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Fundamentals of body support
The bursa-like interface

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Summary

The human body is supported throughout most of life (while we sleep, travel, work and in our spare time). It is estimated that when one is 72 years of age, 62 years have been spent in some form of body support, such as an office chair and a bed. (Goossens 1994).
Body-supporting surfaces are often related to complaints in the neck, back, buttocks, legs and soft tissue (Grieco 1986). Numerous solutions for cushioning the contact area between product and user have been and implemented during the last centuries, but only in the last decades systematic research has been conducted on the underlying mechanical principles and the results of mechanical load imposed on the human skin and muscular skeletal system.
The skin is the interface between body and body support. Within the skin, all kinds of mechanoreceptors continuously monitor the deformation and warn us of damage (pain). The stress-strain relationship shows that there can be a high degree of deformation of the skin (up to 50%) before yield (mechanical damage) occurs. Physiological response however starts at lower deformation of the skin and is more important when evaluating the effect of body support.
Friction turned out to be a significant component factor of mechanical load on the skin (Reichel 1958, Goossens 1994). Friction on the skin consists of three components: the deformation, ploughing and adhesion components. The adhesion component (μ_a) between skin and support surface is the most important component for body support interfaces and it can be influenced by the choice of material and texture.
In the human body, at places where the mechanical load can become too high on bone, muscle tissue or other tissue, bursae are found. Bursae are found in regions where muscles, tendons, or bones rub against other muscles, tendons, or bones. The bursae function in two ways, lubricating points of friction, and dissipating force by distributing it through a fluid medium. Normally, the bursae produce just enough synovial fluid to reduce friction by reducing the tissue bonding. From an engineer's point of view, the advantage this provides is that a bursa separates moving tissue, thereby eliminating tissue bonding (μ_a the adhesion component is relatively small).
One of the more innovative principles for body support is a bursa-like interface that has a strong resemblance with the bursa found in the human body. This bursa-like body support is a pouch that contains a low viscosity liquid and one or more baffles which channel the liquid within the pouch as pressure is applied or shifted across the surface area of the pouch. In this bursa-like body support it is therefore expected, on the basis of biomechanical theory, that the shear force on the body contact surface is very low (zero in theory), and that the small layer of liquid equalizes the pressure at the contact surface.
Both these theoretical findings are confirmed in scientific studies on LiquiCell® (Yu 1995,Goossens 2001). LiquiCell® is based on bursa-like technology. The LiquiCell® pad addresses shear more effectively than other cushioning devices (Goossens 2001). When using LiquiCell® instead of gel there is a reduction of shear stress varying from 24% to 25% (Goossens 2001). When using LiquiCell® instead of foam there is a reduction of shear stress varying from 28% to 39% (Goossens 2001). It was also concluded that the size of the high-pressure area of the buttocks is reduced when each of the LiquiCell® gel and foam cushioned seats are used, but reduced more with LiquiCell® and gel (Yu 1995).
Different studies on comfort and discomfort have shown that mechanical load (pressure as well as shear) influences discomfort. It was also concluded that equal pressure and low shear increase the amount of time that passes before discomfort is noticed. A test (Garcia Lechner and Goossens 2003) showed that, on a hard seat surface without sharp edges that produce high pressure, at least 30 minutes will pass before the comfort limit is crossed i.e. there is a feeling of discomfort. This would explain the fact that people do not value the effect of good cushioning (i.e. low shear and equal pressure) during a short test period.

1 Introduction

The human body is supported throughout most of life (while we sleep, travel, work and in our spare time). It is estimated that when one is 72 years of age, 62 years have been spent in some form of body support, such as an office chair and a bed (Goossens 1994).
Body-supporting surfaces are often related to complaints in the neck, back, buttocks, legs and soft tissue (Grieco 1986). Numerous solutions for cushioning the contact area between product and user have been made and implemented during the past centuries, but only in recent decades has systematic research been conducted on the underlying mechanical principles and the consequences of mechanical load imposed on the human skin and muscular skeletal system.
In an attempt to identify the factors of comfort and discomfort in sitting, Zhang (Zhang et al., 1996) concludes that, amongst other factors, an excessively high mechanical load was one of the factors causing discomfort. In some studies, this relationship between pressure and discomfort was demonstrated (Diebschlag and Hormann 1987; Grindley and Acres 1996; Ballard 1997; Buckle and Fernandes 1998). Most of the cushioning innovations, therefore, focus only on pressure reduction at the contact interface. However, since Reichel (1958) pointed out that shear stress is also a significant factor of the mechanical load and its effect on tissue, attention should also be given to this aspect.

One of the more innovative principles of body support is a pouch that contains a low viscosity liquid and one or more baffles that channel the liquid within the pouch as pressure is applied or shifted across the surface area of the pouch. This pouch is known as a LiquiCell® pad. This kind of body support is called bursa-like interface since it has a strong resemblance with the bursa found in the human body.

The aim of this paper is to present the working principle of the bursa-like interface and discuss some studies that have been done on the mechanical behavior of this type of technology (LiquiCell®). To begin, terms and definitions in this area of research are presented. Since all external forces on the human body enter through the skin, first a short introduction to the human skin and sensory system is presented. Then, the effect of mechanical load on the skin and deeper tissue is discussed in relation to human anatomy. Thereafter, the theory of body support principles and the research on comfort and discomfort follows. Finally, the studies on the bursa-like interface -LiquiCell® pad- are presented.

2 Terms and Definitions

Throughout this document, terms are used that have their origin in both technical and medical fields. In order to make this paper readable to people from both disciplines, the most important terms are defined in this section.

2.1 Bursae

Encyclopædia Britannica (2003) defines a bursa as follows:
bursa (plural BURSAS, OR BURSAE) *any small pouch or sac within the mammalian body between tendons, muscles, or skin and bony prominences, at points of friction or stress. The bursas are classified by type as adventitious, subcutaneous, or synovial.*

Adventitious, or accidental, bursas *arise in soft tissues as a result of repeated subjection to unusual shearing stresses, particularly over bony prominences.*

Subcutaneous bursas *ordinarily are ill-defined clefts at the junction of subcutaneous tissue and deep fasciae (sheets of fibrous tissue); these bursas acquire a distinct wall only when they become abnormal, and they are classified as adventitious by some authorities.*
Synovial bursas *are thin-walled sacs that are interposed between tissues such as tendons, muscles, and bones and are lined with synovial membrane, so called because it exudes synovia, a lubricating fluid. In the human body a majority of synovial bursas are located near the large joints of the arms and legs.*

2.1.1 Synovial bursae

As an example, Figure 1 shows some synovial bursae found in and around the knee joint. At the juncture bones meet, and synovial fluids and membranes reduce the friction. In the body, at places where the mechanical load can become too high on bone, muscle tissue or other tissue, bursae are found. Bursae are found in regions where muscles, tendons or bones rub against other muscles, tendons or bones. The bursae function in two ways: lubricating points of friction and dissipating force by distributing it through a fluid medium. Normally, the bursae produce just enough synovial fluid to reduce friction by reducing the tissue bonding (See 'Friction and the skin'). This reduction of friction, for example, can also be experienced when a car hydroplanes due to a thin layer of water between the tire and the road. However, constant irritation may lead to over-secretion and consequent enlargement and inflammation of the bursa, a condition known as bursitis.

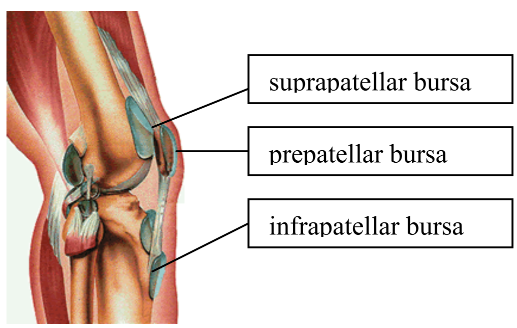


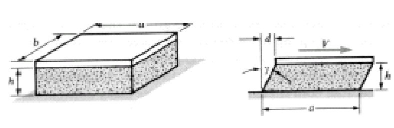
Figure 1 The knee with some bursae. The suprapatellar bursa is located between the deep surface of the quadriceps muscle and the distal part of the femur. The prepatellar bursa is located between the superficial surface of the patella and the skin. An infrapatellar bursa is located between the patellar ligament and the skin. Other bursae decrease friction at the attachment points of the various muscles (Jenkins, 1991).

2.2 Mechanical Load

Throughout this document, the effect of mechanical load on the skin and deeper tissue is studied. Mechanical load can be resolved in pressure and shear or friction. In the case of shear and friction, there may be some uncertainty about the definitions. So in this section these terms are defined.

2.2.1 Shear/friction

Shear (Gere and Timoshenko, 1990)
In the view of mechanical engineers, a shear force (V) is a force that acts parallel or tangential to the surface. The average shear **stress** equals the force V divided by the area over which it acts, see figure. Shear stresses are customarily denoted by the Greek letter τ (tau).
The surface can be any surface, including a surface within the tissue. It can be shown that any load on the skin surface (pressure, shear, pressure and shear) always results in a shear stress in certain cross-sections in the skin.



