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Dynamic Pressure Measurements at the Interface between Residual Limb and Socket —the Relationship between Pressure Distribution, Comfort, and Brim Shape

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SUMMARY

Using a flexible sensor, peak pressures were measured at the interface between the thigh and a simulated above-knee (AK) socket brim, with an experimental subject (a non-amputated person) wearing a simulated prosthesis. Also, dynamic pressure curves were recorded with two amputees wearing their own prostheses.

An "aerostatic" casting procedure, using air pressure to apply uniform pressure to the plaster of paris cast as it hardened, did not provide an adequate AK socket.

The pressure at the tuber ischii is almost independent of the radius of the anterior curvature of the gluteal-ischial seat in the posterior section. The pressure distribution on the gluteus maximus muscle varies inversely with the radius; the smaller the radius, the higher the pressure. The tuber ischii part of the vertical force, on a brim with a radius of 15 mm, is roughly one-fifth of the total vertical force exerted by the gluteus maximus muscle, and therefore the term "gluteal-ischial" seat is more appropriate than "ischial" seat.

The feeling of comfort of an AK socket depends, among other things on the radius of the anterior curvature of the gluteal-ischial seat in the vertical section, as well as on the shape of the brim in the horizontal plane and on the pressure pattern at this brim; these three are interdependent.

The "clamping force" with which the two parts of the Hosmer casting brim are brought together and with which the plaster cast is made might give a good measure of the looseness or tightness of the AK socket; particularly, it may quantify the difference between the usual suction socket with snug brim and the easy-to-don socket for the geriatric amputee.

Internationally there is no agreement about the shape of the brim of the AK socket. Theoretically, this shape should be more in conformity with the bulging of contracted muscles or of a tensed tendon, because these are places with high pressures or sharp pressure gradients. Common workshop practice is already working empirically according to these principles, but dynamic pressure measurements might give them a scientific base. Perhaps in this way it will be possible to find a brim more generally accepted by prosthetists, which would make us more independent of their hands and of their individual ideas about AK socket making.

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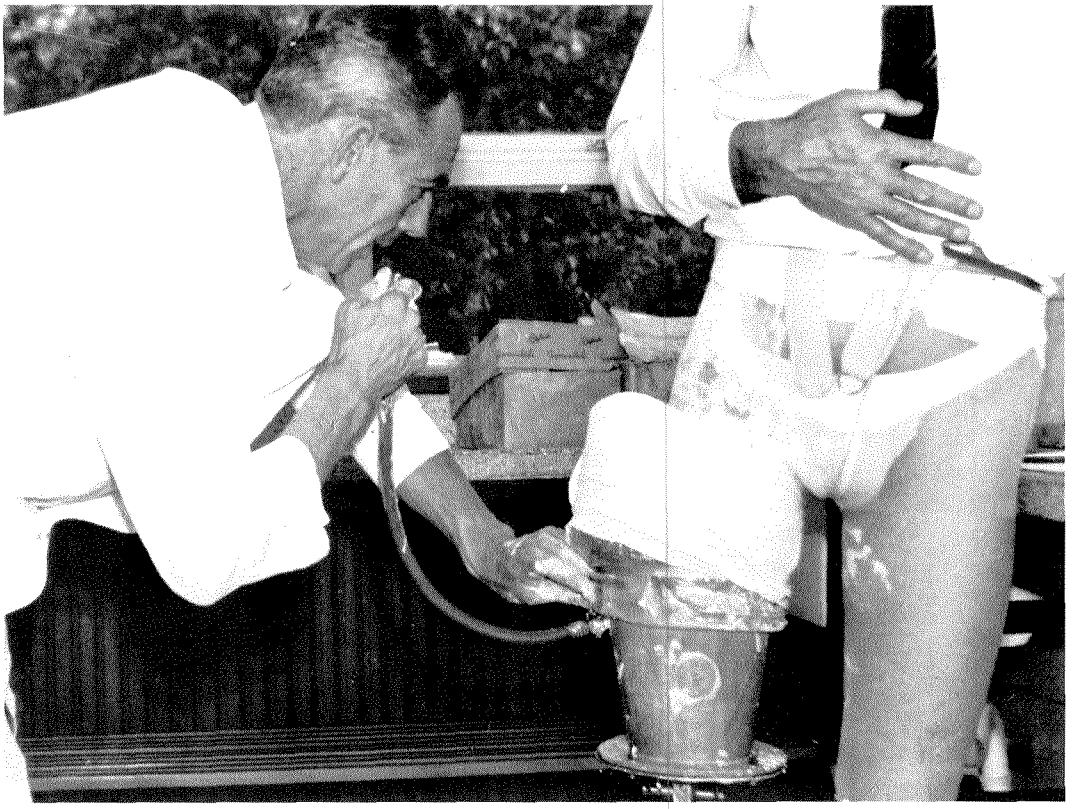


FIGURE 1.
Making a plaster cast of an above-knee stump with the aerostatic procedure.

INTRODUCTION

Program Guide G-5 of the Prosthetic and Sensory Aids Service of the Veterans Administration (1) discusses the Total Contact Above-Knee Socket and puts forward two statements.

First, it states that proximally the pressures have to be sufficient for horizontal and vertical stabilization, and that these pressures diminish gradually to the distal region. Second, it states that the theoretical ideal would be a "hydrostatic" fit with all pressures equal.

These two contradictory postulates form the starting point of our investigation.

Many amputees complain of pain at the brim of their above-knee socket, and they feel this pain near the perineum, particularly at the tuber ischii area, at the inferior ramus of the os pubis and os ischii or at the tendon of the adductor longus muscle. In rare cases, pain is localized at the os pubis, if there is a sharp forward inclination of the pelvis.

In this investigation we considered only pain caused by the shape of the brim and/or the curvature of the gluteal-ischial seat of the above-knee socket, and we tried to find out whether there was a relation between them. (We did not include pain caused by an adherent scar, a detached piece of bone, a painful flexion contracture, inflammation of the residual limb, degenerative hip disease (coxalgia), or referred pain from a spinal nerve as in sciatica.) If an increasing pressure is exerted on the human skin by a blunt object, this will first be felt as contact, then as increasing pressure, and finally as pain. Inversely, it is assumed that if pain is felt, the pressure is undesirably high at that point and the shape of the socket is not optimal.

Our first attempt to eliminate pain was aimed at making a "hydrostatic" fit with all pressures equal, using the aerostatic casting procedure. The technique used shows much similarity with the hydrostatic casting procedure described by Murdoch (2) for the below-knee amputee and used by Redhead (3) for the above-knee residual limb. Independently and at the same time, in our work with the above-knee amputee we have been using air (instead of water) to apply an equal pressure to a plaster of paris wrapping around the residual limb while it hardens. We also used a container with a flexible plastic bag inside, hermetically sealed to the outside (Fig. 1). Through a valve, air could be blown into the annulus between the plastic bag and the container. The above-knee amputee, with his residual limb wrapped with plaster bandage, put it into the plastic bag with a load of approximately 50 x 9.8 N (= 50 kgf). He had to take care not to let his residual limb touch the container medially, or at the back. In this way we made a plaster cast and from it a plaster model and a laminated plastic socket.

As a pilot experiment, a single socket was made for an above-knee amputee with this technique — it turned out to have a brim 3½ cm wider than his regular socket. The amputee

had no control of this new prosthesis due to lack of proximal fixation of the residual limb, both in the frontal and in the sagittal plane. The amputee could stand comfortably but could not walk. Obviously, proximally a higher pressure would seem necessary for proper stabilization. (As we had not yet developed the flexible sensor, no pressures were measured in this stage of the experiments.)

Accepting this preliminary evidence that this aerostatic fit did not provide an acceptable socket brim, we then started using a casting brim and evaluated the dynamic pressure patterns at the residual-limb/socket interface. The experiments consisted of two parts:

1. Measurements of peak pressures on the gluteal-ischial seat and on the anterior curvature of the seat as a function of the radius of this curvature and with special attention to the pressures near the tuber ischii. These pressures have been measured using as subject a person without amputation wearing a simulated prosthesis. By measuring these pressures, we tried to get a better insight into the pattern of these pressures on the gluteal-ischial seat and in particular at and near the tuberosity.

   By changing the curvature of the gluteal brim, we tried to find a relation between the radius of this curvature and any pain which was reported at the brim.
2. The measurement and recording of dynamic pressures in all parts of the above-knee socket, inclusive of the gluteal-ischial seat. Two amputees were subjects for this experiment. The pressures measured in their own previously worn sockets were compared with those obtained with new sockets produced from casts made using a Hosmer casting brim.

