Ergonomics for Global Quality and Productivity
Edited by R. Bishu, W. Karwowski and R. Goonetilleke

The "Comfort" Slip

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Pressure at the human interface is generally considered to be an important parameter in comfort evaluations. However, the ideal pressure distribution for a given application has yet to be validated. In this paper, the spatial summation theory for sensation has been extended to the limit when discomfort sets in to explain the sensation changes that occur when wearing footwear. The maximum pressure tolerance has been used to show how discomfort is affected by contact area.

INTRODUCTION

Interface pressure can play an important role in the development of devices such as seat cushions and shoe insoles. In general, forces can be supported in two ways:

1. "Uniformly" distributed (Sprigle et al., 1990; Weichenrieder and Haldenwanger, 1986) or
2. Concentrated (i.e., load the "stronger" parts of the structure) to reduce "breakage" (Floyd and Roberts, 1958).

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 are very popular among some cultures. All such devices induce localized force, rather than "distributed" force, supposedly creating desired sensations. Hence it appears that concentrated force also has certain advantages and possibly a sensation of comfort or relaxation as defined by Zhang et al. (1996). 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?

The *spatial summation theory* (SST) states that that simultaneous stimulation of many sensory receptors is required to arouse stimulation (Hardy and Oppel, 1937). In simple terms, it means that a greater sensory response is experienced when the area stimulated is larger. If one were to touch or feel someone with a finger or the hand, the sensation induced by the hand would generally be greater than the finger alone. The spatial summation theory has important implications when force distribution is discussed. 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, it is clear that a force distributed over a larger area may increase the likelihood of discomfort as opposed to the same force over a small area. Thus the extension of the spatial summation theory may be used to explain the discomfort experience. In this paper, the validity of the SST extension is shown using maximum pressure tolerance (MPT). In addition, the paper is meant to explain why comfort slips toward discomfort in the long-term when wearing footwear.

Sacks et al. (1985) has 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.

MAXIMUM PRESSURE TOLERANCE

In an experiment performed by Goonetilleke and Eng (1994) under "unmotivated" (Sternach and Tursky, 1965) conditions, it was found 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 when using a probe of 13 mm diameter (249 kPa). Two locations on the dorsum (top) side of the foot were tested. The results are shown in Figure 1. The measurement procedure is presented in Goonetilleke and Eng (1994). There were no significant ($p < 0.05$) differences between locations or between genders. In general, it was found that the pressure tolerance with the two probes were related by the following equation:

$$MPT_{5\text{ mm diameter}} = 3.3 * MPT_{13\text{ mm diameter}}$$

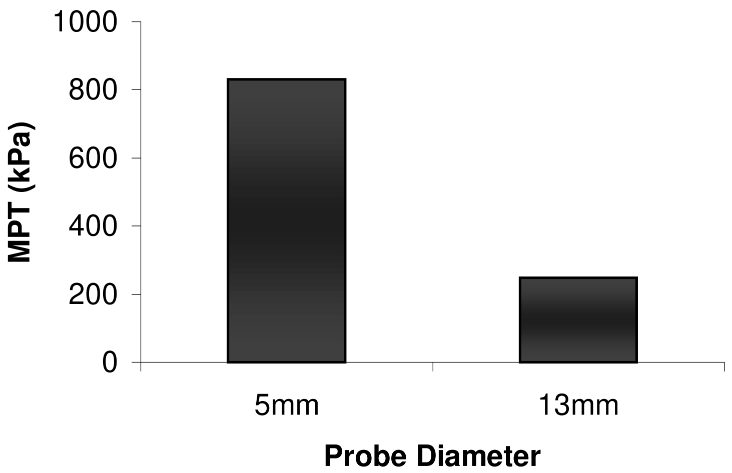

Figure 1. Effect of probe size on the mean value of maximum pressure tolerance.

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:

$$MFT_{5\text{ mm diameter}} = 3.3 * (5/13)^2 * MFT_{13\text{ mm diameter}}$$
or
$$MFT_{5\text{ mm diameter}} = 0.5 * MFT_{13\text{ mm diameter}}$$

In other words, at the maximum tolerable value, the force that a 5 mm diameter probe can exert is half of what a 13 mm diameter probe 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 that of the 5 mm probe. This is a surprising result when the MPT is compared to a "dead" material. For any material other than 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 but has 3.3 times the tolerance, 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 6 (for convenience, rather than 6.8) load bearing areas of 5 mm diameter are chosen to carry the load corresponding to the tolerance level 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 a 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.

