Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine
http://pih.sagepub.com/

Stump-socket interface pressure as an aid to socket design in prostheses for trans-femoral amputees —a preliminary study

V S P Lee, S E Solomonidis and W D Spence

Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 1997 211: 167
DOI: 10.1243/0954411971534287

Stump–socket interface pressure as an aid to socket design in prostheses for trans-femoral amputees—a preliminary study

V S P Lee, S E Solomonidis and **W D Spence**
Bioengineering Unit, University of Strathclyde, Glasgow

Abstract: A system for measuring the stump–socket interface pressure was designed and built using a strain gauged type load cell. The system was utilized to study the pressure distribution in the quadrilateral and ischial containment type sockets. Two volunteer trans-femoral amputees fitted with both types of socket participated in the experiments. Pressures were measured while the subjects were standing and during walking. The maximum pressure recorded for standing was 34 kPa and for walking 95 kPa. Comparison made between the two sockets indicated that higher pressures were recorded at the proximal brim of the quadrilateral socket whereas the ischial containment socket produces a more evenly distributed pressure profile. The pressure distribution on the medial and lateral walls of both types of sockets were similar but in the anterior and posterior walls, significant differences were noted. The results obtained from this study were compared with those found in published literature and the biomechanics of the two types of socket is discussed.

Keywords: trans-femoral amputee, stump, artificial limbs, prosthesis, socket, quadrilateral, ischial containment, biomechanics, pressure

NOTATION

ANT	anterior
AP	anterio-posterior
CAT-CAM	contoured adducted trochanteric controlled alignment method
GT	greater trochanter
IC	ischial containment socket
IT	ischial tuberosity
LAT	lateral
MED	medial
ML	medio-lateral
MM	subject's code
NSNA	normal shape normal alignment
POST	posterior
PU	subject's code
Quad	quadrilateral socket
SCAT-CAM	skeletal contoured adducted trochanteric controlled alignment method
UCLA	University of California Los Angeles

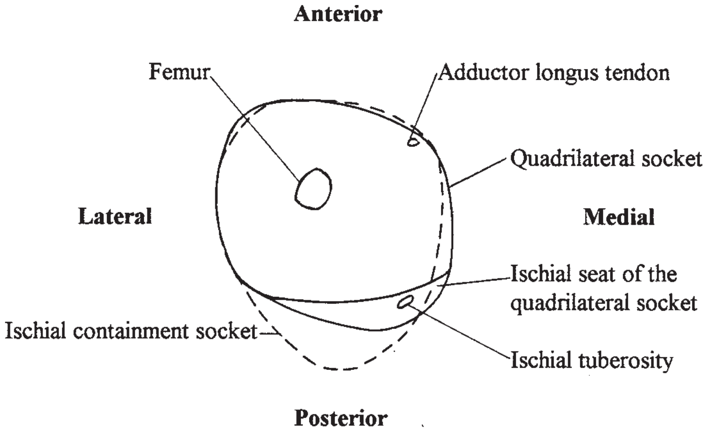
The MS was received on 19 October 1995 and was accepted for publication on 11 September 1996.

1 INTRODUCTION

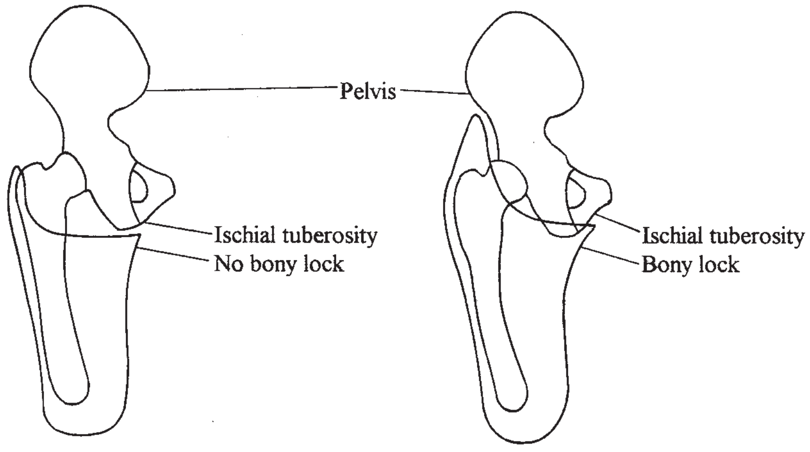
The lower limb amputee achieves ambulation with the aid of an artificial limb. An artificial limb for a trans-femoral amputee consists of an assembly of several component parts; the main components are socket, knee, shank, ankle and foot. The socket is of major importance since it forms the interface between man and machine. Currently, there are mainly two types of trans-femoral prosthetic sockets in use, the quadrilateral (quad) socket developed in the 1950s (**1, 2**) and the ischial containment (IC) socket developed in the 1980s (**3–5**).

The quad socket (Fig. 1) takes its name from its shape when viewed in a transverse plane at the ischial tuberosity level. There are four distinct walls which make up the quad socket. At proximal brim level of the posterior wall, there is a wide ($\approx$25 mm) seat parallel to the ground, known as the ischial seat. A large percentage of body weight is directed to this ischial seat via the ischial tuberosity (IT). The gluteal musculature also transmits vertical force on to this shelf.

The newer socket design possesses an elliptical rather than a quadrilateral shaped brim (Fig. 1). Instead of providing an ischial seat, the configuration encloses the



Plan view immediately distal to the ischial tuberosity, of the two types of sockets obtained from MRI scans



Quadrilateral socket

Ischial containment socket

Posterior view of the two types of socket

Fig. 1 Differences between the quadrilateral and ischial containment sockets

ischial tuberosity and ramus within the socket, hence this design is generally termed IC socket or, quite often, ischial ramal weight-bearing socket. Another feature often purported of the IC socket is the narrower mediolateral (ML) dimension compared to the quad, with a brim that follows closely the contours of the undistorted soft tissues. The IC socket has in recent years appeared under various names according to the developers. These are: normal shape normal alignment (NSNA) (**4**), contoured adducted trochanteric controlled alignment method (CAT-CAM) (**5**), skeletal CAT-CAM (SCAT-CAM) (**5**) and University of California Los Angeles CAT-CAM (UCLA CAT-CAM) (**6**). There are minimal geometrical differences among these IC type sockets and their main feature remains that of ischial containment.