METHODS

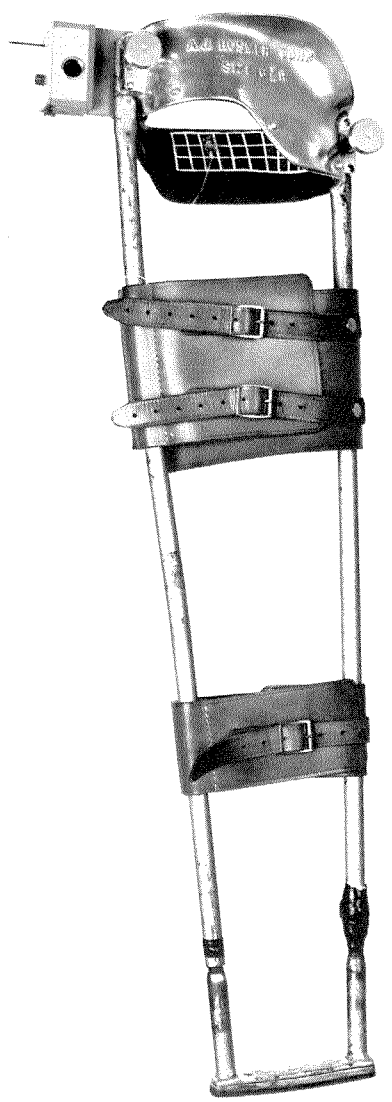
We measured only "normal" pressures; i.e., pressures perpendicular to the local socket wall or seat. We did not consider shear forces parallel to the wall because the skin is very easily moved over subcutaneous tissue, and therefore the shear force will be small. Vlasboom (4) comes to the same conclusion in his thesis. Bennett (5) states that little shear stress will be experienced by flesh within the socket, but a great deal may occur at or outside the brim.

The measurement of normal pressures at an interface is a general problem in prosthetics (6, 7, 8, 9, 11, 12). If a sensor is placed at the interface, the existing pressure pattern is disturbed (13). Another source of difficulty is the fact that the interface between residual limb and socket is usually curved. Since it was our object to measure pressure at any place in any socket of any patient, no existing pressure transducer could satisfy the requirements. Instead, a thin, flexible "sensor disk" was devised and employed to transmit a hydraulic pressure signal from within the socket to a transducer outside of the socket. The sensor's flexibility allows its use on either curved or flat surfaces, to which it is attached by double-coated adhesive tape. The arrangement is described and represented schematically in "A New Method for the Measurement of Normal Pressure between Amputation Residual Limb and Socket" (14).

Data From Simulated Prosthesis

In the first series of measurements, the output signal of the transducer was connected to a voltmeter. During walking the highest pressure occurring at each step was noted, and the mean value of 15 steps was calculated. These experiments were carried out on a healthy subject of 72 years of age, using a simulated above-knee prosthesis. This simulated prosthesis (15) consisted of a series of modified Hosmer casting brims, successively mounted on a Thomas splint (Fig. 2) without knee or ankle joints and terminating distally in a narrow supporting

FIGURE 2.
Simulated above-knee prosthesis: Hosmer casting brim mounted on a Thomas splint.



bar or patten between the heel and ball of the shoe of the subject. The subject wore a second sole or lift on the shoe of the opposite foot to equalize leg length (Fig. 3) and a pantyhose to diminish friction and for easy donning of the prosthesis.

A different kind of simulated prosthesis is the one with 90 deg flexion in the knee and suspended lower leg, allowing an artificial knee to be used and an artificial foot. We preferred the Thomas splint, simulating the gait of an amputee with a peg-leg, because from 80 to 90 percent of the newly amputated patients are more than 65 years old. These geriatric amputees have a high risk of falling, and it is wise to give them a knee with external fixation and to have them walk with a stiff knee.

The Hosmer casting brim is the Berkeley Adjustable Brim designed by the University of California, Berkeley, and produced by A.J. Hosmer Corp. It has only two parts, which could be modified easily for our experiments. The brim of the gluteal-ischial seat is a straight line in the horizontal plane but if viewed in vertical anterior-posterior section it has a curvature with a radius of 15 mm, which is the same from medial to lateral.

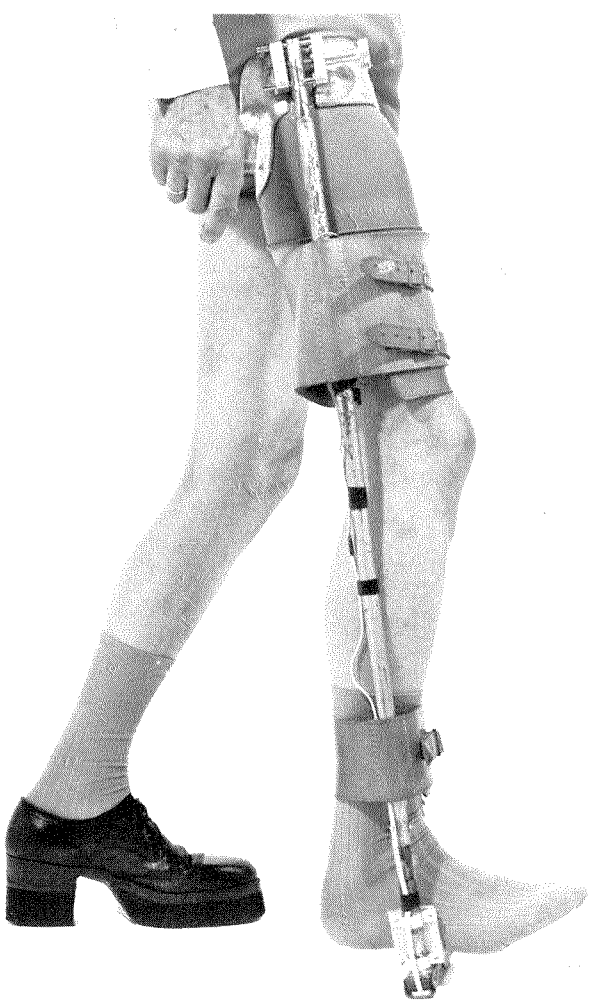


FIGURE 3.
Non-amputated subject using a simulated prosthesis, consisting of a Hosmer casting brim mounted on a Thomas splint. Second sole on the shoe of the opposite foot is provided to keep the subject's pelvis horizontal.

On the medio-posterior half of the casting brim a network of 4 horizontal and 11 vertical lines was drawn (Fig. 4). At the 44 intersections the peak pressures were measured, one spot at a time at successive walking trials under substantially similar conditions. To vary the curvature of the gluteal seat, five additional units of the posterior half of the Hosmer brim were cast in hard plastic with different curvatures: 7.5 mm, 15 mm (that of the original Hosmer brim), 22.5 mm, 30 mm, 45 mm, and 200 mm (plug fit). With each of these brims maximum normal pressures were measured at 44 points during walking.

Data From Amputees

In the second series of experiments, pressures were measured with two amputees who had fundamentally different stumps: a young man (amputee A) of 22 years with a muscular stump and a woman of 55 years (amputee B) with a flabby stump (Fig. 5). These cases represent two extremes, with the firmness of most stumps (including the geriatric stump) between them. The young man had an above-knee amputation because of a tumor and had worn his prosthesis for 1½ years without complaint. The woman was amputated 30 years ago after a car accident and had a suction socket prosthesis at the time of investigation. The sockets of their prostheses were "open" wooden suction sockets, and both had been made with pencil and measuring tape by the hands of the prosthetist; no plaster cast was made. Neither one was a total-contact socket.

On the inside and on the gluteal-ischial seat of the original socket of each amputee, intersecting horizontal and vertical lines were drawn. At each of the intersections, the dynamic pressure curves of 10 steps were recorded. In this way we recorded pressures at 100-120 points in each socket. Both amputees walked on their own shoes on the floor and at their own speeds. Pressure curves were recorded at points successively lower in the socket until the point was reached where no more contact existed between residual limb and socket. (At this level the pressure was equal to the air pressure in the distal part of the socket; in the swing phase the pressure became negative.) As a comparison, for each amputee a suction socket was made with the Hosmer Casting Brim, and pressure curves were recorded in the same way as for their original sockets. Selection and adjustment of the Hosmer brim, the casting procedure, and the modification of the male plaster model were according to the manual of Foort. (17)

The measuring system was improved, allowing simultaneous recording of the curves of dynamic pressure versus time in the walking cycle at four points, using four separate sensors and integrated-circuit pressure transducers. Each of the transducers was followed by an amplifier, allowing pressure calibration, adjustment of zero level, gain selection, sign

