Part B: In-depth study

D1.0 Biomechanics of the sitting posture

This chapter has been largely derived from chapter 1.0 of Sitting Posture, comfort and pressure, assessing the quality of wheelchair cushions.

Sitting posture can best be defined from a bio-mechanical and physiological standpoint, since these disciplines utilise a nomenclature for interpreting specific postures in relation to activities and for analysing disorders relevant to posture. Since the human frame is, simply stated, a complex interplay of bones and muscles we first need a degree of schematisation in order to arrive at a clear definition of sitting posture.
The model of the body which we have adopted for this purpose consists of a chain of motile bodily segments, interlinked, but each possessing a rigid structure. Each segment has its own dimensions and mass.

We can see in figure D1-1 how the model is derived from an x-ray picture (Diffrient e.a.1974): the model consists of a side view only (the sagittal plane):
- the ankle knee and hip joints are represented as simple hinges;
- the pelvis and upper trunk are regarded as separate elements.
- the upper trunk shows a pivot point in the axillary region. This enables us to simulate a kyphosis, an enlarged backward curvature of the thoracic section of the spine; this schematisation is also used in the so-called Kieler Puppe.
- the lumbar and thoracic parts of the spine are connected by a single pivot point; this drastic simplification of reality facilitates a better bio-mechanical analysis;
- the head is linked to the cervical part of the spine by a single pivot point;
- the mass of the bodily segments is deemed to be concentrated in separate centres of mass.

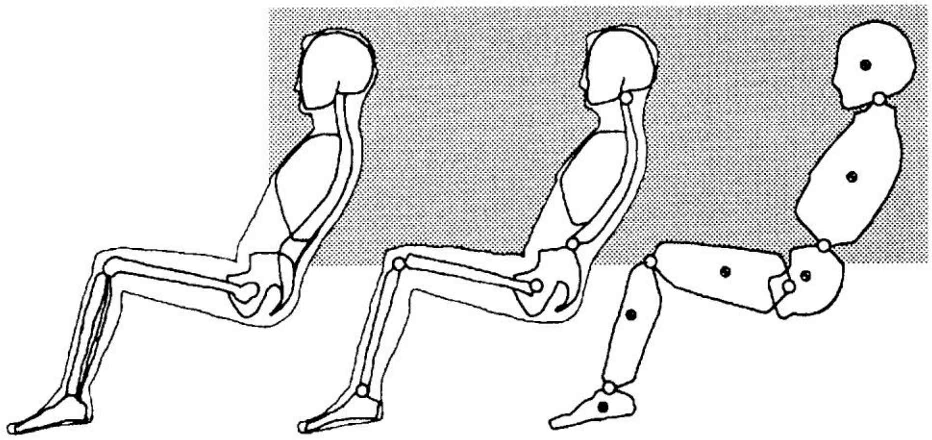


Figure D1-1: Derivation of the bio-mechanical model developed.

In the model it can be seen that there are no muscles included around the joints. This does not mean the assumption has been made that no muscle power is present. The moments, which operate on the pivot points in order to achieve a balance, represent the loads acting on muscles, tendons and ligaments around the joint. The reaction forces in the pivot points form the loads on joints.

If, in a certain posture, balance is achieved without the need for moments to operate on the pivot points, this means that the posture, in theory, can be maintained without any muscular exertion. The model can simply be described as a collection of volumes, each with its own mass and centre of mass, linked together by joints. Figure 1-2 indicates the principal dimensions and masses of the segment components of the bio-mechanical model which has been developed. The data have been borrowed from Damon, Stoudt and McFarland (1971) and a later refinement by van Buchem (1973). The purpose of the model is to enable an analysis of the principles in the bio-mechanical aspects of sitting posture. Seen in this light, an exact determination of the location of the centre of mass of a given segment is less significant than the notion that there is a centre of mass and that, according to the model, an acceleration of gravitational forces begins to take effect at that point. This is also true for the schematised position of the different pivot points.

The model can be used to adequately define a sitting posture, to gain an understanding of the size and direction of the internal and external loads, to optimise sitting posture and to examine the degree of influence that reduction or loss of muscle function has in the ability to maintain a posture.

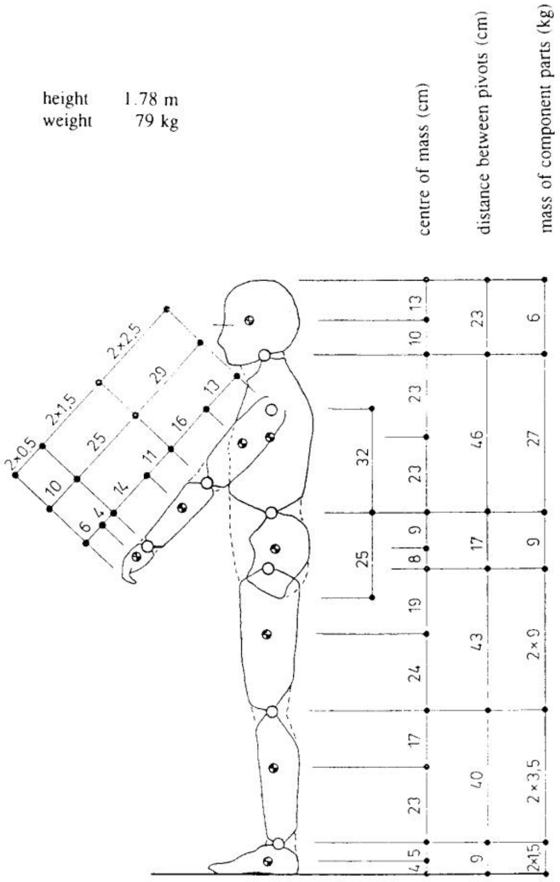


Figure D1-1 : Principle dimensions and masses of segment components of the bio-mechanical model of the human body in cm. and kg.

D1.2 Definition of sitting posture

A sitting posture is defined by the mutual position of the bio-mechanically and physiologically important parts of the body in relation to each other and the general position in space.

In order to establish a link with the sitting posture which is 'afforded' by the chair and to carry out the work pragmatically, the planes of contact along the bodily segments are adopted as reference planes and to this purpose the angles of the different bodily segments are defined in relation to each other. The position of the thighs is defined in relation to the horizontal plane thereby enabling the position in space of the different bodily segments to be calculated.

The classification and definitions used in this study are a refinement of those used by the GMD for wheelchair evaluation since 1978 (Staarink 1978). The basic sitting posture can therefore be defined by the angles φ, α, β, γ and δ .
Unfortunately, there is no general agreement to be found in literature on these definitions.
In figure D1-3 the angles defined are illustrated.

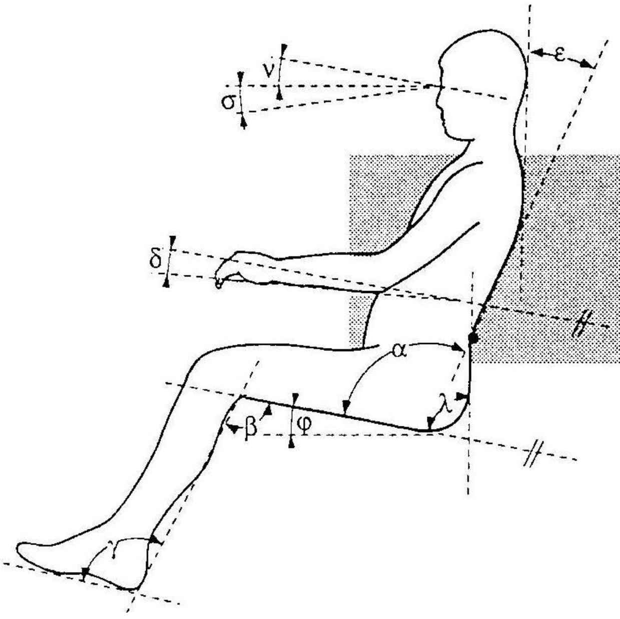


Figure D1-3 : Classification of the nine angles which determine the sitting posture in the sagittal plane.

• Angle φ , the seat angle, represents the position of the plane of contact on the underside of the thighs in relation to the horizontal. An angle above the horizontal plane is given a positive value. Since all the other angles are defined in relation to each other, angle φ determines the actual position of the body in space.

- Angle α , the sitting angle or hip angle, represents the position of the plane of contact on the back of the upper torso segment in relation to the plane of contact on the underside of the thighs. This definition implies that the position of the upper torso segment in space is determined by the angle$(\varphi+\alpha)$, also known as the functional backrest angle.
The size of the angle$(\varphi+\alpha)$ indicates respectively the degree of torso balance and the amount of energy necessary to maintain this posture.

- Angle λ represents the position of the pelvis in relation to the thighs. Angle ë is defined by the angle between the plane of contact on the back of the pelvis and the plane of contact on the underside of the thighs.

- Angle$(\alpha-\lambda)$ describes the shape of the lumbar region whilst the sitting posture is maintained. If the angle is positive the spine displays a lordosis. The size of the angle indicates the degree of the lumbar lordosis. If the angle has a negative value the spine shows a kyphosis, the size of the angle indicating the degree of the kyphosis.

The shape of the lumbar region can be defined for each individual by lumbar depth present whilst in a standing position. This is the greatest depth which can be measured from the plane of contact along the thoracal and sacral part of the back in the direction of the lumbar part of the spine.

- Angle ε represents the position of the head in relation to the torso and is defined by the angle which the plane of contact on the back of the head and the most extreme point of the thoracal back makes with plane of contact along the thoracal part of the back. Angle ε represents total flexion of the head, neck and upper part of the torso segment.

- The angle$\{(\varphi+\alpha) - \varepsilon\}$ represents the position of the head and upper torso in relation to the horizontal plane. This is the angle which the plane of contact on the back of the head and the most extreme point of the thoracal back makes with the horizontal plane. This angle indicates the load on the upper back muscles in maintaining the sitting posture.

- Angle v represents the position of the head in space more clearly than the angle$\{(\varphi+\alpha)- \varepsilon\}$. The reference plane which defines the position of the head is known as the Frankfurter plane and is the plane which runs through the lower edge of the eyes (the orbital points) to the upper side of the entrance to the ear (the tragus). Angle v is defined as the angle that the Frankfurter plane makes with the horizontal plane. Any angle above the horizontal has a positive value. Angle v is about 10° for someone in a standing position whose gaze is directed towards the horizon (Burandt 1978). De Wall et al. (1991), in their study, define the 'o' position of the head as when a person's gaze is directed to 15° below the horizontal plane.

- Angle σ is the angle which the line of sight follows in relation to the horizontal plane. Any angle below the horizontal plane has a negative value. The size of angle σ is determined by angle ε and the flexion of the head and is partly influenced by the upwards or downwards rolling of the eyeballs. The so-called 'easy eye movement' covers a range of approx. 15°. We can surmise from Burandt's figures (1978) that a relaxed gaze makes an angle of 15° to 20° in relation to the Frankfurter plane.

• Angle δ represents the position of the forearms. This is defined as being the angle between the plane of contact on the underside of the forearms and the plane of contact running along the underside of the thighs. Figure D1-3 illustrates an angle ä which has a positive value. When angle δ is the same as angle φ, then by definition the forearms assume a horizontal position.

• Angle β represents the angle between the line running from the back of the knee to the rear of the heel and the plane of contact on the underside of the thighs.

• Angle γ defines the position in the sagittal plane of the ankle joint as the angle between the underside of the foot and the line running from the back of the knee to the rear of the heel.

These definitions of the nine angles in the sagittal plane enable us to define with sufficient accuracy and to quantify the (sitting) posture of the body for the purpose of this study. Asymmetric sitting in relation to the mid sagittal plane, for example when one leans sideways, requires a separate definition.

In theory the 'sitting posture' afforded by a chair can be defined and ascertained using the angles φ, and angle α and λ. To this end the chair needs to be measured in its occupied condition. For a wheelchair the angles β and γ can be included.
Whenever the body is able or given the opportunity to follow these 'angles' precisely, the body will quite literally assume this posture. If this is not possible or this does not occur then in theory another posture results.

D1.3 Internal load

Perception of comfort is achieved by the lack of internal overloading. A number of aspects relating to this have already been dealt with in earlier sections.

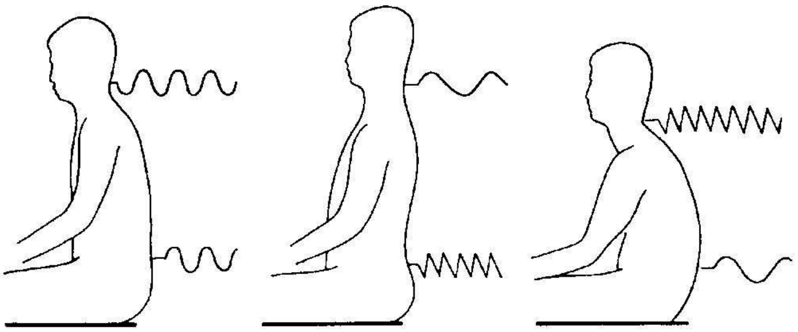
The load on the cervical spinal column depends on the way and degree to which the back is supported.
The mass of upper part of the body is transferred to the seating plane by way of the spinal column and the pelvis. The most heavily loaded part of the spinal column is the lumbar region.
The magnitude of the load depends on:

- the weight of the upper part of the body and whether or not the arms are supported,
- the presence or absence of a backrest,
- the level of muscle exertion applied to maintain a specific posture,
- the sagittal shape of the lumbar spinal column attained during the sitting posture in comparison to its natural shape when held in a standing position;

this shape in the main is dependent on:

- the mobility of the lumbar spine,
- the position of the pelvis in relation to the trunk,
- the hip angle α,
- the profile and dimensions of the backrest.
- the position of the tubera on the seat with regard to the backrest

Static muscle activity occurs primarily when sitting without a backrest. The posture that an individual adopts determines the location and the intensity of the muscle exertion which is required. By relaxing the lower back muscles a kyphotic back will result and initially give a relaxed sensation. No further muscle activity in the lumbar part of the spine is necessary since the vertebrae in relation to each other have achieved their furthest limit on account of the restricted length of the ligaments. This means that the load on the vertebral discs is high as well as detrimental. The load on the ligaments is also high. In order to maintain the head in an upright position with one's gaze directed at the horizon, extra exertion is placed on the neck muscles. These are otherwise relatively relaxed when the lower back muscles are used to form a concave lumbar back. Muscle activity in various sitting postures is shown as an electromyogram (EMG) in figure D1-4; a higher frequency of recorded current indicates a higher muscle activity.



A: lumbar flat B: lumbar lordosis C: lumbar kyphosis

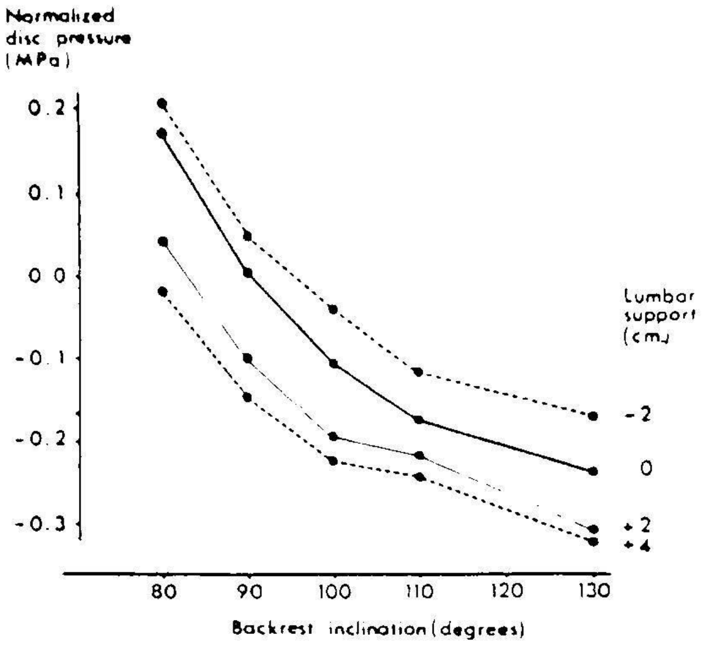
Figure D1-4 : Cervical and lumbar muscle activity for different active sitting postures without a backrest (Schobert 1978).

The load on the lumbar spinal column in relation to the form and size of backrest has been examined in detail by Andersson et al. (1975). They made a large number of in vivo pressure readings in the vertebral discs for different sitting postures. A general conclusion which can be drawn from their measurements is that the natural form of the lumbar spinal column results in the lowest pressure and that this further dependent on the posture.

The pressure in the intervertebra disc L3-L4 in an upright, active sitting posture is one and a half times greater than the pressure in a standing posture. If one arches one's back and hangs in the ligaments of the spine, as is to be seen in situation C of figure D1-4, this pressure can become as much as two and a half times as great. If one chooses to adopt this posture often the result will be a continuous stretching of the ligaments while interrupting the propriocepsis- and enterocepsis, the signals which run from the muscular skeletal system to the brain. This posture appears to be relaxing for the muscles but often leads to a reactive hypertone of the intervertebral muscles in the lumbar region, which in turn can lead to a fixed position of the joint . This posture is highly taxing for the ligaments and joints and therefore undesirable in long use.

The influence of the size of the backrest angle and of the size of the lumbar support on the pressure in the intervertebral disc L3-L4, is shown in figure D1-5.
The definitions used are different from the ones developed in this book. The backrest angle (backrest inclination) is the angle made between a *flat* backrest with the horizontal. The seat angle is 0° in this test.
The *lumbar support* expresses the amount of individual back support in cm. Add 2 cm (+2) in the figure explains that in the lumbar region a 2 cm. thickening is added to the flat backrest which allows a more 'natural' shape of the spine. In effect this is adding approximately 5° to the backrest angle.

The influence of angle α and of the size of the lumbar support on the pressure in the intervertebral disc L3-L4, where angle φ is 0°, is shown in figure D1-5.



The pressure at the point of reference is 0.51 MPa = 3834 mmHg.

Figure D1-5 : The pressure in intervertebral disc L3 - L4 as a function of angle α with as parameter the lumbar support depth where angle φ = 0 °
(Andersson et al. 1975).

The pressure in the point of reference (0,0 on the vertical line) is 0.51 MPa. This implies that -0.1 on the vertical scale is a loss of pressure of about 20%. A substantial loss.

The influence of angle α is considerable. This is to be expected since the normal load component of gravity of the upper part of the body on the intervertebral disc decreases with an increase in angle(φ+α).

With an angle of 100° of the (flat) backrest and a +2 cm. lumbar support, a reduction finds place of 40% in respect of a flat backrest at 90° without specific lumbar support.

An explanation for this can be found in the correction of the lumbar lordosis towards its own natural curve so that the load on the vertebrae will be more even.
Judging from human sitting behaviour, where people do not take the extra pressure on the back too seriously, one must conclude that this extra pressure is low on the hierarchy of momentary perception of comfort.

A sitting posture does not only lead to load being applied on the lumbar spinal column but also of course on all joints in the body. The size of the load is not only dependent on the weight of the part of the body to be supported but also on the muscle strength around the joint which is necessary to maintain that part of the body in position.

A special form of internal load is the load on the seating plane applied by the reaction forces of the seat. The size and direction of these reaction forces depend on the sitting posture. This problem will be dealt with in the next section. The degree of comfort and the way in which the load is transferred to the seating plane depends on the characteristics of the seating support. This is discussed in D3.0: Pressure distribution.

D1.4 External load

The external loads during sitting and their influence on the momentary perception of comfort can be easily demonstrated by looking at the results of a simple exercise in which a group of healthy adult students were asked to look for an appropriate sitting posture for various activities. The participants were asked to find a posture in an adjustable wheelchair in which they could work comfortably at a table, watch television or have a snooze.

The angles were measured in relation to the wheelchair's frame and not as loaded planes of contact in relation to the seated person, meaning that only a comparable interpretation can be ascribed to the values, which is no more than was intended here.

Figure D1-6 shows how the seat plane (angle φ) and the backrest (angle α) were adjusted. The sides of the rectangles indicate the range of standard deviations away from the centre.
The angles were measured in relation to the wheelchair's frame and not as loaded planes of contact in relation to the seated person, meaning that only a comparable interpretation can be ascribed to the values, which is no more than was intended here.

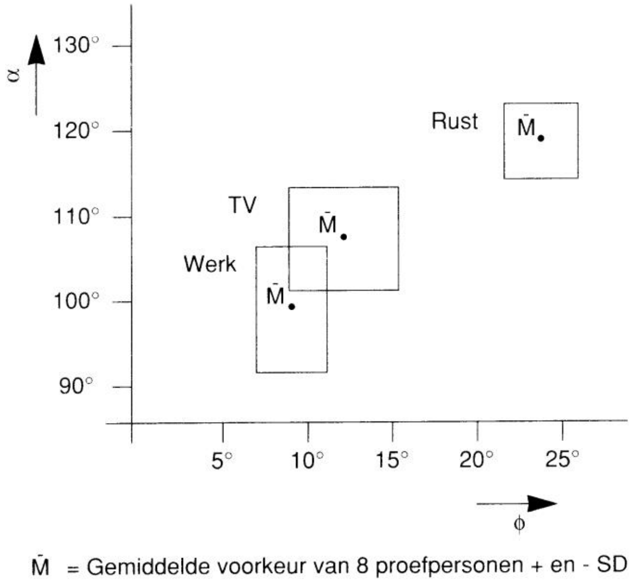


Figure D1-6 : Adjustment of angle φ and angle α in relation to a designated activity in a training exercise (n=8).