Concerning the IC socket Sabolich (**5**) stated that, ‘The old principles of the quadrilateral design simply do not function, since we are dealing with a completely different design in shape, contour, and biomechanical principles.’ An evaluation of the accuracy of this statement is still high on the agenda of any discussion on trans-femoral socket fittings. In an attempt to clarify the claims made for IC sockets, an international workshop was held in Miami, Florida in 1987, to discuss socket design issues and it was suggested that clinical and biomechanical studies be undertaken (**7**). Pritham (**8**) also reviewed such claims and was convinced that the IC socket does not violate any of the biomechanical principles laid down by the developers of the quad socket.

The ML dimension of the quad socket has been criticized as being too wide, allowing femoral abduction (**3**). It has been stated that such movement would subsequently cause the socket and the ischial seat to slide laterally away from the IT, creating high shearing forces on the stump around the ischial seat and the medial brim area of the socket. In contrast, the advocates of IC sockets claim that by enclosing the ischial ramus, a bony lock is created (Fig. 1), preventing such movement. Furthermore, it is claimed that a narrow ML dimension and sloped lateral wall improve proprioception due to the more anatomical shape of the socket and the adduction of the femoral bone (**5**).

Clinical and laboratory evaluations of the IC socket have been carried out by various independent researchers. Flandry *et al.* (**9**) converted five trans-femoral amputees from quad to CAT-CAM sockets and found that the latter increased the mean stride length and mean gait velocity by 0.23 m and 4.1 m/min respectively. Gailey *et al.* (**10**) conducted a study of energy cost on ten unilateral amputees fitted with quad and CAT-CAM sockets. A 20 per cent reduction of oxygen intake was recorded when the amputees used the CAT-CAM sockets.

In evaluating socket design it is considered that pressure at the man–prosthesis interface is an important parameter as it is related to comfort. The aim of the study presented in this paper was to measure the pressure distribution at the stump–socket interface in an attempt to obtain a better understanding of its biomechanical characteristics. The ongoing controversy regarding the quad and IC sockets provided a suitable case study for the project. It must be stressed that the controversy regarding the sockets lies in the biomechanical principles and not with the results of subjective studies conducted (**11–13**), which indicated that the patients show a preference for the IC socket.

The work reported in the present paper also forms part of an ongoing study being undertaken at the Bioengineering Unit of the University of Strathclyde which has the aim of developing an accurate finite element model of the stump in order to investigate the stresses at the interface. The measured pressures provide essential data for comparison with predicted pressures by the model and hence its validation.

2 A REVIEW OF TRANS-FEMORAL STUMP–SOCKET PRESSURE MEASUREMENT TECHNIQUES

In order to obtain accurate, reliable recordings of pressure at the stump–socket interface several issues have to be addressed. Unlike a bag of fluid, the stump consists of regions of skin, fat, muscles and bone, each possessing different tissue properties. This non-homogeneity leads to a non-uniform pressure distribution within the imposed socket shape. Thus, ideally the pressure should be measured over the entire surface area of the stump in order to obtain a complete picture of the pressure distribution. Any device utilized must be capable of measuring pressure at as small an area as is practically possible in order to record localized high pressures. It must not disturb the pressure distribution being measured due to its thickness or protrusion into the socket. It should also accommodate the socket contours and match socket rigidity.

The first known data on stump–socket interface pressures were published in the 1950s (**14, 15**). They were obtained using pneumatic transducers sampling a relatively large area (25 cm^2). Although several pressure transducers, specially designed or commercially available, have been used in the field of body–support interface pressure measurement, relatively few reports concerning socket pressures have appeared in the literature. In particular, there is a dearth of data on pressure patterns in sockets for trans-femoral amputees. Appoldt and Bennett (**16**) used miniature pressure transducers, incorporating a pressure sensitive diaphragm, on to which four semiconductor strain gauges were bonded to measure stump–socket interface pressures on one trans-femoral amputee. The pressure at 25 sites on the quad socket were measured. The maximum pressures detected at the anterior and posterior walls 100 ms after heel contact were 24 and 58 kPa respectively. Maximum pressures at the medial and lateral walls were 21 and 41 kPa respectively 100 ms after heel contact. The maximum recorded pressure at the brim, near the IT, was about 165 kPa. In a further study by the same group **(17)** on two patients, it was shown that the pressure at the interface can vary significantly from day to day and from week to week. The potential sources for such differences included instrumentation errors, subject's gait variation, donning of the prosthesis in a different position, fatigue and volumetric changes of the stump. Van Pijkeren *et al.* (**18**) described the manufacture and use of a hydraulic pressure transducer. The sensing element of the transducer was a bag made by heat sealing two PVC discs, 0.25 mm thick, 30 mm in diameter, which was filled with silicon oil. An oil-filled tube connected the bag to a National Semiconductor pressure transducer, type LX 1600. The total thickness of the fluid-filled bag was approximately 0.6 mm. The flexibility of the bag was reported to be sufficient to match flat, convex or concave surfaces in prosthetic sockets. Using this transducer, a study (**19**) was attempted to correlate interface pressure with the curvature at the ischial brim of the quad socket. The pressure at the IT peaked at approximately 200 kPa and was unaffected by variation of the radius of curvature. Pneumatic transducers based on similar principles as those of hydraulic transducers were used by Krouskop *et al.* (**20**) to measure interface pressures in 18 trans-femoral amputees. Nine of them were fitted with quad sockets and five with NSNA sockets. These sockets were considered comfortable during the study, while another four subjects had sockets which caused discomfort, three being NSNA and one quad. The results of the NSNA sockets indicated that tissue loading was concentrated around the proximal third of the socket and around the distal femur. In the quad socket most of the tissue loading occurred under the brim and some areas around the distal end of the femur also were reported as highly loaded. The pressure distribution in the two sockets was noted to be significantly different, but with pressure values of about the same magnitude. The authors of the present paper consider that the study of Krouskop *et al.* lacks consistency in evaluating socket types, since the patients were fitted with either quads or NSNA sockets and none with both types. The pressure distribution on each subject's stump is expected to vary due to the unique shape and comfort requirements of the individual. Thus, it is considered that comparison made with different subjects on different sockets would be highly inconclusive.