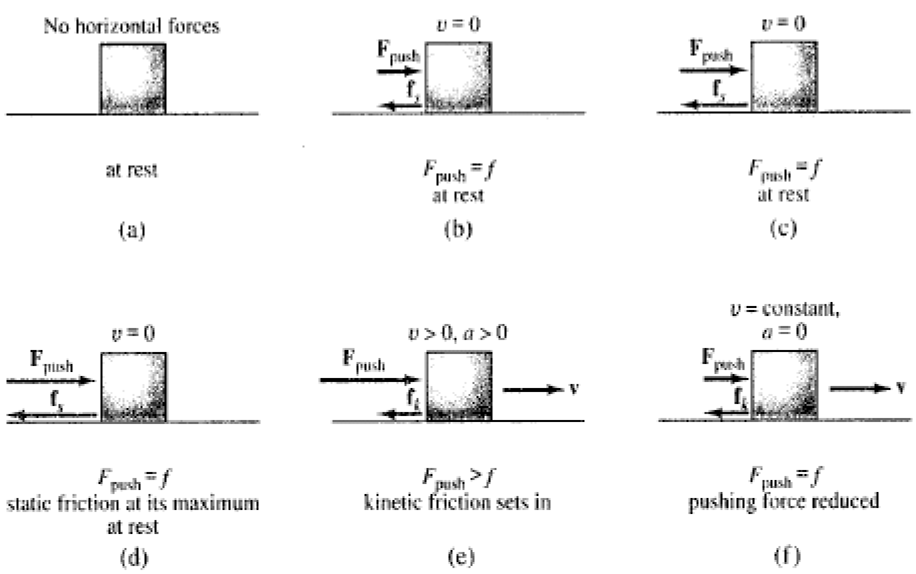
Friction (Fishbane et al., 1996)

Static friction

Friction is a contact force that impedes sliding, and works parallel to the contact area. Suppose that you want to slide a crate from one place to another. You push on it with a small horizontal force, but nothing happens. This is because static friction is acting between the floor and the crate in the absence of motion in such a way as to prevent motion. This force must be variable because it balances each of your own different pushes.

Kinetic friction

Suppose that you finally get the crate moving. The force overcame the static friction because static friction has a maximum magnitude. Once the crate is moving, it is easier to keep it moving at a constant speed. There is still friction opposing your push, but it is now kinetic (or sliding) friction; that is friction associated with motion. The magnitude of kinetic friction is smaller than the maximum of static friction. The entire sequence of getting the crate started and keeping it moving can be seen in the figure below.



Coefficient of friction

The proportionality constant that relates the friction force and the normal force is the coefficient of friction, μ. The (unit less) constant μ is determined experimentally. The maximum value of static friction is generally not equal to the force of kinetic friction, so we distinguish two coefficients: μ_s for static friction and μ_k for kinetic friction. If we write the force of static friction as fs and that of kinetic friction as fk, their magnitudes are given by

Static friction: $0 \leq fs \leq \mu_s F_N$
Kinetic friction: $fk = \mu_k F_N$

However, it has been found that for soft surfaces like the skin the maximum static friction can be described roughly as proportional to the applied pressure (::F_N). Several experiment results (Yamaguchi 1990) indicate that the coefficient of friction is generally due to various combined effects of asperity deformation (μ_d), ploughing in the surface by wear particles (μ_p) and molecule adhesion between surfaces (μ_a). (See also 'The skin')

More accurately, it can be described as a non-linear function of the normal force $fs = \mu (F_N)^q$. Mossel (1998), using that as a basis, came up with the following logarithmic model for friction between the forefinger and stainless steel.

$$0 \leq f_s \leq K \cdot c_p \cdot (E \cdot A_t)^{1-q} \cdot F_N{}^q$$

In which:

K	is a dimensionless factor
c_p	is a pressure distribution factor
E	is the modulus of elasticity of the skin (the amount of stress (force per unit area) required to produce a given amount of strain (stretching))
A_t	is the contact area
q	is a dimensionless exponent smaller than 1
F_N	is normal force

2.2.2 Pressure

Pressure is a force acting perpendicular to the surface, and is defined as the perpendicular force per unit area. In the 1950s, the first pressure measuring devices were developed. Today different systems are on the market to measure the interface pressure between the skin and the body support surface.

2.2.3 Summarized

Pressure is a force acting perpendicular to the surface. Shear and friction are caused by a force acting parallel to the surface. Shear and friction are, in one sense, overlapping definitions. Shear is used for the static situation (no movement) and can act on the contact surface (outside the tissue) but also on a cross-section inside the tissue. Friction is used for both static and dynamic situations and always acts on the contact surface (outside the tissue) (Goossens and Bain in ISO/DIS 16480-1 pre-Draft).
The definitions overlap in the static situation, when acting on the contact surface (outside the tissue); in that case friction and shear are the same force.

2.2.4 Comfort versus Discomfort

Helander and Zhang (1997) performed a study in which 143 emotions or feelings about office chairs were identified and then reduced with cluster analyses to a checklist with 14 items. They concluded that the use of a unidimensional scale – from extreme discomfort to extreme comfort – would be inappropriate, since it is possible that users gave simultaneous ratings of average comfort and average discomfort. The authors therefore presented a conceptual model for sitting comfort and discomfort (See 'Comfort, discomfort and pain') in which there is a link between comfort and discomfort. High values of comfort can be attained only if discomfort is low. They postulated an operational definition of comfort and discomfort, based on empirical evidence, and that will be used throughout the document.

Comfort
Comfort is based on aesthetics and the plushness of (chair) design and a sense of relaxation and relief. (Helander 2003)

Discomfort
Discomfort is based on poor biomechanics and fatigue. (Helander, 2003)

Pain
An unpleasant sensation occurring in varying degrees of severity as a consequence of injury, disease or emotional disorder (Webster, 2003).

Ischemia
Decreased flow of oxygenated blood to tissue.

Necrosis
The localized death of living cells associated with infection or the interruption of blood supply.

3 The Human Body

The entire human body is involved when the body is supported. A load on the body is generally transfered to the skeletal system via the skin and soft tissue. In this section a closer look is taken at the aspects of the human body that are of importance during body support.

3.1 The Skeletal System

A load on the body is generally transferred to the skeletal system. Soft tissue, like skin, underlying fat and muscle act thereby as a cushioning interface for the transfer of the load to the bones (Hobson 1988). The transmitted forces have a potential of damaging soft tissue. The critical factor is not simply the force, but the ratio of the force to the surface area over which it acts. At some parts of the human body, the bony prominences are covered by a relatively thin layer of tissue like the sacrum, hip, heel and ankle. At these locations, the so-called 'force intensity' or stress and deformation is high when using a body support surface. Therefore it is mainly at these bodily places where tissue damage and feelings of discomfort and pain caused by mechanical load can be found (Petersen, 1976).

3.2 The Skin

Because the skin is the contact area for all external forces that act on the body, the skin and the receptors in the skin for mechanical load are discussed here in more detail.
With a total surface area of 1.7 m^2 (2 square yards), the skin is the largest organ of the human body. The skin consists of three parts, namely the epidermis, the dermis, and subcutaneous tissue (Figure 2).

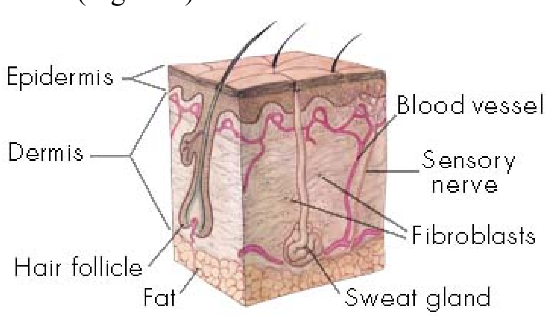


Figure 2 Different layers of the skin. The epidermis, dermis and subcutaneous tissue

The epidermis is the outer layer of the skin and contains living cells in the deeper parts, and dead cells on the surface. Underneath the epidermis, in the dermis, receptor cells can be found for touch, pain, pressure and temperature (Figure 3). The receptor cells have different functions:

- Mechanoreceptors: for touch, vibration, pressure (these are divided in fast and slow adapting receptors);
- Thermo receptors: for temperature;
- Nociceptors: for pain.

The receptors detect specific stimuli and convert them into electrical signals that are conducted through the nervous system to the brain. The mechanoreceptors are sensitive to deformations induced by mechanical load (shear and pressure). The mechanoreceptors measure deformation because an important task of the skin is to resist mechanical trauma. Although the skin is well adapted to many types of trauma, excessive mechanical load (shear and pressure) can result in the formation of various dermatoses (blisters) (Kanerva 1990) and in pressure ulcers. Blisters occur in this deeper part of the epidermis and between the epidermis and the dermis. Pressure ulcers occur at the surface of the skin as well as underneath the skin in muscles and bone.