After the first exercise, the participants were asked to perform the exercise for the working posture and watching television with two layers of smooth fabric on the seat. The effect of using this double layer of smooth fabric is to manifest directly the friction forces between the seat and its occupier if necessary.
The results of this exercise can be seen in figure D1-7.

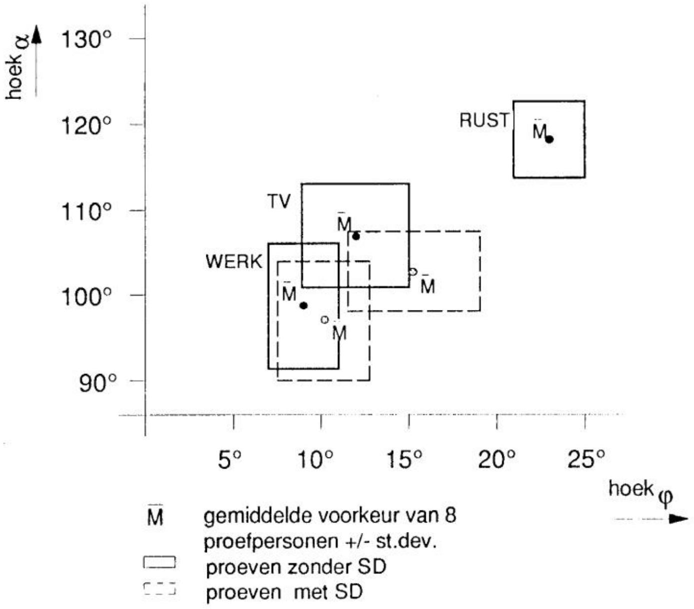


Figure D1-7 : The relationship between angle φ and angle α for different activities with and without the use of a thin, two-layered smooth fabric (SD).

The figure demonstrates that in using the smooth fabric a new correlation between angle α and angle φ results. For both the 'working' posture and the 'television' posture angle φ has increased at the expense of angle α. Figure D1-8 shows the average values of angles α and φ next to each other and also displays the size of the angle(φ+α).

		without smooth fabric	with smooth fabric
Working posture	angle φ	9.0°	10.5°
	angle α	99.0°	97.0°
	angle(φ+α)	108.0°	107.5°
TV watching posture	angle φ	12.0°	15.5°
	angle α	107.0°	102.5°
	angle(φ+α)	119.0°	118.0°

Figure D1-8 : The average values for angle φ and angle α for different activities with and without use of the thin, two-layered smooth fabric.

A number of notable conclusions can be drawn from these findings.

The use of smooth fabric was proved to influence the size of angle φ and angle α a great deal, yet it hardly influences the total result: angle(φ+α).

The position of the trunk in space: angle(φ+α) and the accompanying position of the head appear to be the determining factors in choosing this particular sitting posture. The mutual relationship between angle φ and angle α is determined in terms of the perception of comfort which results from the lack of frictional forces present in the sitting plane.
For the first part of the exercise, that is without the smooth fabric, there was possibly an element of slight friction which was evidently not perceived as being unpleasant for the short period of the test. This is an indication of the influence of time on the perception of comfort.
In order to study the influence of sitting posture on the action of frictional forces the results are presented in figure D1-9 of a preliminary study of the connection between the sitting posture, that is angle φ and angle α, and the degree of the shear and normal stress which results (Staarink 1978). The test was carried out on one female subject with the aid of a Kistler measuring device. The seat and backrest were hard, flat surfaces.

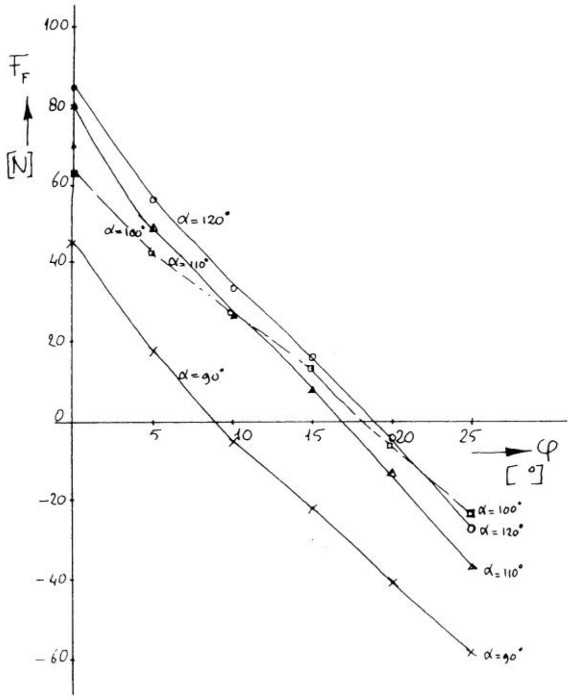


Figure D1-9 : The friction forces F as a function of angle φ and angle α for a female test subject of 60.5 kg and 1.72 m. (Staarink, 1978).

With the exception of the measurement taken for angle α = 100°, the reason for which is unclear, the results present a consistent picture.
There appears to be a specific relationship between angle φ and angle α at all times, for which the frictional force is 0. When angle φ increases, angle α increases. The relationship between these two angles corresponds to the relationship observed in the earlier results of the training exercise and with the results of investigations based on the subjective perception of comfort (e.g. Grandjean 1969). The assumption that this subjective perception of comfort is influenced by the presence or absence of frictional forces in the seating plane would seem to be justified. In view of the earlier acknowledgement of a hierarchy in the momentary perception of comfort, this sort of experiment should certainly not be done in a short period of time.

In addition to the friction force recorded in the above-mentioned exercise, normal force Rz was also measured. The influence of angle φ and angle α on the magnitude of this is illustrated in figure D1-10.
A noteworthy result of this exercise was that the positioning of the ischial tuberosities in relation to the intersection of the seat and the backrest (135 mm and 170 mm respectively) had no effect on the magnitude of the friction force but did exert an little (0 - 5 %) influence on the size of the normal force Rz on the seat. The results are shown in figure D1-10. An explanation for this is not easily found, the positioning of the arms might have an influence on this.

The positioning of the ischial tuberosities on the seat determines the shape of the lumbar spinal column resulting from the sitting posture and partly influences the perception of comfort.

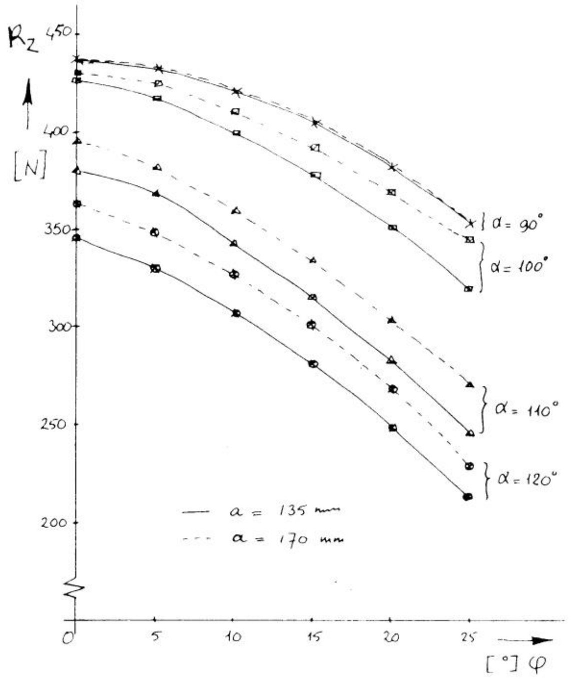


Figure D1-10 : The normal force Rz as a function of angle φ with angle α and distance a from the ischial tuberosities to the backrest as parameters for one female test subject of 60.5 kg and 1.72 m. (Staarink, 1978)

From figure D1-10 one may also conclude that a pelvis that is tilted backwards (a=170 mm) results in a greater seating load (approximately 5% greater) than a pelvis that is more upright (a=135 mm) .

To summarise it can be stated that the sitting posture is to a great extent responsible for the size and the direction of the external load on the body and that, in relation to time, this is one of the determining factors in the perception of comfort.

D1.5 The stability of the upper part of the body

The level of stability in the upper part of the body determines the amount of energy which is required to maintain its posture. The amount of energy, in terms of time, is a determining factor in the perception of comfort. Depending on a back's individual characteristics the way in which this stability is brought about can be cumbersome to a greater or lesser extent on the spine.
The lumbar spinal column (LSC) has two main features which are of significance both for the physiological and the bio-mechanical aspects of sitting posture. These features differ per individual and are:

- the level of mobility and
- the shape of the lumbar spinal column.

The different kinds of lumbar spine an individual may have are:

- an extreme lordosis
- a normal lordosis
- flat
- a kyphosis.

A flat back and a kyphotic back are usually immobile. A mobile back can assume different shapes when the individual is seated depending on the type of support used.

The way in which the stability of the upper part of the body is attained is determined by the location of the centre of mass of the whole upper part of the body: head, trunk and arms in relation to the assumed lumbar pivot point. The centre of mass of the entire upper part of the body with the arms in the lap is roughly in the axillary region.

For an active sitting posture the position of the pelvis or the form of the lumbar spinal column, both of which can influence each other, play a significant role, according to the model used, in the line of action of gravity in relation to the assumed lumbar 'pivot point'. Figure D1-11 illustrates this.

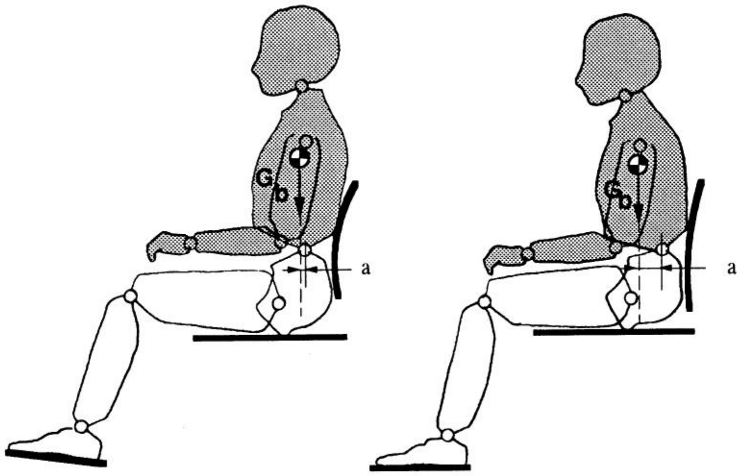


Figure D1-11 : The influence of the shape of the lumbar spinal column on the location of the centre of mass of the upper part of the body in relation to the assumed lumbar pivot point for an active sitting posture.

Drawing A in figure D1-11 shows the line of action of gravity running just in front of the lumbar 'pivot point'. This situation is reached when the mobile lumbar spinal column assumes a lordosis. In such a situation, with the presence of a pelvis support, negligible muscle exertion is required to attain active stability in the trunk. Non-active stability occurs by enlarging angle φ and angle α to such a degree that the said line of action runs along or behind the lumbar pivot. For a back with a normal lordosis this is when angle(φ+α) is approximately 115°.
Drawing B shows the lumbar spinal column in kyphosis. A kyphosis may be a natural individual feature of the back but can also be attained in some situations, for example when an individual takes up a forward sitting position and the pelvis is tilted backwards. The resulting line of action of gravity for this posture runs in front of the

lumbar spinal column. In this particular situation a moment Gb * a is exercised on the lumbar spinal column which must be countered by muscle power, unless the vertebrae have reached their furthest position in relation to each other. This is more or less true in this posture. Earlier the - negative - consequences on the pressure in the intervertebral discs and on the propriocepsis was discussed.

Whether or not an individual has consciously chosen to adopt an immobile kyphotic back described in the above scenario, a 'special' kind of stability is said to exist. Because the lumbar spinal column is immobile it cannot function as a pivot point for the stability of the upper part of the body. The pivot point is relocated to the ischial tuberosities. When the gravitational line of action runs behind the ischial tuberosities, as illustrated in figure D1-12, a non-active stability does indeed occur but this goes hand in hand nonetheless with a substantial moment of force Gb * a on the lumbar spinal column.

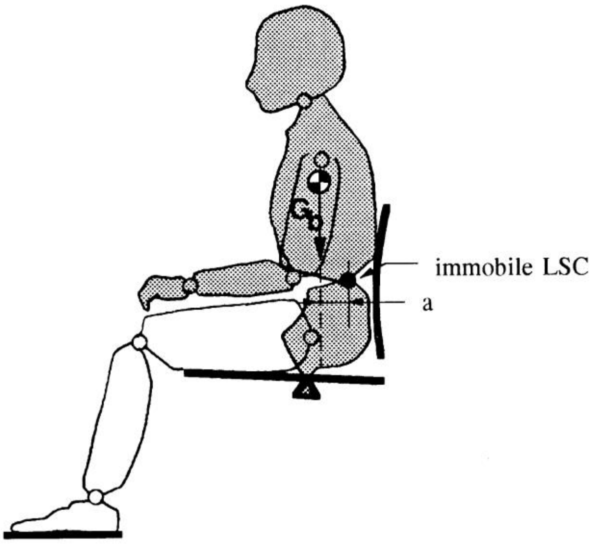


*Figure D1-12 : Stability of the upper part of the body with an immobile lumbar spinal column in relation to the tubera as pivot point and the introduction of a moment load Gb * a on the lumbar spinal column.*

If over a long enough period of time this posture is maintained, the ligaments of the lumbar spinal column will be stretched under the influence of this moment, thereby advancing the state of the kyphosis to such a stage that it becomes irreversible.

A kyphosis of the lumbar back also has consequences for the position of the head in relation to the trunk, as was described earlier. In this situation the solution is once again to afford a posture with anatomically sound stability for the trunk.

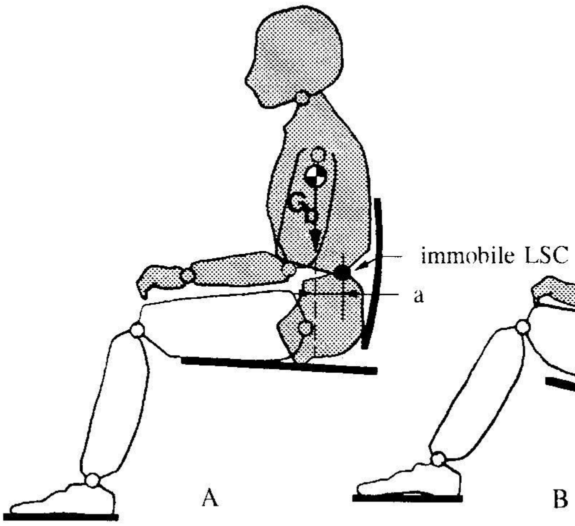


Figure D1-13 : A: An anatomically unsound stability for the torso
B: An anatomically sound stability for the torso by eliminating the moment of force on the lumbar spinal cord and the consequences for the position of the head.

Tilting the sitting posture in figure D1-13 does not only result in the elimination of the extension of the neck but also causes the moment load on the lumbar spine to disappear.

D1.6 Stability of the head

A stable support for the head is found when the head is supported by a headrest in such a way that the centre of gravity of the head lies above or behind its pivot point: the atlas. This is the case when the head is tilted approximately 20° backwards in relation to the horizontal direction of gaze. The centre of mass of the head, remember, lies 20° in front of the atlas when the direction of gaze is horizontal.

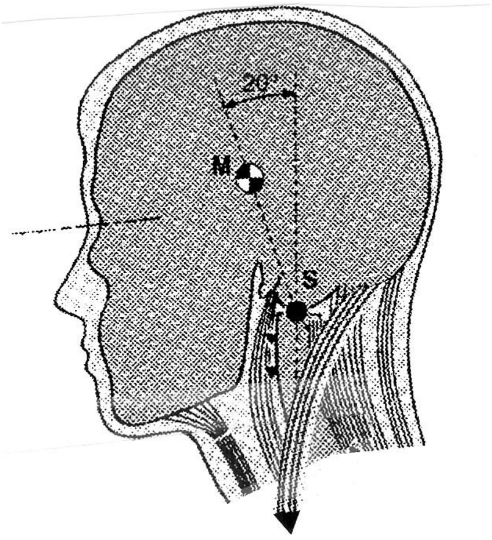


Figure D1-14: The position of the centre of mass in respect to its pivot point

When the head is in balance on the trunk and the gaze is directed at the horizon, changes of posture must have brought about internal forces that have brought It into balance. The moment (force x perpendicular distance) that the centre of mass of the head M develops in relation to the pivot point S, must be compensated by an equal and opposite moment. The mobility function of the muscles in the neck and shoulder area that position the head in relation to the trunk is extraordinarily complicated, but It is clear that in a certain posture, namely, with an angle$(\varphi+a)$ of ca.123°, forces occur in the muscles and ligaments of the neck and shoulders due to passive stretching that apparently give the correct opposite moment needed to balance the head and that therefore little or no active muscle exertion is necessary to keep the head in this position. This posture is experienced as particularly comfortable because the neck and shoulder muscles can relax: in this book it is referred to as the *individually preferred posture.*

D1.7 Summary and conclusions

Biomechanics and an adequate biomechanical model are extremely useful in the analysis and explanation of a number of important sitting posture phenomena. A relevant definition of sitting posture is of great importance here.
A sitting posture is defined by the position of the parts of the body in relation to each other and their collective position in space.
Characteristic for a sitting posture are the position of the trunk in space, angle$(\varphi+a)$, the position of the trunk in relation to the thighs, angle a and the position of the thighs in relation to the horizontal, angle φ.
The position of the trunk in space is measured along the lumbar thoracic transition segment *above* the lowest point in the small of the back. The position of the trunk is, defined in this way, irrespective of the individual shape of the small of the back and is crucial in our approach as this is the only definition that is biomechanically relevant.

Analysis of the equilibrium of forces (of the reactive forces of the seating supports in the various sitting postures) shows that with a correct combination of the magnitudes of angle φ and angle α no frictional forces will be necessary between the seat and the buttocks to maintain equilibrium. A sound sitting posture can be defined as such in view of this.
Stability for the upper body can be readily explained biomechanically by the position of the centre of mass of the entire upper body in relation to the modelled pivot point in the lumbar spinal column.
The definition of the backrest inclination, angle$(\varphi+\alpha)$, has, for this very reason, been based on the position of the upper body in space, measured along the lumbar thoracic transition segment. Anatomically sound stability for the trunk *begins* with an angle$(\varphi+\alpha) >115°$ and is irrespective of the shape of the back.
An anatomically unsound stability occurs when one arches one’s back and ‘hangs’ in the ligaments of the spine. Usually this is the result of sitting on a chair that only affords an active posture when one does not wish to

continually invest the activity required.

The internal loads on joints and intervertebral discs are partly determined by the magnitude of the angles used to define a sitting posture.

The centre of mass of the head lies approximately 20° in front of the pivot point, the atlas. This means that a stable position for the head in rest can only occur when the head is tilted approximately 20° backwards to lean on a headrest.

The special characteristics of the individually preferred posture in which the ‘head is in balance on the trunk’ cannot be explained purely biomechanically. It appears that when the trunk is in such a position that the angle($\varphi+\alpha$) is approximately 123° , forces occur in the muscles and ligaments due to passive stretching as a result of the posture , that apparently result in the exact counter moment necessary to keep the head in balance.
This phenomenon is high in the hierarchy of the momentary perception of comfort.

D2.0 Decubitus, causes and prevention

This in depth chapter is based mostly on the paragraph 2.3 from Sitting posture, comfort and pressure. It has been revised and made uptodate by Drs.Jasper Reenalda, who works as promovendus at the Roessingh Research and Development in Enschede.

Decubitus develops by external pressure on the skin. No decubitus will develop without this external pressure; neither by normal sitting behaviour.
The aetiology of decubitus can be divided in a physiological and mechanical component.

The 'physiological' cause is brought about by poor nutrition of cells over a long period of time, resulting from the poor levels of supply and discharge of nutrition and waste products respectively. This manifests itself in the form of ischaemia, the localised deficiency of blood flow leading to paleness of the skin. The cause of this is compression of blood vessels and lymphatics under the influence of a load. Especially the combination of pull and pressure forces inside the tissues is generally made responsible for this occlusion.

The 'physiological' scenario described above can be reinforced by additional risk factors such as:

- defective vessels as a result of vascular disease;
- insufficient O2 uptake as a result of lung disease;
- a shortage or lack of specific nutrients, iron, vitamin and protein, which is common in patients with a spinal cord lesion.

Bar (1998) has given a fairly detailed synopsis of research results in the field of metabolics, as too has Crawshaw (1989).

The 'mechanical' cause of tissue degeneration can be explained as follows:
Interstitial fluid which is located between cells, acting under the influence of pressure differences, is squeezed out causing changes in volume within the tissue. At the point of contact between these differences in volume shear forces occur which, because of the lack of interstitial fluid, operate directly on the cell walls causing damage. The amount of damage in combination with the quality of the metabolics will determine whether decubitus results or not (Reddy, 1981).
Very often this mechanism is seen as part of the cell deformation theory. Recent research results from TUE (i.e.Bouten et al. 1999-2003) confirm that the deformation of the cells is a very important component in the origins of decubitus. Gawlitta (2007) shows that cells can survive a 24 hours shortage of oxygen, hypoxy, but are quickly damaged as a result of deformity.

The physiological and mechanical components in the first stages of decubitus can influence and re-enforce one another.

Interstitial fluid also plays a role in respect to the metabolics. The one-way discharge of fluid will exert a negative influence on the metabolics and will reduce the capacity of the tissue to recuperate locally.