In recent years, increased use of conductive polymer type pressure transducers in body–support pressure measurement situations has been reported. Basically, these transducers consist of an assembly of two sheets of polymer, usually with the top sheet coated with an elastomer containing carbon or metal powder, while the lower sheet has a silk screened pattern of interdigitated silver conductors. The application of force on the transducer causes an increase in contact area resulting in a decrease of the electrical resistance. The attractiveness of this type of transducer is their extreme thinness (≈0.25 mm) and flexibility. However, the repeatability of the transducer output is highly dependent upon the geometry of the surface on which the pressures are being measured. Non-linearity, hysteresis, creep and other undesirable features are evident, leading to some researchers finding them unsuitable for accurate determination of interface pressure (**21**). Nevertheless, these systems should be independently assessed as they provide a promising technique for measuring socket interface pressure in a clinical situation.

3 METHODOLOGY

Upon comparing results of previous studies, a significantly wide range of pressures is evident from similar sites of measurement. This is inevitable since each prosthetic socket is customized for an individual patient and, moreover, created by different prosthetists. It clearly illustrates the difficulties involved in producing consistent sockets even with well-established and standardized methods of manufacture. The method therefore aimed to eliminate some of the inconsistencies by using one prosthetist to fit both sockets to the same patients.

3.1 Subjects

Two volunteer trans-femoral amputees participated in the tests. The subjects had been active wearers of the IC type socket since 1988. Prior to that time, both amputees had worn the quad socket. Prior to the test, an assessment of the amputees' stump conditions was carried out by an experienced prosthetist. The assessment was performed under the guidance of a standard document described by Wall (**22**). Information regarding condition of the skin and tissue, circulation, pain, joint function and muscle strength were recorded. The level of activity of the subjects was also assessed using Day's (**23**) activity level assessment, and both amputees were found to be highly dependent on their artificial limbs in their daily activities. Table 1 lists the activity level scores and summarizes other details of the test subjects. It might be worth noting that both amputees stated that they preferred the IC to the quad socket.

3.2 Prosthetic sockets and test limbs

Ischial containment and quad suction suspended sockets which were manufactured for each subject were fitted and aligned by the same prosthetist. The test sockets were constructed to incorporate pressure measurement sites. A total of 17 and 15 sites were allocated for the IC and quad sockets respectively. These sites were basically openings made in the socket to allow the pressure transducers to make contact with the stump. Cylindrical nylon adapters (Fig. 2, labelled E) were attached to the sockets at all measuring sites: this enabled the transducer to be located consistently flush with the inner surface of the socket. Only four transducers were available for any one data capture event, therefore threaded flanges on the adapters allowed transducer repositioning for subsequent data capture, while other sites were sealed with airtight nylon plugs.

Table 1 Subjects' particulars

Subject	Year of amputation	Age (years)	Weight (kg)	Day's activity level†	General condition of stump
PU (Left)*	1957	58	80	+4	Shape conical, skin slight redness, evidence of old distal odoema, phantom pain—dull ache
MM (Right)*	1967	47	77	+23	Shape cylindrical, tissue flabby, skin normal, circulation normal, pain at hip joint

* Left/right signifies side of amputation.
† Day's activity score—full range between −70 and +50. More than +30 (very high), +10 to +29 (high), −9 to +9 (average), −40 to −10 (restricted), and less than −40 (inactive).

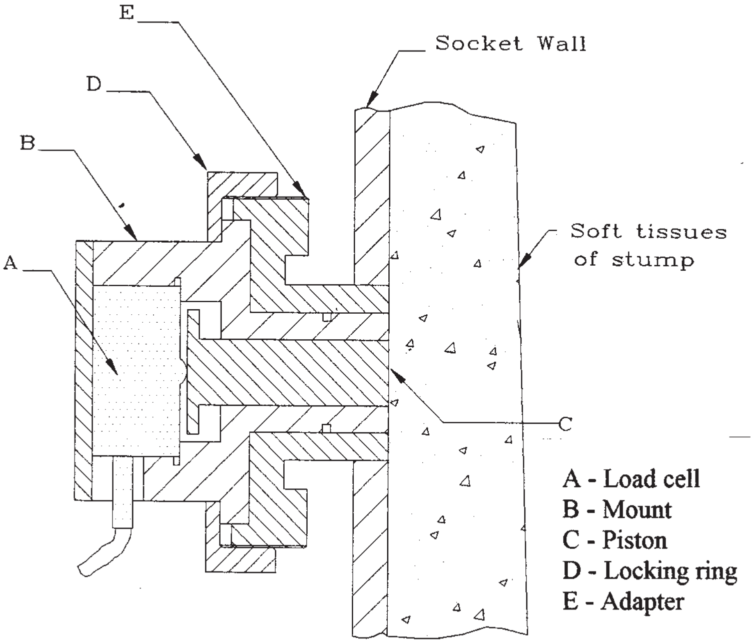


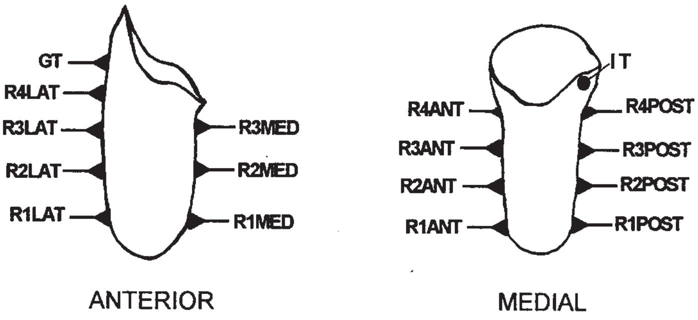
Fig. 2 Pressure transducer assembly

Location of the measurement sites was based on a process of subdividing the long axis of the socket. Two transverse reference planes were initially defined, 50 mm proximal to the distal end of the stump and 25 mm distal to the medial brim of the socket, where the amputee's perineum was located. Measuring sites were positioned on the anterior, posterior, lateral and medial midlines of the socket walls at the level of each of these planes and at points halfway between them. Proximal to the upper reference plane, additional sites were positioned on the anterior, posterior and lateral midlines for the IC (but only on the anterior and lateral midlines for the quad) maintaining a constant vertical distance between sites. Sites were also established at the IT of the IC and quad, and the greater trochanter (GT) on the IC. The sites were labelled to correspond to the anterior (ANT), posterior (POST), medial (MED) and lateral (LAT) sections and to rows R1, R2, R3, R4, from a distal to proximal direction (Fig. 3). The test sockets were manufactured using traditional laminating techniques, except for the incorporation of the adapters at the measuring sites.