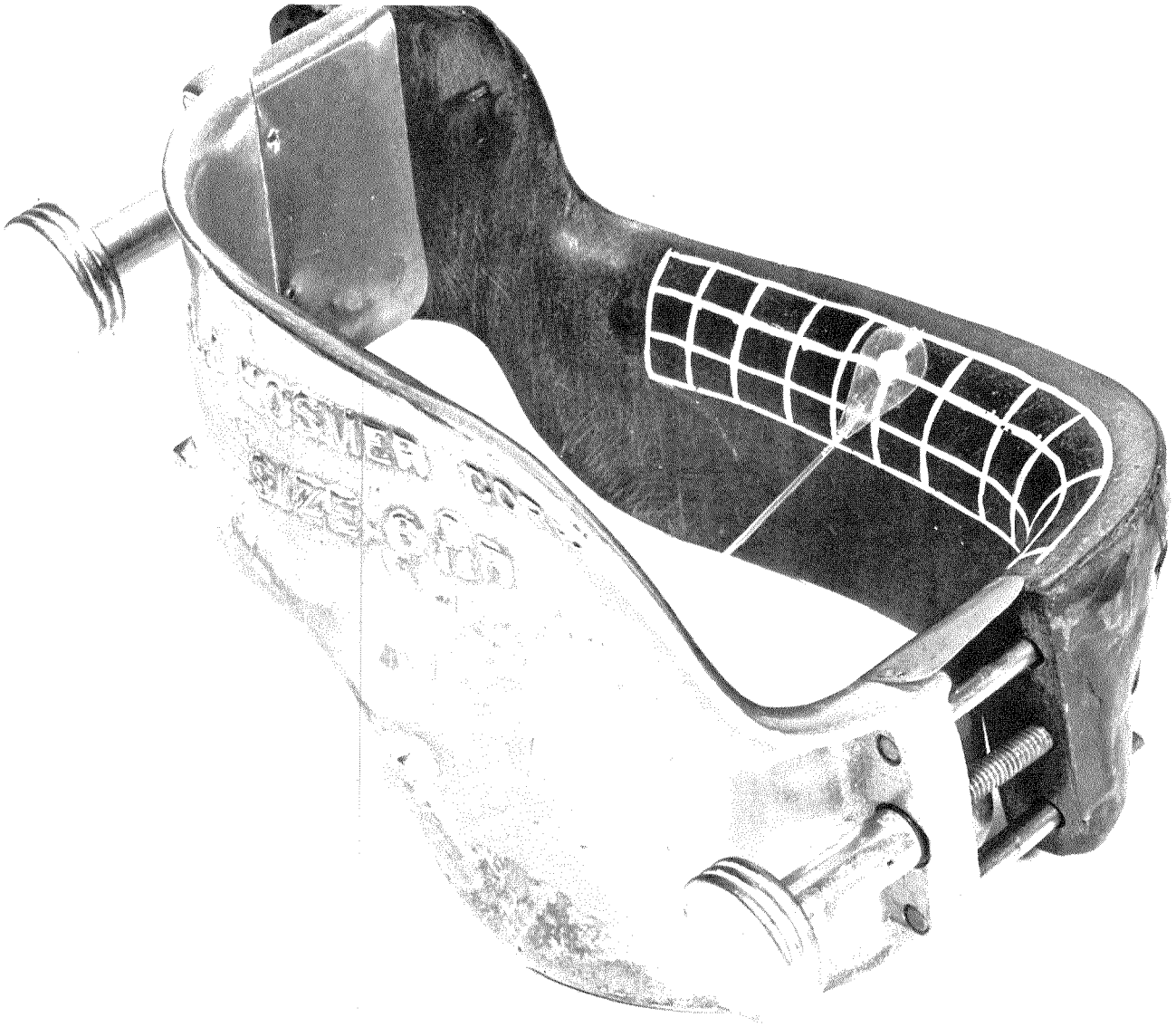


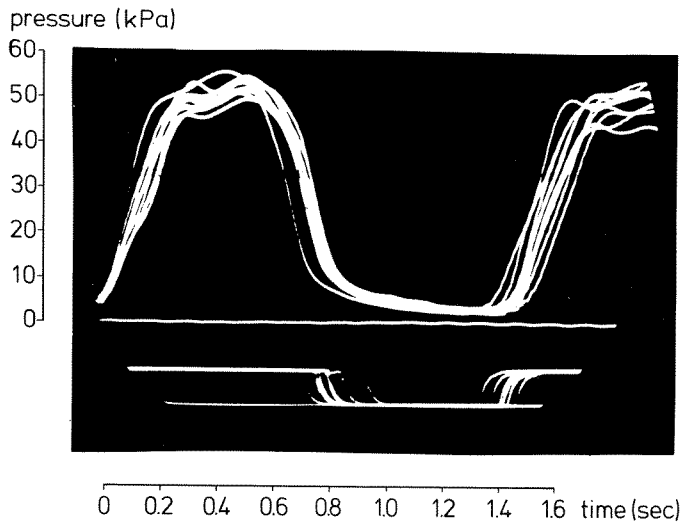
FIGURE 4.
Hosmer casting brim with network of lines. A pressure sensor can be seen on the plastic posterior half.

FIGURE 5.
Flabby residual limb of amputee B.

inversion, and low-pass filtering of the signals. Pressure variation of 0-700 kPa could be measured with a bandwidth of 7 Hz. This allowed us to measure up to 7 harmonics of the basic pressure curves at a walking cadence of 1 step/s.

In order to compare pressure curves which had been obtained either at different locations at the residual limb/socket interface, or at different steps, it was necessary to provide a synchronizing signal related to the step cycle. The heel strike was a convenient moment for synchronization. We used a tape-switch strip under the heel of the prosthesis to detect heel contact. Figure 6-A demonstrates an oscillogram of the experimental person with his pylonlike Thomas splint, showing synchronized heel contact. The consistency of the pressure curves of each of the 10 steps is very good.

The four signals were recorded simultaneously on a 4-channel FM instrumentation tape recorder. In order to keep all its four channels available for pressure signals, the heel strike signal was combined with one of the pressure signals as a short negative pulse.



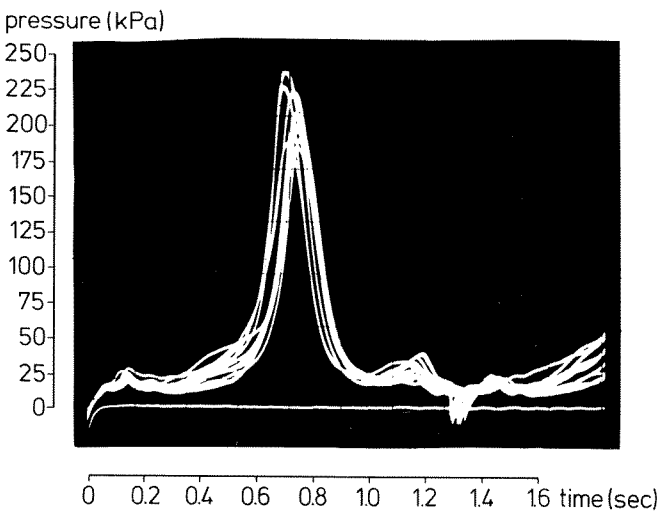


FIGURE 6-A
Oscillogram of improved measuring system, showing 10 synchronized dynamic pressure curves of non-amputated subject in stance phase and in swing phase. (Signal from patten contact appears below zero line.) The place of measurement is near the lateral-posterior corner, just below the level of the gluteal-ischial seat.

FIGURE 6-B
Oscillogram of 10 synchronized dynamic pressure curves of amputee B (flabby residual limb) at a point on the gluteal ischial seat 2½ cm medial of the medio-posterior corner and 1 cm in front of the posterior edge. A negative pulse is added to the signal at heelstrike.

The tape-recorded pressure curves were later displayed on a storage oscilloscope, where the records of 10 steps were superimposed, synchronized by the heel strike pulse (Fig. 6-B).

A general view of the experimental system is shown in Figure 7.

RESULTS

The aerostatic casting procedure used did not provide an acceptable AK socket brim in the first trial, so all further work was based on the brim casting method.

PART 1. First experiment (on a normal elderly subject with Thomas splint). The relation between dynamic peak pressures on the gluteal-ischial seat and the radius of its anterior curvature.

Figure 8 shows the posterior view of the network of lines of Figure 4 redrawn in a horizontal plane and on a straight baseline, neglecting the curve about the posterior medial corner. The peak pressures were assumed to occur in the first half of the stance phase, but could not be timed exactly due to the rather sluggish movement of the needle of the voltmeter. We did not know yet that there are really two peaks, which only became clear when the measurement system was improved. The peak pressures were plotted vertically on the 44 measuring points. This presentation is done for 3 brims with a radius of 7.5 mm, 15mm, and 200 mm respectively.