A completely different mechanism which could play a part in the origens of decubitus belongs to the ischaemic perfusion injury theory (i.e. Pierce et al . 2000) In this theory the asssumption is that the return of the blood to the ischaemic tissue after a sudden release of the pressure is damaging, because of the release of free radicals. In this way a toxic enviroment could happen in that nucleus which kills of the cell.
This theory seems to be opposed to the practice whereby frequent sitting and lifting in a wheelchair is experienced as positive against getting decubitus.
Likelihood is that a speedy release of pressure acts a part in this.

The research into the mechanics of decubitus has started more or less by research from Reswick and Rogers (1976) . They have adapted the connection between time and pressure, measured by Kosiak (1961) by using a dog, to people.
See figure D2-1 for this historic *relationship*
The pressure relates to the interface pressure measured between the skin and the seat.

The clinical relevance of these time-pressure curve is not clear. As the measure parameters and the apparatus can’t and should not be compared and as the prediction and solution parameter is not clear, one can’t draw conclusions on the basis of these two studies about a possible clinical connection between pressure- and timespan.
The only justifiable conclusion seems that pressure-and timespan are
joined together and strengthen one another.

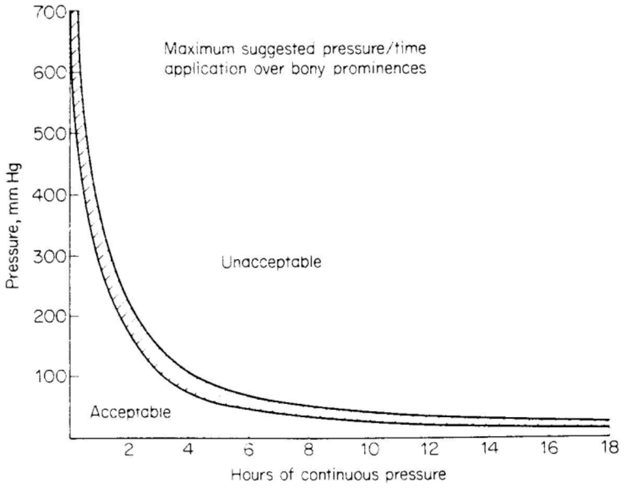


Figure D2-1: The acceptable relationship between the amount of interface pressure and time duration according to Reswick and Rogers (1976).

Unacceptable levels of pressure and time are often linked with the amount of assumed capillary pressure of 25 - 35 mmHg *(Landis 1930)* and the amount of external pressure necessary to block the vessels. This explanation doesn't however appear to go far enough. After all, the pressure measured in the context of the graph is the so-

called interface pressure, measured between the seating surface and the seating support.
The connection between the interface pressure and the internal pressure is not clear. The internal pressure can become two or three times as high. Even cushions with the best pressure distribution cause a much higher pressure internally under the tubera than the capillary pressure.

The lowest internal pressure recorded on the ischial tuberosities, in the cushion tests results carried out in the framework of this study, amounts to 90 mmHg. Given this fact plus the level of capillary pressure experienced it is astonishing that so few people suffer from decubitus. Certain mechanisms must therefore exist which act in a positive way to preserve the tissue.

One explanation might be that small fluctuations in load which will be always present in practice, have a positive influence on the nutritional situation in the cells. It is plausible, that a constant variation in load and, with it, internal pressure, will result in pumping actions in the capillary vessels, thus facilitating the transport of fluids and metabolism.
A pre-condition for this, however, is that the vessels do not block up as a result of distortion due to external and/or internal shear forces. The question remains whether the pumping action, that we have assumed is generated, produces enough pressure to force open the distorted and blocked vessels.

Reddy (1981) links Reswick and Rogers' graph with the relationship which exists between the level of local pressure differences and the level of interstitial fluid flow. Substantial pressure differences will quickly squeeze out interstitial fluid; small pressure differences have the same effect albeit over a longer period of time. Whereas with large pressure differences the chance of acute mechanical damage will be substantial due to the load which acts directly on the cell walls, with a small pressure difference the combination of more limited damage and a prolonged shortage of metabolics will achieve the same results.

Reddy's analysis of one-way interstitial moisture flows can perhaps be applied to the occurrence of distortion. Distortion which results from a combination of pressure and shear forces might be more effective in squeezing out the interstitial fluid than differences in pressure alone. The comparison with squeezing out a sponge springs to mind here. Distortion reduces the interstitial space forcing the fluid out whereby the load - in this case the shear forces - are transmitted directly onto the cell walls. This can cause mechanical damage to the cell. See research done at the TUE.

Most literature (Crenshaw 1989) considers the combination of pressure and shear forces as the most potent factor in causing decubitus.
Friction forces in the buttocks seem to play an important part in the external load and the way in which this is transferred to the internal tissues by way of sliding forces. Experimental animal research has shown that shear forces increase the effect of pressure in damaged tissue (Bennet et al.1979).
Besides the height, time and manner of the load there are a number of risk factors in the human being or in the external circumstances which can influence negatively the origins of decubitus.

D2.1 Analysis of internal load

The external load on the buttocks is formed by the reaction forces of the seat. The size and direction of these reaction forces are determined by the sitting posture (D1.0). The distribution of these forces across the buttocks is determined by the characteristics of the support element.
The absence of friction forces in the form of reaction force of the seat on the buttocks does not mean that there might be no shear forces internally.
In figure D2-2, which includes a cross-section of the pelvis, load is represented by a single normal force: F. This force is transmitted to the pelvis, which responds with reaction force RF. RF can be resolved in RFn, a perpendicular force on the pelvis, and RFs, a force in the pelvis plane. The 'normal' external point load, F, results not only in pressure stress internally on account of RFn, but also in shear pressure on account of RFs. This can lead to distortion of tissue.

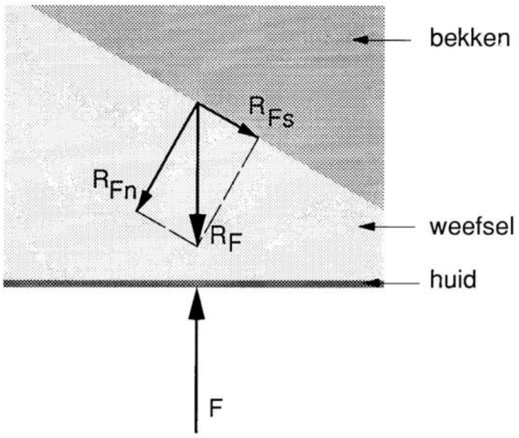


Figure D2-2 : External load F with internal reaction forces.

The internal shear force RFs can be compensated by an equally strong opposing force. This might result for example in an external force F2. In figure 2-3 we can see that RF1s and RF2s cancel each other out. The normal forces RF2n and RF1n reinforce each other.

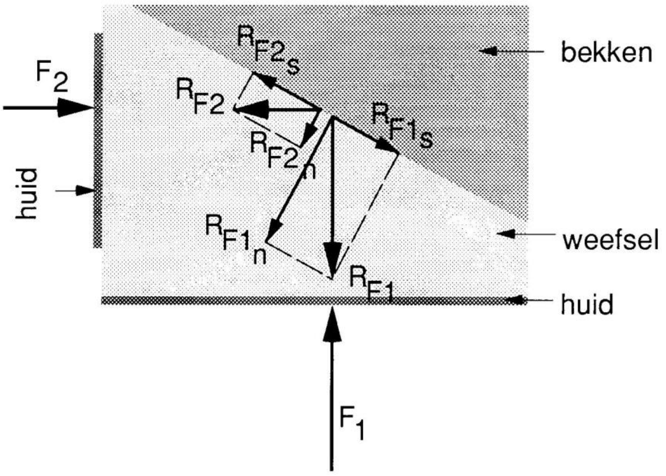


Figure D2-3 : External load F1 and F2 with internal reaction forces.

In actual fact the reaction of the supporting element to the load exerted by sitting consists of an infinite number of point loads, F. The distribution of F in F1 and F2 (and F3: the third dimension) determines the eventual outcome internally.
We can compare the first example of figure D2-2 with a support consisting of a hard cushion. The impression made on it is slight. As a result lateral support is absent. Shear forces occur internally which distort the tissue. As the skin surface under load is relatively small, the reaction forces of the seat are high.
In the second example of figure 2-3 the support structure adapts to the shape of the buttocks and a lateral force F2 is produced, which impedes the development of shear stress. Distortion of the tissue is slight or absent and by the enlargement of the surface under load, the tissue helps absorb the load to a large degree. On average this becomes lower causing even smaller pressure. Internal shear forces can be 'neutralised' by different directions of external load.
In addition to size and direction of the external load, equality is also a significant factor. Differences in pressure can lead to localised variations in volume due to interstitial moisture transport. At the point at which these variations meet, 'suspension forces' (Meijer 1991) develop, which have shear forces as components. These may have a detrimental effect on the cell walls, as has already been discussed. Figure D2-4 gives an illustration of the development of these shear forces at the surface where variations in volumes meet.

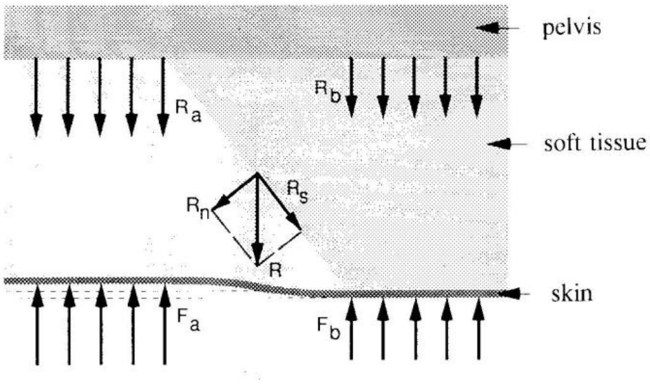


Figure 2-4 : The development of shear forces at the point where variations in volume - resulting from differences in pressure - meet.

Important is the distinction between the superficial and deeper decubitus.
Superficial decubitus (gradations according to a.o. the NPUAP gradingscale) originates in the skin and continues from grade1-4. By 4 being a full thickness lesion.
Deep decubitus starts internally and extends outwards.
You can't scale deep decubitus with the uptodate classification.
Superficial decubitus most likely starts by trauma to the skin (damage by external friction forces during transport) while deep decubitus most likely is the result of longterm pressure c.q. load on one point. At the moment this distinction gets a lot of focus and one is trying to give it a place on the existing decubitus scale.

Studies all seem to point towards the fact that deep decubitus develops internally in the vicinity of bone protrusions such as the ischial tuberosities. The internal pressure near to these protrusions is higher than directly beneath the skin and much higher than the so-called interface pressure which is measured between the skin and the supporting element.
Animal experimental research (Le et al.1984) and Finite Elemental Modelling (TUE and many other places are researching this) have shown that the internal pressure is higher than the active external pressure and has reached a maximum in the muscle tissue under the bone protrusion. In preventing decubitus one aims at the lowest possible maximum values of the external load which can be recorded using the interface pressure values.

A comparison of the 'internal' results taken from this study with those of the interface pressure, measured using the OPM (Oxford Pressure Monitor) under the 'test buttock' - a simulation of the human buttocks with built-in pressure sensors - , the very same picture is found. See D3.0

In preventing decubitus one aims at the lowest possible maximum values of the external load which can be recorded using the interface pressure values.
One assumes that this will result in the lowest possible internal load. The aim also is to work towards a dynamic load equal to normal sitting behaviour.

Normal sitting behaviour is characterised by movement and changes in position. This means, bio-mechanically speaking, that new balances of forces are being constantly formed and that internally tissue is placed under continually changing loads.

The assumption is made here that dynamic sitting behaviour and, with it, variation in load might effectuate pumping action in the vascular system. This might maintain the flow of fluids and therefore the metabolics, despite the fact that internal pressure is higher than capillary pressure. This can only be achieved on condition that the vessels have not been twisted closed as a result of distortion. This theory, or assumption, underlines the enormous influence which distortion and the associated internal shear forces have on the development of decubitus.

The pathology of decubitus is not present at all in normal sitting behaviour, despite the high to very high levels of pressures which occur.

Loads which give discomfort also give off stimuli which signal a change of movement and therefore a change in the load. If these stimuli are absent or a response to the signals cannot be given - as is the case for many wheelchair-users - , the process has to be influenced by three additional factors:

- to realise an anatomically justified, stable sitting posture without creating friction forces the posture needs to be optimized
- the pressure-distribution properties of the cushion, which need to be optimal so that both the load on the areas around the ischial tuberosities and the level of disfiguration to the tissue are minimized,.
- both major and minor changes in posture must ensure variation in load as well as the assumed pumping action.

Variations in load should also maintain the volume of interstitial fluid at the same level.

To summarize it can be said that mechanical damage is caused by the emission of interstitial fluid under the influence of pressure and time, which enables distortion forces to act directly on the cell walls. Necrosis develops by deformation of the cells.

Physiological damage is caused by a deficient metabolism over a prolonged period, which is caused primarily by the blockage of fluidmoisture flows. The level of internal load, the extent of distortion of the tissue and the length of time the load is exerted are strongly linked to the chances of developing decubitus.

The level of internal pressure and disfiguration are dependent on the size of the external load and the way in which this is applied. The size of the load depends in turn on the sitting *posture*, and the way in which this is transmitted onto the buttocks is determined largely by the qualities of the sitting *support*.

An hypothesis has been developed by which is presumed that an dynamic sitting behaviour has as a result a dynamic load who which could give a pumping action in the arteries. This would keep the bloodstream in pumping action. In turn it would keep the blood flow and therefore the metabolism, despite the fact that the internal pressure will be higher with the load than the capillary pressure.

D2.2 Influence of moisture and heat on the development of decubitus

Sitting on a cushion which has an high heat regulation it is difficult to discharge the body heat and one will start to sweat. This fluid will have to evaporate via the seating or taken away. If this does not happen there will be liquid moisture between the skin and the seating. On the other side a cushion with a good heat regulation will discharge heat as well as moisture. The heat and moisture regulating properties of a cushion will work together. Besides the moisture from sweating there will be moisture through incontinence between the buttocks and the sitting support.

The influence of heat and moisture on getting decubitus as a totally different one. Heat has a physiological influence while moisture has a mechanical influence.
A temperature rise of 1-C gives a rise in the cell metabolism of 10 % (Fisher1978)
That implies that the need of oxygen and nutriments is in keeping with it. With insufficient supply of oxygen and nutriments because of closing off the veins the tissues will be damaged sooner.

Moisture weakens the skin (maceration) and expands the surface. Wellknown are the rimples on the fingertips after a long soak in the bath. Laboratary experiments with pieces of skin in a controlled moisture surrounding show that the pull strength decreases by 75% by a relative moisture increase from 10% to 98% (Stewart 1980). The skin of the buttocks has an important function by transmitting the weight of the trunk to the sitting support and so has a great influence on the pressure distributing properties of the buttocks. A softened skin has a negative influence on this pressure distributing possibility. In the In Depth chapter V3:0 Pressure distribution the skin function will be discussed further. As well as the physical and mechanical influences heat and moisture increase the risk of infections.

D2.3 Risk factors in the development of decubitus

The primary cause of decubitus can be found in the constant distortion of tissue which brings about mechanical and/or physiological damage to the cell. Distortion is caused by external load. Without external load decubitus would therefore not exist! In preventing decubitus a distinction should be made between primary factors on the one hand, and risk factors which can have a negative influence on the primary process on the other.
The previous section dealt with how the development of decubitus might be accelerated by the effects of moisture and heat.
There are however, in addition to moisture and heat, other risk factors related to the individual or due to outside circumstances which may have a detrimental influence on the process. A summary of the previously mentioned factors plus a number of additional ones is summarised below.

Human-related factors, acting independently on external factors, include the following:

- insufficient or absent motoric movement i.e. inadequate sitting behaviour.
- little or no sensibility: the warning mechanism for overloading is ineffective or completely absent;

- atrophy: a reduction in the volume of muscle and fat tissue; this can lead to an unchanged weight i.e. the upper half of the body exerting much greater pressure on a reduced buttock surface; muscle and fat tissue form part of the buttocks' own pressure-distribution capacity: the less there is the higher the pressure exerted on the bone protrusions;
- the physiological and mechanical attributes of the skin;
  - the physiological quality of the skin can be measured by how the blood flow responds after a (test) load has been removed.
  - the tensile strength and elasticity of the skin are in some way dependent on the thickness of the skin, which varies per individual.
- reduced vascularisation caused by vascular disorders; this has an adverse effect on the metabolism;
- insufficient oxygen saturation of the tissue due to lung disorders;
- posture abnormalities and asymmetry due to scoliosis, contractures and bone formation can result in localized pressure increases;
- irregularities in the skin, e.g. scar tissue: this can lead to internal increases in pressure;
- excessive transpiration and incontinence.

The most significant risk factors which arise from user circumstances can be summarised as follows:

- the sitting posture: the sitting posture is responsible for size and direction of the external load given the supported body weight;
- cushion properties:
  - the pressure-distribution capacity
  - the moisture and heat regulation.

2.4 The relationship between the temperature reaction of the skin and the size of the external load

When using cushions in practice, the presence of erythema (superficial inflamation) on the buttocks provides an indication that pressure-distribution is not optimal. This is the way that tissue reacts to too long and too high a load. Bar (1988), in his doctoral thesis, makes an analysis of the relationship between the temperature reaction of the skin and the size of the external load.
As the contents of this study provide an interesting and practically oriented addition to this chapter, a short summary is given of the research results.

Bar, in his thesis, presents the results of dynamic pressure readings taken over a period of 2 hours on 25 disabled test subjects on 3 different wheelchair-cushions: an unspecified model of Roho air cushion; a 5cm gel cushion on 2.5 cm layer of 'Aberdeen'-type foam (unknown in the Netherlands); and a 10 cm thick foam cushion with a density of 100 kg/m3 protected with a vinyl cover.
All test subjects had spinal cord lesions: 7 cervical, 13 thoracal and 5 lumbar.

Bar measures the 'interface pressure' directly under the ischial tuberosities for a period of 2 hours using an improved OPM with a diameter of 28 mm in which air was replaced by liquid. Test subjects were left to pick and choose the tasks themselves.

The pressure readings which Bar measured under the right and left-hand tuberosities are illustrated in a pressure versus time histogram presented in figure D2-5. The pressures are presented at intervals of 30 mmHg and the times are set out vertically.

Immediately following the pressure readings the erythema and the temperature of the skin under the tuberosities were measured in relation to time and noted down. Bar makes a distinction between 'marked erythema' *(non-blanchable erythema)* and 'fading erythema' *(blanchable erythema).*

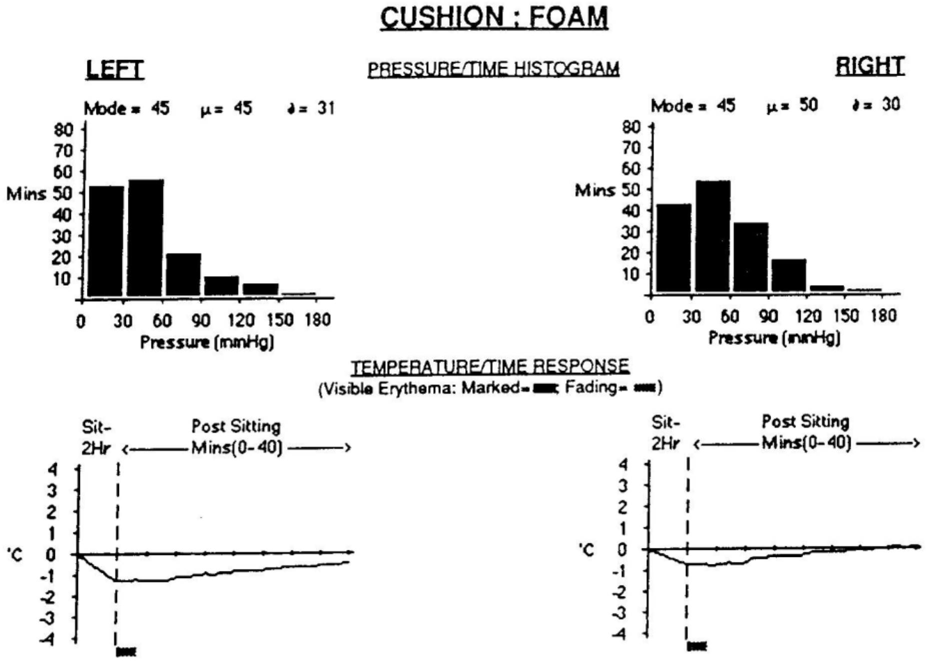


Figure 2-5: Bar (1988) : example of pressure versus time histogram for left and right-hand buttocks recorded for one test subject over a period of two hours and the temperature reaction of the skin combined with the level of erythema on completion of the test.

What is interesting about these histograms is the fact that the pressure on the ischial tuberosities appears to be a dynamic phenomenon. They illustrate that pressure, and with it load, can vary greatly over time. Individual differences in pressure on the same cushions can also clearly be seen.

Furthermore there appears to be a relationship of some sort between the amount of external pressure, the thermal reaction of the skin and erythema.

The thermal reaction of the skin is defined as being the difference in skin temperature of tissue under the greatest load directly under the tuberosities and tissue 5 cm away from the tuberosities in relation to the starting temperature for the test with the test subject lying in bed.

Bar identifies three types of skin reaction:

- the 'mild response' : this reaction appears to occur at average levels of external pressure smaller than 80 mmHg.

- the 'moderate response'; this appears to occur at average pressures of between 60 and 115 mmHg.
- the 'severe response' which is observed at average pressures of more than 90 mmHg.

This means that the difference between the 'mild' zone and the 'severe' zone is no more than 10 mmHg and that the 'moderate' zone generously overlaps the two.