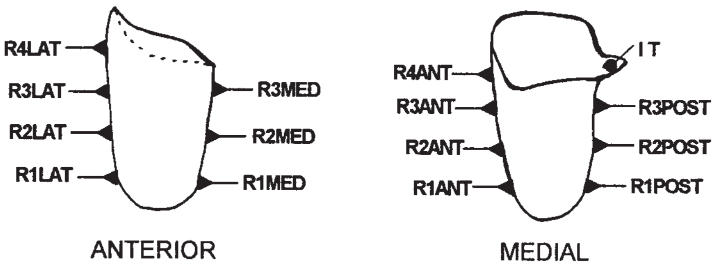
Each socket was assembled on to a modular limb which incorporated a stance-flex Endolite stabilized knee with pneumatic swing phase control and Multiflex foot and ankle (supplied by Chas. A. Blatchford and Sons Limited, United Kingdom).

3.3 Pressure transducer

The pressure transducers were specially constructed as shown in Fig. 2. A load cell model ELM 602-1, labelled A in Fig. 2, was incorporated, which was supplied by Entran International. This cell is basically a stainless steel cylindrical casing incorporating a sensitive diaphragm on to which miniature strain gauges in full Wheatstone bridge configuration are bonded. The specification of the load cell is given in Table 2. The transducer was thoroughly tested to determine its sensitivity, non-linearity and hysteresis and was consequently found to be suitable for pressure measurement in the current application. Although the transducer itself measures 15 mm in diameter and 6 mm in thickness, in order to ensure that it was secured flush with the inner surface of the socket, it was housed in a nylon mount (labelled B in Fig. 2), increasing the overall dimensions to 35 mm diameter, 17 mm thick. A cylindrical piston (labelled C in Fig. 2), which was kept continuously in contact with the diaphragm, transferred normal pressure from the stump tissues to the load cell. To facilitate connection and disconnection of the transducer to the adapter E, the threaded locking ring D was provided. The locking ring could be rotated independently on the transducer mount, thus avoiding the need to rotate the transducer with the associated danger of damaging its wires. Only four transducers were available for the test, therefore several test runs were required before pressure readings could be acquired from all sites. Airtight nylon plugs similar in shape and size to the transducer mounts sealed the sites where pressures were not being measured, thus ensuring that socket suction was not lost. The wires from the four transducers were connected to the amplifiers via an umbilical cord approximately 8 m long, permitting the subjects to walk freely. Calibration of the fully assembled transducer was performed using dead weights up to 200 kPa. It was estimated that the error of the transducers was ± 1.4 kPa.



Measurement sites - IC socket



Measurement sites - quad socket

Fig. 3 Location of measurement sites (for notations see text)

Table 2 Load cell specification (FS = full scale)

Range	2 lbs (8.89 N)
Non-linearity	±0.5%/FS
Hysteresis	±0.5%/FS
Sensitivity	4.735 mV/FS*
Operating temperature	−40–120°C
Thermal sensitivity shift	±5%/FS
Frequency range	0–900 Hz

* Unique to individual transducer.

One of the main concerns in the study was the determination of an appropriate contact area for the pressure transducer, i.e. the diameter of the nylon cylindrical piston. Pressure gradients and shear stresses exist at this area giving rise to a difference between mean and peak pressures applied on the sensor surface. Ideally, the sensitive area has to be as small as possible, however, this is often constrained by practical problems. In this study, the area was determined using the theoretical analysis proposed by Ferguson-Pell (**24**). A suitable radius, r, for the transducer sensor was obtained from equation (1).

$$r = \frac{3EP_p}{2K} \tag{1}$$

where P_p is the peak pressure, K is the pressure gradient and E is the percentage difference between peak and mean pressure. A 5 per cent difference between the peak and mean pressure could be maintained with a sensor of radius 2.81 mm, assuming a peak pressure of 100 kPa and a pressure gradient of 2.67 kPa/mm. The majority of interface pressures measured in previous studies for trans-femoral amputees fall within the range 0–100 kPa, except at bony areas of the stump where localized pressures of above 200 kPa have been reported. In order to cater for the latter (though in the present study no pressure above 100 kPa was recorded), the transducer chosen had a load range of 0–9 N, which gives a maximum pressure of 362 kPa based on the selected piston radius of 2.81 mm.

3.4 Equipment set-up

Figure 4 shows a schematic diagram of the equipment set-up. Data acquisition software 'Bioware' (supplied by Kistler Instruments AG, Switzerland) installed in a 486 personal computer was used to acquire data from the pressure transducers. The software also provided data capture and analysis for one Kistler force platform and also a Kistler axial load transducer (Load washer model 9031A). Eleven channels were used, four for pressure measurement, six for ground reaction forces and moments from the force platform and one for the axial transducer. All data were captured simultaneously.