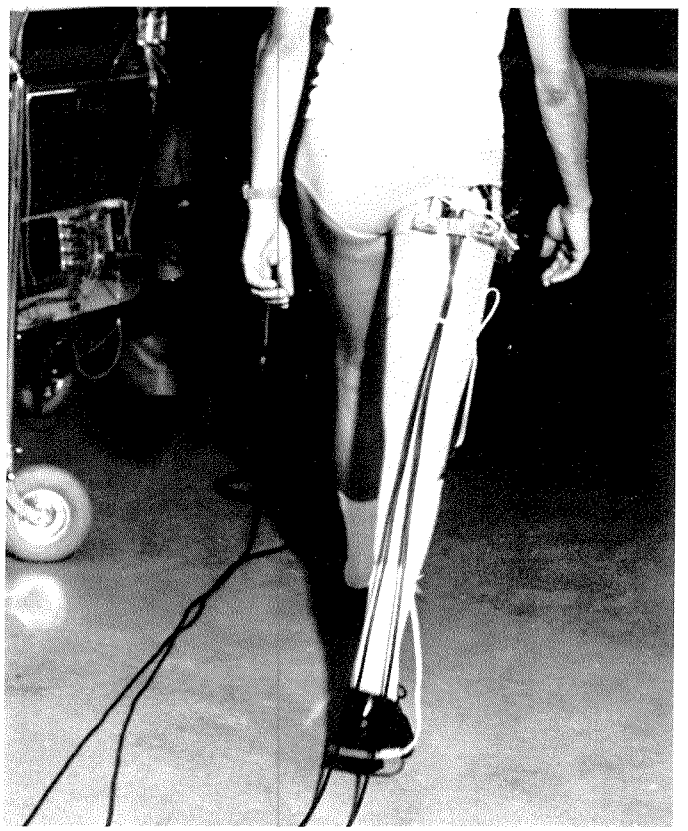


FIGURE 7
General view of dynamic pressure recording with amputee A.

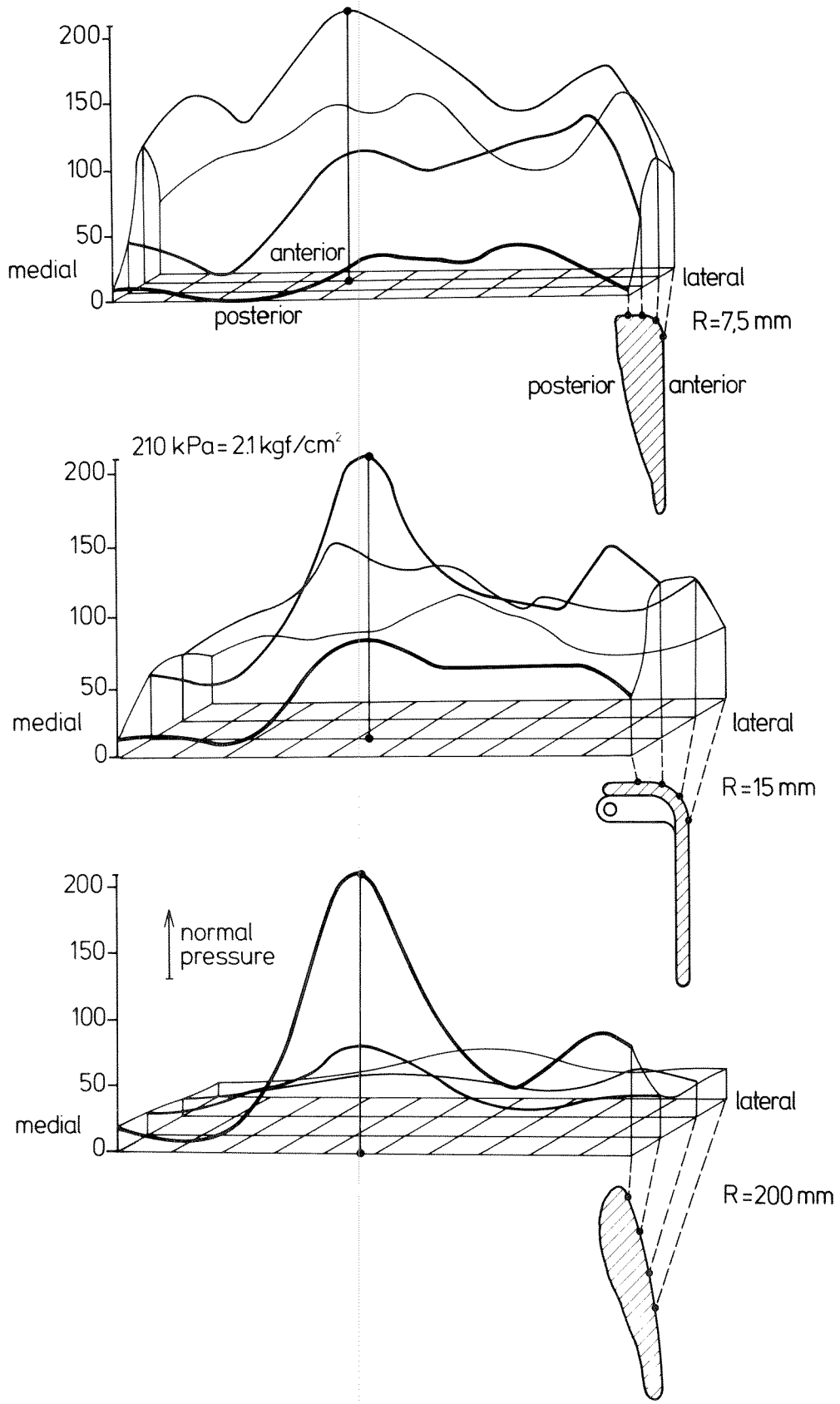


FIGURE 8.
Posterior view of peak pressures for three curvatures, plotted vertically on the network of lines of Figure 4 redrawn in a horizontal plane and on a straight baseline. Data are from the first experiment using a non-amputated elderly subject walking with a Thomas splint. Cross sections of the gluteal-ischial seat show the positions of the four horizontal lines.

If the 3 sketches are compared, the maximum pressure is at the tuberosity and appears about the same for all 3 curvatures. Therefore, in our case it is almost independent of the curvature. For the Hosmer brim it is 210 kPa (approximately 2.1 kgf/cm^2). An estimation can be made of the normal force exerted by the tuber ischii (generally somewhat obliquely on the rounded seat) in relation to the weight of 70 x 9.8 N (= 70 kg) of our experimental person. Therefore, an area was assumed in horizontal projection, on which this force is acting. A surface of 2 x 2 cm is chosen around the point of the tuber pression. Theoretically, this area is a point because it is the contact between the two curvatures of the tuber itself and the brim — in practice this force will be spread to a broader area, because of the intermediate layer of the gluteus muscle. The thick layer of firm muscle of a young amputee spreads this force over a broader area than the thin layer of flabby muscle of an old woman; 4 cm^2 is thought to be a reasonable average. The force on this surface will be 4 x 2.1 = 8.4 x 9.8 N. The total or integrated vertical force exerted by the measured part of the gluteus muscle is calculated at approximately 50 x 9.8 N (50 kg). This result shows that for the 15-mm brim, the tuberosity part of the force (8.4 x 9.8 N) is roughly only one-fifth of the part of the gluteus muscle (41.6 x 9.8 N). Therefore, it is more appropriate to use the term "gluteal-ischial" seat than "ischial" seat. Müller and Hettinger (6) in their investigation on static pressure measurements, come to 10 percent for the one-leg position and 16 percent for the two-legs position, respectively.

As a whole, the pressures of the gluteus muscle on the 7.5-mm brim are very high as compared with those of the 200-mm brim. There is an inverse relation: the greater the radius of the gluteal-ischial seat, the smaller the pressures on the gluteus muscle. Bennett (16) studied the effect of three anterior socket brim radii upon simulated flesh (Spence gel) and investigated their relation to local compressive and shear stress in the flesh. His conclusion is that the optimal brim radius is ½ inch (1.27 cm) — but this result is hardly comparable with ours, as Bennett experimented with the anterior brim and with a horizontal load.

Comfort

A prosthesis has three main qualities: function, comfort, and cosmesis. As to function, an immense quantity of literature has been published. Every time a new material is used (for instance leather, aluminum, wood, or plastics) cosmesis plays an important part in the overall judgment. But about comfort, as far as we know, no literature exists. Probably because the feeling of comfort is subjective, attempts to measure it objectively are rare. Our experiments, even if on only one or two subjects, attempt to contribute.

First, we will try to give a definition: Comfort is the feeling that the socket fits well around the residual limb in its whole length, but especially near the brim — that is to say, not too loose, not too tight, and without pain when loading the prosthesis with full body weight. Good alignment and adequate function of the prosthesis are conditio sine qua non. The suspension should be adequate, and donning of the prosthesis should not be too difficult even for the geriatric amputee.

Another definition: The subjective opinion of the amputee that walking with the prosthesis is not a disagreeable experience. Elucidation: the socket should fit well around the stump, the prosthesis should be well steerable, the alignment must be all right, the knee, ankle joint, and suspension should be adequate, and pain may not be felt while walking. Comfort is overlapping function and cosmesis.

While walking with the different brims, the experimental subject judged a radius of 30 mm or 45 mm more comfortable than one of 7.5 mm, which was felt as sharp and painful when walking. (The 200-mm brim was comfortable too, but in this case there is no longer a gluteal-ischial seat, and the brim is a "plug fit", with the rather flexible conical residual limb attempting to fit the conical brim under load as if it were a rubber plug inserted in a bottle.) Moreover, the brim with the 7.5-mm radius caused an abrasion of the skin (Fig. 9). These two observations support our opinion that the radius of the curvature is an important factor contributing to the comfort of the socket.