In the case of 'mild response' no erythema was discernible. For 'moderate response' the 'marked erythema' disappeared within 12 minutes and completely faded away after a period of 20 to 30 minutes ('fading erythema'). In the case of 'severe response' the recorded levels of erythema were not much greater than those for 'moderate response', the difference being primarily in the temperature change on recovery as illustrated in figure D2-6.

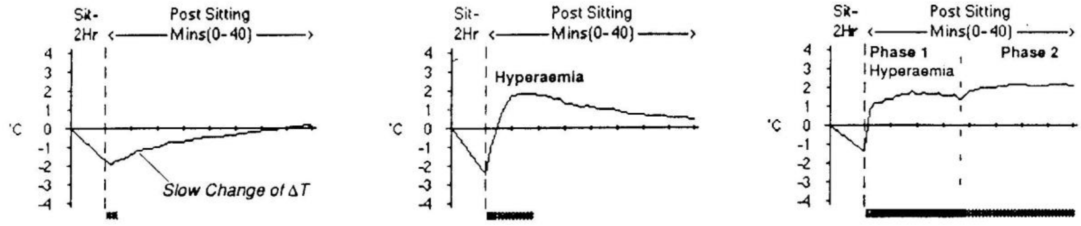


Figure D2-6 : Bar (1988) : temperature response and erythema after two hours of sitting.

In additional tests using healthy subjects Bar establishes the relationship between externally applied pressure and the oxygen pressure pO2 which can be measured on the skin. He used a model 33/34 Roche Electrode oxygen sensor for this purpose.
In the study the average pressure is situated between 80 and 110 mmHg whereby the pO2 approaches 0 at 100 mmHg.

He used this information from the pressure-time histogram to extricate the tissue condition of the wheelchair user and so to come to the decubitus risk factor. Considering all the many asides one can place by this research and the enormous variation of external risk factors this method is not applicable for general use in interpreting the up to date pressure load results.

The value of Bar's study lies primarily in the fact that the dynamics of load have been recorded and that the link is made between the skin response and the average interface pressure value.

D2.5 Prevention

Decubitus is a complex problem in which there are many parameters influencing one another in various ways. At the foundation obvious physiological causes but also mechanical causes play a part in it. Therefore preventing decubitus can only be

successful if in as many areas as possible the start of it can be stopped. To optimalize only a few parameters will not give the right result. A good pressure-distribution is certainly an important parameter but absolutely not the only one.
To get the optimum in the pressure-distribution , in effect of the sitting support ,one starts therefore by the optimum of the sitting posture. The sitting posture is responsible for the amount and direction of the external load on buttocks and back. The starting posture in the wheelchair is the posture by which one realizes an anatomically correct stablity. This posture is also favourable to a right pressure-distribution. With the right support of both arms one reduces the sitting pressure by about 20%.

Pressures which develop internally below the buttocks ,looking at time,are always too high to prevent decubitus A dynamic sitting behaviour helps to influence the size and place. Besides one assumes that dynamic sitting behaviour and so load changes could start a pumping action in the bloodvessels. This in turn could keep part of the bloodflow in tact and so too the metabolism, despite the fact that the internal pressure higher is than the capillary pressure. On condition that the veins are not distorted by twisting. Deformation develops a.o. by changes in volume caused by pressure differences.

In normal circumstances the wrong kind of load provokes a changing posture and so too a difference in the load. This promotes a natural sitting behaviour. By many wheelchair users
this provocation to change the sitting behaviour is missing. Therefore it is of the utmost importance that one learns to adopt the conscience sitting behaviour which results in the dynamic load. This is an important task for the therapists. The various options of the wheelchair, like tilting can be useful in changing position when one does not have enough material ability.

A cushion which optimizes and regulates warmth and moisture play an important part by preventing decubitus.

D2.6 Characteristics of wheelchair users

According to workers in the field the most commonly quoted characteristics of wheelchair-cushion users are those associated with an increased risk of decubitus. Many techniques exist to measure the risk of decubitus. In the Netherlands there is a so-called 'consensus group' which has published a brochure on the subject of decubitus prevention and treatment (Haalboom 1992), more recently de Nederlandse Gezondheidsraad (1999)).

Characteristics of wheelchair-users have been identified on the basis of cushion characteristics. In selecting these characteristics a distinction can be made between those characteristics associated with features of sitting and those characteristics which are associated with cushion design e.g. those taking into account transpiration and incontinence.

Characteristics of cushion users are:
- the degree of sensitivity to decubitus;
- the presence or absence of sensibility;

- the ability to modify posture or lift;
- a normal or excessive level of transpiration;
- the level of inconvenience from incontinence;
- the symmetry or asymmetry of the pelvis.

These characteristics are defined in more detail below:

- Sensitivity to decubitus in the buttocks:

Factors which play a role in sensitivity to decubitus include degeneration of the gluteus muscle by a process of atrophy, defective vascular refill or defective vascularization which influence blood circulation, and excessive bodyweight in relation to the seating surface.

- Sensibility:

The perception or not of stimuli which result from load as a result of sitting. Excessive load is usually registered by the body and signals sent to the brain. The brain reacts by issuing stimuli which lead to a change in sitting position and therefore a change in the load. This mechanism protects the body against prolonged localized load.

- Changing position:

The possibility to change the position of the buttocks in relation to the seat. These changes in position result in a change of load, usually a localized reduction. A change in position can be brought about by a so-called lifting action by which the load on the seating surface is relieved by pushing the body upwards using the arms on the armrests. It can also be achieved by periodically changing sitting posture, e.g. by changing to a posture specific to the task being carried out or by movements resulting from spasticity.

- Excessive transpiration:

A level of moisture discharge during sitting which places special requirements on the moisture regulating capacity of the cushion. The influence of moisture on the development of decubitus is thought to be considerable. This is discussed further in section D2.2.

- Incontinence:

A level of incontinence which places special requirements on the cushion. We are concerned here mainly with loss of urine which cannot be otherwise absorbed by incontinence pads.

- Asymmetric sitting posture:

A level of asymmetry in respect of the pelvis and/or thighs in the medial plane which places special requirements on the cushion.

This feature is extremely important for a small group of users. In the present study no test methods have yet been developed to measure cushion attributes in relation to this feature.

In theory a large number of user groups for cushions can be identified on the basis of these various user characteristics. After consultation with a number of individuals working in the field, a total of 10 user groups were initially identified and the viability of this distinction was assessed.

This assessment eventually narrowed the selection down to three user groups and three kinds of use.

The following user groups can be distinguished:

Group 1:

- able to modify position,
- not sensitive to decubitus,
- sensible.

A cushion for this type of user can be defined as a "low-risk user cushion" (LRUC).

Group 2:

- able to modify position,
- sensitive to decubitus,
- sensible or non-sensible.

A cushion for this type of user can be defined as a "medium-risk user cushion" (MRUC).

Group 3:

- not able to modify position,
- sensitive to decubitus, and
- sensible or non-sensible.

A cushion for this type of user can be defined as an "high-risk user cushion" (HRUC), since users in this group are sensitive to decubitus and cannot modify their position.

Some explanation is required as to how the categorization was arrived at:
No differentiation is made in Group 2 and 3 in respect to sensibility. They can lift as well as understand that they must lift. An intact sensibility might well stimulate lifting further but training for groups with a non-intact sensibility is focused on continuous movement and the result is therefore the same.
Group 3 users are not able to modify their position or lift. An intact sensibility can provide reason enough for the individual to request assistance in modifying position when a measure of discomfort is perceived. This will usually happen during or immediately after the process of sitting down. For this reason the group carries a risk which, relatively speaking, is somewhat smaller. The prolonged nature of sitting without movement (or lifting) however makes this group extremely susceptible and comparable to the group with a non-intact sensitivity.

With regard to cushion construction, a distinction is made between moisture regulation and moisture control. The following three kinds of use can be differentiated:

- normal use: where no excessive transpiration or unacceptable incontinence is present;
- use in situations where excessive transpiration is present;
- use in situations where non-manageable incontinence is present.

The categorisation of 3 user groups and three types of use eventually leads us to the conclusion that there are five different cushions:

- a low-risk user cushion for normal use
- a medium-risk cushion for normal use
- a medium-risk cushion for use in situations of excessive transpiration
- a high-risk cushion for normal use and excessive transpiration;
- a high-risk cushion for use in situations of non-manageable incontinence.

D2.7 Summary and conclusions

Decubitus is primarily caused by constant deformation of tissue which in turn damages the cells mechanically and/or physiologically. Distortion is caused by external load. Risk factors both in respect of the individual and the user conditions may also play a role in the development of decubitus.
The lowest internal pressures measured under the ischial tuberosities are at least 2 times as high as the capillary pressure of 30 mmHg. This means that in- and outflow systems become blocked as a result of sitting load. Blockage of these systems can, over a prolonged period, have damaging physiological effects. Very high localised pressures can lead to mechanical damage of the cell. There appears to be no clinically established acceptable level between the amount of external load (i.e. the interface pressure) and time.
The relationship between time duration and pressure of Reswick and Rogers is not applicable in individual cases and therefore not to be used clinically. The same is true of the results and conclusions of Bar.

The effect of time on the development of decubitus is not only influenced by the excessive deficiency in nutrients to the cell, but also by the discharge of interstitial fluid between the cells when placed under load. It is feasible to imagine that, as a result of this, cells are damaged mechanically at a faster rate. As the interface pressure on the ischial tuberosities is only half of that of internal pressure, it is an astonishing fact that so few people actually suffer from decubitus. It would therefore appear that there are regulating mechanisms and circumstances which help keep the nutritional processes in working order. One of these regulating mechanisms might take place in situations where the almost ever-present dynamics of the load facilitates a kind of pumping action which in turn temporarily sets the transport of nutrients in motion. A condition for this taking place is that the vessels have not been twisted closed as a result of the load placed upon them. Shear forces in the tissue, in particular, are held responsible for this.
It is important therefore that wheelchair users, despite there disabilities, aim for a natural- dynamic sitting behaviour in an anatomically correct sitting posture.

D3.0 Pressure-distribution

This in depth chapter is based mostly on chapter 3.0: Analysis of pressure distribution from Sitting posture, comfort and pressure.

Pressure-distribution during sitting is brought about by interaction between the characteristics of the sitting support and the characteristics of the buttocks. A number of characteristics relating to the individual and a number of characteristics relating to the cushion influences this process.
A general pattern of the so-called interface pressure is presented in figure D3-1.

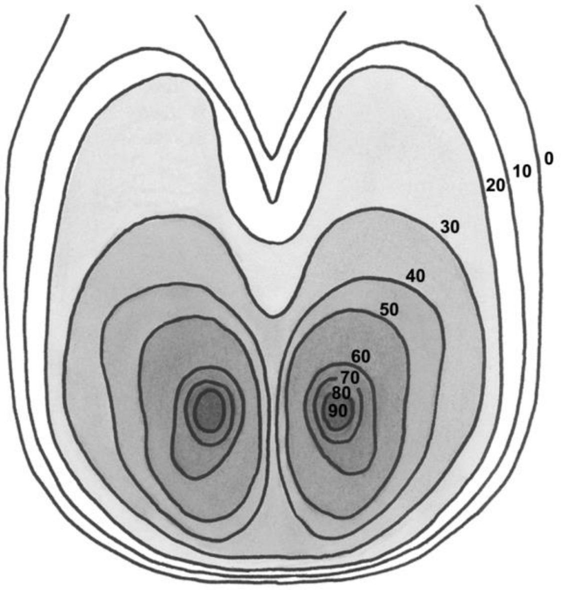


Figure D3-1 : A general pattern of the so-called interface pressure

This pattern reveals that the highest pressure is likely to occur directly underneath the ischial tuberosities. A sitting support's pressure-distribution is understood to be its capacity to spread the load across the buttocks in such a way that pressure under the ischial tuberosities is minimised. Low pressure levels not only give a feeling of comfort but are also an important factor in the prevention of decubitus amongst wheelchair-users. The sitting posture seems to be responsible for the size and direction of the external load on the buttocks as is discussed in the In-depth chapter V1-0 Bio-mechanics of the sitting posture . There are no friction forces needed in order to have the right load balance in the buttocks for the correct sitting posture.

This chapter will elaborate further on the interaction between characteristics of the buttocks and the properties of a sitting support. The question will be addressed as to how satisfactory levels of pressure-distribution can be achieved on the basis of this interaction.

An understanding of how pressure-distribution is effectuated in or by a cushion is not only necessary for effective cushion design but also in the optimum application of cushions in individual situations, especially in situations where the cushion's primary function is to prevent decubitus.

Despite many publications on this subject the tools required to carry out the analysis of pressure-distribution are minimal. Most studies limit themselves to an examination and presentation of results of pressure-distribution tests carried out on a number of different cushions using a small test population. Smaller than average maximum pressure values, when measured across the whole of the test population, are taken as proof that one particular cushion is qualitatively better than another. Analyses of why one individual should achieve a better pressure-distribution using a particular cushion as opposed to another, are thin on the ground even though this information which might result from this could be effectively applied in case treatment. Analyses of the reasons why one particular cushion is better than another are few and far between. Important test conditions such as the sitting posture and the support structure are not specified unless they form the central theme of the study (e.g. Hobson 1992, Engel 1986). Results are often related to the materials used or the systems applied and then generalised (e.g. Bar 1988, Goossens 1994). The lay reader might be forgiven for thinking that he has lost his bearings

As part of the analysis of the pressure distributing performance of cushions this chapter will make recourse to a number of test results from simple experiments using foam as a pressure-distributing medium, in order to develop these principles of application. The conclusions drawn from this exercise will be used to explain the performance of air and water filled cushions.
Test data for this analysis will be based on readings for the maximum internal pressures, taken on the ischial tuberosities of a test dummy which in shape, size and structure closely resembled human buttocks.

D3-1 Test Buttocks

The text buttocks is a measuring tool with which the internal pressure in the relevant places in the buttocks while seated can be taken.

The test buttocks represent that part of the human behind in the sitting posture which comes into contact with the sitting support. The test buttocks consist of a hard structure of male pelvis and thighs, Mark 3B, surrounded by a soft structure of silicone mass, enclosed by a synthetic skin comprising a somewhat stiffer silicone material reinforced by a tricot fabric.
The shape and size of the test buttocks were taken from an impression of a male test subject weighing 75 kilos with a sitting weight of 62 kilos and a hip width, in the seated position, of 36 cm. This choice has been made as it is more or less a critical buttocks

A total of 19 pressure sensors were applied at strategic places in the test buttocks:
9 on the bone, 9 directly underneath these bone sensors on the inside of the skin and one 'floating' pressure sensor. The positioning of the pressure sensors was determined by a number of factors. The ischial tuberosities and the sacrum would

appear to be the most vulnerable spots during sitting. Decubitus predominantly forms in this region. Corresponding bone and skin sensors were placed to enable an analysis of the internal transmission of forces and to enable a comparison with Lee's results (1984). Two sensors were placed symmetrically opposite to each other as control parameters. The 'floating' sensor complements the cross-section. The fact that full symmetry of the sensors was not realised resulted from financial considerations only. Figure D3-2 shows the positioning and coding of the pressure sensors.

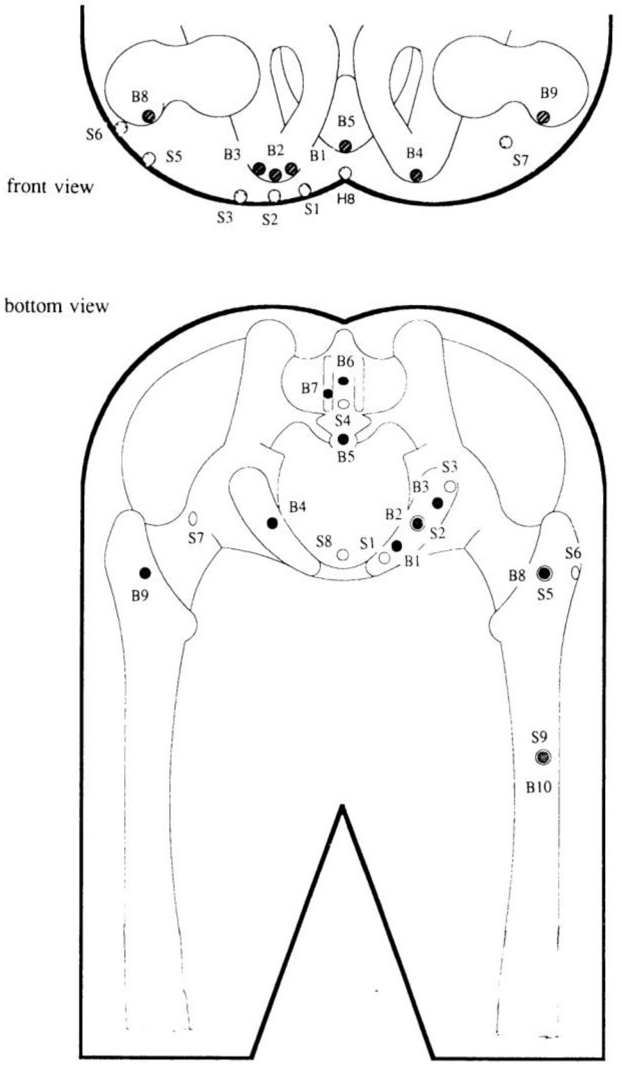


Figure D3-2: Positioning en coding of pressure sensors in the test buttocks,

The test buttocks were suspended on a Zwick dynamometer which could be adjusted beforehand to provide a constant load. The cushion was subjected to a force of 600 N, being the sitting load of a person weighing 75 kg.

In order to find out to what extent the results achieved with the test buttocks equate with real-life results, a series of comparative tests were carried out on a flat board, using the so-called pre-load cushion, the 100 mm thick DRAKA foam cushion.

These tests consisted of measuring the interface pressure by means of the OPM on the cushion. Pressure readings from the tests buttocks were compared with the readings taken using the same cushion and using the test subject who provided the 'casting' for the test buttocks.
This comparison provides a practical validation of the test buttocks.

The basis for this comparison is formed by the foam on a horizontal, hard and flat support. Two tests were carried out on the test subjects:

- an active, upright posture without the use of a backrest:
  i.e. a normal lordosis of the lumbar spinal column, the pelvis adopting a position which fits this posture;
- a slumped sitting posture without the use of a backrest:
  i.e with a kyphosis of the lumbar spinal column with the pelvis tilted backwards.

The OPM's test cell was placed directly under the ischial tuberosities of the test buttocks and those of the test subject. The results of this exercise are presented in figure D3-3. The table also includes the results of the tests carried out on 'Demo F' cushion, used as a point of reference in the cushion survey discussed later. This cushion had the same composition as the pre-load cushion but was covered by a very flexible stretch cover.

		zitgewicht/belasting	positie:onder tuber
TS: active upright sitting posture	OPM	62.2 kg	61 mmHg *
TS: slumped sitting posture	OPM	62.2 kg	105 mmHg *
Test buttocks *	OPM	600 N	85 mmHg *
Test buttocks **	OPM	600 N	98 mmHg
Test buttocks **	Pressure sensor H2	600 N	144 mmHg
Test buttocks **	Pressure sensor B2	600 N	166 mmHg

* Draka 9018 100 mm on flat board without cover.
** 'Demo F': Draka 9018 100 mm on flat board with loose fitting stretch cover.

Table 4-2 : The interface pressure of test buttocks and test subject (TS) and the pressure in the test buttocks of skin and bone sensors directly under the tuberosities.

The results reveal a number of points. Firstly, the magnitude of interface pressures for the test buttocks, 85 and 98 mmHg, and those taken for the test subject, 61 and 105 mmHg. It is interesting to note that an active sitting posture with tensed-up muscles reveals a lower interface pressure than for a relaxed posture where the pelvis is tilted backwards. Tensed-up muscles are more 'robust' than relaxed muscles. The weight of the upper half of the body is transmitted via the spinal column through the pelvis to both ischial tuberosities. More robust buttock muscles evidently spread this transmitted force outwards more effectively than do more flaccid buttock muscles. This proves the point that the buttocks possess a pressure-distribution capacity of their own. The test buttocks reveal an interface pressure with values which lie between those recorded for the test subject. Since pressure-distribution is 'individual' by nature and depends on the shape, dimensions and composition of the buttocks, this conclusion alone provides us with enough evidence to carry out a comparative survey and assessment of cushions on the basis of the criteria selected. Since the test subject has a 'critical' pair of buttocks in relation to the population, the test instrument meets the precondition that the tests need to be carried out in a 'critical' fashion.

The second interesting aspect of the results is in the comparison of the test buttocks' interface pressure with those internally. The results taken for the test buttocks correspond to the findings of Le (1984), which contend that the pressure in the neighbourhood of the protruding areas increases and is considerably higher than external pressures. The skin sensor S2 under the ischial tuberosity shows a lower pressure reading (144 mmHg) than the bone sensor (166 mmHg). This latter value is almost twice as high as the interface pressure measured between the test buttocks and the cushion (85 mmHg).

D3.2 Structure of buttocks and cushion

In order to understand how a cushion works it is necessary to analyse the structure and shape not only of the cushion but also of the buttocks. If we take a closer look at the structure of the buttocks we will see that in many ways they resemble the structure of a cushion. Both the buttocks and the cushion have structures in which 'hard', non-deformable parts as well as 'soft', deformable parts can be identified. Likewise these deformable and non-deformable parts are contained within an outer 'sealing'.