The axial transducer was constructed as a washer with

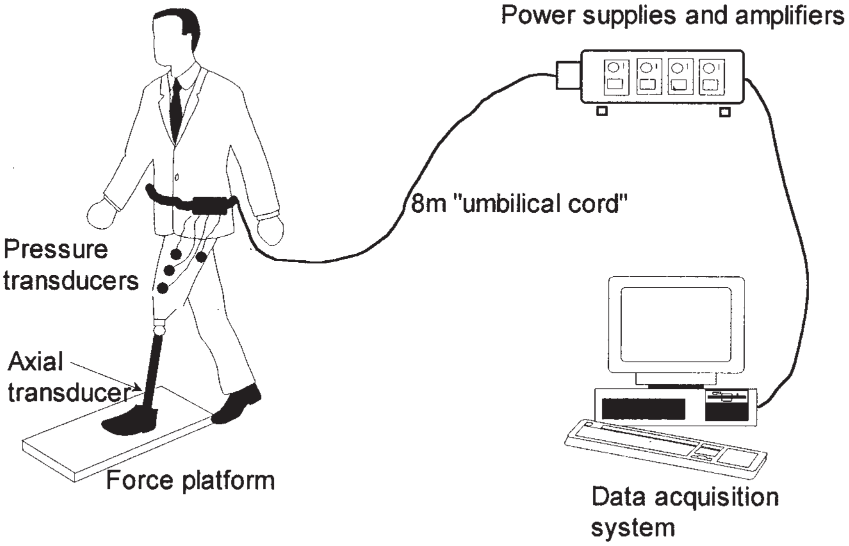


Fig. 4 Pressure measurement test set-up

external and internal diameters of 28.5 mm and 13 mm respectively, and a thickness of 11 mm. It was fitted between the foot and shank of the prosthetic limb through the foot bolt. Originally it was obtained to measure the axial load on the artificial limb. However, this device was not capable of isolating moments which significantly affected the axial load recorded. In this study, only temporal information was extracted from the axial transducer, which served only as a switch to indicate the instants of heel strike and toe off.

3.5 Test procedures

Prior to data acquisition, the subjects were asked to walk with the prosthesis for at least 15 min to become accustomed to the test socket. All data collection was performed on the same day without the subjects doffing the socket at any interval during the test.

The tests on each subject were divided into a static and dynamic stage. In the static test, the subject was positioned close to the force platform. Force platform data and interface pressure acquisition began about 2–4 s prior to the subject stepping on to the force platform, with equal weight on each foot as in a normal standing position. Recording was continued for a further 6–8 s, enabling a collection of stable static measurements of interface pressure and ground reaction forces. Since only one platform was used, ground reaction forces of the prosthetic limb only were recorded. The axial transducer was disabled during the static test.

For the dynamic test the subject was asked to walk a distance of approximately 8 m at normal walking speed, stepping on to the force platform with the prosthetic limb at approximately midway through the walk. Data capture lasted for 10 s and began only after one complete step of the artificial limb. Data collected included ground reaction forces, interface pressures and axial transducer signals.

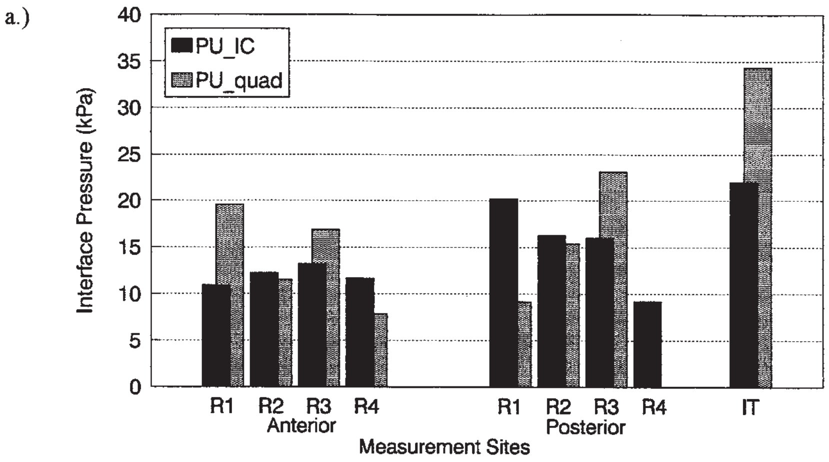
A total of eight and nine sets of transducer placements for the quad and the IC socket respectively (four transducers at a time) were required to complete the pressure measurements in each test routine. For each transducer placement, three recordings were made. This meant that the subject with the quad socket was required to stand 24 times for the static test and walk 24 times for the dynamic test, while in the case of the IC socket the corresponding figure was 27 times. In order to avoid fatigue of the patient, rest periods were allowed at regular intervals.

4 RESULTS AND DISCUSSION

Results corresponding to the two test routines stated in the methodology are presented. The average normal standing pressures were obtained with the subject standing stationary on the force platform for approximately 6 s. In the walking test, pressures were considered only at the particular step when the prosthesis contacted the force platform. The pressures were averaged for all trials but not for all steps in a single trial. Prior to the process of averaging, the data was normalized to 100 per cent of the gait cycle. The pressure patterns for the different walking trials were repeatable with the standard deviation for the majority of the sites being within ±5 kPa. A comparison of the results with those given by Appoldt and Bennett (**14**), this being one of the most detailed investigations published, is also made.

4.1 Normal standing pressure

The pressure generated at the interface on the various sites while standing for subject PU is shown in Fig. 5.



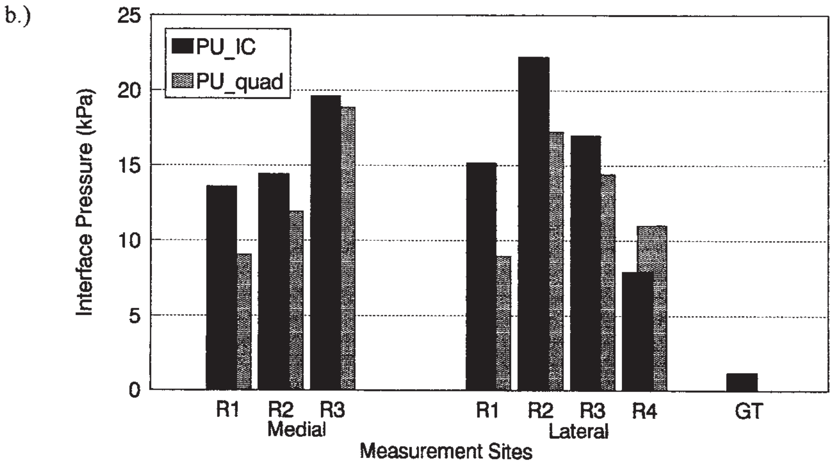


Fig. 5 Normal standing interface pressure in subject PU: (a) anterior and posterior sites, (b) medial and lateral sites (quad = quadrilateral socket, IC = ischial containment socket)

The values ranged from 1 to 34 kPa, with the maximum pressure being recorded at the site of the ischial tuberosity on the quadrilateral socket. A range of 5–19 kPa was recorded from subject MM with site R3POST yielding the maximum value, again for the quad socket.

