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Designing to minimize discomfort

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Background

Pressure at the human interface has received considerable attention over the years since it can cause injury, pain, discomfort, and/or possibly improve comfort. When we wear clothes, shoes, neckties, sleep on a bed, sit on a chair, use a headset, use hand tools during manual work, or use arm rests or elbow supports to reduce muscle fatigue, the forces from these external sources/implements exerted on the body are quite varied, but in all cases act on limited areas. Even though forces on the human body are unavoidable, comfort in many cases appears to be obscure and certainly not guaranteed. Comfort encompasses many different characteristics and has varied definitions: for example, it has been defined as a lack of discomfort (Hertzberg, 1972) and more recently it has been associated with feelings of relaxation and well-being (Zhang et al., 1996). In creating the second definition, however, Zhang et al. pointed out that poor biomechanics may turn comfort to discomfort even though good biomechanics is not a necessary and sufficient condition for comfort. It is not the intent of this paper to look at the disparities in the two definitions. The objectives of this article are instead:

- To review the effects of force on human tissue in the published literature
- To attempt to explain scientifically some of the design strategies currently used and
- Most importantly, to stimulate ideas for innovative designs and research to minimize discomfort at interfaces such as seats, footwear, and hand-tools, etc.

Concentrate or Distribute? - The literature

It is clear that pressure at the human interface can cause discomfort, and minimizing the discomfort is appealing from a consumer's standpoint. Common sense tells us that force or pressure can cause discomfort, pain, and possible injury if not managed well. Common sense also gives two key strategies to adopt when a material is subjected to a force:

1. Distribute the force "uniformly" (Sprigle et al., 1990; Weichenrieder and Haldenwanger, 1986) or
2. Concentrate or load the "stronger" parts of the structure to reduce "breakage" (Floyd and Roberts, 1958).

Floyd and Roberts (1958) concluded that when sitting most people feel comfortable when the weight of the body is carried primarily by the ischial tuberosities. Pressure mappings have shown that the buttocks area of a luxury automobile seat is less loaded when compared to an economy car seat (Gross et al., 1994) thereby contradicting Floyd and Roberts' (1958) criteria. Sanders and McCormick (1987) on the other hand suggest that the weight be distributed rather evenly throughout the buttocks area, but minimized over the thigh areas, a profile obtained by contouring the seat pan or varying the cushion density. Which one of the two strategies is *really* better for the human body? This question is rather difficult to answer for any particular scenario as is evident from the aforementioned research publications. An engineer trained to design and develop mechanical gadgets would approach the problem by adopting a common sense (Shafer, 1996) approach by distributing the forces acting at the human-"equipment" interface rather than concentrating the load. A sense of comfort is associated with a bean bag comprising macrospheres of rigifoam or the like. From an engineering perspective, it appears that such a cushion conforms to the buttocks, relieving high pressure and distributing force over a larger area of soft tissue thereby supporting the common sense approach of distributing the force rather than concentrating the loads. But are bean bags really comfortable or is it that we use them in environments where the user is already in a relaxed state?

Pressure distribution to improve comfort is an aspect faced by many ergonomists and engineers. However, there is little understanding of the exact pressure distribution or redistribution that is needed to achieve "comfort" or even reduce discomfort. It is hoped that the reader may begin to have innovative ideas about method(s) to support the human body after reading this paper.

The Material Analogy

The distributed force theory makes sense from a material standpoint. It stems from the way materials behave when subjected to loads. If, for example, a structure needs to be built using an I-beam or 2 by 4 pieces of wood or any other basic structural element, it is logical to distribute the load so that deflections or deformations are minimized, the phenomenon known as creep is minimized, and hence the "closeness" to failure is reduced. Ergonomists adopt similar reasoning when addressing repetitive strain injuries (RSI). The fundamental failure that occurs in RSI may be attributed to a mechanism closely linked with material failures: fatigue (Bishu et al, 1990). Hence one may think that human tissue behaves like any other "dead" material and most theories relating to materials is applicable to human tissue. Is this assumption valid? This paper is an attempt to reveal some of the approaches adopted, to uncover myths surrounding pressure-discomfort hypotheses, and to rethink the design process to make products more appealing to consumers.