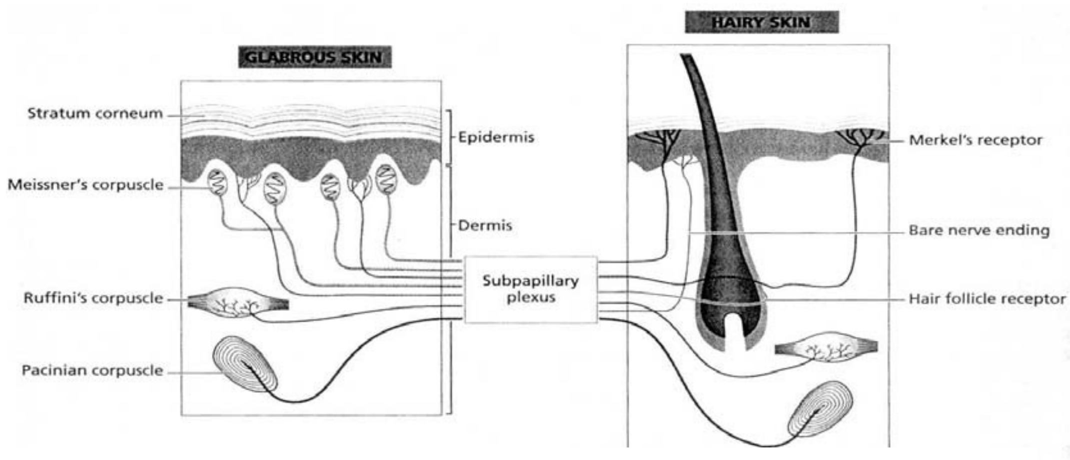


Figure 3 Receptors for hairy and glabrous skin. [Source: Textbook of Dermatology, 1998, Rook, Wilkinson, Ebling]

3.3 Mechanical Properties of the Skin

The ability of skin to undergo extreme elongation results in its being deformed around objects. This deformation increases the area of contact, decreases stress, increases friction and, at low force levels, decreases trauma (Armstrong, 1985).

3.3.1 Stress-strain relationship

The stress-strain relationship of the skin, can be divided into three distinctive phases that correspond to straightening and alignment, extension and finally fracture of the fibrous components of the skin (Bader and Bowker, 1983).

Many investigators have made stress-strain measurements of the skin to calculate the modus of elasticity; the amount of stress (force per unit area) required to produce a given amount of strain (stretching).

Kenedi (Kenedi, Gibson et al., 1975) applied variable force to excised tissue and measured the strain. The resulting stress-strain curve shows the skin to be non-linear with a large initial deformation occurring at the application of force. They also examined the time required by skin to recover from a periodically maintained stress and found that the skin will not return to its original condition unless it experiences the stress and strains to which the skin normally is subjected. In other words, skin remains deformed when put under higher stress than it experiences in normal situations.

Kenedi et al. (1967) reported that the modulus of elasticity increases from near zero at strains of less than 20% to approximately 138 MPa (mega Pascal) at strains between 30 % and 50 % (Figure 4). Also Ridge and Write (1967) reported such a curve linear force-displacement relationship for skin under tension. They showed that initial stretching of the skin is associated with straightening of the collagen bundles, which act like weak springs. The second stage of strain was associated with the stretching of the uncoiled fibers, which act like stiff springs. The final stage corresponds to an ultimate elongation, before yielding, of 30%-50%.

The amount of stress needed to produce mechanical yielding is called tensile stress. Tensile strengths are based strictly on mechanical responses, not on biological responses. Physiological changes such as occlusion of blood flow occur at stress levels much less than those required to produce mechanical yielding. Kenedi et al. (1967) define the biological usefulness of skin as that amount of strain which produces blanching or occlusion of the cutaneous blood flow. Blanching limits of skin based on in situ measurements at various locations of the forearm can be seen in Figure 5. Therefore, physiological responses to stress may be more important in the design of body supports than are passive mechanical responses (Armstrong 1985).

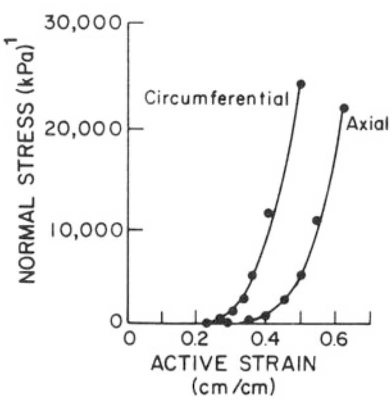


Figure 4 Elasticity of the skin [Source: Kenedi et al., 1967]

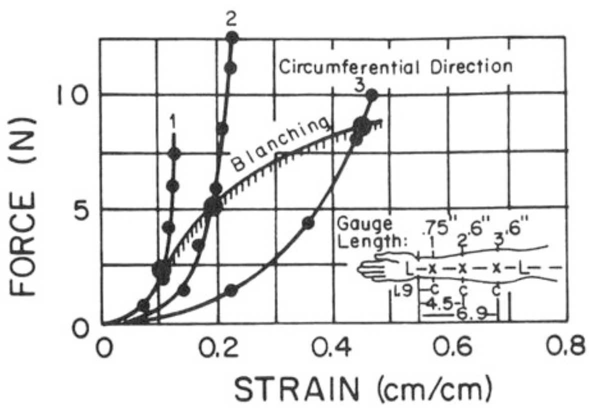


Figure 5 Blanching of the skin [Source: Kenedi et al., 1967]

3.3.2 Friction and the Skin

Skin and polymers appear to behave similarly with respect to friction and do not follow the basic laws of friction that exist for solid materials (Bobjer et al., 1993). Several experimental results (Yamaguchi 1990) indicate that the coefficient of friction is generally due to various combined effects of asperity deformation (i.e. deformation caused by microscopic irregularities on the surface) (μ_d), ploughing in the surface by wear particles (μ_p) and molecule adhesion between surfaces (μ_a). The surface of the skin contributes to these different factors according to the following mechanisms (Bobjer et al., 1993):

μ_d The friction due to asperity deformation. The deformation of the dermal ridges of the skin contributes to this factor during static and sliding conditions.

μ_p The ploughing component is low when the soft surface of the skin slides against a hard surface.

μ_a The adhesion component depends on lubricants at the interface. Oil and lard have a reducing effect on this component of friction, there is also an unknown effect of proteins and an increasing effect of sweat on textured surfaces.

3.3.3 Techniques to Measure Properties of the Skin

Diridollou et al. (Diridollou et al., 1998) provide an overview of several techniques that have been used to study in vivo the mechanical properties of human skin, with those most frequently encountered in the literature being based on:

- Tonometric (pressure) measurements that evaluate the ability of the skin to withstand vertical forces of extension (pressure);
- Traction, which applies linear displacement in the horizontal displacement of the skin;

- Indentation, which uses the application of a negative trust through a disc or point glued to the skin;
- Torsion, which applies a torque to the skin;
- Suction, which applies a negative pressure to the skin;
- Durometer ratings of the skin. The durometer rating of the skin can be addressed when dealing with shear. Materials with a low durometer tend to bond with solid surfaces of contact. This bond must be broken before movement can occur. The skin will tear if the force required to break the bond is greater than the tensile strength of our skin at the points of contact. Excessive wear will occur if the bond is at or near 50% of the tensile strength of our skin. An example of this condition occurs when one places the tongue against a cold metal object.

3.4 Conclusion

The skin is the interface between body and body support. Within the skin all kinds of mechanoreceptors continuously monitor the deformation and warn for damage (pain).
The stress strain relationship shows that there can be large deformations of the skin (up to 50%) before yield (mechanical damage) occurs. Physiological response, however, starts at lower levels of deformation of the skin and is more important when evaluating the effect of body support.
Friction of the skin consists of three components: the deformation, ploughing and adhesion components. The adhesion component between skin and support surface is the most important component for body support interfaces and can be influenced by the choice of material and texture.

4 The Effects of Mechanical Load on the Body

The prior sections identified friction, shear and pressure as the elements of mechanical load. The properties of the skin were also discussed. This section addresses the effect of mechanical load on the body in relation to the body's contact points and the anatomy of the contact points. Different reactions of the body can be seen, varying from severe damage, such as pressure ulcers and blisters, to discomfort and pain.

4.1 Contact with the Body

4.1.1 Deformation at the Bony Prominences

Figure 6 shows a model of a seated subject in contact with a body support surface (Staarink, 1995). It can be seen that the load L of the body is transmitted to the support surface as support forces F. In his study, Staarink implemented 14 pressure sensors (dots) in a dummy to record the pressure at different places underneath the skin. He showed that the highest pressures were measured at the bony prominences, in this example 22.5 kPa at the ischial tuberosities, and that much lower pressures were measured at the contact surface with the cushion (8.5 kPa) in the example. These high differences in pressure cause high levels of deformation at the tuberosities. High levels of deformation of the skin will trigger the mechanoreceptors (and in some cases the nociceptors) in the dermis of the skin and disturb blood circulation. Because soft tissue is compressed most near the bony prominences, these areas of the body receive special attention when evaluating body support surfaces.

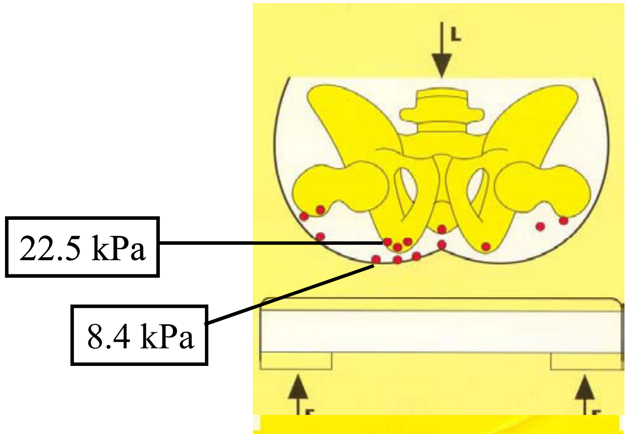


Figure 6. Pressure sensors in a dummy to record pressure underneath the skin [Source: Staarink 1995)

4.1.2 Different Layers at the Interface

Figure 7 again shows a subject seated on a cushioning material, but now in greater detail, showing the different layers that can be found between skin and the outside world.

