Shear stress measured on three different cushioning materials

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Summary

Shear force is an important component of the mechanical load on a person that is supported by a surface. Too high shear force leads to occlusion of blood flow, which is seen as one of the most important factors behind pressure sores and discomfort.

In the present study the influence of three different cushioning materials (LiquiCell of LiquiCell Technologies, Inc., gel and foam) on shear stress is evaluated with the shear sensor from the Erasmus University of Rotterdam.

It is concluded that the LiquiCell cushion produces significant 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 significant 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.

Introduction

Shear force is defined as a force that acts *parallel* to a surface (whereas pressure acts perpendicular to a surface). When the shear force acts over a certain area it is called shear stress (in accordance with the definition of pressure as a force on a certain area). See Appendix A.

Different authors showed that shear stress has a significant influence on occlusion of the blood flow within the tissue. Goossens (Goossens, Zegers et al. 1994) showed that shear stress had a significant influence on the reduction of blood flow on the sacrum of healthy subjects. Bennet (Bennett, Kavner et al. 1979; Bennett, Kavner et al. 1981; Bennett, Kavner et al. 1984) showed that the combination of pressure and shear was particularly effective in promoting blood flow occlusion in the palm of the hand. Zhang (Zhang and Roberts 1993) came up with a biomechanical model to estimate the influence of pressure and shear components on blood flow occlusion. Occlusion of blood flow is seen as one of the most important factors behind pressure sores and discomfort.

Intermezzo pressure sores and discomfort

Pressure sores 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, that can be influenced directly, are concerned with pressure, shear, temperature and humidity. All authors agree that the most important cause of pressure sores is the mechanical load (pressure and shear) on the skin. Although most authors agree that pressure sores are due to prolonged tissue ischaemia caused by the mechanical load through which the capillaries are closed and diffusion of oxygen and metabolites to the cells is 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 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 controlled also by regulatory mechanisms, which partly can be nervous.

In a review of literature Lueder (Lueder 1983) gave a general overview of approaches to the assessment of comfort relevant to the design of office furniture. The author concluded that although substantial research exists, little insight is available into the meaning of comfort. More recently Zhang et al. (Zhang 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 too high a mechanical load) was one of the factors of the cause of discomfort. In some studies this relation between pressure and discomfort was demonstrated (Diebschlag and Hormann 1987; Grindley and Acres 1996; Ballard 1997; Buckle and Fernandes 1998). In a 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.

Tissue load in lying and sitting and thus occlusion of blood flow can be influenced in two ways. Firstly, by changing the mutual positions of the body supporting surfaces. Secondly by changing the material and profile of the seat or backrest. In literature mostly the influence of the material on pressure is evaluated. And although different kinds of cushioning are developed to reduce the shear stress as much as possible, no studies can be found on their effectiveness. The reason for this is that pressure measurement systems are commercially available, and a sensor that measures shear stress is not. However, in the Erasmus University of Rotterdam there is a sensor that can measure shear stress acting on subjects in a sitting and lying position (Goossens, Snijders et al. 1997). LiquiCell Technologies, Inc. produces LiquiCell a fluid-filled bladder (membrane) that is designed to dramatically reduce friction (shear forces), reduce pressure and absorb shock.

In the present study the influence of three different cushioning materials (LiquiCell of LiquiCell Technologies, Inc., gel and foam) on shear stress is evaluated by means of the shear sensor from the Erasmus University of Rotterdam.

Materials and Methods

The shear sensor that was used is 27x15x3.5 mm, in size and thus the contact area is 4.05 cm^2. Six of these sensors were fixed on the cushion with double-sided tape. They were positioned at the location where the right ischial tuberosity of the subjects rests on the cushion. The subjects sat for 2 minutes on the sensors before the measurements took place. After that period 100 measurements were done in 20 seconds.

In order to vary the shear force that acted on the seat, three different seat angles (5° forward, 5° backward and horizontal 0°) were randomly installed for each subject. The backrest was not used during these tests. In this way the shear force on the seat covered the wide range of shear forces that can be expected in all kind of body supporting products (saddles, office chairs, forward tilted seats, standing aids etc.).

Three different cushions were used, one with the LiquiCell, a gel cushion and a foam cushion. These cushions were positioned upon a layer of foam. The entire seat on its turn was installed on a special chair on which the adjustments of the angles could be made, and on which the total shear force on the seat could be measured. Figure 1 shows a picture of the measurement situation.