The human posterior consists of the pelvis which is surrounded by soft tissue and sealed by skin. The weight of the upper part of the body is transmitted by way of the spinal column into the pelvis. In effect, the skin has the function of holding the mass of soft muscle and fat tissue together. The softer parts combine together with the skin to form a pressure-distributing medium in relation to the pelvis.

The cushion is also composed of deformable and non-deformable parts. The non-deformable parts transfer the reaction forces of the chair frame to the deformable parts of the cushion. In turn the soft parts of the cushion act as a pressure-distributing medium on the buttocks. Figure D3-4 depicts the structure of the buttocks and the cushion.

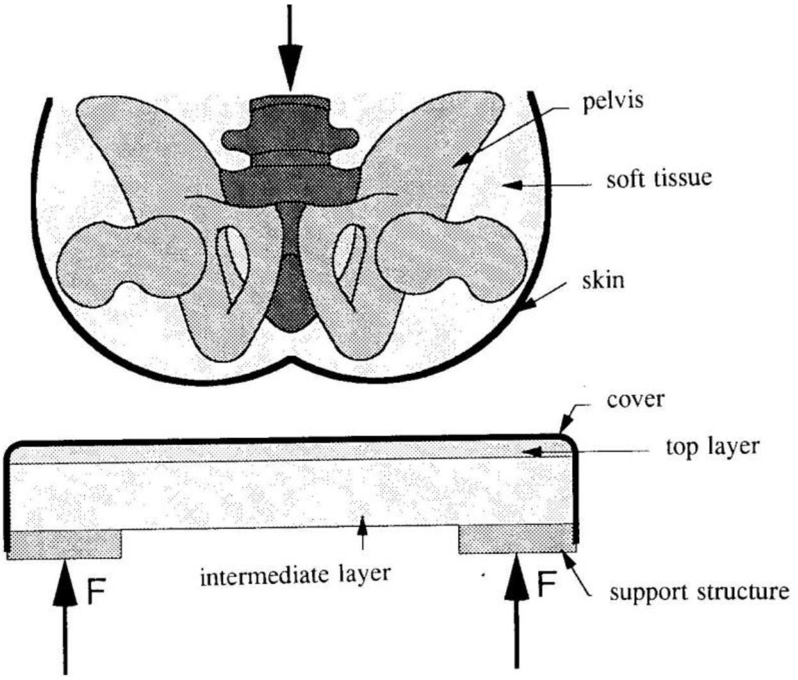


Figure D3-4: Structure of the buttocks and cushion in the frontal cross-section of the ischia.

How is pressure-distribution derived?
When an individual sits down, the buttocks and the cushion, both similar structures, press up against each other. The way in which these structures respond to each other depends on the characteristics ascribed to the 'materials' involved.
If the cushion's 'resistance to deformation' is greater than the buttocks' 'resistance to deformation' then the buttocks will deform. If, conversely, the cushion's 'resistance to deformation' is smaller than that of the buttocks then the cushion will adapt to the shape of the buttock.
The notion that the buttocks form a structure with a specific individual shape and mass of soft material which cannot be remoulded, is important in this respect. The shape and composition of the cushion on the other hand can be selected and, if necessary, should be in conformity with the shape of the buttocks.
The ultimate objective is to minimise the pressure exerted on the ischial tuberosities and to prevent deformation of the buttocks.

D3.3 Analysis of pressure distribution in foam cushions

A general characteristic of foam is that its reaction force as a result of indentation increases, the greater the indentation becomes. When an increase in indentation is no longer possible, even when load is increased, this is called 'bottoming'. A general load-indentation graph for foam is shown in figure D3-5.

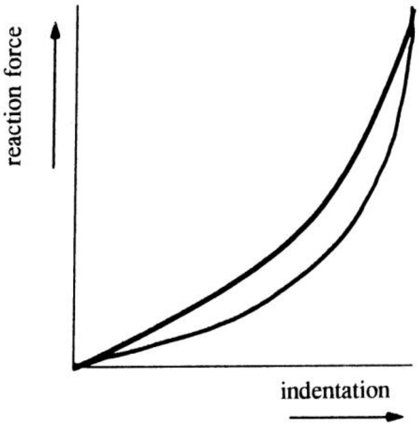


Figure D3-5 : Generalised relationship between load and indentation in respect of foam.

In order to gain a better understanding of how pressure distributing properties of a foam cushion work, a number of simple experiments were carried out. Firstly the influence, which the thickness of foam has on the pressure under the ischial tuberosities, was monitored. For the purposes of this experiment DRAKA 9018 foam was used with a density of 35 kg/m3 and a hardness of 110 N based on DIN 53577. This foam is a commonly used type in cushions. The foam was placed on a hard flat board which served as a support structure.
The foam was subjected to a load, consisting of a 600 N test buttocks.

The results of these experiments are shown in D3-6. The pressure under the ischial tuberosities appears to decrease as the thickness of the foam increases.

	thickness mm	max. pressure mmHg mm	absolute indentation %	relative indentation
Foam Draka 9018 on flat board	60	319	50.5	84
	80	216	60.9	76
	100	161	73.8	74
	120	126	73.3	61

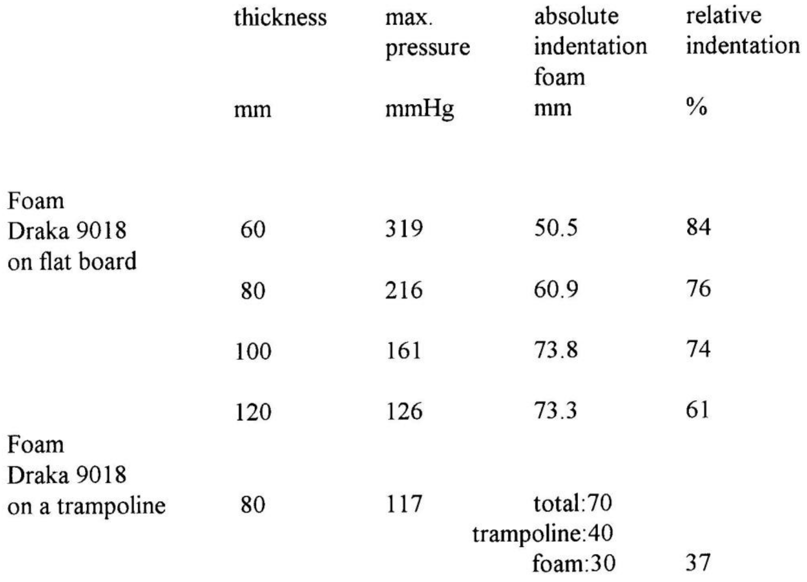
Figure D3-6: The influence of foam thickness on indentation, pressure and relative indentation, measured under the ischial tuberosities, for a load of 600 N using a test buttocks.

Absolute indentation increases with the thickness of the foam except in the changeover from 100 mm to 120 mm thickness. This means that the test dummy sinks yet deeper into the cushion. The surface under load is enlarged as a result of this increase whereby the average pressure and apparently the maximum pressure decrease. The figures recorded for relative indentation, arrived at by dividing the absolute indentation by the original thickness, are worthy of note. The decline in maximum pressure is more or less proportional to that of the relative indentation: the lower the relative indentation, i.e. deformation of the foam, the lower the maximum pressure.

What can also be concluded form this data is that the characteristics of foam with similar thicknesses can be compared effectively by their load-indentation relationship. Moreover we can conclude that, for situations where foam is used in supporting elements, thickness and relative indentation are the most significant factors in determining the load situation and, in this case, maximum recorded pressure.

D3.3.1 Influence of the support structure on maximum pressure

A piece of 80 mm thick Draka 9018 foam, which gave a maximum pressure- reading on the tuberosities of 216 mmHg, was placed on a so-called 'trampoline'. The trampoline consisted of a wooden frame in which an open fabric was suspended. The fabric when subjected to a load sags by about 4 cm, depending of course on tautness with which the cushion has been fixed to the frame. The trampoline can best be compared to the sling type sittings used in wheelchairs, though these are suspended in two directions. The result of this combination, i.e. the foam 'cushion' and the trampoline, produced an improvement, i.e. a decrease, in maximum pressure. The 216 mmHg measured in the previous test now became 117 mmHg, almost half of the original pressure reading. The results are compared in D3-7.



	thickness mm	max. pressure mmHg	absolute indentation foam mm	relative indentation %
Foam Draka 9018 on flat board	60	319	50.5	84
	80	216	60.9	76
	100	161	73.8	74
	120	126	73.3	61
Foam Draka 9018 on a trampoline	80	117	total:70 trampoline:40 foam:30	37

Figure D3-7 : Influence of the support structure on the maximum pressure under the tuberosities for 80 mm thick foam: Draka 9018.

If we deduct the trampoline's 40 mm sag from the absolute indentation of 70 mm for the foam on the trampoline and then calculate the remaining relative indentation, it is reduced to 37%, half of the original 76%.
This result can be accounted for by the fact that the foam on the trampoline requires a smaller degree of deformation, in order to accommodate the contours of the buttock, whilst the surface under load is increased at the same time. With small, even indentations in the foam a balance of forces is achieved. Small levels of indentation also mean lower reaction forces. For the cushion which was placed on the flat board the level of indentation is high, and at its highest directly under the tuberosities. This is also where the reaction forces of the foam will be greatest. The simple conclusion we can draw from this exercise is that in this case the support structure plays an important role here in forming the shape of the buttocks in the foam, when subjected to load without causing any great deformation in respect of the foam. Indentation in the foam is small and even, whilst an enlarged surface under load is realised. This enlargement however is not sufficient to explain the spectacular 50% reduction in maximum pressure. An enlargement in the surface under load by 1 cm means roughly a 10% increase in the surface area. In theory the average pressure will be reduced by around 10%. The decrease in maximum pressure is however much greater and can best be accounted for by the fact that the modest size of the foam's reaction forces do not deform the buttocks, meaning that their shape remains intact, thus optimising the pressure-distributing capacity of the buttocks themselves.

In order to evaluate this proposition, the mould, which was used to manufacture the test dummy, was deployed as a sitting support. This sitting support can be described as a hard contoured shell which almost perfectly matches the shape of the buttocks, but which allows absolutely no possibility for indentation (i.e. adaption). In effect the measurements refer to the test dummy's own pressure distributing capacity when its shape is left intact. In table 3-3 we can see that the results of this have been added to those of the previous table as well as the results of the test dummy on a flat board.

		pressure	indentation foam	indentation
	mm	mmHg	mm	%
Foam Draka 9018 on flat board	60	319	50.5	84
	80	216	60.9	76
	100	161	73.8	74
	120	126	73.3	61
Foam Draka 9018 on a trampoline	80	117	total:70	
			trampoline:40	
			foam:30	37
Hard contoured shell: mould	--	153	0	

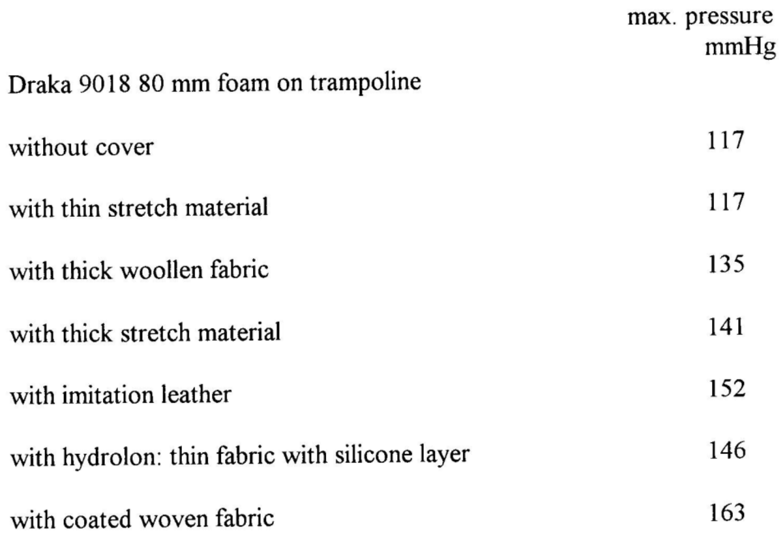
Figure D3-8: Influence of the sitting support on maximum pressure when fully adapted to the shape of the buttocks.

The result is not as good as that for the 80 mm foam on the trampoline, but better than that for the 100 mm foam on the flat board. Since the mould is essentially a support structure without a pressure-distributing medium but which is fully adapted to the shape of the buttocks, the result can be considered as being brought about by the buttocks' own pressure distributing capacity when its shape remains intact.
As a result of this the conclusion might be that the buttocks' own pressure-distributing capacity is astonishingly high if the conditions stated are met. A cushion will therefore develop satisfactory pressure-distribution when it is able to make maximum use of the buttocks' own pressure-distributing capacity. This is achieved when the cushion, under load, assumes the shape of the buttocks without deforming them.
When foam is used as a pressure-distributing medium, the support structure can play a significant part in helping to effectuate adaptation to the shape of the buttocks.
Another conclusion, which can be drawn from these and other results taken from pressure-distribution studies in respect of individuals (Engel 1986, Chung 1988), is that every pair of buttocks possesses its very own pressure distributing capacity depending on the size, shape and structure of hard and soft parts which act in combination with sitting weight.

Pressure-distribution capacity will be increased in proportion to the level of harmonisation between the support structure and the properties of the foam in respect to each other and in respect to the shape and size of the user's buttocks.

D3.3.2 Influence of the cover on pressure distribution in foam cushions

All the experiments done with foam were, up to this point, carried out without using a cover. Figure D3-9 lists results for tests carried out using a number of different kinds of covers for an 80 mm foam trampoline cushion.



	max. pressure mmHg
Draka 9018 80 mm foam on trampoline	
without cover	117
with thin stretch material	117
with thick woollen fabric	135
with thick stretch material	141
with imitation leather	152
with hydrolon: thin fabric with silicone layer	146
with coated woven fabric	163

Figure D3-9 : Influence of the cover on the pressure under the ischial tuberosities (mmHg).

The evidence is that the cover has a significant influence on pressure-distribution. As a rule of thumb it can be said that the stiffer a cover is, the more the maximum pressure is likely to be. This cannot however be said for hydrolon, as this is a material which is quite thin and supple, though the rigidity of the silicone coating might well be a factor accounting for its relatively high maximum pressure.

The degree of influence that the cover has on the pressure-distribution qualities of a cushion can be accounted for by so-called the 'hammock effect'. The origin of the hammock effect can be explained by the fact that a disparity exists between the projected surface of the buttocks before the load is applied and the actual surface during load. The difference must be initiated at some point during the sitting-down process. Figure D3-10 shows that this originates at the sides of the cushion.

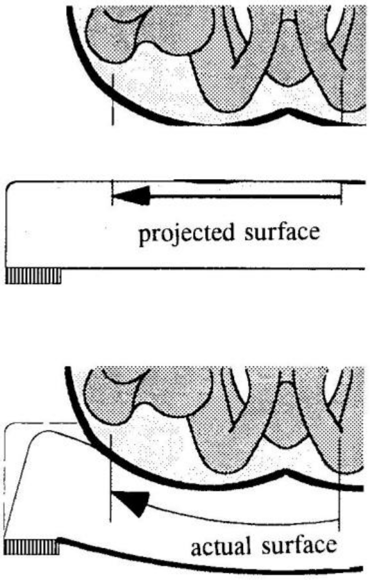


Figure D3-10: The difference between the projected surface and the actual surface.

The deformation of foam in a horizontal plane which accompanies this produces a reaction force FR which offers resistance to this deformation. The tensile stress in the surface under load shows a tendency to stretch the surface once more. This tendency prevents the surface from fully assuming the shape of the buttocks.

This increases pressure on the tuberosities since in the main it is the buttocks which are flattened out as a result of the tensile stress.

The 'hammock effect' can be best identified with the aid of a model which was designed for this purpose. The effect on the non-elastic cushion on the size of the indentation can be clearly seen in Figure D3-11 and Figure D3-12. The photos were both taken from the same standpoint. The indentation of the cushion in photograph 1 is clearly greater than in photograph 2. The effect of this on pressure-distribution can quite clearly be seen on account of the thickness of the foam under the tuberosities of the test dummy. The distance in Figure D3-11 is greater than in Figure D3-12.

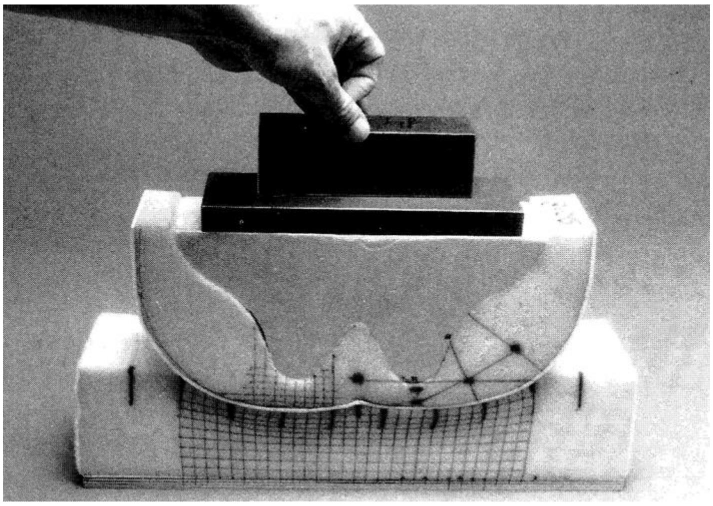


Figure D3-11: Indentation in partly cut foam without cover.

It is clear that with the help of a range of different types of cover the hammock effect shown here also occurs in the foam despite the protection of a cover when the foam has an unimpaired horizontal structure. The cover reinforces this effect. The cover indents the foam at the sides causing reaction force Ft. Without the cover the deformation caused by the buttocks will 'pull' the foam in a horizontal direction causing the reaction force. In the latter situation the reaction force will probably be somewhat smaller as a result of the foam's elasticity.

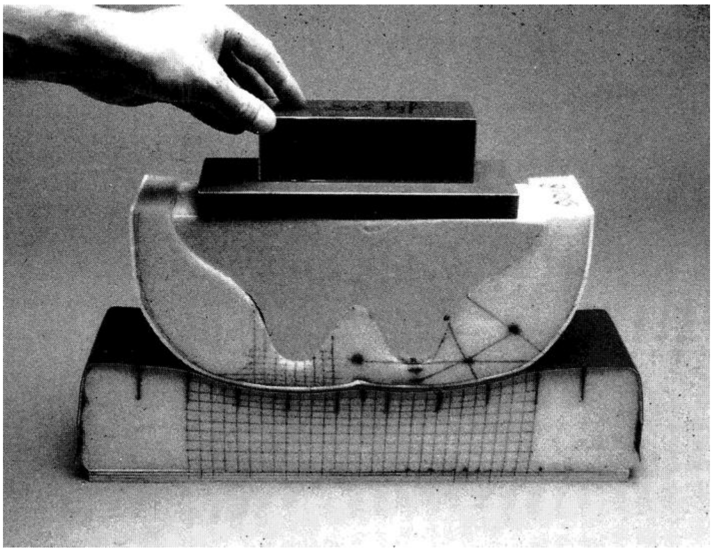


Figure D3-12: Indentation in partly cut foam with imitation leather cover.

By cutting into the foam, either completely or partially, its horizontal structure is eliminated, preventing the occurrence of tensile force.
To summarise, we can identify two types of reaction forces which together counterbalance the load L:
The vertical reaction forces caused by indentation; and the horizontal force caused by the 'hammock effect' which sets in motion a small vertical component: FRh.

In figure D3-13 this is shown.

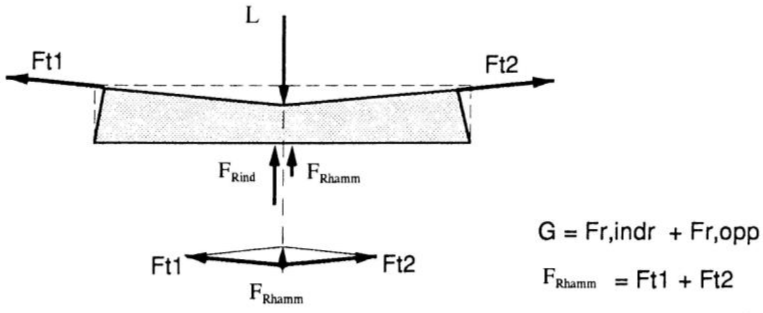


Figure D3-13 : Schematised model of the interplay of forces in a cushion under load.

The uniformity and size of these reaction forces caused by cushion indentation will largely depend on the shape of the support structure under load, as has been previously shown. The more this shape resembles the shape of the buttocks the more equal and smaller the indentation of the foam will be and with it the reaction forces. Figure D3-14 illustrates this for a cross-section. The same effect indeed applies to a longitudinal section.

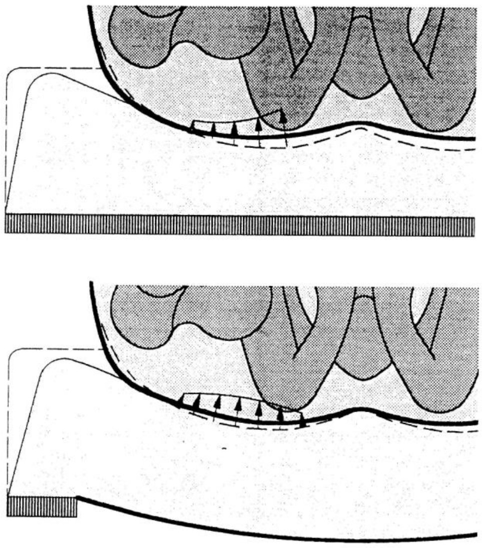


Figure D3-14: Influence of the shape of the support structure on the uniformity of the indentation in cross-section.