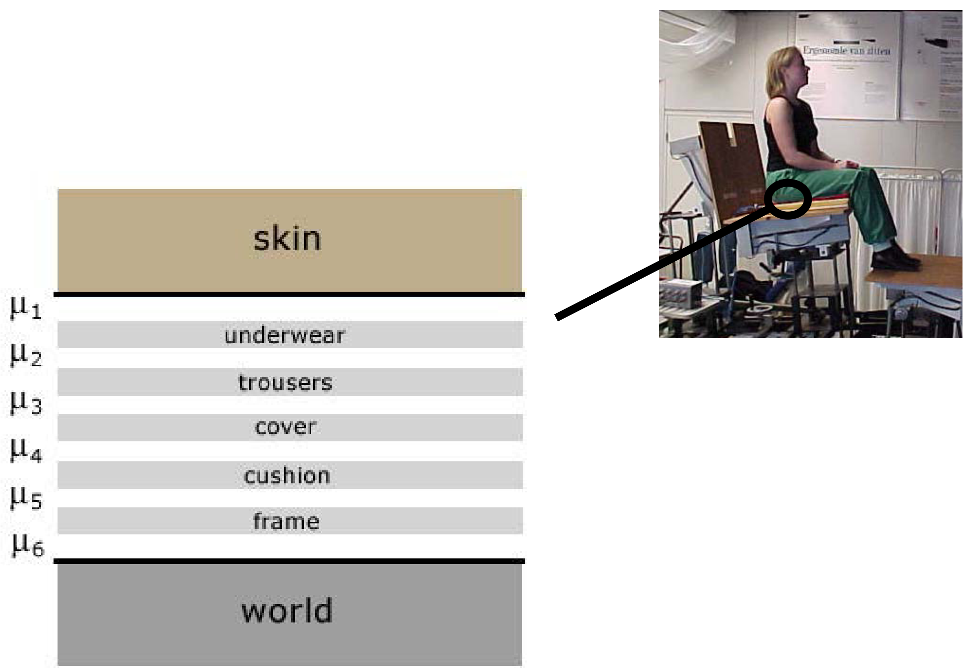


Figure 7 Different layers at the interface. From skin to world contains 6 surfaces that make contact. Each two surfaces with their own coefficient of friction.

A shear force transverses all of these layers and it is the coefficient of friction (μ) between each layer (in this case from μ_1 to μ_6) that defines the maximum shear force that can be guided through. Because the shear force has to go through all the layers, it is the lowest coefficient of friction that determines the maximum shear force that can act on the skin ($fs = \mu\ (F_N)^q$). The pressure (equivalent to F_N) is the same through all surfaces. The other defining factor in the maximum shear stress is the distribution of pressure over the surface. This is because highest shear stress occurs at regions of highest pressure, which are the bony prominences (Goossens 1997).

In daily life, situations with the lowest friction coefficients between different layers can be recognized easily. For example, when sitting on a couch with a cushion that is not fixed to the seat surface (the frame). In this case, μ_5 determines the maximum allowable shear force for static equilibrium and when the shear force becomes too high, the sitter and the seat cushion slide out of the couch.
Another example is when sitting in a hospital bed wearing a pair of pajamas. In this case, μ_3 (between trousers and sheet) determines the maximum allowable shear force, and the subject slides over the sheet out of the bed when his position requires too high a shear force for equilibrium (Goossens 1994).

4.2 Reactions of the Body to Mechanical Load

Mechanical contact forces on the body lead to a reaction of the body that can be categorized from severe injuries to discomfort. In the following paragraphs these reactions are discussed.

4.2.1 Pressure Ulcers

A pressure ulcer is an area of localized damage to the skin and underlying tissue caused by pressure, shear, friction and/or a combination of these [National Pressure Ulcer Advisory Panel, 1995]. Pressure ulcers are classified in four grades, based on the severity of the lesions.

- Stage I: A Stage I pressure ulcer is an observable pressure related alteration of intact skin whose indicators as compared to the adjacent or opposite area on the body may include changes in one or more of the following: skin temperature (warmth or coolness), tissue consistency (firm or boggy feel) and/or sensation (pain, itching). The ulcer appears as a defined area of persistent redness in lightly pigmented skin, whereas in darker skin tones the ulcer may appear with persistent red, blue, or purple hues.

- Stage II: Partial thickness skin loss involving epidermis, dermis, or both. The ulcer is superficial and appears clinically as an abrasion, blister or shallow crater.

- Stage III: Full thickness skin loss involving damage to, or necrosis of, subcutaneous tissue that may extend down to, but not through, underlying fascia. The ulcer appears clinically as a deep crater with or without undermining the adjacent tissue.

- Stage IV: Full thickness skin loss with extensive destruction, tissue necrosis, or damage to muscle, bone or support structures (e.g. tendon, joint capsule). Undermining of tissue and sinus tracts also may be associated with Stage IV pressure ulcers.

Most pressure ulcers develop near bony prominences such as the sacrum, ischium, hip, heel and ankle (Figure 8). At these spots, the skin and underlying tissue are relatively thin, and the load distribution under the skin is restricted to a relatively small area. This results in high load concentrations and relatively large deformations (because of concentrated pressure and shear) at these bony prominences when the weight of the body is supported by the body support surfaces.

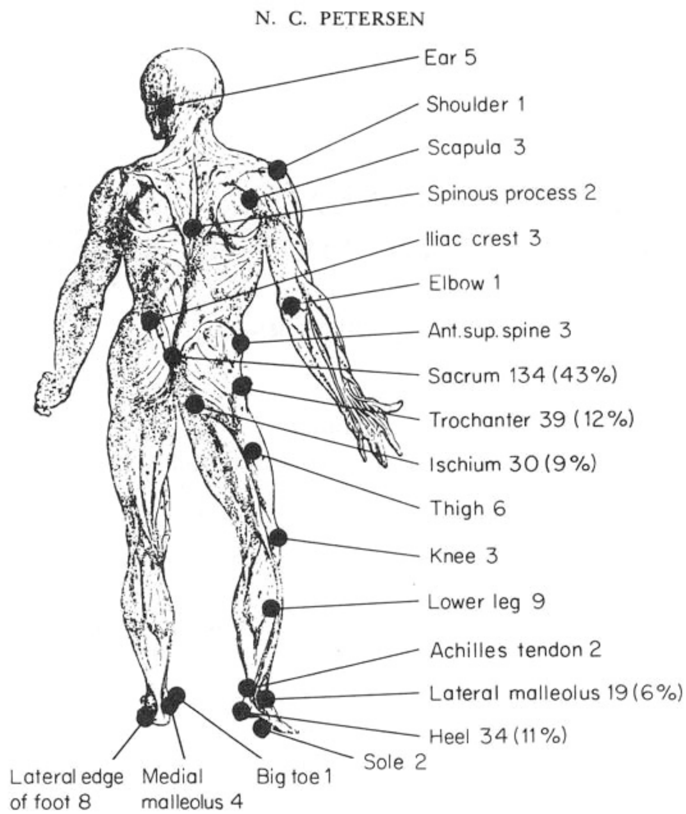


Figure 8 Most pressure ulcers can be found near the bony prominences [Source: Petersen 1976]

Pressure Ulcer Factors

Pressure ulcers are caused by factors that are classified generally as intrinsic and extrinsic. The intrinsic factors are related to the patient's clinical condition and both the nature of the illness and its severity are relevant. The extrinsic factors, which can be influenced directly, are concerned with pressure, shear, temperature and humidity. All authors in scientific literature agree that the leading cause of pressure ulcers is the mechanical load (pressure and shear) on the skin.

Although most authors agree that pressure ulcers are due to prolonged tissue ischemia caused by the mechanical load, through which the capillaries are closed and diffusion of oxygen and metabolites to the cells is also hindered, other extra mechanisms are reported in literature.

Reddy et al. (1981) studied the effects of external pressure on interstitial fluid dynamics using a simple mathematical model, concluding that the squeezing of interstitial fluid may also play a role in ulcer formation. Meijer (1991) states that it is most likely that local blood circulation under influence of the mechanical load is also controlled by regulatory mechanisms, which partly can be nervous.

When studying the mechanical properties of the skin, it was found that forces acting on the body surface will lead to stresses and strain (deformation) in the underlying tissue, and in a final stage to wounds known as decubitus or pressure ulcers. Various studies have been reported in literature that focused on the effect of exerted force and effect on the skin.

Kosiak (Kosiak 1959) applied different levels of pressure for different periods of time on dogs' hind limbs. He found that ischemic ulcers in dogs were produced by both high pressure applied for short periods and low pressure applied for long periods. This was also found in humans by Reswick and Rogers (1976) (see Figure 12).

Shear

It was Reichel (1958) who started to focus attention on shear force as an important component of the mechanical load and its effect on tissue. Since the publication of his article, various authors have confirmed the importance of shear stress as a factor in pressure ulcers.