The area of the skin defect shown in Figure 9 could anatomically not be precisely identified; it was not at the tuber ischiadicum, but more lateral and distal, corresponding with the bulging muscles of the hamstrings. This is confirmed when an X-ray photograph of the pelvis is laid upon Figure 9; then the middle of the abrasion is 7 cm distal and 6 cm lateral of the tuber. The pressure between socket and skin at this area was lower than the maximum measured pressure of 210 kPa, therefore normal pressure was not the only factor involved. Perhaps the shearing forces on skin which is just outside the brim at rest, but chafed during walking, were the cause of the abrasion.

Murphy (10) in his paper applying the Donnell principle to prosthetic devices (sockets, corsets, bands or braces) comes to the conclusion that diminished or "tapered" stiffness towards the edges would diminish stresses, and merely rounding the surface in contact with the skin would have some similar effect. Applied to the socket wall, he proposes a variable radial stiffness of this wall according to the stiffness of the tissue which it touches (11). These two suggestions probably also contribute to comfort.

PART 2. Second experiment (on two amputees) Comparison of the distribution of midstance pressures in the original socket with that in a Hosmer casting brim socket for two AK amputees.

A. Pressure patterns in the two sockets for the muscular stump (Fig. 10)
   - (i) In the original socket, the variation of midstance pressures in the two proximal cross-sections is greater than in the Hosmer brim socket.
   - (ii) Midstance pressures in all 4 cross-sections of the Hosmer brim socket are more nearly uniform, but higher, than in the original socket.
   - (iii) These higher pressures indicate a closer fit of the socket.
   - (iv) In both sockets these pressures are gradually lower in distal regions.

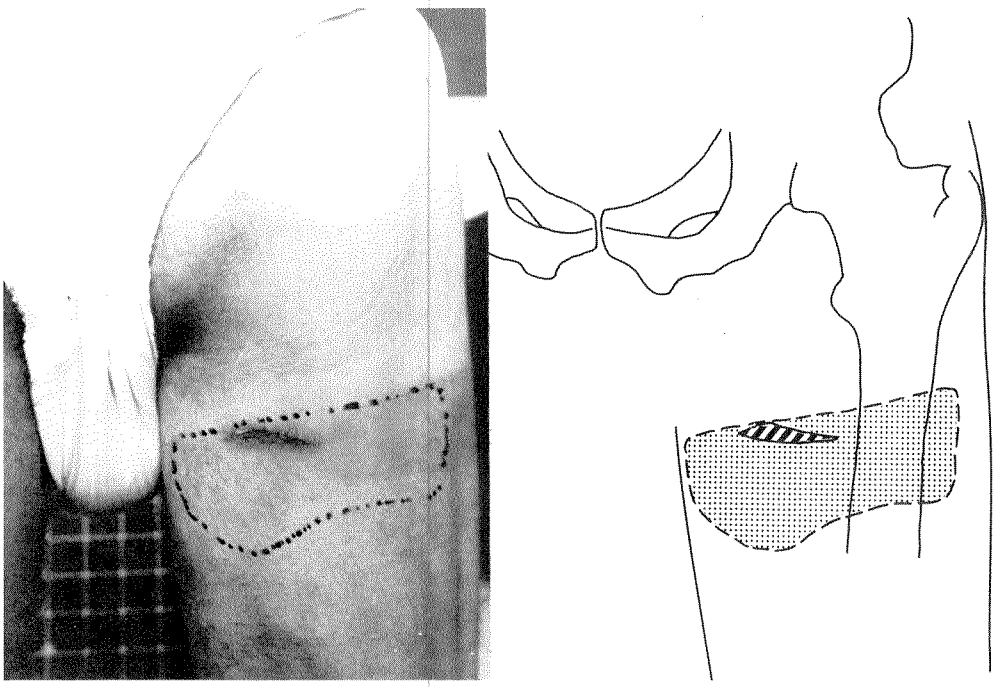
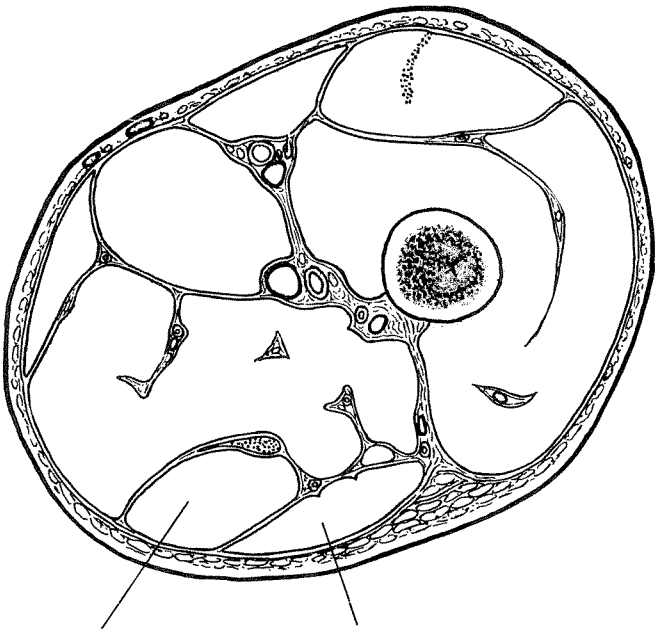


FIGURE 9.
(A) Abrasion of the skin caused by 7.5-mm-radius brim. Dotted line drawn on original Polaroid print indicates extent of area showing redness and abrasion with brim curvature of 7.5 mm. In (B) the same areas are drawn in upon a tracing of a corresponding X-ray photograph of the subject, to show position of the abrasion relative to the tuber ischiadicum. (C), below, represents an anatomical cross-section of the right leg 5 cm below the gluteal-ischial seat.



(v) These pressures on the medial wall are higher than expected, particularly for the socket from a cast made with the Hosmer brim.

B. Pressure patterns in the two sockets of the flabby stump (Fig. 11)
   (i) We expected that a flabby residual limb would give more equal pressures all around. However, it turned out that these pressures, as seen in the first and to a lesser extent in the second cross-section, vary considerably. The explanation might be that underlying muscles still contribute significantly to these pressures.
   (ii) In the Hosmer brim socket, these pressures in all 4 cross sections are again more equal, but not higher than in the original socket. The reason might be a looser fit than that made for the muscular stump. We call the force applied to bring the two parts of the Hosmer brim together before applying the wet plaster of Paris cast the "clamping force". Although we followed the instructions of the developers (16) in making the casts and modifying the plaster models, the clamping force probably was smaller for subject B with the flabby stump than for subject A with the muscular stump.
   (iii) In both sockets these pressures gradually diminish distally.
   (iv) These pressures on the medial wall of the most proximal cross-section of the Hosmer brim socket

AMPUTEE A — MUSCULAR STUMP (Figure 10)