The average pressure diminishes when the surface under load is relatively large. Smaller indentation of the foam also has the effect therefore of reducing any possible 'hammock effect' which may occur. The result is therefore twofold.

Solving the 'hammock effect' practically can be done by dividing the surface into smaller sections. To achieve this, the foam is cut in two directions. As a result the indentation characteristics of the foam are indeed modified. To achieve the best result, an elasticated stretch cover should be used; otherwise the effect will be nullified.

D3.3.3 Summary

The pressure-distribution performance of a foam cushion can be analysed and understood by asking four questions:

- to what extent does the support structure contribute to a change in the shape of an individual's buttocks? In other words: what level of deformation, or in this case indentation, is the foam expected to attain?
- how is the link between indentation and reaction forces of foam realised and what level of relative indentation is achieved?
- to what extent does (undesirable) tensile stress occur in the surface under load as a whole and what is the effect of the cover on this phenomenon?
- has anything been undertaken to reduce the reaction forces operating on the ischial tuberosities?

This last question has not been addressed in these experiments, but can in theory be applied to a cushion to improve the results yet further. For example a less hard foam material might be used in the locality of the ischial tuberosities.

D3.4 Analysis of pressure distribution of air and water filled cushions

The essential difference between foam cushions on the one hand and air- and water-filled cushions on the other hand is in the relationship between indentation and reaction force. For foam cushions the reaction force increases slowly in proportion to the indentation. For air- and water-filled cushions hardly any reaction force occurs during indentation and balance is achieved almost immediately. A pneumatic or hydrostatic pressure occurs within the system, the level of which is determined by size of load L and the area of the surface S under load.

As a formula: $p = L / S$

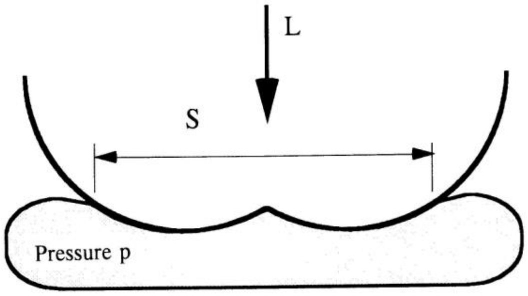


Figure D3-15: Influence of the area of the surface under load on the size of pneumatic or hydrostatic pressure.

In practice this means that the balance is adjusted according to cushion design and the level to which it is filled, i.e. the amount of air or water in the system, the size and shape of the buttocks and the size of the sitting weight.

To clarify this two examples are given:

A sitting weight of 600 N on 1000 cm2 of buttock surface gives a pressure in the system of 45mmHg, on 1200 cm2 38 mmHg.

In theory this pressure forms a uniform external load when tensile stresses in the cushion sealing would not occur by the pneumatic or hydrostatic pressure.
These tensile stresses produce the same effect as the 'hammock effect' discussed earlier and impede conformity to the shape of the buttocks.
The size of this tensile stress, which occurs in this type of pressure-distributing medium, is directly proportional to the size of the pneumatic or hydrostatic pressure p in the system. Pressure p in the system not only needs to be kept to a minimum on account of pressure-distribution but also in order to minimise the hammock effect.

The degree to which conformity can be realised depends therefore on the tensile stress which is produced in the surface under load in its entirety as a result of pneumatic or hydrostatic pressure in the system. The level of pneumatic or hydrostatic pressure depends in turn, firstly, on the amount of air or water in the system, since for low pressures the buttocks must be able to sink to a sufficient depth, and, secondly, on the size and shape of the buttocks.
Krouskop (1986) after analysing 14 test subjects with differing postures found that the average optimum interface pressure for an air-pressure of 35 mmHg with individual optima lay between 23 and 46 mmHg.

There are two basic solutions with regard to air- and water-filled cushions. These are:

- an air/water cushion whose surface consists of a single component,
- an air/water cushion whose surface is divided into a number of smaller components.

Both solutions exist in different versions:

- the cushion comprises one single air/water cell: all smaller cells, if any at all, are connected to each other, or
- a partition has been made between the left and the right-hand sides to take into account improved sitting stability.

Both principles are illustrated in figure D3-16 and D3-17 respectively.

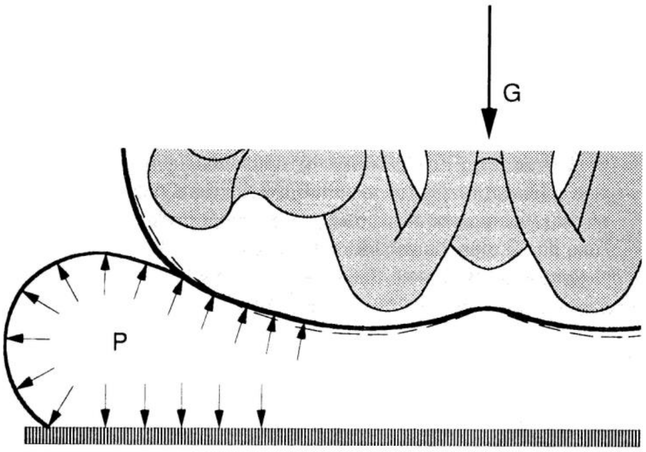


Figure D3-16: Air cushion consisting of a single cell.

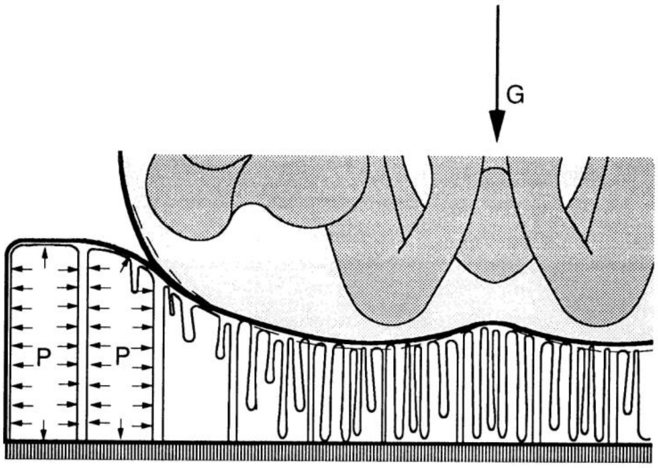


Figure D3-17 : Air cushion consisting of a number of cells and fitted with an stretch cover.

In both cases the level of pressure p depends on the size of the surface under load. If the surface under load is the same, the pneumatic or hydrostatic pressure will also be equal.

For cushions incorporating one cell only, the pneumatic pressure will result in tensile stress in the surface under load, which may manifest itself as the hammock effect preventing full conformity. Higher pressures will be observed internally under the ischial tuberosities.

For air-cushions, which consist of a number of air cells, the surface under load is divided into small individual sections, so that no tensile stress at all can develop on the surface under load in its entirety. The prospect of the hammock effect will therefore be eliminated. It does, however, occur in each of the individual cells, but the effect on the resulting conformity is minimal.

The material properties of the cover in combination with the nature of the deformation of cells has a bearing on the development of hard or soft 'edges', which may result in localised areas of higher pressure.

The sitting stability in transverse is slight with this type of cushion. The cushions are wobbly. The sitting stability can be improved by closing off the link between the right -and left cushion- halves. This needs to be done after one is seated on the’ open’ cushion.
To finalise this general analysis, a few remarks concerning the difference between air filled, water filled, fluidised gel and non-fluidised gel cushions need to be made. There are no fundamental differences between air filled, water filled and fluidised gel cushions in respect to pressure-distribution. Apart from minor differences caused by variations in density, in all cases pressure is dependent on the size of the surface under load, whereas the tensile stress in the cushion casing is dependent on pressure p in the system. The extent to which this tensile stress impedes conformity is related to the extent to which the tensile stress occurs in the surface under load in its entirety.

The difference between air filled, water filled and fluidised gel cushions manifests itself in the form of other characteristics. This is due to the viscosity of the material, the density and heat capacity.

D3.5 Analysis of hybrid cushions

There is a large number of cushions on the market today which incorporate a number of pressure distributing media, such as:

- fluidised gel on a layer of foam
- foam - fluidised gel - foam
- an aircell system embedded in foam
- foam padding in an air-filled cushion consisting of one cell only
- etc, etc.

Sometimes these cushions incorporate their own support structures, but as a rule they do not. More often than not a recommended support structure is not included when the cushion is supplied.

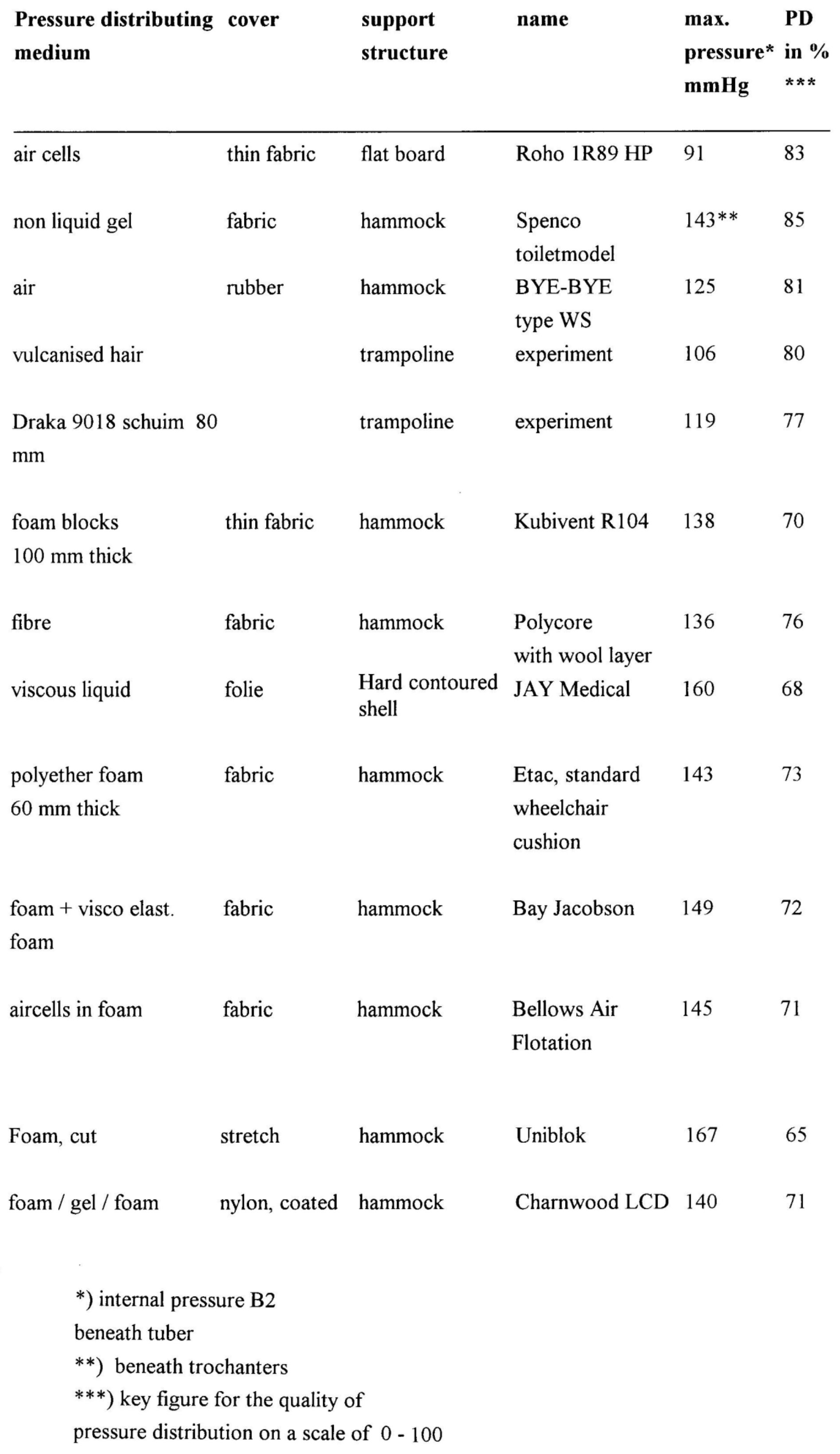
The reason for combining different pressure distributing materials is not just for the purposes of pressure-distribution but also on the basis of other important attributes such as stability, surface softness, shock absorption, heat regulation etc.
Every system has its pros and cons. By imaginative combinations one can try to minimise the disadvantages whilst at the same time maximising the advantages.

The pressure-distribution performance of these hybrid cushions can in theory be explained and interpreted on the same basis as for foam and air/water filled cushions discussed in the previous sections. During indentation however a 'counteractive' element on the one hand may develop between the different materials, but on the other hand a 'cooperative' element may be present.
The use of foam within an air-filled cushion, consisting of a single cell, produces, depending on the indentation characteristics of the foam, a pneumatic pressure which is, or may be, relatively lower due to the reaction forces of the foam. The effect of this is a relatively small tensile stress in the surface under load.
The use of a number of air cells embedded in foam results in the surface of the air cells under load becoming smaller, causing higher pneumatic pressure. It will depend

on the indentation characteristics of foam to what extent the foam will accommodate the buttocks.
The use of fluidised gel 'pockets' on or in foam has probably its greatest influence on heat regulation.

The different systems, materials and constructions each have there own possibilities and restrictions.
In figure V3-18 the results are shown of various commercial and experimental cushions. In the below one can see that good results can be obtained with different types of pressure-distributing and load bearing constructions. Note that the lowest internal pressure measured is 90 mmHg.

The maximal pressure measured as in the figure D3-18 above has been measured *internal* straight under the ischial tuberosities on the bone with the test buttocks. Notice that the pressure *between* the buttocks and the cushion: the so called interface pressure as on average in this research is about a half.
The pressure distributing quality as in this figure is shown as the key figure: PD: pressure distribution. The PD is expressed in a percentage of the load not taken up by two small areas around the tubera, in other words: the higher the percentage the better the load distribution of the cushion.



Pressure distributing medium	cover	support structure	name	max. pressure* mmHg	PD in % ***
air cells	thin fabric	flat board	Roho 1R89 HP	91	83
non liquid gel	fabric	hammock	Spenco toiletmodel	143**	85
air	rubber	hammock	BYE-BYE type WS	125	81
vulcanised hair		trampoline	experiment	106	80
Draka 9018 schuim 80 mm		trampoline	experiment	119	77
foam blocks 100 mm thick	thin fabric	hammock	Kubivent R104	138	70
fibre	fabric	hammock	Polycore with wool layer	136	76
viscous liquid	folie	Hard contoured shell	JAY Medical	160	68
polyether foam 60 mm thick	fabric	hammock	Etac, standard wheelchair cushion	143	73
foam + visco elast. foam	fabric	hammock	Bay Jacobson	149	72
aircells in foam	fabric	hammock	Bellows Air Flotation	145	71
Foam, cut	stretch	hammock	Uniblok	167	65
foam / gel / foam	nylon, coated	hammock	Charnwood LCD	140	71

*) internal pressure B2
beneath tuber
**) beneath trochanters
***) key figure for the quality of
pressure distribution on a scale of 0 - 100

Figure D3-18 : Overview of pressure distributing properties (PD) of different kind of cushion constructions, pressure distributing media and support structures.

D3.6 Summary and conclusions

The human posterior consists of the pelvis which is surrounded by soft tissues and sealed by skin. The weight of the upper part of the body is transmitted by way of the spinal column into the pelvis. The skin has the function of holding the mass of soft muscle and fat tissue together. The softer parts in combination with the skin form a pressure-distributing medium for the pelvis.
The pressure-distribution of the buttocks is at its most effective when their shape is maintained under load.

The pressure-distribution performance of a cushion is aimed at maintaining the shape of the buttocks when placed under a load. The cushion must adapt to the shape of the buttocks without such deformation of the cushion leading to high reaction forces. The shape of the support structure and the characteristics of the pressure-distributing medium are major contributing factors.
There is a fundamental difference between the performance of foam cushions and the performance of air filled and fluidised cushions. The deformation of foam produces a reaction force which increases in proportion to the increase in deformation, i.e. indentation. In a number of concrete cases the relative deformation appears to play an important role. The reaction force of air-filled and fluidised cushions depends on the way the surface reacts under load. The characteristics of the cover, or in the case of air-filled and fluidised cushions, the cushion sealing can exert a negative influence on pressure-distribution, since, when subjected to a load, it can, in combination with the pressure-distributing medium, bring about tensile stress in the surface under load which in turn impedes full conformity. There is a positive relationship between the pneumatic or hydrostatic pressure in the system and the tensile strength stated. The tensile strength in the surface under load can be positively affected by dividing the surface into a number of smaller surfaces.

The pressure distributing performance of a cushion chosen at random can be analysed and understood in theory by providing answers to the following four questions:

- To what extent does the support structure contribute to the conformity with the shape of the buttocks? In other words to what extent will the pressure-distributing medium be indented, or - in the case of foam - what level of relative pressure will be produced?
- What is the link between the indentation and reaction force of the pressure-distributing medium being used?
- To what extent does an (undesirable) tensile stress develop in the surface under load in its entirety and what is the influence of the cover on this phenomenon?
- Is the principle of pressure-distribution capable of reducing localised reaction forces under the ischial tuberosities?

It appears that the easier, read less resistance, the cushion conforms to the shape of the buttocks, the better the pressure distribution is. The form of the cover plays an important role here in. A hammock in general gives a better result than a flat board.

The interface pressure measured under the tubera is about half of the internal pressure taken internally under the seat bone. The results of the interface pressure therefore cannot be compared to the capillary pressure in the veins.

D4.0 Measuring, analysing and optimising sitting posture and pressure distribution in practice

In this chapter an account is given of the methods followed in the Pilot Project SMS Seating Advice that was carried out by the company P.R Stella and rehabilitation centre Het Roessingh in Enschede, the Netherlands. This pilot project started in Januari 2006 and will continue until the end of 2007.

D4.1 Aims and intention of the pilot project SMS Seating Advice

P.R. Stella has developed analysis software with which the results of pressure measurements taken in the seating interface can easily be interpreted and compared. This is the Sit Measurement System: SMS.
Interface pressure measurements cannot be evaluated without taking the parameters of the sitting posture into consideration. The optimisation of pressure distribution begins with the optimisation of the sitting posture. In section A of this book, a reference framework has been developed for the measurement and evaluation of a sitting posture. On the basis of the analysis of general sitting behaviour, a *general basic posture for wheelchair users* was defined. This basic posture was derived from an *anatomically sound, stable sitting posture,* that *begins* with a – defined – functional backrest inclination, angle($\varphi+\alpha$) of 115°, with the condition that the back must be individually supported in its individual natural curve. Another reference posture, the *average individually preferred posture* was also defined. In this posture the neck and shoulder muscles can relax because the head is in balance on the trunk and here also the back is given individual support. This posture has a functional backrest inclination, angle($\varphi+\alpha$) of approximately 123°.

Rehabilitation centre Het Roessingh aims to continue to be a centre of expertise for professional evaluation of individual sitting postures and seating support. The optimisation of *seating support* begins, as we have already mentioned, with the optimisation of the sitting posture. The one cannot be considered without the other. P.R. Stella’s long term goal is to introduce and promote the use of interface pressure measurement as an instrument for the optimisation of individual seating support. In the short term the results and analyses of interface pressure measurements will be used to optimise both the SMS analysis software itself and its practical use.

Together they aim to convince the care sector of the advantages of interface pressure measurement in the optimisation of sitting postures and seating support in terms of the reduction of symptoms for wheelchair users in the long run and an improvement of the quality of life of wheelchair users and therefore ultimately a reduction of (total) costs for the care sector.

The results of the pilot project so far show that there is great scope for improvement of standard wheelchairs. An individually optimised sitting posture based on anatomically sound stability is almost impossible to realise in any standard wheelchair.

D4.2 Measuring and recording a sitting posture

The seating angles – the seat angle, angle φ and the functional backrest inclination, angle(φ+α) – are defined along the relevant parts of the body under load (see chapter D1). They should then be measured 'under load' and on the body.
To facilitate this, two simple instruments have been developed following the principle that a strip is placed between the body surface under load that is to be measured and its support and that this strip is joined to another, parallel strip in such a manner that it protrudes from under the body. Using this parallel strip the position of the body part in space can be measured.
Measuring this angle is a difficult procedure. After some time one develops a feeling for the values found. If there is any doubt about the results, one should repeat the measurements.
Figure D4.1 shows the instruments for measuring the seat angle, angle φ. The lower part of the instrument with rounded corners is placed under the thigh lengthwise in front of the ischial tuberosity. Then a digital spirit level is placed along the protruding part of the instrument and the value is read, as is shown in figure D4.2.

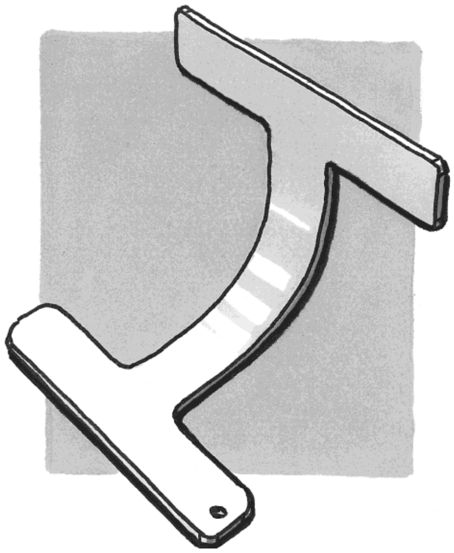


Figure D4-1: Aid for measuring the sitting angle φ under load.