Dinsdale (Dinsdale 1974) studied the effect of repeated pressure with and without friction in normal and paraplegic swine. He found that in those animals that received both pressure and friction, ulceration occurred at lower pressure levels than in those animals that received only pressure.

In relation to this last study, cut-off pressure can be defined as the level of external pressure on the skin at which ischemia of the skin can be expected. Goossens (Goossens, Zegers et al., 1994) found that cut-off pressure is significantly lower when a combination of pressure and shear are applied to the skin, compared to a situation in which only pressure is applied.

4.2.2 Blisters

Blisters (Falcon-Braun, 1969; Stoughton 1964) result from the accumulation of fluid between the cells of the epidermis of the skin or between the cells of the epidermis and dermis of the skin. Some form of cell damage is necessary to cause the fluid to enter the spaces of the previously damaged sites (Moschella, Phillsbury et al., 1975). This blister resulting from the cell damage ends up with some benefit of protection. And although blisters are produced in a wide variety of ways (eczema, infection, burns), the type of blisters that this document focuses on are called friction blisters in literature, but ‘mechanically induced blisters’ would be a better term.

Mechanically Induced Blisters

In order to understand friction blister formation in greater detail, it is necessary to have some idea of the anatomy of the dermo-epidermal junction (the junction between the epidermis and the dermis), as revealed by electron microscopy (Burton 1990). The dermo-epidermal junction includes the basal cell layer, the basal lamina (which is electron dense) and the upper papillary dermis (Figure 9).

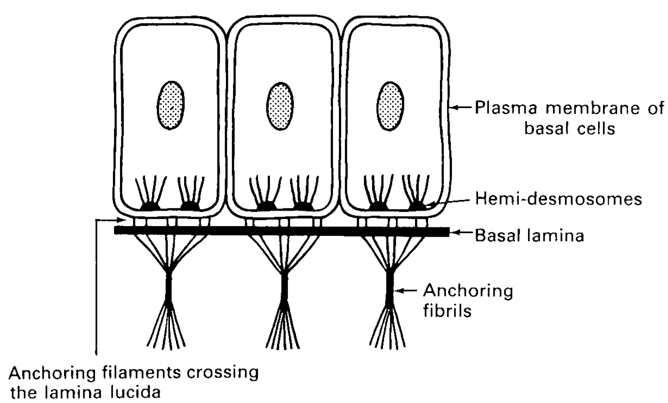


Figure 9 the dermo-epidermal junction. [Source: Essentials of Dermatology, 1990, Burton]

The narrow space that separates the membrane of the basal cell from the basal lamina is called the lamina lucida. This space contains a few anchoring filaments that cross from the basal cells to the basal lamina. Friction blisters are intra-epidermal blisters; the following mechanisms occur for these types of blisters (Figure 10):

Spongiosis	The cells become separated by accumulation of oedema fluid.
Epidermal cell necrosis	The cells become swollen and vacuolated to produce an appearance called ‘balloon degeneration’
Damage to intercellular ‘cement’	Cells that form intercellular cement lose their cohesion and drift apart

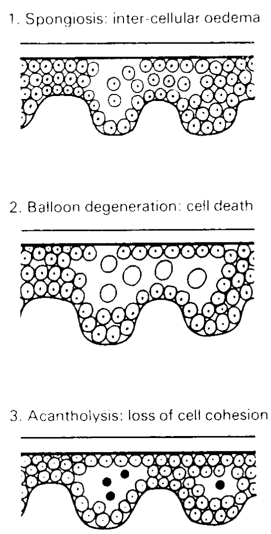


Figure 10 Mechanisms for intra-epidermal blister formation [Source: Essentials of Dermatology, 1990, Burton]

The factor responsible for friction blisters is reportedly a mechanical fatigue phenomenon rather than that induced by wear, heat, enzymes, pressure, stretching of ischemia (Comaish, 1973). These blisters are more easily produced in the old than in the young, in women than in men, and in hot than in cold skin (Paechy, 1971).

Shear
The shear force parallel to the skin surface is the leading factor in the formation of these blisters (Samitsz 1985 in Kanerva 1990). This force results in epidermal cell necrosis (cell death) and this causes an intra-epidermal slit which fills with fluid. The necrosis is due to repeated cellular distortion, which denatures the cellular protein (Moschella, Phillsbury et al., 1975).

Pressure
Pressure bullae, can be a sign of a variety of neurological diseases (Arndt et al., 1973). This phenomenon occurs in patients who have been immobilized for prolonged periods on pressure sites. The cutaneous lesions are due to pressure-induced ischemia (no blood flow through capillaries).

4.3 Comfort, Discomfort and Pain

In this paragraph the effect of shear and pressure on comfort and discomfort are discussed.
In a review of literature, Lueder (Lueder, 1983) gave a general overview of approaches to the assessment of the comfort-relevant design of office furniture. The author concluded that although substantial research exists, little insight is available into the meaning of comfort. More recently Zhang (Zhang et al., 1996) concluded that comfort and discomfort are two

different and complementary entities in ergonomic investigations. In an attempt to identify the factors of comfort and discomfort in sitting, the authors conclude that amongst other factors, poor biomechanics (meaning an excessive mechanical load) was one of the factors that caused discomfort. In some studies, this relationship between pressure and discomfort was demonstrated (Diebschlag and Hormann 1987; Grindley and Acres 1996; Ballard 1997; Buckle and Fernandes 1998).

Comfort is an extensive concept that is mainly related to subjective influences. Therefore, comfort is not easy to quantify (Annett, 2002). Despite this fact, several authors, such as Shackel et al. (1969), Corlett and Bishop (1976), Helander and Zhang (1997) and Straker et al. (1997), developed 'comfort-scales' with which the amount of comfort and discomfort experienced can be assessed. However, it must be stressed that this assessment remains a subjective process. Therefore, several authors have tried to find objective parameters to which comfort could be related. The pressure distribution, i.e. the variation of pressure on the seat surface, was pointed out by several authors to correlate well with seat comfort (Kamijo et al., 1982, Yun et al., 1992, Thakurta et al., 1995, Park and Kim 1997, Milivojevich et al., 2000, Tewari and Prasad 2000, Ebe and Griffin 2001, Demontis and Giacoletto 2002).

Although comfort and discomfort are studied by various authors, discomfort is apparently not exactly the opposite of comfort (Helander and Zhang 1997).

Helander and Zhang (1997) performed a study in which 143 emotions or feelings about office chairs were identified, and reduced them with cluster analyses to a checklist with 14 items. They concluded that the use of a unidimensional scale from extreme discomfort to extreme comfort would be inappropriate, since it is possible that users gave simultaneous ratings of average comfort and average discomfort. The authors also presented a conceptual model for sitting comfort and discomfort (Figure 11) in which there is a link between comfort and discomfort. High values of comfort can be attained only if discomfort is low. They postulated an operational definition of comfort and discomfort, based on empirical evidence.

- Discomfort is based on poor biomechanics and fatigue.
- Comfort is based on aesthetics and the plushness of chair design and a sense of relaxation and relief.

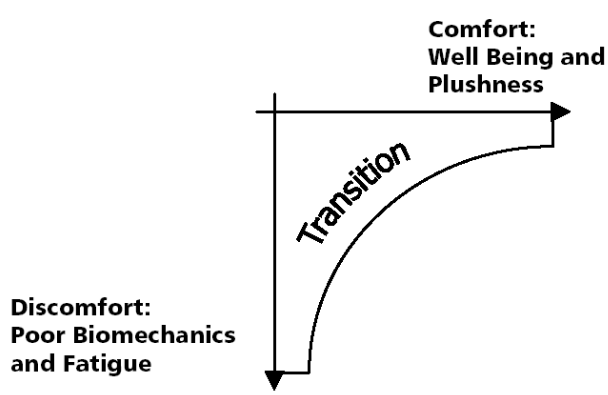


Figure 11 A link between comfort and discomfort. High values of comfort can be attained only if discomfort is low [Source: Helander 2003]

Seat discomfort may be experienced when sitting over a long period of time, or when a wrong sitting position is adopted. When seat discomfort is experienced for a long time, circulatory deficit and even a preliminary stage of decubitus lesions may be developed. This deficiency, which is called ischemia, caused by an increase of tissue pressure, results in un-physiological changes at the capillary level (e.g. deformation of vessels, decrease of lumen and oedema). As a result, tissue destruction can occur. Resistance to these conditions of diminished blood supply varies from tissue to tissue. Nerve and muscle tissue is very prone to being harmed by the lack of blood supply, even for short periods of time. Whereas bones and tendons will still be vital after several hours of total blood occlusion.