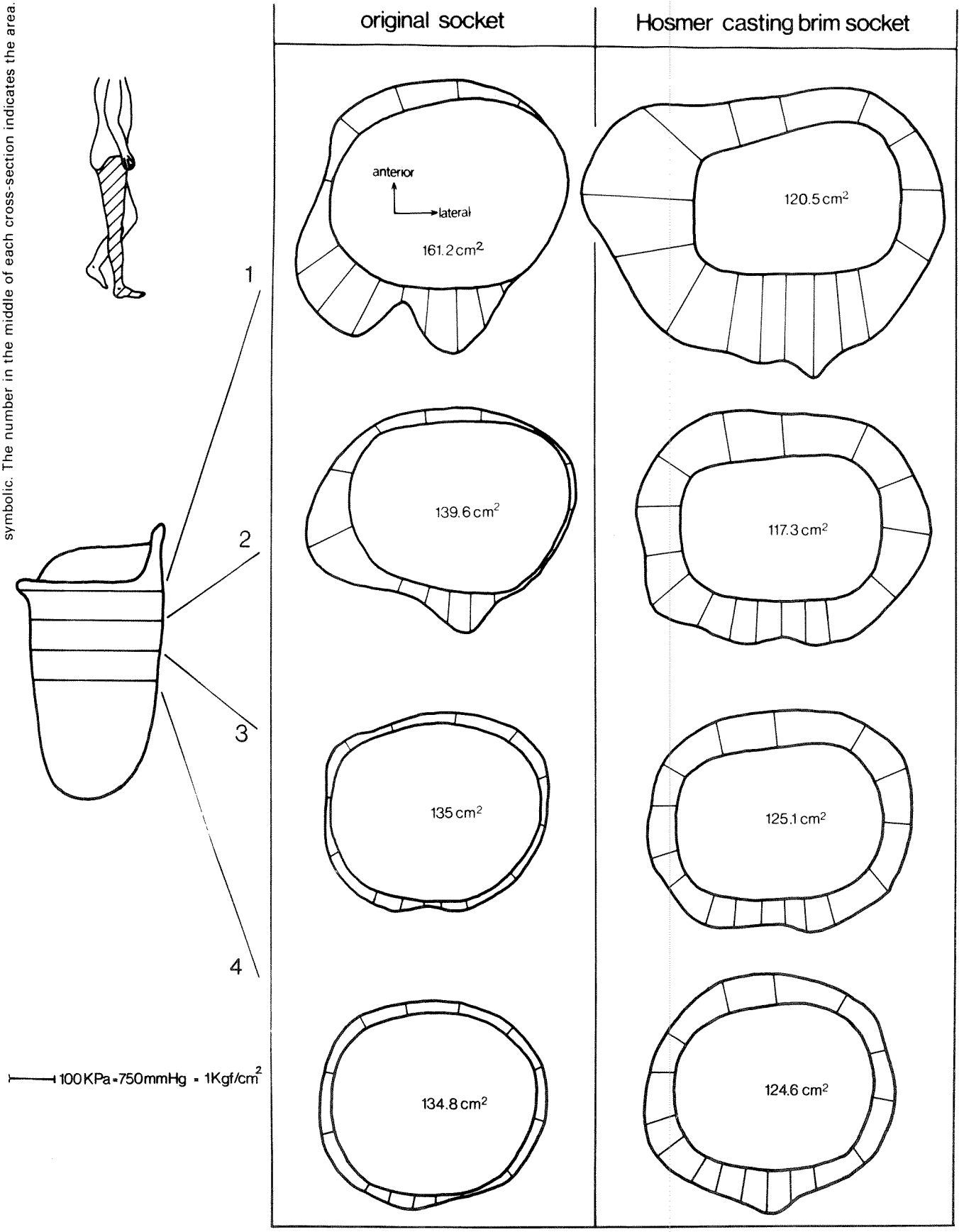


FIGURE 10. Four horizontal cross-sections of the original socket and of the Hosmer casting brim socket of Amputee A, with dynamic midstance pressures plotted on the residual limb outline. For this and Figures 11 and 12, the sketches of the amputee and the socket are symbolic. The number in the middle of each cross-section indicates the area.

Bulletin of Prosthetics Research BPR 10-33 (Vol. 17 No. 1) Spring 1980

AMPUTEE B — FLABBY STUMP (Figure 11)

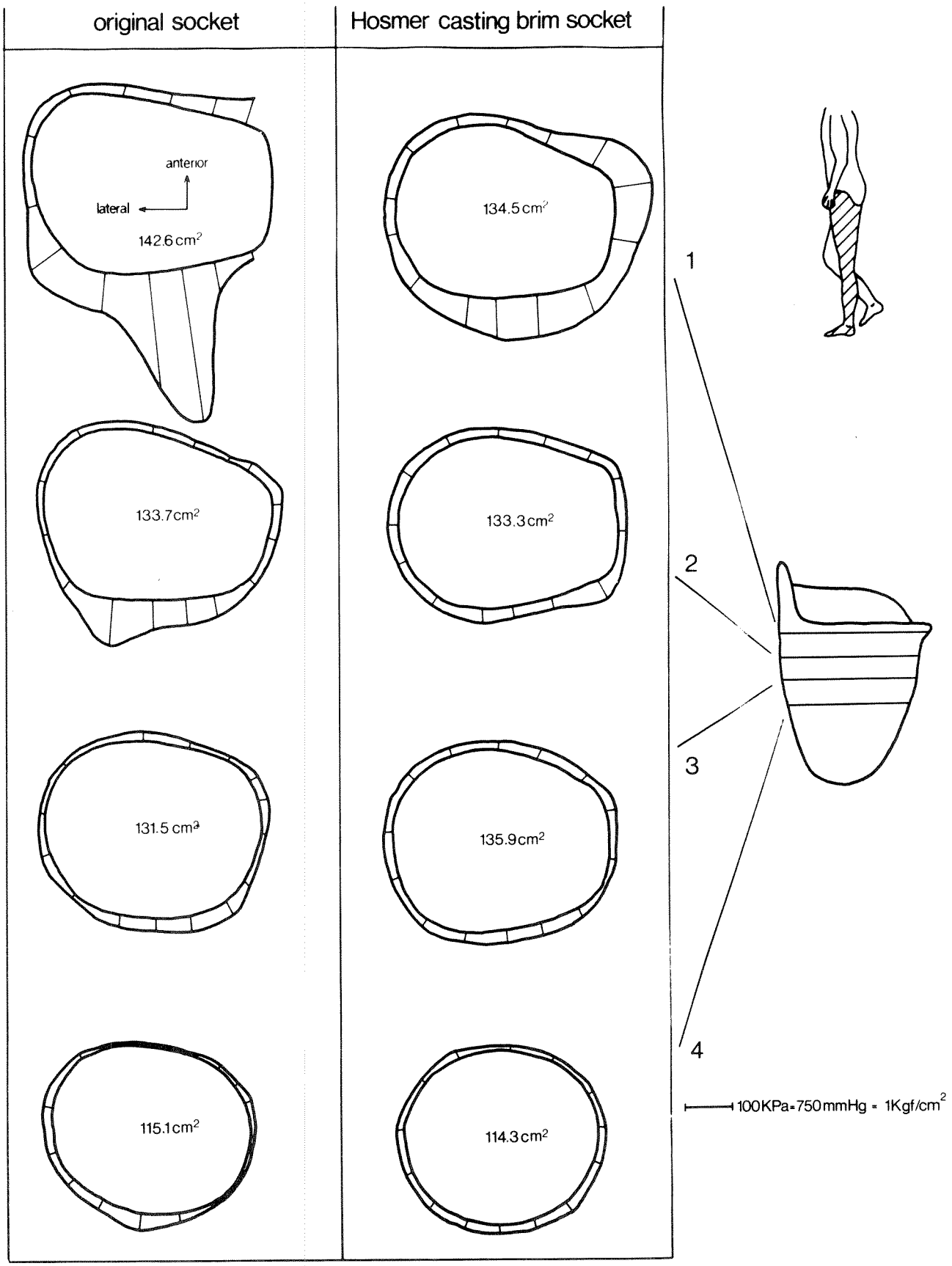


FIGURE 11. Four horizontal cross-sections of the original socket and of the Hosmer casting brim socket of amputee B, with dynamic midstance pressures plotted on the residual limb outline.

are again higher than expected. In the original socket this could not be measured, as the medial wall was too low. If an amputee complains about pain in this region, sometimes the medial wall is lowered. This is seen by many prosthetists as a mistake and in view of these high pressures it must be considered as attacking the symptom but not the cause (18).

Variation with time of dynamic pressures in the original socket of amputee A.

In Figures 10 and 11 the midstance pressures at four different levels are shown, whereas in Figure 12 the pressures at level 1 are illustrated at 6/18th (33 percent), 9/18th (50 percent), 10/18th (56 percent), and 14/18th (78 percent) fractions of the walking cycle. At any point, maximum pressure may occur at a different moment of the walking cycle. For instance, at the adductor longus tendon this maximum takes place at approximately 50 percent (late stance) and in the medio-posterior part of the brim at 33 percent. At the adductor longus tendon the maximal pressure at 50 percent of the cycle exceeds the midstance pressure and there is a sharp pressure gradient — perhaps because in the original socket no channel was made for this tendon. This might tempt us to the thesis that at places of high pressure more room should be given. This is true for the adductor tendon but it is doubtful for the high pressures at the medial wall and probably not true for the high pressure at the tuber ischiadicum. Further research should bring more clearness into our view of these apparently contradictory problems.

DISCUSSION

When, in a pilot experiment, a single socket was made with the aerostatic casting technique, we found the brim was approximately 3½ cm too wide — that is to say too large in antero-posterior as well as in medio-lateral direction. This result corresponds with orthopedic workshop experience; if a plaster cast is made of an AK residual limb, the prosthetist often makes proximally a constricting ring with his plaster bandage and gives a final touch to the cast with supplementary pressure from his hand at the place of the gluteal-ischial seat. If he uses a measuring tape, he makes the brim of the socket approximately 3 cm narrower than his tapemeasure indicates. When in the pilot-experiment socket the brim was 3 cm too wide, there was insufficient proximal stabilization of the stump, and our amputee could not walk with such a prosthesis. This preliminary finding, though lacking statistical support, seems to agree with the statement of the VA Program Guide (1) that the pressures in the proximal residual limb region have to be of sufficient magnitude to provide adequate horizontal (antero-posterior and medio-lateral) stabilization of the stump.

It may be objected that only the experiment with one person led us to the conclusion that the aerostatic casting procedure did not provide an acceptable AK socket brim. This is true, and therefore further experiments with different versions of the same technique are necessary to give more insight into this problem. For instance, higher uniform pressure in the proximal region might be used.

The assumption in the Program Guide that in the distal region the pressures are significantly lower is in agreement with our measurements. Numerous measurements on four sockets support this observation. The typical decrease of pressure at distal levels seems to fit the UCLA concept of "tension analysis". (19)

Actually, the dynamic pressure distribution is usually dependent on numerous variables; it is a function of the radius of the curvature of the gluteal-ischial seat, the shape of the socket (especially of the brim), the firmness or softness of the underlying tissue (e.g., bone, tendon, bulging muscles, or flabby tissue), the contraction or relaxation of the stump muscles, the close or loose fit (i.e., the clamping force) of the socket, and the phase of the walking cycle.