The Tissue Trauma and Pain Perspectives

Another aspect supporting the distributed force strategy involves tissue trauma leading to pressure sores or decubitus ulcers as a result of "high" loading (Reswick and Rogers, 1976; Webster, 1991). It has been clearly demonstrated in many research works that pressure sores are a major problem in health care (Dinsdale, 1974) and one major cause is localized pressure on parts of the body. Kosiak (1959) reported a study linking pressure over bony prominences and their allowable *duration* to reduce the incidence of pressure sores thereby suggesting certain *guidelines* for human support interfaces (Figure

1). In general, an inverse relationship exists between tolerable pressure and time. Reswick and Rogers (1976) suggest that tissue with larger masses such as those in the thigh areas can support higher pressures for longer periods of time. Furthermore, there exists literature that indicates that pressures above 4 - 4.7 kPa are undesirable and put the tissues at risk from ischemia if *left in one position* (Kosiak et al 1958; Dinsdale, 1974; Reswick and Rogers, 1976). “Capillary closing pressure is perhaps not ideal as an upper limit for safe interface pressure since interface pressures can differ from pressures within tissue. However, an alternative has yet to be agreed on in the literature” (Allen et al, 1993)

Based on the above compressive pressure criteria, active cushions, which operate on the basis of periodic pressure relief in the form of a pressure wave, have also emerged. In a way, such active cushions may be viewed as units which impart “concentrated” loading of a certain level with reduced duration of exposure. In other words, they create a *concentrated strategy of short duration*.

Pressure distribution has been used to control ulceration in diabetic patients too. However, “the clinical management of pressure-induced sores is confusing because of the variety of techniques employed and the paucity of scientific information on their success” (Ryan and Byrne, 1989). Many different guidelines and criteria have emerged over the years as shown in Table 1.

Pressure (Pascal) = Force (Newton)/ Area (meter^2)

Stress* (Pascal) = Force (Newton)/ Area (meter^2)

where Area is the cross-sectional area of the applied force.

* Stress may in the form of a compression, tension or shear.

Insert Table 1 and Figure 1 about here

If we assume a maximum weight bearing area of about 200 cm^2 (approximately a US size 8 on a Brannock device) for one foot, then for a person weighing 80 kg, the average compressive stress on the foot is 39 kPa (nearly ten times of the pressure that would cause ischemia!). Physiological blood pressure studies have indicated that continuously applied pressure between 15-20 kPa interrupts the arterial blood flow and long-term effects of such occlusions include necrosis (skin cell death) and ulceration (Baumann et al., 1992). Ulceration is generally thought to occur when there is *prolonged* tissue ischemia caused by a pressure that exceeds the capillary pressure. Houle (1969) proposed that the maximal seating interface pressure should not exceed the capillary blood pressure of 32 mm Hg (4.3 kPA). To give the reader some idea about pressure during sitting, consider the values reported by Kosiak et al. (1958): mean pressures of about 43 kPa were found around the ischial tuberosities when sitting on a unpadded flat wooden surface, which is nearly ten times the pressure that would cause ischemia! Yet, sitting on hard “floor” surfaces, cross-legged, for prolonged periods of time is common practice in the Indian (Helander, 1995, pp. 58-59; Kroemer et al, 1994, pp. 366) and Japanese cultures. In the same study, a 2 inch (5 cm) foam rubber padding was able to reduce the pressure to about 21 kPa (still five times the pressure that would cause ischemia!). Drummond et al. (1982) using a micro-computer based pressure scanner, showed that approximately 18% of a body’s weight is distributed over the ischial tuberosity; 21% over each thigh; and 5% over the sacrum. The distribution is of course altered depending on the seat geometry and the foam durometer. In relation to the foot, past research (Bauman et al., 1963; Silvino et al., 1980) has shown that clinical pain in the plantar areas tends to occur when pressures exceed 255 kPa (over 60 times of the pressure that would cause ischemia!). Clearly, there appears to be inconsistency among researchers. To further complicate issues, Sacks et al. (1985) proved that the load is unimportant and claimed that the skin blood flow changes are influenced by only 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 will be further explored in the section, Maximum Pressure Tolerance, to explain interface designs with concentrated loading.

Many researchers have postulated that that the lack of pressure sores in people with normal sensations is due to their continuous variations in pressure patterns through the support interface. Whether this phenomena is due to a force distribution over a larger contact area is still to be explored.

Shear or friction has also been identified as an important stress. Unfortunately, shear stresses are not as observable as compressive stresses. “Moreover, they are much higher within the deep tissue than at the surface. ... pressure sores (are) likely begin in the deep tissue” (Tsay, 1991). As a result of measurement difficulties, no guidelines exist for shear stress at the human interface. However, simple experiments performed by Bennet (1976) have shown that pinch stress (normal to the surface with deformation) results in significant reductions in blood flow, and compressive stress (normal to the surface without deformation) and horizontal shear stress (parallel to the surface) have similar reductions in blood flow. The compressive stresses experienced in real life generally result in both compression and pinch shear (or tissue distortion, a primary cause of pressure sores) and it is hence appropriate to consider the formation of sores using guidelines for compressive stresses since the thresholds will be further lowered in the presence of the horizontal shear stress. “The relation between mechanical pressure and the development of plantar ulcers is widely accepted and in fact unquestionable” (Baumann et al, 1992).