Reswick and Rogers (1976) published their famous 'pressure-time tolerance curve' (PTTC) as shown in Figure 12. This curve served as a guideline for the time a person could spend with a certain amount of pressure before exceeding a limit that was taken as acceptable. After that limit, an unacceptable zone is entered in which there is a high risk of developing decubitus lesions. The variables that describe this limit are the amount of pressure and time.
In the etiology of decubitus injuries, three factors are of main importance: 1) the level of pressure exerted on the person, 2) the level of shear force and 3) the period during which pressure and shear force are exerted. There is a presumption that, as in the Reswick and Rogers curve, there might also be a 'pressure-time tolerance curve' (PTTC) for discomfort. In contrast to decubitus lesions, there is no such curve reported in literature. In a recent study by Garcia Lechner and Goossens (2003), such a curve was defined, with the aim of getting designers of chairs and other body supports to take the pressure-time tolerance for discomfort into account while designing these products. When a designer has to develop a chair for sitting during short periods, as for example in a subway, he can keep in mind that people will sit on that seat for no longer than 15-20 minutes. This would mean that users could be liable to higher pressures (deformations because of mechanical load) before the discomfort limit is exceeded. Conversely, if the designer has to develop a chair for longer sitting periods, as for example in a flight of a couple of hours, the pressure (better it is to say: the deformations because of mechanical load caused by pressure and shear) exerted should be kept lower so that comfort is experienced for a longer time. The results of the study of Goossens and Lechner show that on a hard as well as on a soft surface subjects found themselves comfortable for some time (about 30 minutes), but on the hard surface without sharp edges with high pressure the discomfort limit is reached earlier than on the soft surface with lower pressure.

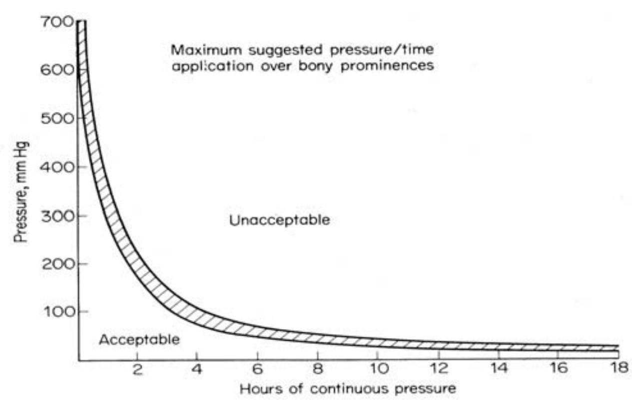


Figure 12. Pressure time tolerance curve for pressure ulcers [Source: Reswick and Rogers 1976]

In another recent study Goossens (Goossens 2000) showed that different combinations of pressure and shear (for example high shear and low pressure, and high pressure and low shear) when applied to the outside of the skin still have the same effect inside the skin. In this way it was demonstrated that not only pressure relates to discomfort but also shear stress. For both aspects of the mechanical load (pressure and shear) it can be concluded that a reduction leads to less discomfort.

4.3.1 Conclusion

It can be concluded that different studies have shown that there is an influence of mechanical load (pressure as well as shear) on discomfort. It can also be concluded that equal pressure and low shear increase the amount of time that passes before discomfort will be noticed. A test showed that on a hard seat surface without sharp edges that produces high pressure, at least 30 minutes will pass before the comfort limit is crossed, i.e. there was a feeling of discomfort. This would explain the fact that people do not value the effect of good cushioning (i.e. low shear and equal pressure) during a short test period.

4.4 Pain

Referred pain is a phenomenon that has been known almost since the practice of medicine began. This section is mainly focused on cutaneous pain, although trauma, disease process or vascular problems may also result in nervous signals.

Pain, pressure, warmth, cold and location can all be discerned by humans whose skin is appropriately stimulated. The exact nature and degree of the specificity became apparent with the discovery of isolated peaks of sensitivity to touch, warmth, cold, or pain over most of the body surface (Boring, 1942 in Boff et al., 1986). Pain was identified as a separate identity with the finding of a separate receptor group for the stimulus, the nociceptors. This group of nerve endings carries the message 'pain' to the brain. In studies it was shown that the nociceptors show responses to firm pressure, to heat at painful levels and to pricking (Torebjörk, 1979)

In addition to the variation in the physiological response of the nociceptors, many studies are conducted into the psychophysical response of humans to painful stimuli. Depending on the kind of stimulus employed to produce pain, the categories of response may range from 'something felt' through 'something strong and unpleasant but not painful' to something strong and clearly painful' (Boff et al., 1986). To determine the pain threshold, it was concluded that although one may know the stimulus level, the threshold for pain is a highly labile quantity. It therefore can be concluded that the psychophysical response to a range of stimuli of the nociceptors may lead to a range of responses varying from day-to-day and person-to-person.

4.4.1 Behavior

Although the psychophysical responses to the stimuli from the nociceptors lie in a large range, they are partly responsible for (sitting) behavior (Branton 1969). In naturalistic studies of sitting (Branton and Grayson 1967) it was observed that spontaneous behavior regularly produces a variety of postures with highly significant differences in frequency and duration. Branton (1969) concludes that the variety of postures that represented an 'urge to move' is caused by ischemia of the tissue. The author concludes that the high pressure on the skin and tissue under the ischial tuberosities creates bodily states which make change of position desirable, and thus is a necessary condition for the 'urge to move' to become manifest. This finding is also confirmed in a study of Bar (1991) in which he studied the pressure-time relationship on the ischial tuberosities using dynamic pressure measurements. Bar (1991) concluded after 2 hours of dynamic pressure measurement on the ischial tuberosities of each subject that postural changes or repositioning were characterized by significant changes in pressure lasting longer than a few minutes (macro-movements), and that variations in trunk position and limb movements lead to changes in pressure of a few seconds duration (micro-movements). He observed that a change of posture could occur, represented by a large shift in pressure distribution, followed by the presence of small pressure oscillations indicating further small trunk or limb movements.

Bhatnager et al. (1985) observed the postural changes of four seated individuals. They found that the frequency of postural changes or fidgeting increased by more than 50% over the three hours of observation. The total frequency of posture changing was an indicator of postural stress and discomfort. In a study of fourteen subjects, Pustinger et al. (1985) found fewer episodes of motion and fewer health complaints at an adjustable workplace compared to a fixed workplace. Increase in movement was also found to have an adverse effect on productivity. Mark et al. (1985) also found considerably less movement at properly adjusted computer workstations.

4.4.2 Movement and the Skin

Bader (1990) studied the recovery characteristics of soft tissue subjected to externally applied cyclic loads using transcutaneous gas tension measurements. The author found that the response of all subjects to cyclic loading at the sacrum and ischial tuberosities could be characterized under one of two distinctive forms, both having physiological implications. The first type of response, in terms of loading and recovery, was a normal physiological reaction, as typified by reactive hyperemia. The author states that this normal response may be a direct result of the mechanical stresses that can induce the release of biochemicals, which are vasodilators. The alternative response suggests an impaired control mechanism. The time permitted for tissue recovery was inadequate and would inevitably lead to diminished oxygen levels on repeated loading and, eventually, tissue ischemia.

Because most patients with spinal injury do not shift their weight (change posture) because a lack of sensation in the legs and buttocks, Cumming et al. (1986) designed a microprocessor-based device in order to reduce the risk of tissue breakdown for paraplegic patients. The device measures the time interval between weight shifts of the patient with sensors in the seat, and uses audible alarms to tell the patient when to perform a pressure relieving liftoff.

Bar (1991) found that relatively small changes in position (micro-movements) could produce large changes in pressure on the ischial tuberosities when sitting on foam cushions. He also found that on gel cushions the micro-motions could be absorbed to some extent by the ‘flow’ of the gel leading to lower changes in pressure. He also hypothesized that if the gel was allowed to move freely it would distribute pressure evenly throughout the supporting medium, and absorb micro-motions better. This last effect was demonstrated on the bursa-like interface LiquiCell® by Goossens (2001).

4.5 Conclusions

The body reacts to mechanical load in different ways. As a result of prolonged pressure and shear, localized damage to the skin and underlying tissue can be found. The resultant wounds are known as pressure ulcers.

In some cases the more superficial epidermal layer is damaged and cells in the epidermis become separated, damaged or die (necroses) because of an external pressure or shear. When the damaged area fills with fluid, these wounds are called blisters. This blister resulting from the cell damage ends up with some protective benefits.

The natural response of the body to areas where the mechanical load on bone and muscle tissue becomes too high is the formation of a sac with a smooth membrane called a bursa. An early warning to high mechanical load on the body is the feeling of discomfort.

When the nociceptors are stimulated, pain will be felt, but the psychophysical response varies from day-to-day and person-to-person. However, all subjects will show an ‘urge to move’ when ischemia of tissue occurs.

Redistribution of pressure and neutralization of shear leads to less discomfort and can only be obtained though the cushion material of the body support surfaces.

5 Body Support Surfaces

In order to optimize the mechanical load that acts on the skin during body support, different cushions have been developed. Especially for the prevention of pressure ulcers, many foam cushions, cushions incorporating gel or water, and even air fluidized cushioning can be found. All cushioning materials, except foam, need a cover to keep the medium (gas, liquid, gel) together. To obtain an understanding of the principle by which the different cushioning materials work, this paragraph discusses them from a biomechanic perspective.

When considering the biomechanical behavior of different body support surfaces, including consideration of the cushion and the cover (top layer), the following models can be seen (Holscher, Goossens et al., 1994). Figure 13.