Figure 1. [Left] The measurement of shear stress on the right ischial tuberosity of a subject while sitting on the LiquiCell cushion in the backward tilted situation. [Right] Detail of the six shear sensors that are placed underneath the right ishial tubersoity (subject has lifted her buttocks for the picture).

Twenty healthy subjects were used in this test (mass 66 (s.d. 12) kg, length 175 (s.d. 10) cm). In order to exclude the influence of the different kinds of trousers, the subjects all wore a pair of trousers that is worn in the operation room. In total 9 combinations were measured for each subject (3 angles, 3 cushions), and between every combination the subject stood up to allow angle adjustments to be made. In every situation (for example angle 5° backward, cushion LiquiCell) the shear stress on the right buttock was measured 100 times on 6 sensors, and then averaged. The maximum value of the six sensors was then used for statistics. The unit for shear stress is kPa, kilo pascal. (With 13.3 kPa= 100 mmHg).

Statgraphics 8.0 was used for data analyses. The non-parametric Wilcoxon Signed Rank Test was used to test the following hypotheses with a level of significance = 0.05:

H0: There is no difference in maximum shear stress between the cushions
H1: At least one of the cushions differs from the others

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Results

In figure 1, 2 and 3 the mean values and error bars of 2 times the standard error of mean of the shear stress [in kPa] on the different cushions can be seen for the three different angles of the seat.

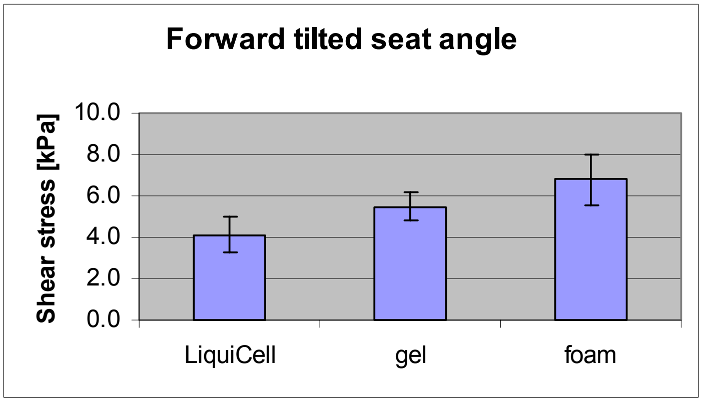

Figure 1. Maximum shear stress under the right tuberosity when sitting on a forward titled seat.

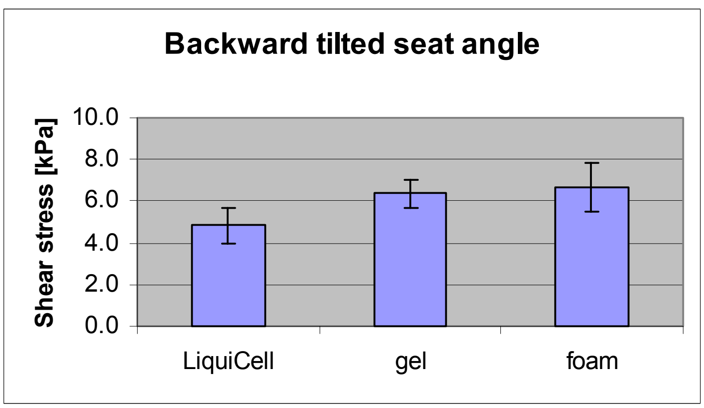

Figure 2. Maximum shear stress under the right tuberosity when sitting on a backward titled seat.

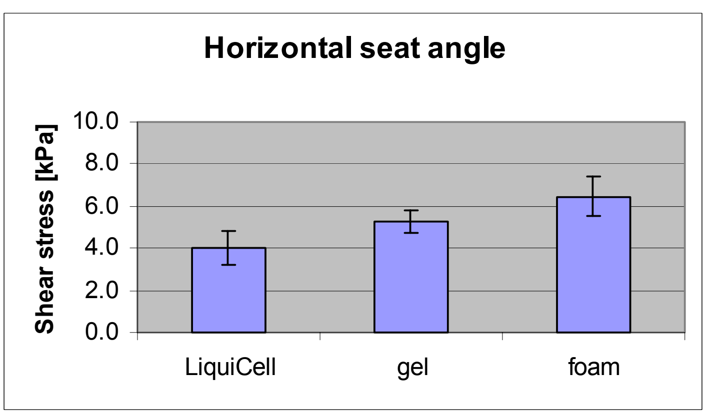

Figure 3. Maximum shear stress under the right tuberosity when sitting on a horizontal seat.