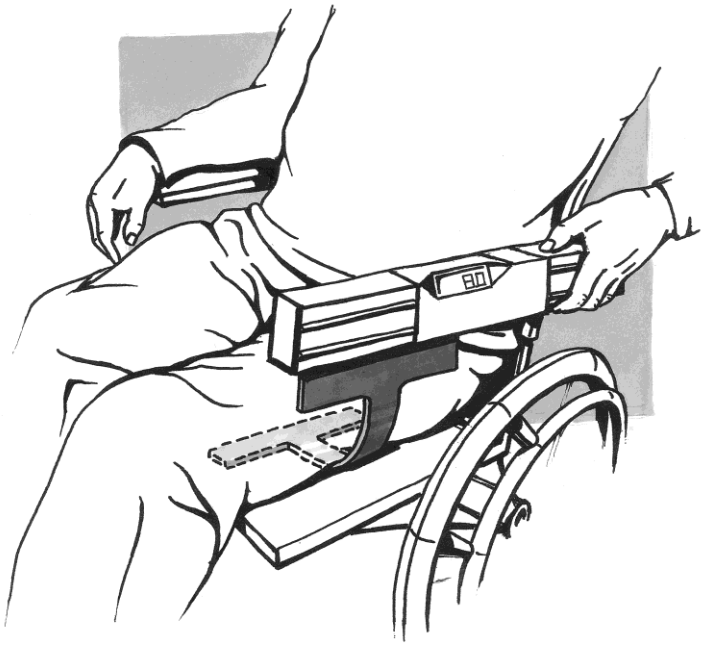


Figure D4-2: Measuring angle φ.

By way of control, a second measurement is carried out with the other leg and the value recorded. If the values differ by more than 2° without any visible reason for this, the measurements should be repeated.

Measuring the functional backrest angle is, if possible, even more difficult because the back is not always completely support by the backrest. The measuring instrument consists of a metal strip, bent in such a manner that three sections are formed. The end sections are parallel to each other and the middle section is at an angle of 165° to both of them. This situation is shown clearly in figure D4.3.

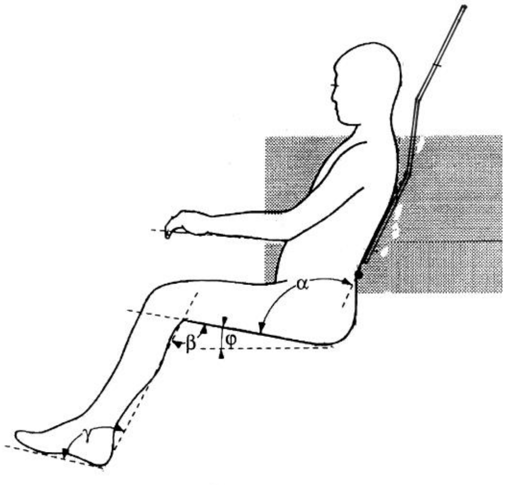


Figure D4-3: Measuring aid and experimental set up for measuring the functional backrest inclination, angle(φ+α) under load.

The lower part of the instrument is placed against the back above the small of the back. The bend in the instrument is placed at the height of the thoracic kyphosis. The measurement is taken along the protruding parallel section of the instrument. If the instrument shows, for example, 67º, the functional backrest inclination, angle(φ+α) is 180º - 67º = 113º.

In principle, the backrest inclination is measured along the body. As in existing wheelchairs the back and the backrest are not always in good contact, it is necessary to check that the instrument is in fact in position along the body. In order to avoid interference from protruding spinal vertebrae, the instrument is placed to the left and then to the right of the spine. Measurements are carried out on both sides and they may not differ by more than 1º and if they do the procedure should be repeated by way of control.

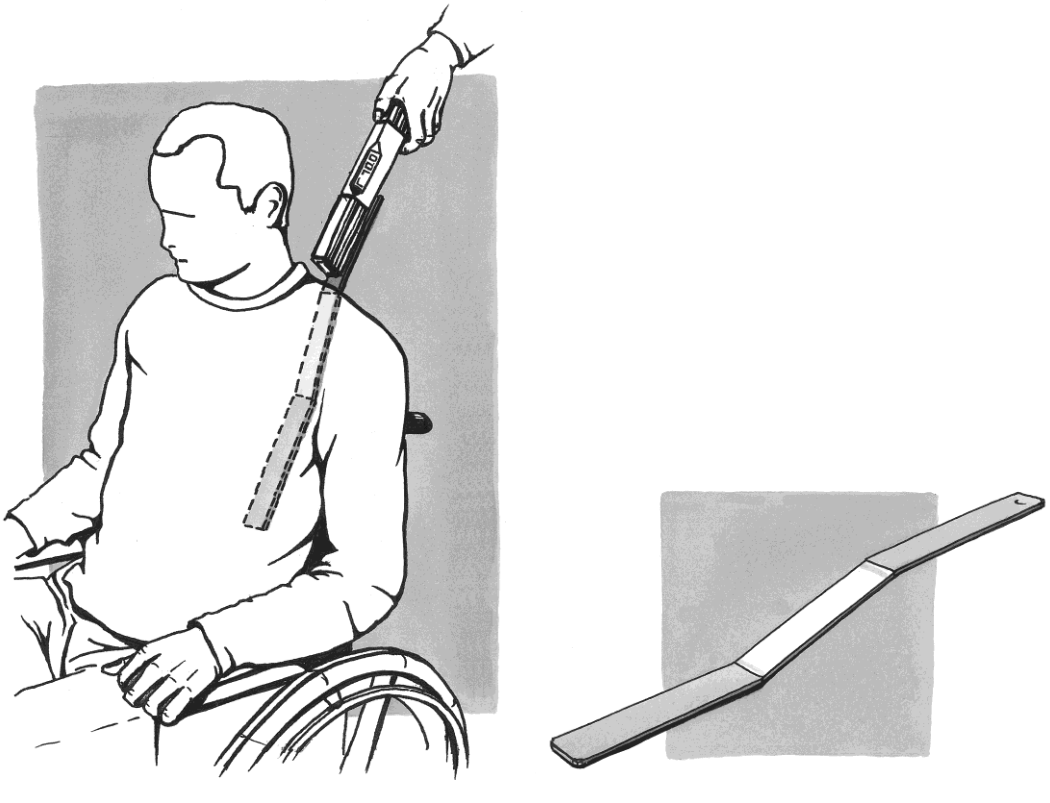


Figure D4-4: Measuring the functional backrest inclination, angle(φ+α) under load.

Once the seat angle and the backrest inclination have been measured the basis for the sitting posture has been established, but the extent of individual support for the back remains to be examined. The question is, in other words, to what extent does the back support facilitate the individual curvature of the back? It is essential to obtain information in advance from the client's doctor or therapist about the *mobility* and the *curvature* of the lumbar spinal column for this analysis. Sufficient space must be created for the buttocks to allow the pelvis to remain upright and allow the spinal column to follow its natural curvature. It is easy to see and especially to feel how much space there is for the buttocks in an empty chair. Measuring the position of the pelvis, angle λ, in any given situation under load is extremely difficult in a wheelchair partly because of the construction of the wheelchair itself.

Sitting height, width and depth of the wheelchair are all aligned to the anthropometric dimensions, the length of the lower leg, the width of the hips and the length of the thighs. These dimensions can best be measured in the empty wheelchair with an instrument that uses a sitting depth defined as the distance between the front edge of the seat to the place in the backrest where the upper part of the pelvis rests.

D4.3 Analysing and optimising sitting posture.

The optimisation of a sitting posture begins once the choice for the type of wheelchair and the type of sitting posture has been made. There is a choice between an unalterable sitting posture and a sitting posture that the user can vary to suit their activities: this, so-called tilt adjustment, gives the user the possibility to adjust the wheelchair into a good transfer posture (angle $\varphi = 0^\circ$), an anatomically sound stable posture (angle$(\varphi+\alpha) > 115^\circ$) and an individually preferred posture (angle$(\varphi+\alpha) =$ approximately 123°) by means of tilting the entire posture with a constant hip angle, angle α of approximately 104°. The problems involved in choosing the type of wheelchair are not explored further here.

An optimisation or intervention is, in principle, intended to afford the client an anatomically sound stable posture with an individual support for their back with the correct relation between the hip angle, angle α and the sitting angle, angle φ. *This should also involve an analysis of the existing sitting behaviour and recommendations for the desired sitting behaviour.*

The optimisation of a sitting posture begins with the analysis of the existing sitting situation and the existing sitting behaviour, and an analysis of the ability, or lack of ability, of the wheelchair user in combination with the characteristics of the lumbar spinal column. At this stage a number of questions and notions are of importance.

A. Is the wheelchair user’s condition due to illness or old age, or is it a congenital condition?
Congenital conditions can effect physical and motory development as a result of which one may encounter greater deviations from the reference postures than are usually seen.

B. What is the situation of the shape and mobility of the lumbar region? In other words, what can and should the end result of the individual support for the back be?
It makes sense to load even an immobile, stiff back in an anatomically sound manner, as otherwise a permanent kyphosing moment will be put upon the lumbar spine.

C. Is there any suggestion of impaired sensory perception or of a dysfunctional control system?
If this is the case the basic sitting posture for the wheelchair should be based on the individually preferred posture with the head in balance on the trunk. The average individually preferred posture has an angle$(\varphi+\alpha)$ of 123°.

In view of the correct equilibrium of forces, it is important that with every angle$(\varphi+\alpha)$ the correct angle φ is chosen in order to avoid frictional forces in the seating surface. A comfortable sitting angle or hip angle, angle α for the basic posture lies between 103º and 105º. This results in a seating angle, angle φ of approximately 12º. This is sufficient to prevent frictional forces in the seating surface.

Fitting a wheelchair begins beforehand with adjustment of the chair to the desired posture and dimensions as well as possible. Then, the functional result, the realised sitting posture, is measured. This is also the first step when one wishes to analyse and optimize an existing sitting situation.

The resulting measurements of the seating angle and the backrest inclination are then analysed and compared to the desired reference posture. At the same time a visual inspection of the symmetry or asymmetry of the posture is carried out, and an examination of the way in which the head is carried; specific behaviour that denotes stability or instability is observed, and an impression is formed of the way in which the back is supported and of the position of the pelvis.

The symmetry or asymmetry of the posture can be checked with the help of a number of reference lines as shown in figure D4.5. It is important to discover the cause of any asymmetry and to examine whether anything can be done to improve the situation.

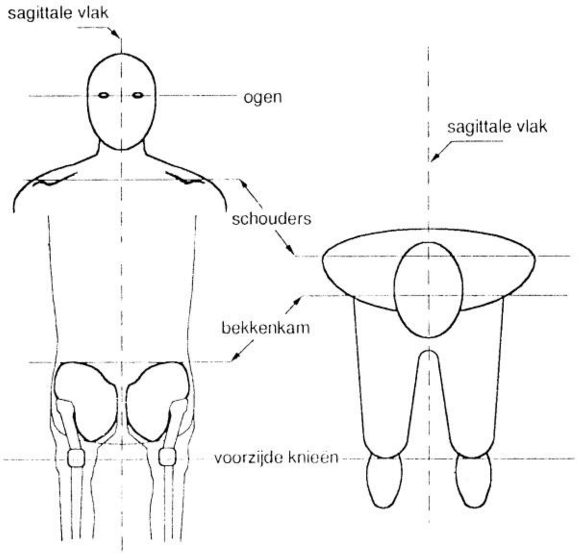


Figure D4-5: Reference lines to determine the symmetry/asymmetry of a posture.

In a sitting posture with anatomically sound stability, the trunk should, in principle, rest stably against a backrest with a normal backrest cross-section profile. Sitting behaviour can cause the stability to be lost as the trunk slips sideways resulting in an asymmetrical sitting posture. If the wheelchair user cannot correct this situation themselves then an undesired situation arises that could, in the long term, lead to deformity of the lumbar spinal column. This can be prevented in various ways. In the first place, the stability of the posture can be made less critical, for example, by choosing an angle$(\varphi+\alpha) > 118º$. Next, extra side supports can be fitted at the height of the lowest point of the waist triangle, and it is important to discuss the existing sitting behaviour and the desired sitting behaviour with some emphasis. Conscious and correct sitting behaviour is conditional for sound wheelchair use.

The measured values of the posture angles are compared to the desired values for an anatomically sound sitting posture, and, depending on the adjustment possibilities of the wheelchair, a strategy is determined as to how this can be realised immediately in this wheelchair or how it can be improvised temporarily in order to determine whether the therapist and the wheelchair user are satisfied with the result.
The first step for posture adjustment is individual support for the back; the rest follows on from there. The reason for this is that individual back support has a great influence on proprioception and therefore also on the control system in the brain and on the perception of comfort. It is easier to realise that a back that is not individually supported will transmit the ‘wrong’ signals and so have a negative effect on the optimisation process.

With the present generation of wheelchairs that afford only one sitting posture, it is a difficult task to realise individual support for the back. The backrest can often not be brought above the seat and the back support is usually flat, without any profile, so that there is little space for the buttocks and the pelvis will nearly always be tilted too far back. Also, the backrest is often too low. In order to render such a wheelchair suitable for a sitting posture with an anatomically sound stability, one must improvise with additional aids that facilitate the individual shape of the back and that create space for the buttocks.

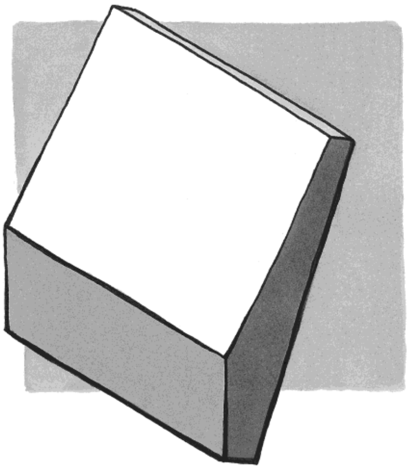


Figure D4-6: Wedge-shaped cushion as aid in a conventional wheelchair to create space for the buttocks and to achieve an anatomically sound stability.

Once the back has been individually supported, then the posture is measured again to judge whether this has produced the backrest inclination that will give *this* wheelchair user anatomically sound stability. One easy way to test this is to use an electrically adjustable tilt unit to slowly tilt the wheelchair further backwards. This unit has been developed in the pilot project. While this is happening one must observe the position of the head and see what influence this all has on the sitting behaviour of the wheelchair user.

During this whole procedure one should be prepared for two totally different aspects. Firstly one should be aware that the changes of posture can influence the stability of the wheelchair. In wheelchairs with a stability that renders them suitable for doing *wheelies* this could be too critical. It is easy to measure the stability by placing an angle measure device on a straight piece of the frame, for instance one of the armrests, and reading the value (backwards is positive!), and then bringing the wheelchair with its user into balance on the back wheels and reading the value again. The difference between these two values is the stability of the wheelchair. With a stability of 14º it is easy to make a wheely, with a stability of approximately 18º this becomes more difficult.

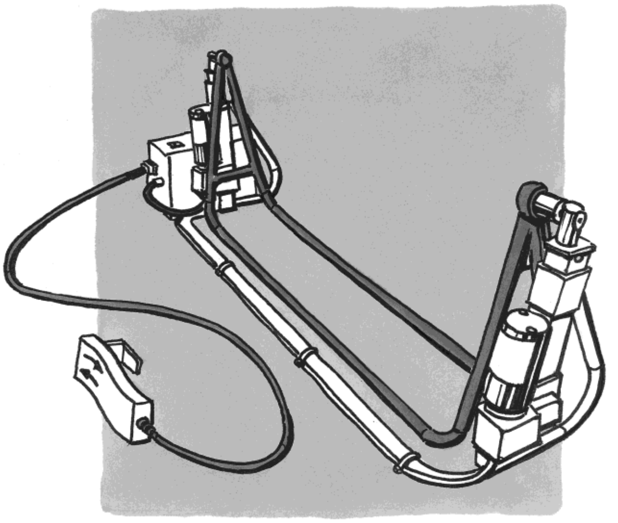


Figure D4-7: Electrically adjustable tilt unit for finding stability during fitting.

A second important aspect that one should consider during fitting is of a completely different nature. When a wheelchair only affords one sitting posture, the general aim is to sit the wheelchair user in an anatomically stable sitting posture. Stability *begins* with an angle($\varphi+\alpha$) of 115º. That is to say that the stability is critical in this posture. With a greater backrest inclination the stability will become less critical and the feeling of stability will increase. Moreover, the head will also be more in balance on the trunk and the perception of comfort will become heightened. This posture is well suited to watching television or carrying on a conversation, but less suited to having a meal or to handicrafts at the table. The danger therefore lies in optimising the posture to one in which one can carry on a conversation as this is what is happening at the time of the fitting. The fact that the wheelchair will only afford one posture means that one must find a compromise for the posture. There is a very real danger that one will forget this fact at the time of fitting.
Habit and specific sitting behaviour play an important role in the existing situation, which in turn is often the cause of complaints such as a painful shoulder or problems with the buttocks. Changing, having to change or wishing to change these habits and this behaviour is difficult: the body and the control system in the brain have, after all, adapted themselves to the existing situation over a long period of time. Wheelchair users will not always be able to experience a new and, objectively seen, better posture immediately. They will have to get used to the new situation and that takes time.

It is therefore of the greatest importance to afford new wheelchair users anatomically sound stability and individual back support and to inform them of all aspects of good sitting behaviour from the very beginning. This will prevent many problems.

As well as affording a good sitting posture, it is essential to teach the wheelchair user how to sit down properly in the afforded posture. If the tuberosities are not correctly positioned on the cushion in relation to the backrest then this will directly affect the extent to which the back is individually supported. Moreover, a pelvis that is tilted too far backwards has a negative effect on the pressure distribution, a fact that has become clear during the pilot project.

A special situation arises when, due to problems, a sitting posture has to be optimised in a wheelchair with electrically adjustable tilt in combination with an electrically adjustable backrest. The backrest adjustment is, in principle, intended for adjusting the sitting angle, angle α. The position of the trunk in space, angle($\varphi+\alpha$), should, in principle, be realised by means of the tilt mechanism. The desired range of adjustment of the sitting angle, angle α, is usually only very limited in active use: 103° - 105°. With a smaller angle the tummy would quickly become too confined and with a larger angle the chance of frictional forces in the seating surface is greatly increased. The adjustable backrest can be used to create a more comfortable posture for resting or sleeping, at least, if the seat angle, angle φ has a large enough range. Quite apart from the specific – ergonomic – demands that can be made on the movement of the backrest, it should now be obvious that sensible use of the adjustment possibilities will require a lot of instruction for the user. Otherwise the solution could prove to be much worse than the problem as was clearly shown in one case in the pilot project.

After this general description of what goes on during a fitting, here are a few remarks on special situations.

For the spinal column to be in a correct vertical position, it is important that the pelvis, or the sacrum, should be level. Should there be any discrepancy in the level due to unequal height of the tuberosities or to atrophy of the gluteus maximus on one side, then this should be corrected *in the supporting structure*.

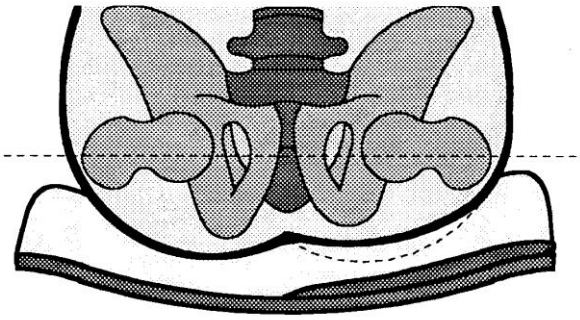


Figure D4-8: Correcting asymmetry in the pelvis by raising part of the supporting structure.

If there is any asymmetry in the spinal column with a scoliosis, for example, then it is of the greatest importance that one proceeds from a very stable posture (angle(φ+α) > 118°), as otherwise the effectiveness of the usual three point support will be seriously lessened. Moreover, a greater angle(φ+α) will ensure more favourable loads on the spinal column and, at the same time a reduction of the load moments (force x perpendicular distance) that cause the scoliosis to increase.

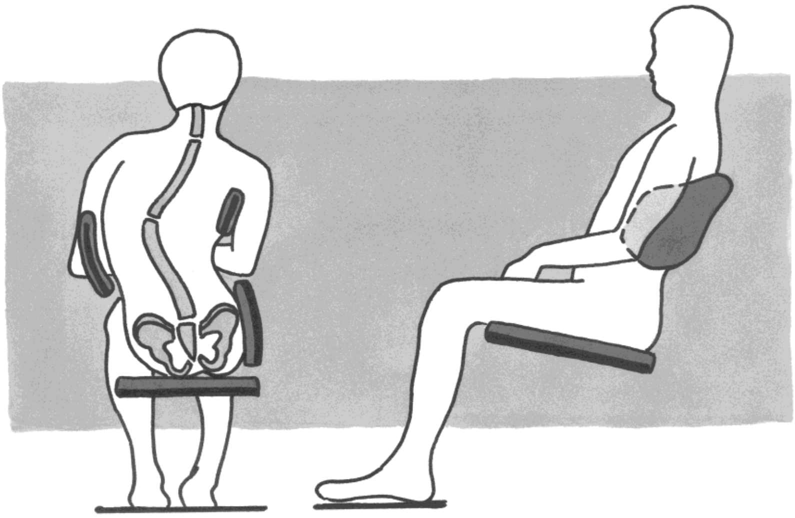


Figure D4-9: An effective three point support for a scoliosis in a stable sitting posture with a backrest inclination, angle(φ+α) > 118°.