The second statement (that a hydrostatic fit with all pressures equal would be theoretically ideal), though not disproven, is not supported by our study. It was impossible to walk with the single socket made according to the aerostatic casting procedure used, and therefore it was impossible to measure the dynamic pressures. Moreover, locomotion studies show that at different fractions of the walking cycle different muscle groups are active, and therefore pressures exerted by these muscles against a rigid socket wall must vary with time and place and cannot be equal (18).

All this suggests that no equal pressure distribution at the brim can be obtained dynamically at any moment of the walking cycle. An apparent exception is seen with a high clamping force, whereby variations of the pressure curves represent smaller fractions of a consistently high pressure (Figure 10, Hosmer casting brim socket, midstance). And at the distal end of the stump a more equal distribution is obtained, as Figures 10 and 11 show; this is true for the original and the Hosmer brim sockets, and for amputees A and B. Nevertheless, we agree with the VA Program Guide G-5 (1) that sharp pressure gradients and high pressures should be avoided by adequate socket design. The use of dynamic pressure measurements would provide the guidelines to do so.

Clamping force

In Figure 10, midstance pressures in all 4 cross-sections of the Hosmer brim socket are twice or three times as high as in the original socket. This corresponds with a tighter fit of the socket, confirmed by subjective opinion of amputee A and caused by the markedly smaller cross-sectional area. These areas of level 1, 2, 3 and 4 of amputee A are in the Hosmer brim socket, 25 percent, 16 percent, 7 percent and 8 percent smaller than in the original socket. For amputee B (Fig. 11) these values are 6 percent smaller, 0.3 percent smaller, 3.3 percent greater and 0.7 percent smaller than in the original socket.

A close fit can be brought about by a greater "clamping force", this is the force with which the two parts of the Hosmer brim are clamped together during hardening of the cast of the residual limb. A suction socket has a close fit to prevent air leakage between limb and socket; however, the socket for the geriatric amputee has to be wider for him or her to be able to put on the prosthesis without assistance, and it is generally

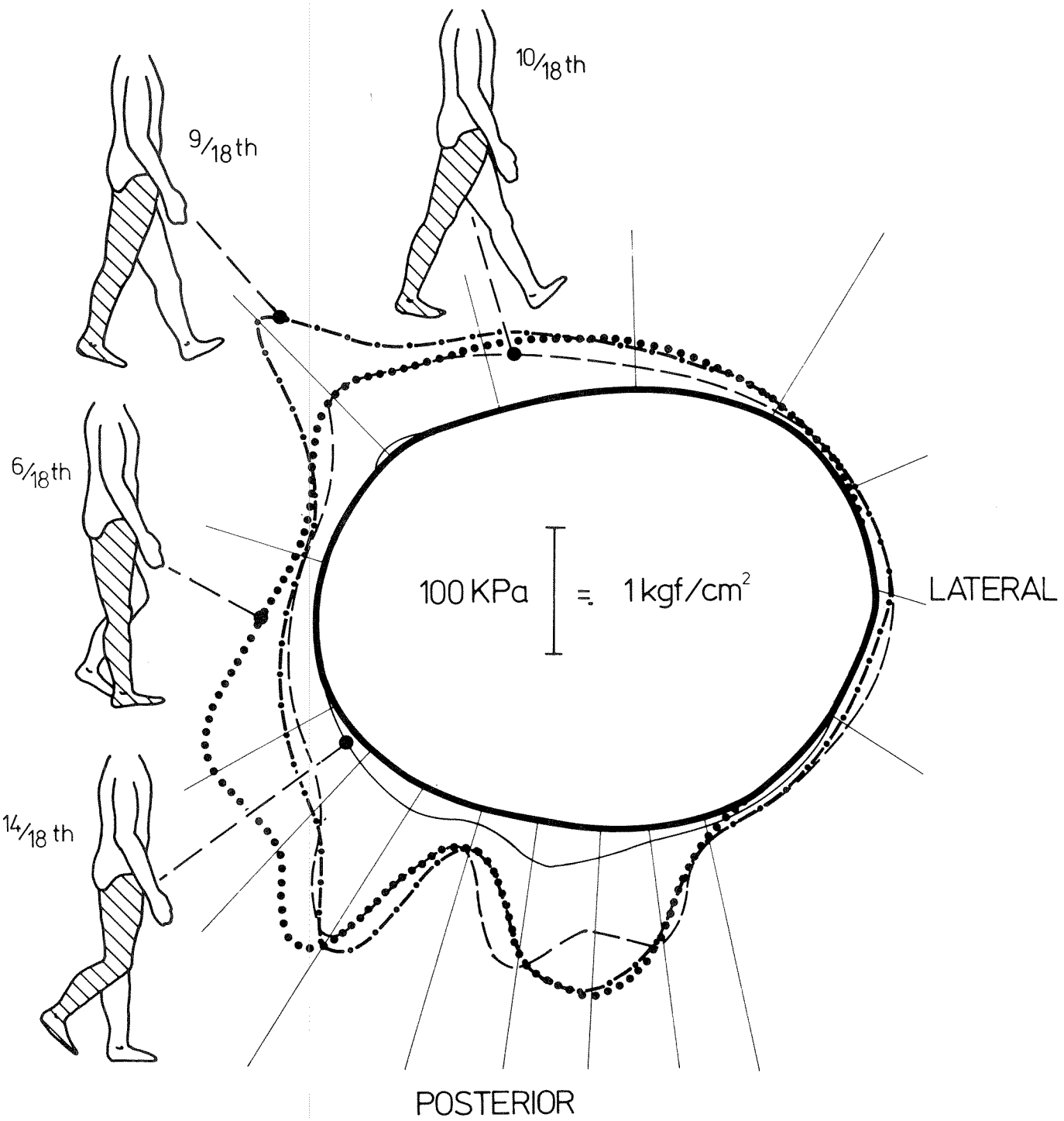


FIGURE 12.
Dynamic pressures at the 6/18th (33 percent), 9/18th (50 percent), 10/18th (56 percent), and 14/18th (78 percent) fractions of the walking cycle following heelstrike at the level just below the gluteal-ischial seat of the original socket of amputee A (level 1 of Figure 10). (Note: the kgf equivalent for 100 kPa is an approximation.)

worn with some type of suspension. The clamping force is a measure to differentiate between these two kinds of sockets, and the addition of a calibrated spring may be helpful to control it properly. Amputee A did not associate the close fit of the Hosmer brim socket with a feeling of discomfort; he experienced comfort-or-discomfort, and tightness-or-looseness, as two different feelings. Our non-amputated subject had the same opinion; his feeling of comfort was more dependent on the radius of the curvature of the gluteal-ischial seat than on the tightness of the fit of the simulated brim on his thigh.

Shape of the Brim

Of all factors mentioned above as having an influence on dynamic pressures at the brim, there are three which can be altered by changing the socket form: the radius of the anterior curvature of the gluteal-ischial seat, the clamping force, and the shape of the brim in the horizontal plane.

There are as many differences in the shape of the brim as there are prosthetists, and they vary from circular or oval to triangular or quadrilateral. The quadrilateral casting brim of the University of California, Berkeley (Fig. 13) is probably the simplest one and it is commercially available as the Hosmer Casting Brim. The shape of the U.S. Navy socket (Fig. 14) was quite different and gave laterally more room for the gluteus maximus. Kuhn (20) (Fig. 15) distinguished six different shapes from total absence of muscle relief (flabby stump) to the athletic stump with strongly marked contours.[a] In England the triangular brim (Fig. 16) designed by McKenzie has been and still is in regular use (personal communication). Because there are so many different shapes, it is obvious that none of these is recognized as the ideal one.

In trying to find a relation between the shape of the brim and the pressure pattern, it seems illogical to make a plaster cast or to take measurments solely of a relaxed stump. If a casting brim is used or a measuring tape and pencil, the muscles are relaxed, whereas in walking these muscles contract periodically but not simultaneously. There are also long periods when muscles are inactive, especially with geriatric amputees.

This consideration led us to study the difference of outline of a residual limb with relaxed compared with contracted muscles, using the following procedure. Amputee A put on his residual limb a nylon panty-hose of which the leg was cut off half way. A small roll of plaster of paris bandage was laid around the limb and held up with the turned-up panty-hose. The roll was pulled up to get it as near as possible to the tuber ischii (Fig. 17). In this way a plaster ring-cast was made with relaxed muscles and another one with contracted muscles (Fig. 18). This was also done for amputee B with flabby residual limb (not shown).

The cross-sectional area of the muscular residual limb just below the tuberosity was 7 percent greater at contraction, and for the flabby residual limb the increase went to 16 percent.