Of course, there are secondary factors (such as skin temperature, age, infection, moisture, body type i.e., fat/muscle distribution, collagen formation and nutrition, fibrinolytic activity) which do not directly cause a pressure sore, but contribute towards their formation when mechanical stress is present (Pfeffer, 1991; Torrance, 1983).

Many types of therapeutic and flotation beds are commercially available. Even though the marketing claims for these devices are impressive, there have been only a limited number independent evaluations of these devices (Krebs et al, 1984) and most (or nearly all) evaluations have been with respect to the normal or compressive stresses (pressures) only (e.g., Bader and Hawken, 1986; Krebs et al, 1984; Ryan and Byrne, 1989, etc.).

Beds, Cushions, Insoles and other Human Interfaces

Interface pressures have governed the development of many devices in the form of fluidised beds, seat cushions, shoe insoles with claims of reduced pressure sores and in some cases, claims of improved comfort. In general, it appears that injury can be minimized through pressure distribution and lowering pressure magnitude over human tissue. It is also claimed that injury is generally preceded by discomfort. If this statement is true, then logical reasoning implies that distributing force, thereby distributing pressure or reducing pressure at a particular location should result in a reduced level of discomfort. This argument is really only one side of the story.

Look at the flip side: Krouskop (1985) found that mattresses with a uniform pressure distribution make people restless thus causing concern about 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, beaded car seat covers popular in the eastern cultures, massage mats made of wooden slats or “massage” rollers are popular. All such devices induce localized force rather than “distributed” force, supposedly creating desired sensations rather than discomfort. Hence it appears that concentrated force also has certain advantages and possibly a sensation of comfort or relaxation and well-being as defined by Zhang et al. (1996) and possibly related to biomechanics. In addition, if uniform pressure is the ideal pressure distribution for optimal comfort, interface design is comparatively easy, especially since pneumatic or hydrostatc balloons or bladders can be designed to give this “constant” or uniform pressure at the interface.

Pressure-Comfort Modelling

Many pressure measuring devices are commercially available (Bader and Hawken, 1986; Ferguson-Pell and Cardi, 1992; Fredrick and Hartner, 1993; Olson, 1991). However, comfort predictions based on interface pressure have proved to be not very easy (SATRA, 1992) even though there are a few reported studies that have successfully modeled the pressure-comfort relationships using mathematical and statistical techniques (Gross et al, 1991). These mathematical models are very useful from a product standpoint (Gross et al, 1992). But, the primary weakness of such extensive studies has been the lack of scientific evidence of why some interface pressure profiles deliver “optimal” comfort.

Spatial Summation Theory

Let us now look at a related theory from the sensory literature. It states that that simultaneous stimulation of many sensory receptors is required to arouse a stimulation; a property referred to as *Spatial Summation* (Hardy and Oppel, 1937). In simple terms, it means that a greater sensory response is experienced when the area stimulated is larger. It is a rather obvious but neglected issue. For example, 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.

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 (Figure 2). The measurement procedure is presented in Goonetilleke and Eng (1994). There were no significant ($p < 0.05$) differences between locations or between genders. This simple experiment has been validated for many other locations even though the results are not yet published.

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

Insert Figure 2 about here

It is logical for a layman to look at the maximum *force* (or maximum force tolerance, MFT = MPT* Area) that can be supported rather than at the pressure. The force relation between the two probe sizes would thus 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. What is surprising? The surprise comes from the difference that is seen in MPT, when compared to a "dead" material. For any material other than human tissue, there is generally no difference in MPT at the breaking point. The MPT value corresponding to breaking strength for a material is indicated using stress (force/area), which is independent of area[1].

If the maximum force is such that even though only half of the force can be supported with a 5 mm probe, it has 3.3 times tolerance thereby implying a counter-intuitive suggestion for loading on the human body (a not so common-sense approach!). Consider the force supported at the tolerance level 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 amount of force that could be tolerated 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. In the above discussion, it should be noted that there is a minimum distance in order to distinguish the localized forces as separate forces (rather than a distributed force over the complete area). This distance may be variable depending on the body characteristics (such as size, sex, fat/muscle distribution, clothing, etc.) as well as the location on the body at which the pressure is exerted (e.g., arm, leg, foot back, etc.).