Comparison between the sockets reveals evidence in the quad socket of higher distal than proximal pressure on the anterior wall and the opposite occurring on the posterior wall, perhaps indicating that the patient was tending to flex his stump. The IC exhibits a more even spread of pressure on the anterior wall and higher distal than proximal pressures on the posterior wall.

Considering the medial and lateral walls a similar pressure pattern emerged for both sockets with the IC exhibiting higher pressures at all sites except R4LAT and the difference in pressure was found to be more pronounced at the distal sites.

4.2 Normal walking pressure

The dynamic test results were normalized to 100 per cent of the gait cycle, based on the exact time of heel strike and toe off detected by the axial transducer. Figure 6 shows the dynamic pressure profile recorded on subject PU with the quad socket. In the majority of sites the pressure variations measured throughout stance showed a typical two peak curve for both types of socket. This was also the case for subject MM with the first peak occurring at approximately 12–16 per cent and the second at about 37–44 per cent of the gait cycle. The maximum pressure of just over 90 kPa that occurred at

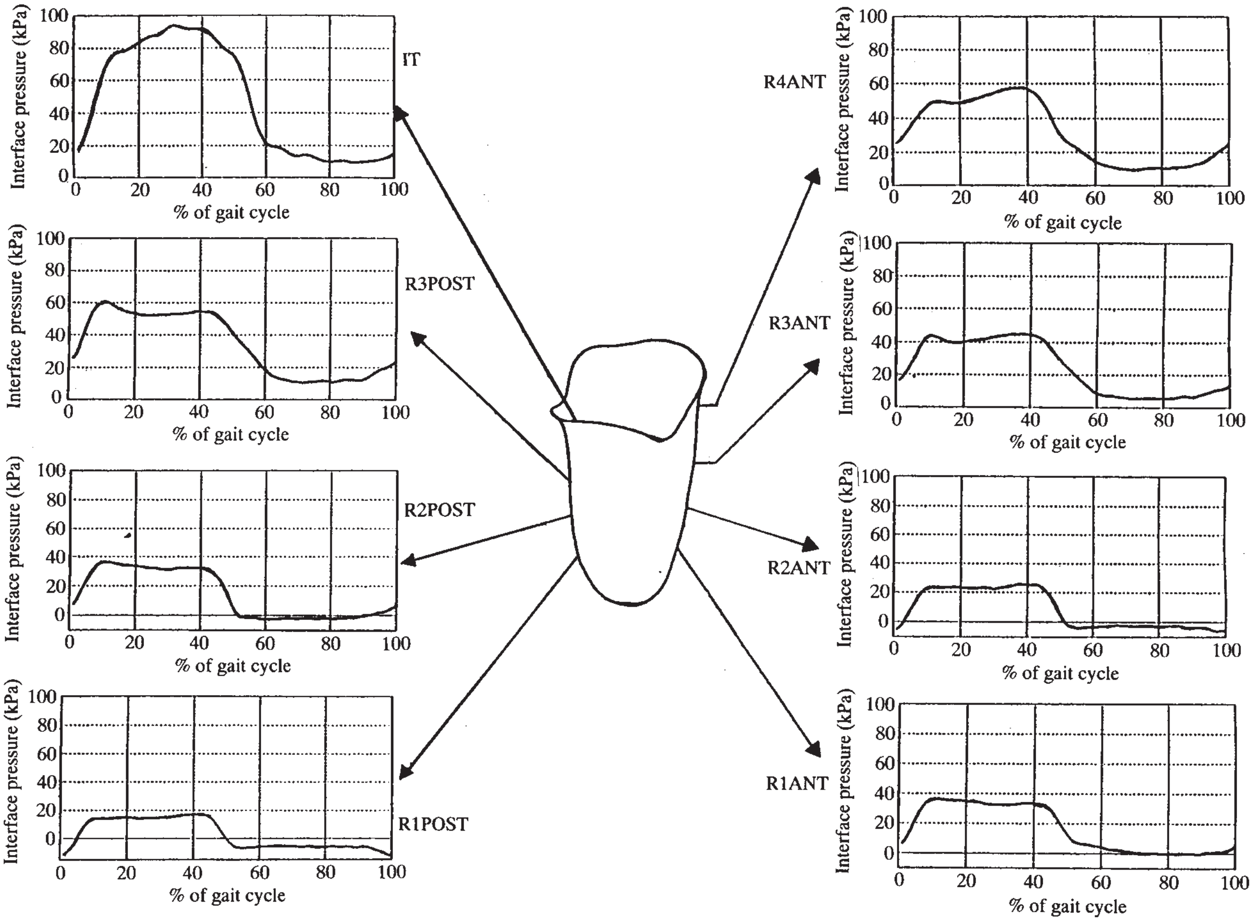


Fig. 6 Dynamic pressure profile in subject PU (quad socket, anterio-posterior plane)

33 per cent of the gait cycle was once more found at the IT site of subject PU's quad socket, while subject MM's maximum pressure (≈ 70 kPa) was located at R2LAT site of the IC socket occurring at 19 per cent of the gait cycle. Unlike other sites, both gave a single peak pressure profile.

Comparing the two socket types, differences in the pressure distribution were noted. The IC sockets for both subjects showed a more evenly spread pressure profile, while in the quad higher pressures were concentrated mainly at the proximal medial and posterior walls. In the IC socket for subject PU, the sloped surface provided at the ischial tuberosity reduced the loading on it compared to the quad, which may explain the higher pressures recorded at the distal posterior site.

4.3 Comparison of results with those of Appoldt and Bennett's (16) investigation

It should be pointed out that this comparison should be viewed in a qualitative basis, since an exact match of the measurement sites was not possible and the measurements were taken from different subjects. Appoldt and Bennett measured dynamic pressures 100 and 470 ms after heel strike. In the absence of complete temporal information, these timings were assumed to approximate 10 and 40 per cent of the gait cycle respectively. Comparisons were made only with the quadrilateral socket, since only this type of socket was used in the Appoldt and Bennett studies. The results from patient PU are graphically compared with those of Appoldt and Bennett in Fig. 7. The pressure distribution pattern follows closely at 10 per cent of the gait cycle for all socket walls. However, the low pressures reported by Appoldt and Bennett at the medial and lateral walls at 40 per cent of the gait cycle were not seen in the present study.