The shape of the ring-cast of the relaxed and of the contracted limb is round or oval, and is transformed to

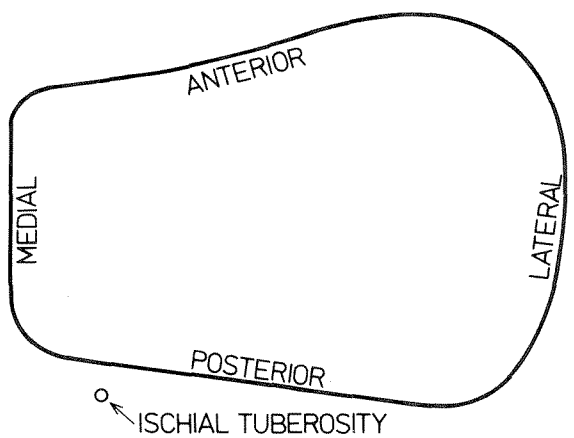
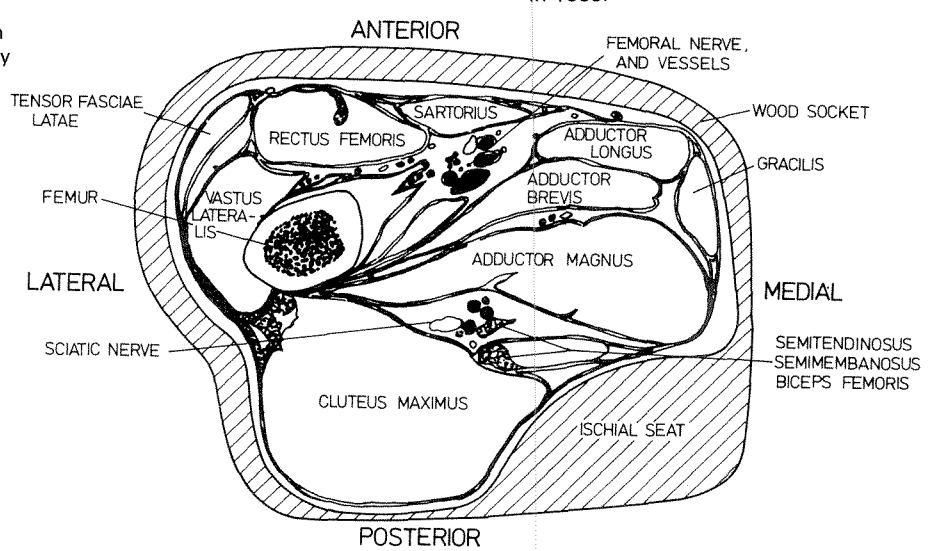


FIGURE 13
Quadrilateral shape of the socket brim of the University of California, Berkeley

FIGURE 14
Shape of the brim of the U.S. Navy Socket in 1959.



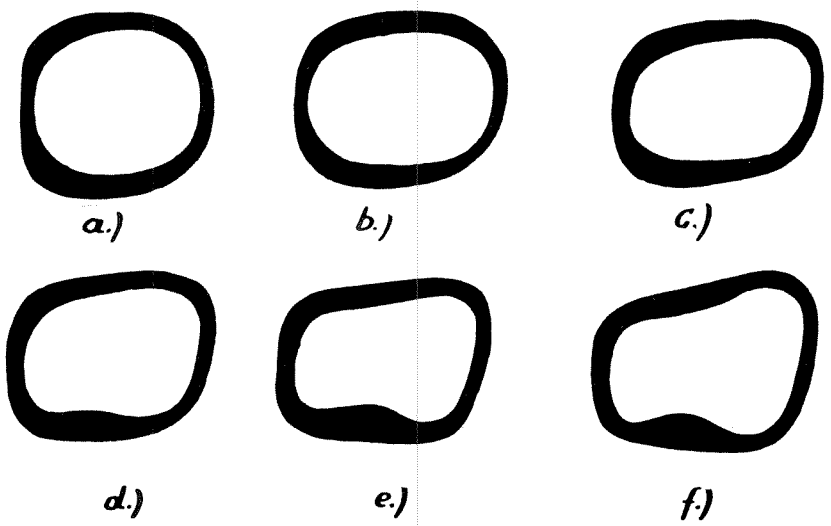


FIGURE 15 [a]
Different shapes of the brim according to muscle development. Kuhn (Germany). In top row: A is a "stovepipe" used only for a stump without bony support; B is for a big flabby stump; C is for a stump without muscle relief; D for a stump with "average" muscle development; E for a muscular stump; and F for an athletic stump (meticulous profiling for muscles is necessary).

quadrilateral in the casting brim by compression in the anterior-posterior direction. In making the ring-cast all muscles are contracted, while in walking only part of them contract, and with the geriatric amputee this is a still smaller part. Though the contracted residual limb outlines formed by the ring-cast method do not exactly correspond with the outlines while walking with the prosthesis, the above mentioned procedure gives some suggestion about the small residual limb deformation by muscle contraction—and the big deformation by the shape of the brim.

Conclusion

The peak pressure at the tuber ischii is almost independent of the radius of the curvature of the gluteal-ischial seat. The peak pressures on the gluteus muscle vary with the radius: the smaller the radius, the higher these pressures, and inversely. The tuberosity part of the vertical force for the 15-mm brim is roughly only one fifth of the force exerted by the gluteus muscle as a whole. Therefore, it is more appropriate to use the term "gluteal-ischial" seat than "ischial" seat.

The experimental subject (non-amputated) judged a radius of 30 mm or 45 mm to be more comfortable than one of 7.5 mm, which was felt as sharp (and which produced an abrasion). The feeling of comfort of an above-knee socket seems to depend more on the radius of the curvature of the gluteal-ischial seat and on the shape of the brim than on a high or low clamping force applied to the two parts of the Hosmer casting brim. The clamping force might give a good measure of the looseness or tightness of the socket. Particularly, it offers a way to give a possibility to differentiate between the suction socket and the easy-entry socket for the geriatric amputee.

[a] These drawings are derived from an article published in 1956 (20); at present the shape of the muscular stump (picture e) is most generally used (personal comunication).

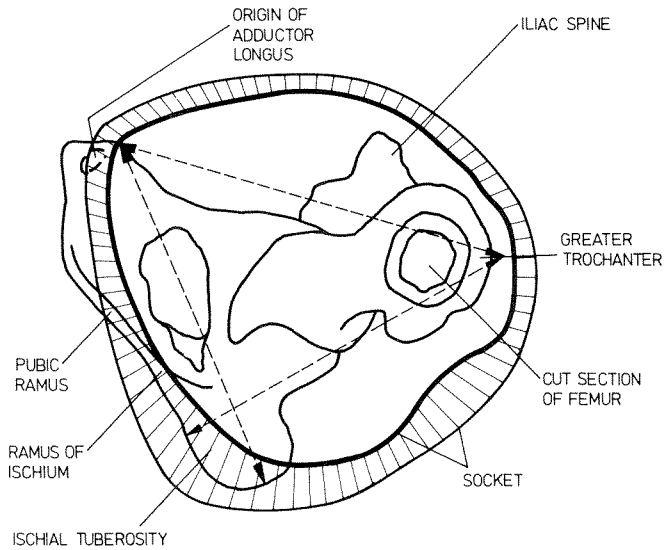


FIGURE 16
Triangular shape of the brim designed by McKenzie (England).(Right leg as seen from below.)

Internationally there is no agreement about the shape of the brim of the above-knee socket. Dynamic pressure measurements as described give more insight into this problem. Theoretically this shape should be in conformity with the bulging of contracted muscles or a tense tendon, because these are places with high pressures or sharp pressure gradients. Common workshop practice is empirically working according to these principles, but dynamic pressure measurements might give them a scientific basis.

Perhaps in this way it will be possible to find a brim that will be more generally accepted by the prosthetists, which would make us more independent of their hands and of their individual ideas about socket making.

FIGURE 17
Making a ring cast of the relaxed and of the contracted stump of amputee A.

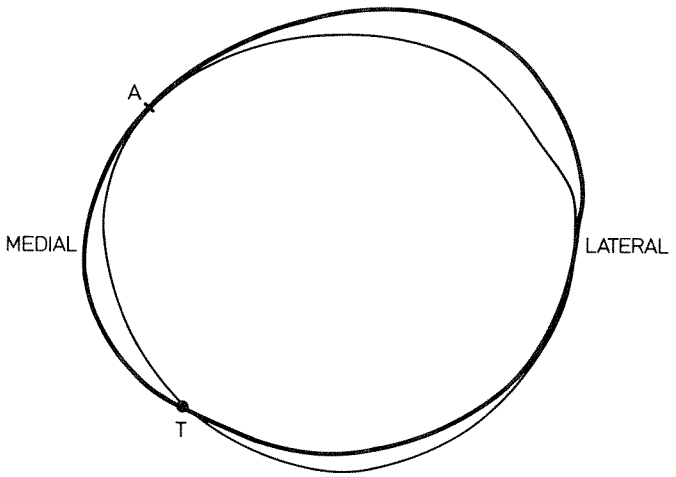


FIGURE 18
Circumference of the relaxed and of the contracted stump of Amputee A (thin line = relaxed muscles, thick line = contracted muscles). A = adductor tendon, T = tuber ischiadicum.

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