THE SLIP

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 results of Goonetilleke and Eng (1994) 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. One may thus conclude that perceived sensation and contact area appear to have a relationship similar to that shown in Figure 2. The term sensation is used since we are not sure whether comfort is the same as sensation. However, a negative sensation may be viewed as discomfort. Traditional thinking of distributing forces may be successful only in the upper half, when forces are very low or below a critical value, F_{crit}. The bottom half will not be seen at very low forces or forces below F_{crit}. Hence the decision to distribute or concentrate forces is really dependent on the magnitude of the pressure exceeding a critical or threshold pressure (P_{crit}) for a given surface area.

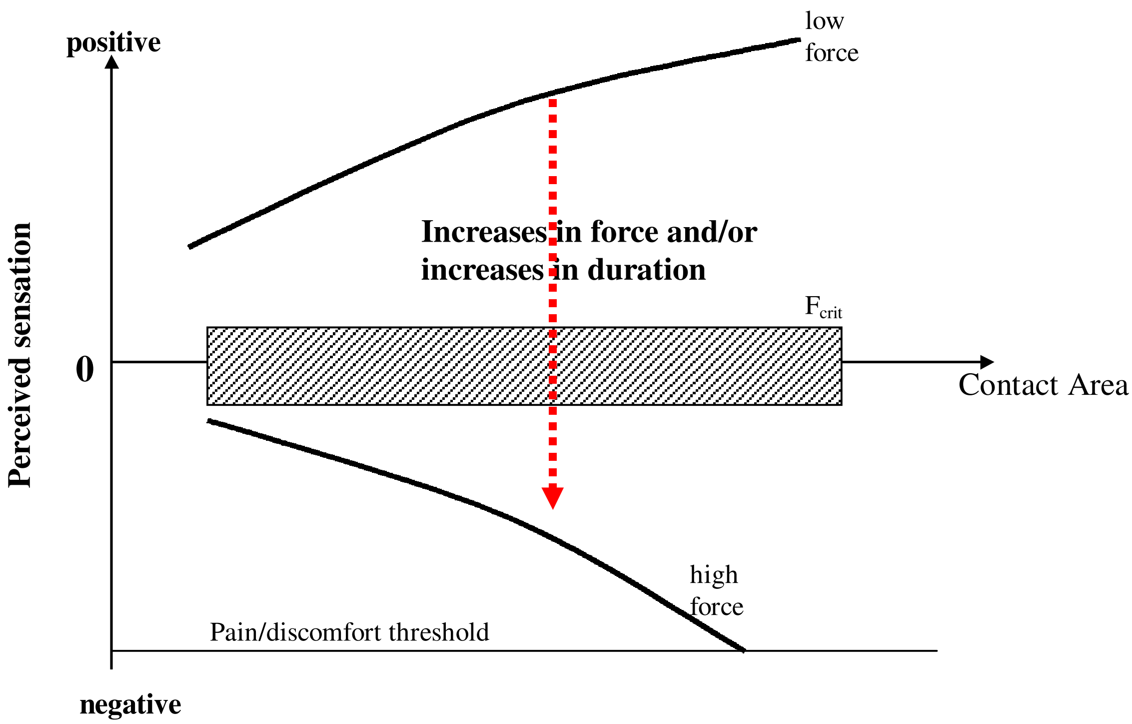

Figure 2. Hypothetical relation between perceived sensation and contact area.

The extension of the spatial summation theory, the *discomfort hypothesis*, appears to be true in real life. Some “high-end” commercial footwear adopt what are referred to as “dynamic fit sleeves” made of an elastic material making the user believe that it will conform to the foot thereby giving a better “fit” and uniform pressure and thereby high sensation. In the short-term or at point of purchase, such footwear is 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 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 2). 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 thereby making the wearer experience greater discomfort when compared to a shoe that does not have a dynamic fit sleeve (bottom half of Figure 2). In other words, over time, the sensation curve “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. When designing any object or device to be used by a person, the key is to identify the threshold (F_{crit} or P_{crit}) to delineate between the experience of a positive sensation and discomfort. If the pressures are such that they are below P_{crit}, then it would be best to distribute the forces. When the pressures are "high" and closer to the MPT, the designer needs to consider a more localized or concentrated force to relieve discomfort caused by simultaneous neuron firings over larger areas.

CONCLUSIONS

It is no doubt an impossible task sometimes to concentrate pressures over smaller regions, if there is a high risk of damage in terms of pressure sores or ulcerations especially in those who have a lack of or reduced sensation. The ideal pressure profile may be a combination of the two strategies to give a showroom or point of purchase feel with a distributed force but a less dicomforting support with concentrated force as proved by mattress overlays, shoe insoles, etc. Understanding the pressure-sensation or pressure-discomfort relationship may depend on the variability of pressure tolerance with stimulus area.

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ACKNOWLEDGMENTS:

The author would like to thank the Research Grants Council (RGC) of Hong Kong for making this paper possible.