4.4 Medio-lateral (ML) stabilization

The direction and the anticipated distribution of forces acting on the stump of the trans-femoral amputee during gait were given by Radcliffe (**25**) (Fig. 8a). According to Radcliffe the resultant of the vertical forces acting between the stump and the socket passes through a point, the support point. This support point acts as a fulcrum with the pelvis as a lever subjected to two end

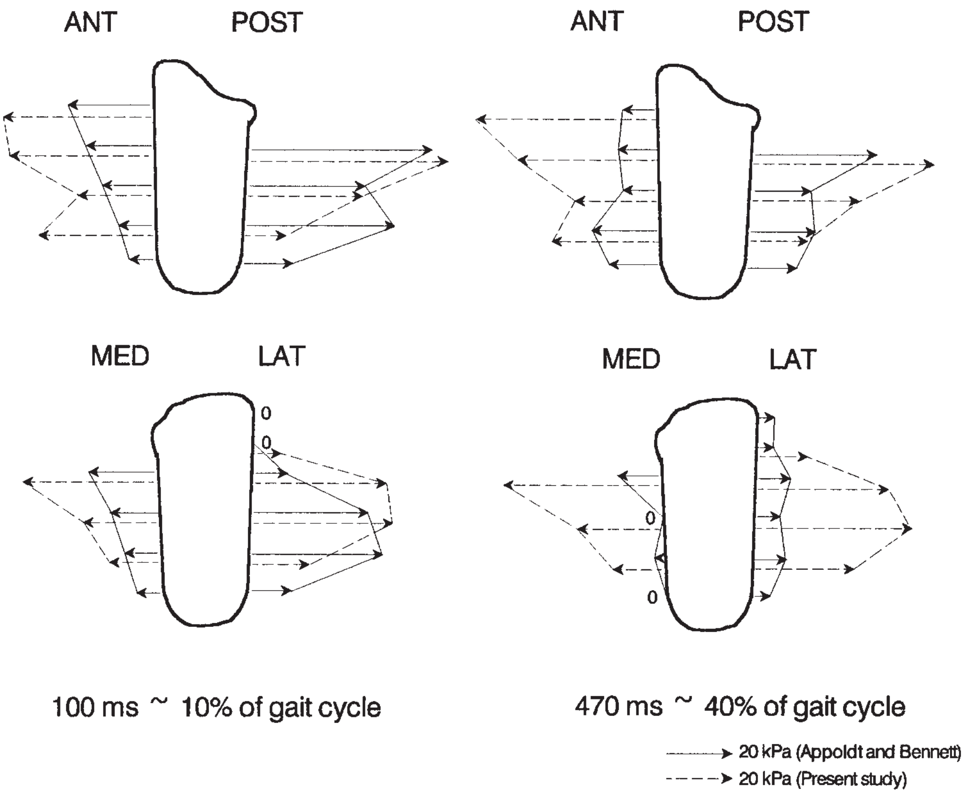


Fig. 7 Comparison of subject's PU quad socket pressures with Appoldt and Bennett's study

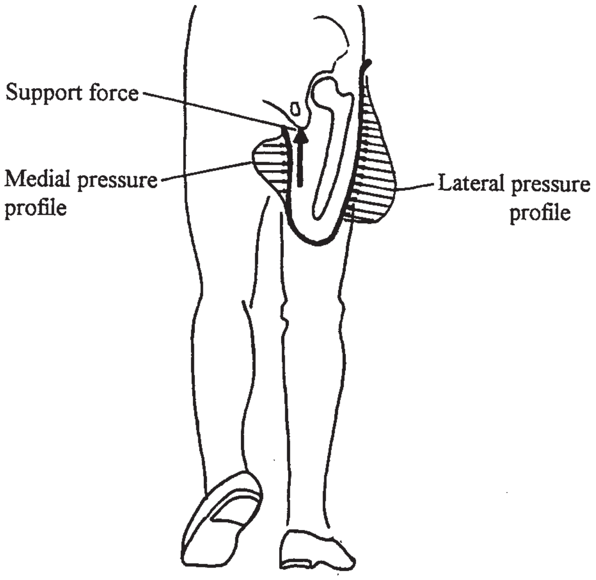
loads, the body weight and abductor muscles' tension. During prosthetic leg stance phase, body weight will cause the pelvis to rotate towards the unsupported side. Restriction of this motion, and thus maintenance of an approximately level pelvis, is achieved by contraction of the abductor muscles of the supporting leg. Contraction of the abductor muscles causes abduction of the femur bringing the femoral remnant, especially the cut distal end, closer to the lateral wall of the socket. Abduction of the femur and stump against the socket walls generates a moment which leads to an increase in the distal lateral and proximal medial pressures. Without accommodation, the localized pressure at the distal lateral aspect can lead to severe discomfort and hence to gait deviations. The prosthetist, therefore, aims to reduce this distal tip pressure by creating a small relief in the lateral wall while maintaining an intimate contact with the remainder of the lateral aspect of the stump.

The pressures recorded at 10 and 50 per cent of the gait cycle at the medial and lateral socket walls follow the expected pressure distribution, as described above in Fig. 8a, for both subjects on both sockets. Figure 9 illustrates the pressure distribution for one subject (PU) in the ML plane for both the IC and quad socket. The lateral pressure increases towards the distal end until it reaches a maximum at the second last site, then reduces at the most distal site showing that the desired relief was achieved. Medially, the proximal site shows that a high pressure exists and this pressure is reduced by more than 50 per cent towards the distal end.