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[2] and contact area appear to have a relationship similar to that shown in Figure 3. 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.

Insert Figure 3 about here

Discomfort Hypothesis and its Application

[1] Note that the breaking strength of “dead” material is independent of area since it is a constant.
[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.

The extension of the spatial summation theory, which I call 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 (another nebulous term!). 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 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 thereby making the wearer experience greater discomfort when compared to a shoe that does not have a dynamic fit sleeve (bottom half of Figure 3). 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.

In similar fashion, Reed et al. (1991) found that seat comfort evaluations at the beginning and end of extended driving situations disagree. It is well known in automotive circles that long-term driving comfort might be achieved only at the expense of the static “showroom” comfort (Lee et al, 1993). If uniform pressure at the sitting interface is ideal, then why is it that static and dynamic (or extended duration) comfort are different? It is not clear whether the discomfort hypothesis can be used to explain this result, without further information on the seat pressures.

The Last Words

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. In the light of the discomfort hypothesis, the thought of a bed of nails is not so bad after all!

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Table 1.
Discomfort and Injury Criteria for sitting and standing interfaces

Criteria	Source
Maximum seating interface pressure should be less than the capillary blood pressure of 4.3 kPA	Houle (1969)
Maximum pressure under ischial tuberosities of 3 N/cm^2 (or 30 kPa) based on capillary blood pressure	Diebschlag et al (1988)
Continuously applied pressure between 15-20 kPa interrupt the arterial blood flow and long term effects of such occlusions include necrosis (skin cell death) and ulceration	Baumann et al. (1992)
Clinical pain in plantar areas tends to occur when pressures exceed 255 kPa	Bauman et al, (1963); Silvino et al (1980)

Ravindra S. Goonetilleke (Pressure distribution on human tissue: Is it common sense?)

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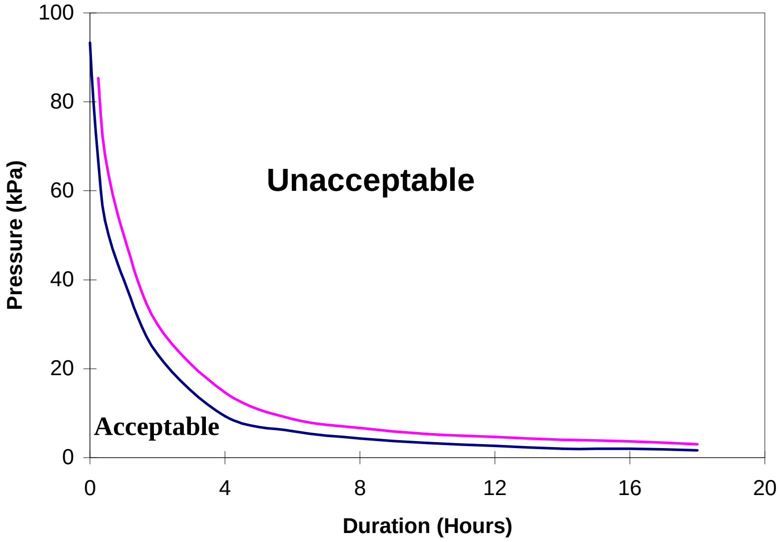

Figure 1. Allowable pressure over bony prominences as suggested by Kosiak (1959). The curve is a guideline and not a rule.

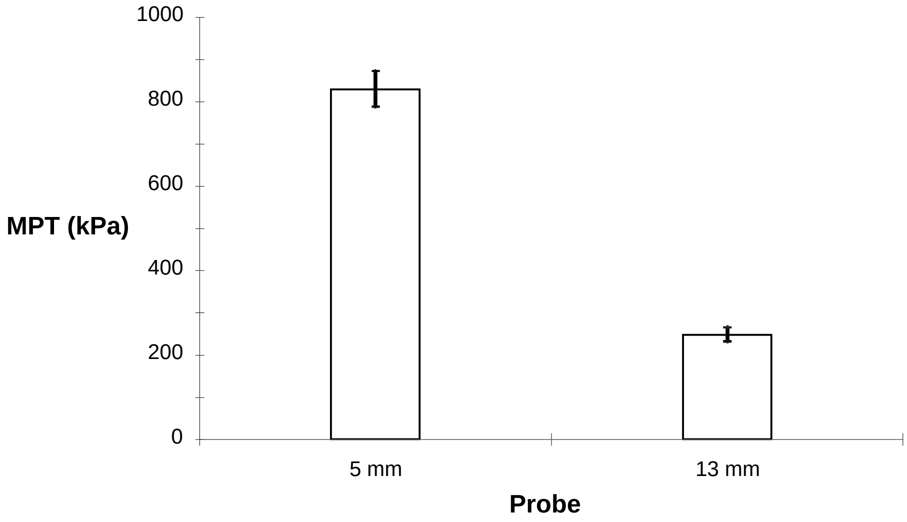

Figure 2. Effect of probe size on the mean value of maximum pressure tolerance.