D4.4 Measuring and interpreting pressure distribution

When a person is sitting, the weight of the upper body is conveyed down the lumbar spinal column into the pelvis and then transferred via the ischial tuberosities and a thin layer of soft tissue to the seat. The seat reacts with a reactive force that is equal to the total weight of the load on the seat. This reactive force is the load on the buttocks.

This load is seen to be unevenly distributed across the buttocks. In figure D4.10 a general pattern of this distribution has been included as can be measured between the buttocks and the seat: the so-called 'interface pressure'.

This pattern is characteristic and is found in all experiments. The highest pressure is always observed under the bony protrusions in the buttocks, the ischial tuberosities. This is also the area where usually most problems occur. The pressure distributing capabilities of a cushion should indeed be understood to mean the property of reducing the pressure under the tuberosities as much as possible. The tuberosities need to be relieved of their load. As the total sitting load remains constant in any one posture, then the areas around the tuberosities must take on – a little – more load: the pressure is ‘distributed’ to the benefit of the pressure under the tuberosities.

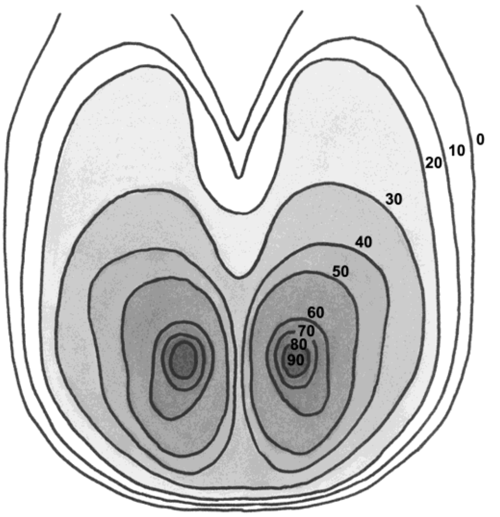


Figure D4-10: A typical pattern of pressure distribution across the buttocks showing that the interface pressure is highest under the ischial tuberosities and decreases towards the outer edges.

The pressure distribution of a cushion is measured using a pressure mat. A large number of pressure sensors are built into this mat to measure the interface pressure, the pressure *between* the buttocks and the cushion. The pressure sensors usually used are based on the principal of reduction of electrical resistance under load. The sensors are individually calibrated and the results are recorded by a software programme. Calibration should be repeated frequently. During a measuring session the resistance of a sensor is read with a frequency of between 5 and 15 times per second and is compared with the calibration data. The pressure can be calculated from these readings.
Modern systems have a heart-to-heart distance of less than 16 mm between sensors, which means that a pressure mat contains approximately a thousand sensors. The measuring accuracy of such a system is not very high, and varies per system and with the age of the mat.

A pressure measurement is a random indication at one moment in time and is determined by a great many variables. Many of the variables are connected to the sitting posture. Recognising and controlling these variables is the first requirement for a good pressure measurement and for a correct interpretation of a pressure measurement.
It is important to pay attention to the symmetry of the posture while measuring, to the clothing (it should not be too tight or folded double), to the way in which the arms are supported, to the position of the head (the gaze direction), the position of the footrests, the positioning of the pressure mat on the seat, et cetera. Measurement should be repeated completely at least once, that is to say right from placing the pressure mat, in order to gain a good impression of the quality of the measurements and to exclude any coincidences. In practice this is barely feasible.

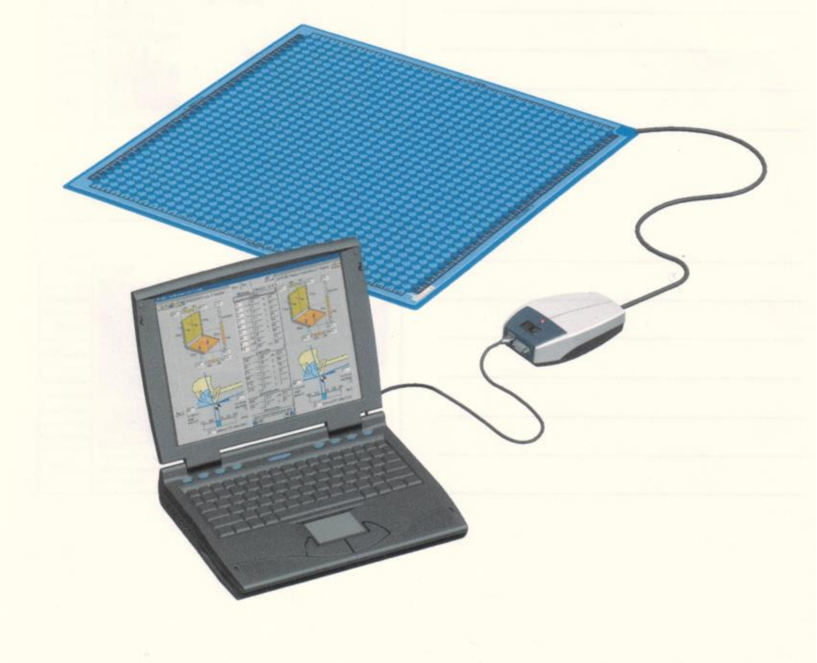


Figure D4-11: The SMS – Sit Measurement System.

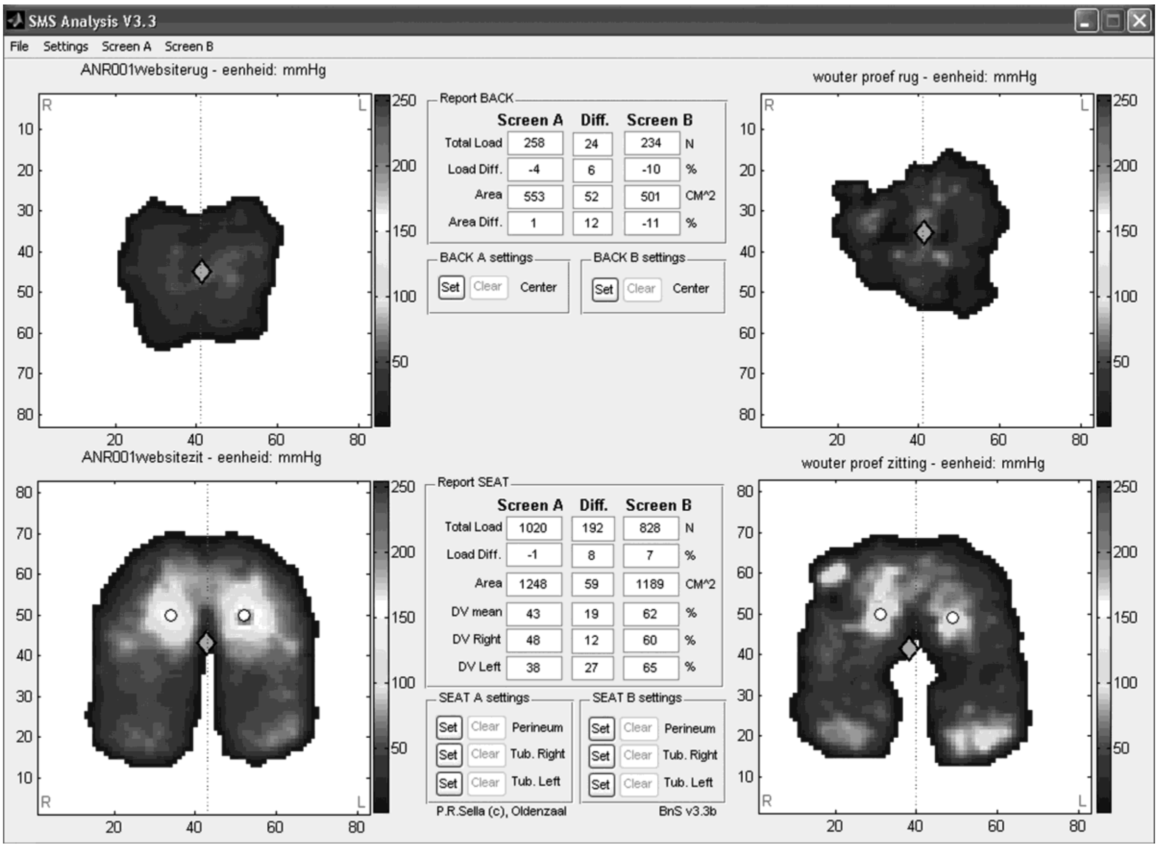
The reason for pressure distribution is to distribute the locally high load under the tuberosities as well as possible over the buttocks. It is, in fact, the intention that the load under the tuberosities should be as low as possible. Here lies the judgement criterion for the quality of pressure distribution.
The SMS software has been developed on the basis of this essential aspect of pressure distribution. The large quantity of data is brought down to a few representative index numbers with which the pressure distributing qualities of a cushion can be defined. A very important index number is the index number for pressure distribution: PD

The following example will clarify the algorithm behind the index number PD. Take a person weighing 75 kg: their sitting weight will be approximately 600 N. This is the load that the cushion will bring to bear on the buttocks.
Suppose that the small areas around the tuberosities absorb 200 N of that load, then that means that the rest of the buttocks absorb 40 N. That is 400/600 = 66% of the total load.
Suppose now that, after intervention, those same small areas around the tuberosities absorb 150 N, then the rest will absorb 450 N. That is 450/600 = 75% of the total load.

This example shows that as the percentage becomes higher, so the load on the tuberosities becomes lower. That is precisely what is intended. In fact, with this approach a simple and effective index number has been defined for the extent of pressure distribution PD on a scale from 0 to 100. An important advantage of this approach is, moreover, that the results from multiple pressure sensors are involved in the evaluation. This increases the accuracy of measurement.

In the SMS software, algorithms have been developed to detect the position of the tuberosities and an acceptable size for the area around the tuberosities has been chosen for calculating the PD.
The algorithm that calculates the PD does this in such a way that equivalent pressure under the tuberosities will always result in the same magnitude of the index number for PD with different sitting weights or different people. This approach can be used for calculating the PD of the complete buttocks but also for calculating the PD of either the left or the right side.

There is no accepted level of pressure distribution that will guarantee the prevention of decubitus for every wheelchair user. The individual – physical – variables are too widely spread for this. Therefore it is necessary to aim to realise the maximum feasible for each and every individual. The SMS software is a great aid for this.
SMS has a screen option where the results of a measurement session, for example, after intervention, can be compared to a previous result. The pressure scans will be shown side by side on screen and the relevant index number are also displayed next to each other and can therefore easily be compared.



Report BACK

	Screen A	Diff.	Screen B	
Total Load	258	24	234	N
Load Diff.	-4	6	-10	%
Area	553	52	501	CM^2
Area Diff.	1	12	-11	%

Report SEAT

	Screen A	Diff.	Screen B	
Total Load	1020	192	828	N
Load Diff.	-1	8	7	%
Area	1248	59	1189	CM^2
DV mean	43	19	62	%
DV Right	48	12	60	%
DV Left	38	27	65	%

Figure D4-12: The SMS comparison screen.

As well as the key figures for pressure distribution, PD Left, PD Right some index numbers are calculated with which the magnitude of the PD can be analysed and finally explained: *Sitting weight* left and right, and *Load area* left and right.

D4.5 Cushions: covers, pressure distributing media and support constructions

In order to be able to manipulate the pressure distributing effect of cushions one has to understand the construction and working of various types of cushions. See also chapter D3.

A cushion always consists of:
- a support construction that conveys the sitting weight to the frame,
- a pressure distributing layer,
- usually a soft top layer,
- an upholstered cover.

There are various types of pressure distributing media:
- foam, in various densities (kg/m3) and hardness or rigidity,
- rubberised hair/natural fibres, in various densities (kg/m3) and hardnesses,
- air, in various constructions,
- liquid gel, in various constructions or combinations,
- non-liquid gel (proves to be hardly effective in distributing pressure),
- combinations of these, for example, foam and liquid gel.

If the support construction has the shape of the buttocks or takes on this shape under load, then this means that the pressure distributing medium that is on top of it will only have to change shape slightly to take on the shape of the buttocks. When foam or rubberised hair are used as a pressure distributing medium this results in a spectacular improvement of the distribution of pressure compared with the same material on a flat plank of wood.
A soft top layer can be added to improve the softness of the surface and may also play a role in the regulation of heat and moisture. The cover should be smooth, soft and stretchy as otherwise the quality of the pressure distribution may be negatively influenced due to the introduction of an extra horizontal aspect, known as the hammock effect. The quality of the cover also has an effect on the magnitude of the softness of the surface. Folds in the clothing should disappear into the cushion, not into the skin!

Foam behaves, in principle, like a spring: the greater the compression, read distortion, the greater the reactive force. This distortion does not only have a vertical, but also a horizontal, component. Vertical incisions break the horizontal relationship which causes the cushion to be softer at that point. This can be used strategically in certain places, such as for example, around the tuberosities.

One possible exceptional application of foam is in so-called *custom contoured seats,* as long as the *support construction* really is custom contoured and positioning on the cushion is not too critical. Most existing custom contoured seats are cut in foam with a flat plank as support construction after an impression of the buttocks has been made. In view of the properties of foam, this approach is far from optimal. It is far

better to make a custom contoured support construction and to cover this with a layer of fairly soft foam.
Individual back supports are also often cut from a bock of foam. This approach does not result in an aesthetically pleasing or good support.

Rubberised hair or coir has properties comparable to foam, depending on the density and rigidity. In any case, this material also has a definite horizontal component in the reactive force to the sitting load and the support construction will have a great influence on the extent of the necessary distortion. As long as it is covered with a fabric that allows moisture to permeate, this type of pressure distributing medium has *excellent* heat and moisture regulating properties. These aspects are extremely important for the perception of comfort and in the prevention of decubitus.

The pressure distributing working of cushions filled with air, water or liquid gel is based on one and the same principle. The pressure distributing medium is necessarily enclosed in a casing. It takes very little force to distort the pressure distributing medium inside the casing. Equilibrium occurs as soon as the pressure of the fluid or air in the casing is equal to the average pressure on the surface under load. As a result of the air or hydrostatic pressure, an undesired tensile stress will, in principle, arise in the casing. This problem is alleviated by dividing the surface into very small, separate components that are connected with each other, comparable to the incisions made in foam cushions. This is the principle of the well-known Roho cushion.
Due to this principle, Roho cushions do not afford any sitting stability at the sides unless a left and a right compartment are created that can be closed off from each other. During the closure between these compartments one has to sit ‘properly’ and symmetrically, and to sit down in that manner after every transfer. In practice this proves to be rarely the case.
The pressure that occurs *within* this sort of system lies in the region of 35 mmHg. A comparable pressure is often found as the average pressure in interface pressure measurements. An important variable in this sort of system is the amount of air that is in the system. If there is too much air one will be balancing on top of the cushion and the surface under load will be too small; if there is too little air then there is a risk that one will sit *right through* the cushion and that there will be no pressure distribution whatsoever. The top surface that arises under load, a crumpled layer of distorted rubber sacks, renders interface pressure measurement using pressure mats extremely difficult. Because of this, measurement results are difficult to interpret.

A liquid gel cushion that is still popular at the moment, the Jay cushion, is in fact a combination cushion, as not all of the cushion is filled with liquid gel. The liquid gel is mainly around the area of the tuberosities and is contained in a sort of open dish with an open back as support construction. The rest of the buttocks is supported by another pressure distributing material. Making the fluid thicker or mixing in micro balloons or the like, has, in principle, no effect on the pressure distributing working, but does affect the specific gravity and the speed or lack of speed with which it adapts to the shape of the buttocks.
Existing air, water and liquid gel cushions have no special facilities that reduce the pressure at the location of the tuberosities. This is possible with cushions that use foam as pressure distributing medium.

A good cushion also has the following properties:

- it is lightweight,
- it can easily be taken out of the wheelchair, replaced and fixed,
- it offers good stability at the sides,
- it has a solution to reducing the pressure where the tuberosities are located,
- it allows and easy transfer,
- it has a cover that allows moisture, but not water, to permeate,
- it has good moisture and water regulation.

D4.6 Analysing and optimising pressure distribution

Optimisation of pressure distribution, that is, of the seating *support*, begins with optimisation of the sitting posture. The sitting posture is after all responsible for the magnitude and direction of the external loads on the buttocks and the back. The relation between angle φ and angle α must be chosen such that frictional forces in the seat are absent from the equilibrium of forces.

Cushions cannot 'resolve' these frictional forces.

A good sitting posture provides anatomically sound stability for the trunk. This stability arises with an angle($\varphi+\alpha$) of approximately 115º. An anatomically unsound stability arises with a smaller angle($\varphi+\alpha$), if one 'hangs in one's back' with one's pelvis tilted backwards.

The sitting posture and the manner in which the back is supported determine the position of the pelvis and the extent to which the natural individual shape of the spinal column can be adopted. The position of the pelvis influences the pressure distribution. The pressure distributing ability of the buttocks is best utilized when the *shape* of the buttocks is maintained *under load.*

In order to gain insight into the time aspect of the load and therefore the extent of the risk, it is necessary to analyse the sitting behaviour. Here it is important to to discover the extent to which the wheelchair user is aware of the risk of decubitus and the extent to which they are capable of doing anything about it by consciously changing posture or lifting themselves. The possibilities of the given wheelchair, such as a tilt mechanism, also play a role here. Where there are possibilities for active sitting behaviour then the wheelchair user should be *properly* instructed and should adopt this behaviour.

There are a number of general initial points that are important for the analysis and optimisation of pressure distribution.

- A good cushion takes optimal advantage of the inherent pressure distributing capabilities of the buttocks;
- A good cushion therefore takes on the shape of the buttocks without distorting them. This happens when the forces needed to distort the cushion are low. The cushion must distort, not the buttocks;
- A good cushion maximizes the surface under load;
- A good cushion has a soft, preferably open top layer with a stretchy, cover that allows moisture to permeate;
- In a good cushion the tuberosities will be relieved of more load by letting the rest of the buttocks carry a little more load.

Knowledge of and experience with the various pressure distributing systems and support constructions are a definite requirement for the optimisation of pressure distribution.

Optimisation of the seating support begins with the optimisation of the sitting posture to an anatomically sound, stable sitting posture. Correct positioning of the pelvis in space is an advantage for the individual support of the back and vice versa, and it also takes maximal advantage of the pressure distributing ability of the person's buttocks. In the optimal sitting posture, the coccyx is not put under (extra) load. Now the pressure distribution is measured again in the optimised sitting posture and the result is compared with the earlier result. Two situations can now arise:

- the pressure distribution result is not worse, but better;
- the pressure distribution result is worse.

Our experience after measurements with 35 people in 2006 in the pilot project SMS Seating Advice is that posture optimisation nearly always gives an improvement in the pressure distribution results.
If the result is better, the question arises as to whether this is – for the time being – enough, or if it could be even better. If the result is worse, then one must analyse why this is the case and whether is the present circumstances or with a different cushion this can be resolved.
In fact, in both cases an analysis of the pressure distribution situation should be carried out: how do the characteristics of the person's buttocks relate to the properties of the cushion? In appendix 1, a checklist, *buttocks – cushion analysis,* has been included for this analysis.

The whole process of optimisation of the sitting posture and the seating support is highly taxing for someone in rehabilitation because of the transfers and having to lift for the pressure mat to be placed. This means that it is not possible to try out a great number of cushions.
Testing of any new cushion should, therefore, be based on a well made 'calculated guess'. This is possible if one possesses a lot of knowledge on pressure distributing systems and has amassed plenty of practical experience.

D4.7 Summary and conclusions

Systematic measuring, analysis and optimisation of sitting posture do not only result in a sitting posture with anatomically sound stability and individual back support but also improves pressure distribution.
After seating giving advice consultancies to 50 people in 2007, there is confirmation that an anatomically sound sitting posture begins with an angle$(\varphi+\alpha) > 115^\circ$, and that there is a clearly noticeable tendency that the pressure distribution is improved when the sitting posture is optimised on these principles.
The optimisation of pressure distribution can only be realised by understanding the way in which pressure distribution occurs in a cushion and by comparing the results of pressure distribution measurements taken with various supports in a sitting posture with anatomically sound stability. SMS analysis software has proven to be an extremely helpful instrument for this task.

Appendix 1 Checklist for buttocks – cushion analysis

Analysis of the buttocks:

- how great is the seating load?
- how large is the surface under load?
- how much soft tissue does the user have: more or less than normal?
- how much risk is there of decubitus?
- Is there any suggestion of a relapse?

Analysis of the cushion:

- what is the principle of the pressure distributing medium?
- can the pressure distributing medium be influence/adjusted?
- how hard / soft is the cushion?
- have any special measures been found in the pressure distributing medium?
- what sort /shape is the support construction?
- can the support construction be influenced?
- in the case of a hammock: how great is the sag?
- is there sufficient soft top layer present?
- is the cover supple enough?
- how good are the moisture and heat regulating properties?

Analysis of the buttocks on the cushion:

- where are the tuberosities in relation to the backrest?
- what is the position of the pelvis / shape of the back?
- how great is the surface under load?
- how much is the cushion being depressed (if possible penetrate the cushion with measuring rods)?

What is impeding the realisation of good pressure distribution?

- does the cushion easily take on the shape of the buttocks?
- does the shape of the support construction aid the adaptation to the shape of the buttocks sufficiently?
- is the pressure distributing medium soft enough?
- is the top layer soft enough and permeable to moisture?
- have special measures been taken to reduce load on the tuberosties?
- is there enough soft top layer present?
- is the top layer smooth, supple and stretchy enough?
- does the cushion afford enough sitting stability?
- is a transfer easy?