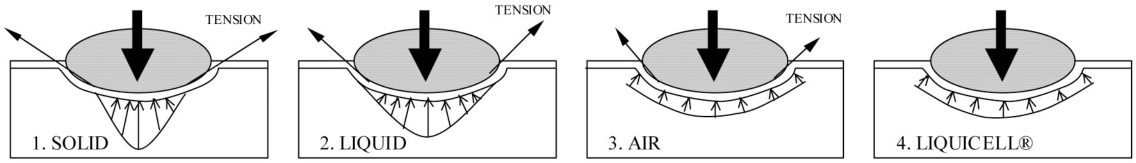


Figure 13 Biomechanical behavior of three different cushions, with a solid, liquid and air medium between body and cushion. LiquiCell® – a bursa-like interface - is a special combination of cushion and cover.

The medium of the cushions may be divided into three groups, whereby the bursa-like interface, LiquiCell® is discussed as a special case in group 2.

5.1 Solid

This group contains solid cushions (foam, high-density gel) in gradations from normal polyurethane foams and latex, to special foams such as the so-called 'memory foam' and gel with high density. In order to establish a large contact area between body and cushion, the material must be soft. The force equilibrium between body and cushion is achieved by three factors:
a) The increase of the force with the increase of the imprint of the body (depth of the body) into the cushion [cushion behaves like a spring];
b) The enlargement of the contact area;
c) The tension in the cover.

Because of factor a) and c) there is no uniform pressure distribution over the cross-section but rather an un-equalized pressure build-up with the maximum in the middle.
And because of factor c), the tension in the cover, there is a shear force between body and cushion. In this situation the cover of the cushion will be under tension and helps carry the load. This is the so-called 'hammock effect' (Nicol and Min 1997), resulting in an extra pressure and shear force at the contact surface.

5.2 Liquid

This group contains fluid media such as water or gel that have to be separated from the body by some kind of cover. The purpose of the cushions is to keep the body 'floating' and therefore the density of the media must be greater than the density of the body (approximately 1000 kg/m3). In order to separate the body from the medium, an enveloping cover is used. The equilibrium between body and cushion is achieved by three factors:
a) The increase of the force with the increase of the imprint of the body (depth of the body) into the cushion;
b) The enlargement of the contact area;
c) The tension in the cover.
There is no uniform pressure distribution because of factors a) and c). Compared to situation 1 (solid), the influence of factor a) on pressure build-up is less, because the pressure build-up of liquids is smaller than of solid media. In this situation the cover that keeps the fluid together will be under tension, this is the so called 'hammock effect' (Nicol and Min 1997), resulting in extra pressure and shear force at the contact surface.

5.3 Air

This group contains all gaseous media (mostly air) that are put in a closed cushion system. Also this medium has to be separated from the body by some kind of cover. The equilibrium between the body and the cushion is now achieved by two factors:
a) The enlargement of the contact area;
b) The tension in the cover.

There would be a uniform pressure over the cross section of the medium, because there is no increase in force in gas with the increase of the imprint of the body. But because of the tension in the cover (factor b) there is no uniform pressure distribution on the body. Also in this situation, a shear force in introduced because of the tension in the cover.

5.4 Bursa-like Interface

Earlier a bursa was defined as having the following attributes:

- Dissipates force and pressure by distributing it through a fluid medium.
- Provides lubrication at points of friction.

From an engineer's point of view, an extra advantage of this is that a bursa separates moving tissue, thereby eliminating tissue bonding (μ_a the adhesion component)

A bursa-like interface utilizes a man-made structure also known as a bursa-like pouch, which emulates the bursae of the body. A bursa-like pouch has the following attributes:

- Contains a baffled pouch such that the volume of the medium is so small that there is no pressure build-up to surrounding areas of contact because of the increase of the imprint of the pouch when contact is made.
- Provides a thin layer of fluid on the entire contact surface,
- Provides a liquid interface layer to prevent bonding. This interface layer has a friction coefficient of 0 (comparable with that of a layer of ice).

5.4.1 LiquiCell®

LiquiCell® can be seen as a special case of a cushion with a liquid medium (situation 2, Figure 13). But in the LiquiCell® cushion, the volume of the medium is so small, that there is no pressure build-up because of the increase of the imprint of the body in the cushion. Instead of pressure build-up, the liquid in the LiquiCell® provides a thin layer of fluid on the entire contact surface that has a friction coefficient of 0 (comparable with that of a layer of ice). In Figure 14 it can be seen that for a bursa-like interface $\mu 4$ and $\mu 5$ are 0, and thus allow the cover to move freely with the body without introducing shear force at the contact area.
In a LiquiCell® cushion it is therefore expected that the shear force on the body contact surface is very low (zero in theory), and that the small layer of liquid equalizes the pressure at the contact surface. Both these theoretical findings are confirmed in scientific studies (Yu 1995,Goossens 2001).

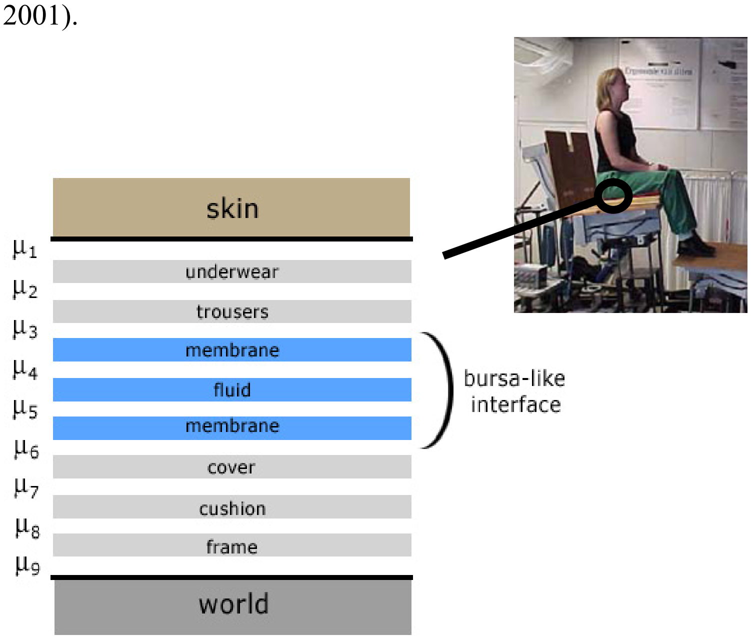


Figure 14. Bursa-like interface between trousers and cover

5.5 Conclusion

The theory shows that the support principle of LiquiCell®, because of the low viscosity fluid, will in theory lead to equalized pressure and shear at the contact surface. In this sense LiquiCell® resembles the natural response of the body to areas where the mechanical load on bone and muscle tissue becomes too high, namely the formation of a sac with a smooth membrane filled with fluid (bursa).

6 Studies on a Bursa-like Interface (LiquiCell®)

In the previous paragraphs it was demonstrated that a bursa-like interface has, in theory, a positive effect on the pressure and shear on the body support interface. Pressure is equalized and shear is low. It was also shown that pressure and shear have an effect on discomfort, and that this effect is noticeable after some period of time (30 minutes). In this paragraph, the findings of scientific studies that were performed on the LiquiCell® padding are presented.

6.1 Bursa-like Technology - LiquiCell®

In the section entitled "Body Support Surfaces", it is shown that, in theory, a body support that is based on the principle of the bursa-like interface would lead to low shear and equal pressure on the contact surface. Bursa-like technology implements the bursa-like interface into body support surfaces in two ways:

Directly to the object (i.e. an Ultra-thin bursa-like comfort-enhancing pouch placed within a bicycle seat, a chair, a seat cushion, a helmet, kneepads, shoulder straps, etc.).

Directly to clothing worn (i.e. an Ultra-thin bursa-like comfort-enhancing technology pouch that is placed within bike shorts, gloves, shoes, etc.).

It is the combination of two aspects of the LiquiCell® pad that contributes to the shear forces being reduced. First, the fluid used is a low viscosity liquid. This is very important, because when using a high viscosity liquid, the friction coefficient of the layer does not allow the cover of the cushion to move freely with the body, and thus introduces shear forces (Figure 15).

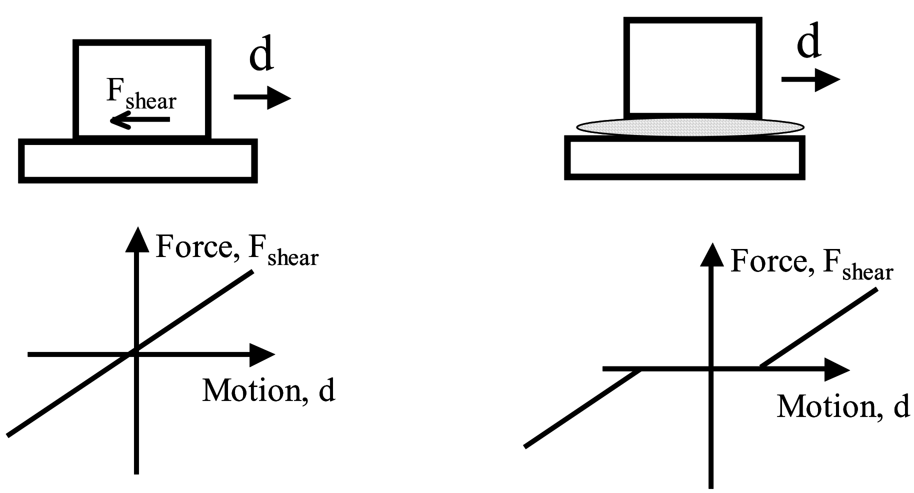


Figure 15 Difference between high viscosity liquid (left) and low viscosity liquid (right). The high viscosity liquid always results in a shear force when the upper part of the cushion is moved to the right. The low viscosity liquid has no resistance against movement of the top layer and allows movement without shear forces. Shear forces are only then introduced if the movement is greater than the bag flexibility. In the case of LiquiCell®, that only occurs with relatively large movements of several centimeters.