In table 1 the results are summarised.

	Forward tilted seat		Backward tilted seat		Horizontal seat	
	mean [kPa]	std. error [kPa]	mean [kPa]	std. error [kPa]	mean [kPa]	std. error [kPa]
LiquiCell	4.1	0.3	4.8	0.3	4.0	0.2
gel	5.5	0.6	6.4	0.6	5.3	0.4
foam	6.8	0.8	6.7	1.6	6.5	0.7

Table 1. Results of the measurements of shear stress on the right ischial tuberosity on four different cushions.

The reduction in shear stress can also be presented as a percentage of reduction of LiquiCell compared to gel and foam. This can be seen in table 2.

	forward		backward		zero	
	reduction in % over gel	reduction in % over foam	reduction in % over gel	reduction in % over foam	reduction in % over gel	reduction in % over foam
LiquiCell	25	39	24	28	24	38

Table 2. Results of the measurements of shear stress on the right ishial tuberosity when calculated as the percentage of shear stress reduction compared to gel and foam.

In all cases the H0 hypotheses had to be rejected and thus the conclusion is drawn that there are significant differences in maximum shear stress between the cushions. In table 3 an overview is given, when there is a significant difference between the cushions the P-value is printed **bold**. (A P-value of 0.05 means that the H0-hypotheses is rejected with 95% reliability, and P-value of 0.001 shows a reliability of 99.9 % of drawing the right conclusion).

In the forward tilted situation, P-value of difference between cushions:

	LiquiCell	gel	foam
LiquiCell	X	0.07	**0.001**
gel		X	0.107
foam			X

In the backward tilted situation, P-value of difference between cushions:

	LiquiCell	gel	foam
LiquiCell	X	**0.05**	**0.038**
gel		X	0.420
foam			X

In the horizontal seat surface situation, P-value of difference between cushions:

	LiquiCell	gel	foam
LiquiCell	X	0.07	**0.005**
gel		X	0.185
foam			X

It can be seen that the LiquiCell cushion produces in every situation significant lower shear stress on the right ischial tuberosity than foam. When using LiquiCell instead of foam there is a reduction of shear stress varying from 28% to 39%. The difference between LiquiCell and a gel cushion is significant for the backward tilted situation (P=0.05) 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%. There is no significant difference in maximum shear stress under the right ischial tuberosity between a gel cushion and a foam cushion.

Conclusion

Maximum shear stress under the right ischial tuberosity was compared on a healthy population while sitting on three different cushions: LiquiCell of LiquiCell Technologies, Inc., a gel cushion and a foam cushion. It is concluded that the LiquiCell cushion produces significant lower shear stress than the foam cushion. No significant differences were found between the gel cushion and the foam cushion. The difference between LiquiCell and a gel cushion is significant for the backward tilted situation (P=0.05) 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). The LiquiCell cushion produces the lowest shear stress in all cases.

References

Ballard, K. (1997). "Pressure-relief mattresses and patient comfort." Prof Nurse **13**(1): 27-32.

Bennett, L., D. Kavner, et al. (1979). "Shear vs pressure as causative factors in skin blood flow occlusion." Arch Phys Med Rehabil **60**(7): 309-14.

Bennett, L., D. Kavner, et al. (1981). "Skin blood flow in seated geriatric patients." Arch Phys Med Rehabil **62**(8): 392-8.

Bennett, L., D. Kavner, et al. (1984). "Skin stress and blood flow in sitting paraplegic patients." Arch Phys Med Rehabil **65**(4): 186-90.

Buckle, P. and A. Fernandes (1998). "Mattress evaluation--assessment of contact pressure, comfort and discomfort." Appl Ergon **29**(1): 35-9.

Diebschlag, W. and M. Hormann (1987). "[Improving seating comfort in wheelchairs for the prevention of pressure sores]." Rehabilitation (Stuttg) **26**(4): 153-83.

Goossens, R. H., C. J. Snijders, et al. (1997). "Shear stress measured on beds and wheelchairs." Scand J Rehabil Med **29**(3): 131-6.

Goossens, R. H., R. Zegers, et al. (1994). "Influence of shear on skin oxygen tension." Clin Physiol **14**(1): 111-8.

