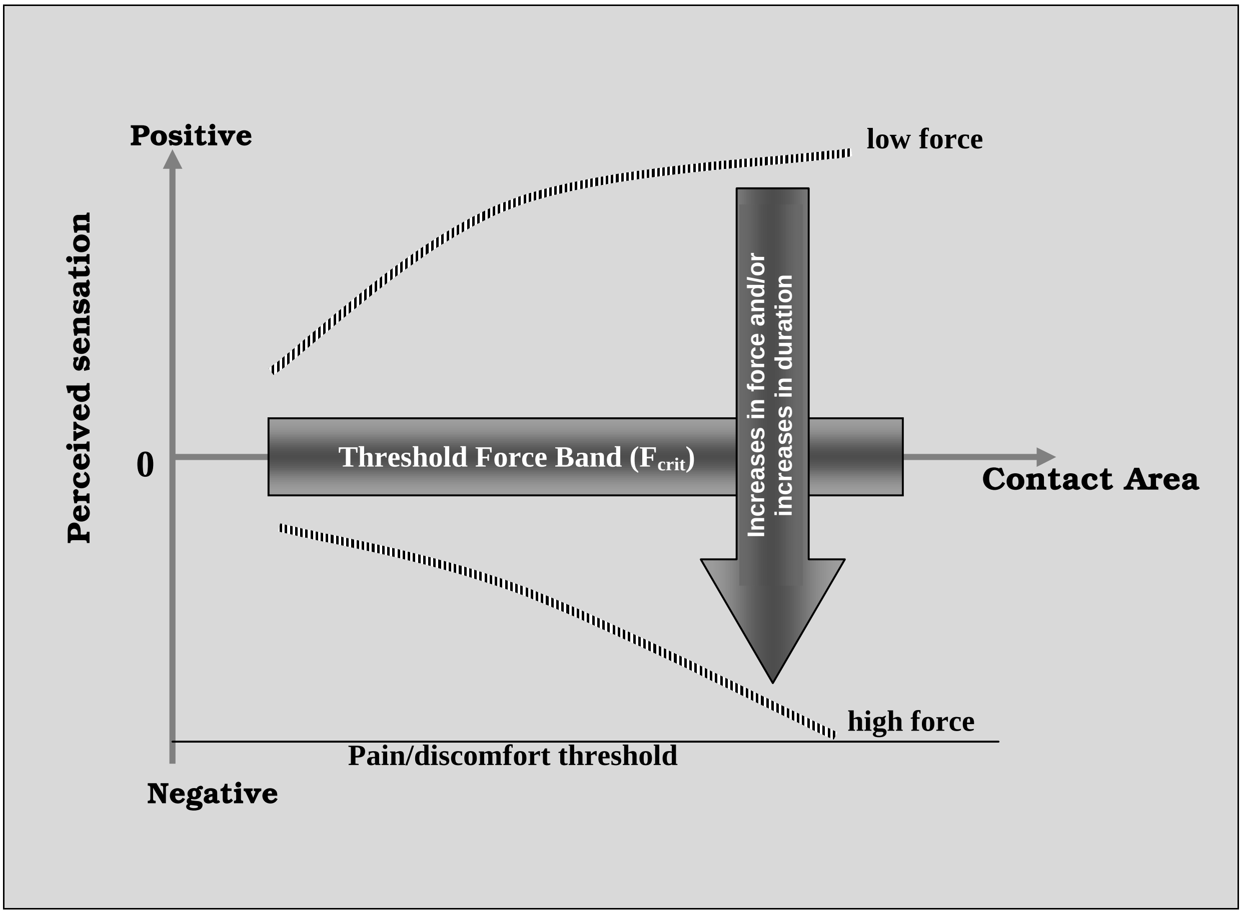

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