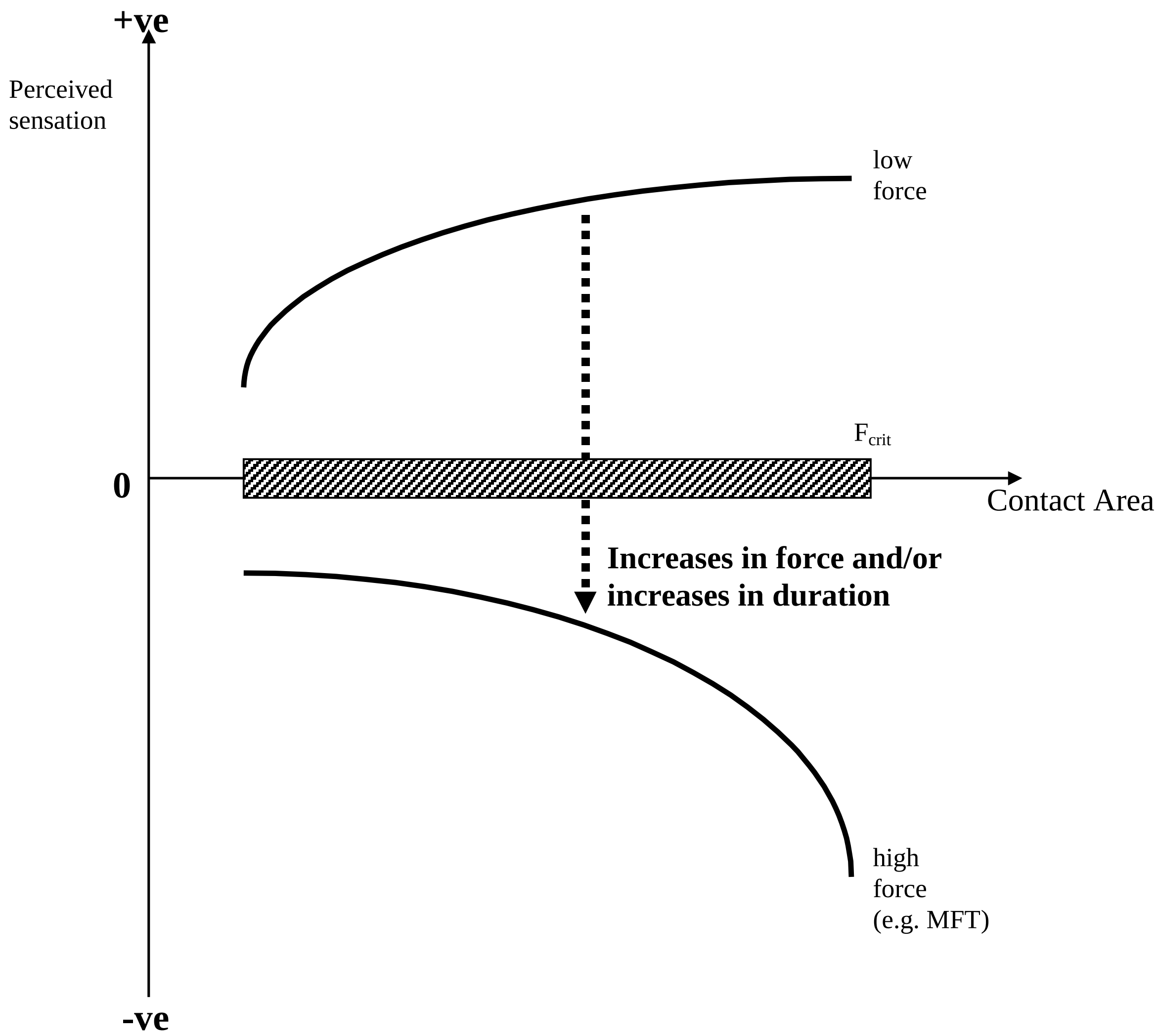

Figure 3. Hypothetical relation between perceived sensation and contact area. Exact shape of curves are still unknown.