Goossens, R. H. M. P. M., Teeuw R, Snijders CJ. (2000). Decubitus risk: is shear more important than pressure? IEA 2000/ HFES 2000 Congress, San Diego.

Grindley, A. and J. Acres (1996). "Alternating pressure mattresses: comfort and quality of sleep." Br J Nurs **5**(21): 1303-10.

Lueder, R. K., , . (1983). "Seat comfort: A review of the construct in the office environment." Human Factors **25**: 701-11.

Zhang, I., Helander, M.G., Drury, C.G., (1996). "Identifying factors of comfort and discomfort in sitting." Human Factors **38**: 377-89.

Zhang, M. and V. C. Roberts (1993). "The effect of shear forces externally applied to skin surface on underlying tissues." J Biomed Eng **15**(6): 451-6.

Appendix A

A short memo about friction and shear

May 1999

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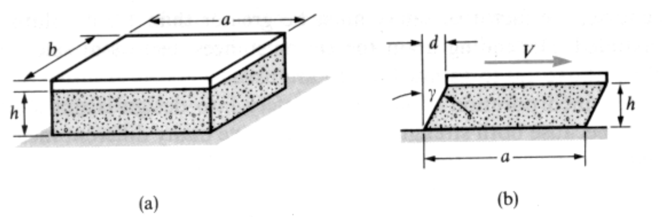
This memo was written in order to give clearness in the definitions of friction and shear, especially in combination with load on the human body and thus pressure sores.

Definitions

Shear

(Gere and Timoshenko, 1990)
According to the world 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, so also an (imaginable) 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.



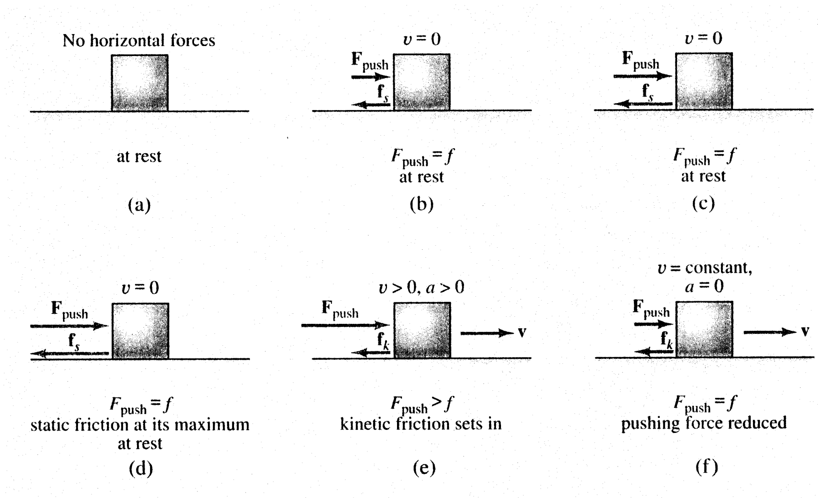
$$\tau = \frac{V}{a \cdot b}$$

Friction

(Fishbane et al., 1996)
Friction is a contact force that impedes sliding, and works parallel to the contact area. Let us 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. Why not? **Static friction** acts 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. 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. The proportionality constant that relates the friction force and the normal force is the **coefficient of**



friction, μ. The (unitless) 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 $\mathbf{f}_s$ and that of kinetic friction as $\mathbf{f}_k$, their magnitudes are given by

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

However, it has been found that for **soft surfaces** like the skin the maximum static friction can be described as a non-linear function of the normal force ($f_s = \mu\,(F_N)^q$) . Mossel (1998) used that as a basis found 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
A_t is the contact area
q is a dimensionless exponent smaller than 1
F_N is normal force.

Conclusion

Out of the above, the following can be said. Shear and friction are in one case overlapping definitions. Shear is 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 as well static as dynamic situations and always acts on the contact surface (outside the tissue).

The overlap in definitions is in the static situation, when acting on the contact surface (outside the tissue); in that case friction and shear are the same force.

References

Gere J.M., Timoshenko S.P. Mechanics of materials. Second SI Edition, PWS Engineering, Boston, Massachusetts, 1990.

Fishbane P.M., Gasiorowicz S, Thornton S.T. Physics for scientists and engineers. Second edition Extended, Pretince Hall International, Inc., 1996.

Mossel W.P. Modelling skin friction. In: Global Ergonomics. Eds. Scott P.A., Bridger R.S., Charteris J. Elsevier 1998, 429-435.