Secondly, the layer is very thin. This is important because a thick layer of fluid several centimeters thick would introduce extra pressure at the cross section of the support surface because of the indentation of the cushion (Figure 13, situation 2). For example, 1 cm of indentation in a cushion filled with water, increases the pressure by 0.1 kPa, simply because of the weight of a layer of 1 cm of water.
Because, with a thin layer, the imprint is equal at the bony prominences (tuberosities in the case of sitting), the pressure will be more uniformly distributed and thus lower compared with a thick layer of fluid.

6.1.1 Shear

Shear force is an important component of the mechanical load on a person that is supported by a surface. Excessive shear force leads to occlusion of blood flow, which is seen as one of the most important factors behind pressure ulcers and discomfort.
In a study performed by Goossens (2001), the influence of three different cushioning materials (LiquiCell® of LiquiCell Technologies, Inc., gel and foam) on shear stress is evaluated with a shear sensor from the Erasmus University of Rotterdam with seat angles -5°, 0°, 5 ° (Figure 16.)

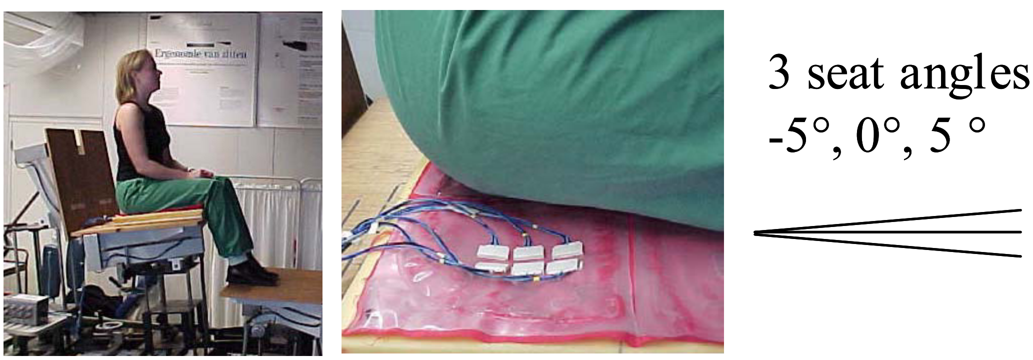


Figure 16 Shear stress measured at Erasmus University of Rotterdam. The seat angles that were used in the test were: 5 degrees forward tilted seat, a horizontal seat and a 5 degrees backward titled seat.

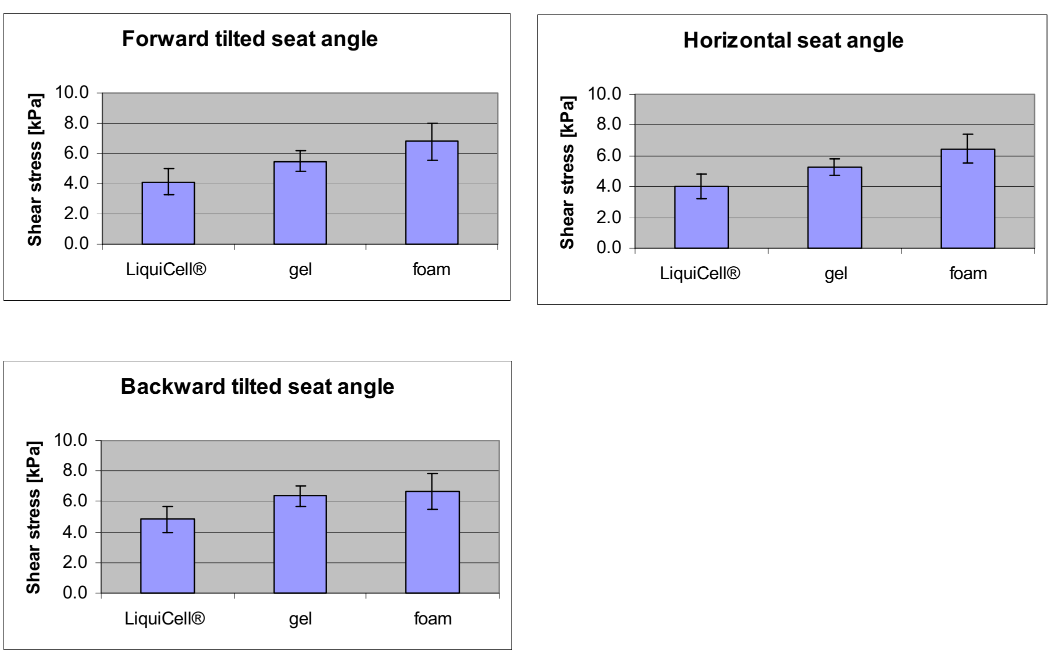


Figure 17 Results of the test on shear stress on the buttocks of subject when sitting on different cushioning materials at different angles.

In Figure 17 the results of this test are shown as mean values, and error bars of 2 times the standard error of mean of the shear stress [in kPa] on the different cushions are shown for the three different angles of the seat.

It is concluded that the LiquiCell® cushion produces significantly lower shear stress than the foam cushion in situations when a shear force acts forward (P=0.001), backward (P=0.038) and in the horizontal position of the seat (P=0.005). When using LiquiCell® instead of foam, there is a reduction of shear stress varying from 28% to 39%.
It is concluded that the LiquiCell® cushion produces significantly lower shear stress than the gel cushion in situations when a shear force acts backward (P=0.038) and at the P=0.10-level in the horizontal position of the seat (P=0.07) and when the shear force acts forward (P=0.07). When using LiquiCell® instead of gel, there is a reduction of shear stress varying from 24% to 25%.
No significant differences were found between the gel cushion and the foam cushion.

6.1.2 Pressure

In a study conducted into pressure on the LiquiCell® padding (Yu et. al. 1995), the influence of different cushioning systems on the pressure distribution patterns was evaluated.
Twenty-four subjects participated in an experimental setup in which a bicycle was mounted on a stationary exercise frame, which allowed the rider to peddle the bike in a manner similar to being on the road. Three cushioned seats (LiquiCell®, gel and foam) and a non-cushioned seat were tested. The pressure was measured with a TekScan system.
A significant difference was found in the number of sensor cells with low-pressure readings. The test showed that the average number of sensor cells with low-pressure readings under the LiquiCell® and gel seat conditions were significantly greater (P<0.01) than those with the foam and non-cushioned seats. There was no significant difference between the LiquiCell® and gel cushion conditions and between the foam and none. These results suggest that the low-pressure area is significantly larger when the LiquiCell® or gel-cushioned seat is used.
It was also concluded that the size of the high-pressure area of the buttocks is reduced when each of the LiquiCell®, gel and foam cushioned seats are used, but reduced more with LiquiCell® and gel.

6.2 Conclusion

The above findings from these two studies, both on pressure and on shear, confirm the effects on pressure (equalized) and shear (low) of LiquiCell® that were expected in the light of theory.

7 Conclusions

The body reacts to mechanical load (pressure and shear) in different ways.
In the normal mechanical load situation, the mechanoreceptors in the skin are sensitive for deformations induced by mechanical load (shear and pressure). The mechanoreceptors measure deformation because an important task of the skin is to resist mechanical trauma. In cases when mechanical load is too high, different responses from the skin and underlying tissue can be seen. In some cases the more superficial epidermal layer is damaged -mostly by means of friction - and cells at the epidermis become separated, damaged or die (necroses) because of an external pressure or shear. When the damaged area fills with fluid, these wounds are called blisters. As a result of prolonged pressure and shear, localized damage to the skin and underlying tissue can be found and the resultant wounds are known as pressure ulcers.
The natural response of the body to areas where the mechanical load on bone and muscle tissue becomes too high is the formation of a sac with a smooth membrane called a bursa.

LiquiCell® is based on the working principle of a bursa and is a pouch that contains low viscosity liquid and one or more baffles that channel the liquid within the pouch as pressure is applied or shifted across the surface area of the pouch. In this sense, LiquiCell® resembles the natural response of the body to areas where the mechanical load on bone and muscle tissue becomes too high, namely the formation of a sac with a smooth membrane filled with fluid (bursa and blister).

Biomechanical modeling shows that the support principle of LiquiCell®, due to the low viscosity fluid, will in theory lead to equalized pressure and lower shear at the contact surface. Two scientific studies, one on pressure and one on shear, confirm the effects on pressure (equalized) and shear (low) of LiquiCell® that were expected in the light of theory.

Different studies on comfort and discomfort have shown that mechanical load (pressure as well as shear) influences discomfort. It was also concluded that equal pressure and low shear increase the amount of time that passes before discomfort is noticed. A test showed that, on a hard seat surface without sharp edges that produced high pressure, at least 30 minutes passes before the comfort limit is crossed, i.e. there is a feeling of discomfort. This would explain the fact that people do not value the effect of good cushioning (i.e. low shear and equal pressure) during a short test period.

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