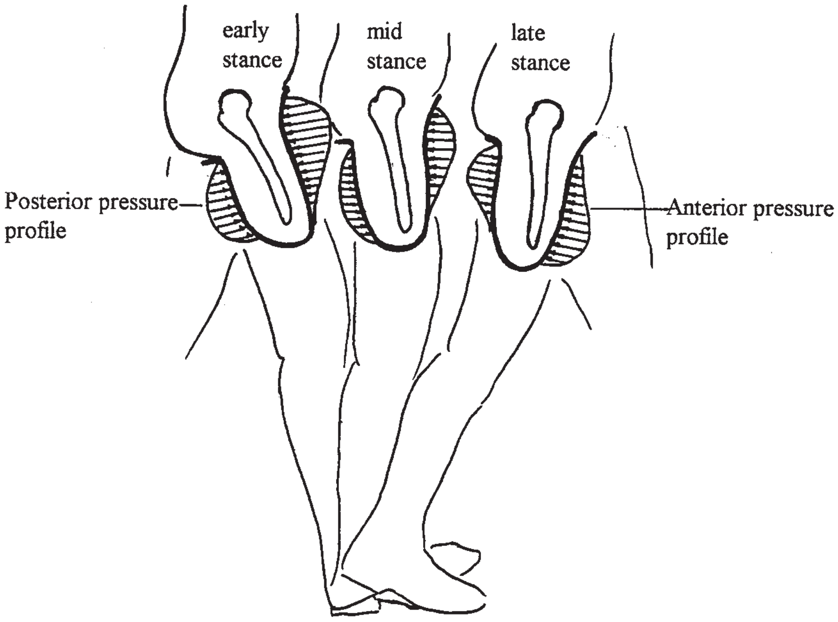
4.5 Anterio-posterior (AP) stabilization

Prosthetic knee stability can be achieved by a variety of methods, e.g. locked knee, weight activated lock or in a simple uniaxial free knee, voluntarily controlled by the amputee. With a uniaxial free knee the expected pressure pattern is as follows. At heel strike the hip extensors act to produce pressure at the proximal anterior and distal posterior socket walls. This pattern maintains up to the point of heel off when the ground reaction force passes behind the knee joint. In late stance anterior socket pressure is concentrated distally while posterior pressure can be found proximally as the hip flexes to propel the prosthesis into swing phase (Fig. 8b).

The AP pressure distribution for subject PU wearing the IC socket at 10 per cent of the gait cycle is shown in Fig. 10. The diagram follows the expected pressure distribution pattern shown in Fig. 8b at early stance but the difference between the pressure pattern on the anterior and posterior walls of the socket is less pronounced. At 50 per cent of the gait cycle the pattern remains the same as in early stance but the magnitude of the pressures decrease. This is not in agreement with the pattern shown in Fig. 8b which predicts a reversal of the load actions from hip extensors being active to



a) Predicted interface pressure pattern and support force during stance in the medio lateral plane



b) Predicted interface pressure pattern due to the action of the hip musculature only (supporting force not shown) in the anterior - posterior plane

Fig. 8 Predicted pressure distribution pattern in the quad socket [adapted from Radcliffe (**25**)]

the hip flexors being active. The pressure distribution throughout stance on subject MM with the IC socket displays similar characteristics.

In the quad socket during early stance, the pressures are concentrated at the proximal part of the socket with much reduced pressures at the distal part of the socket. As with the IC socket, no reversal of the pressure distribution at late stance takes place, the pattern remaining the same as in early stance but with reduced values. Exactly why the measured pressure pattern in the AP plane differs from that predicted in Fig. 8b at this stage of the investigation is not clear. A reason for the difference could be due to the fact that Fig. 8b assumes a free knee under voluntary control whereas the prosthesis used in this study was fitted with a stabilized prosthetic knee. Furthermore, the recorded pressures comprise the combination of pressures caused by weight transmission and by the propulsion forces. Before comparisons can be made, these two effects must be separated. However, it is considered that additional measuring sites are

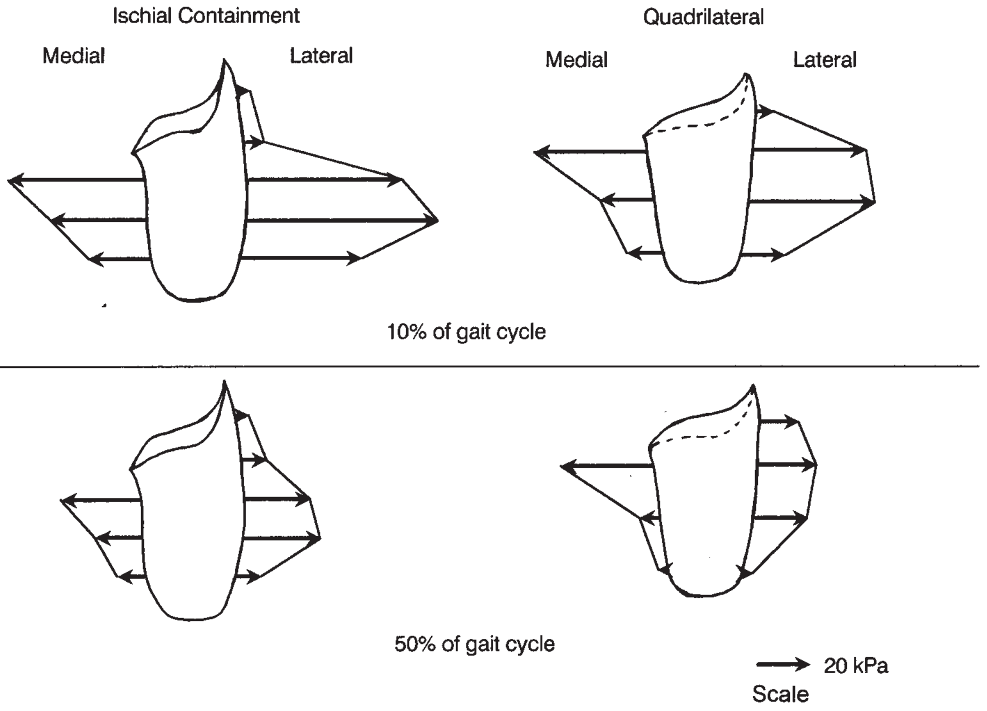


Fig. 9 Interface pressure distribution for subject PU at 10 and 50 per cent of the gait cycle in the ML plane

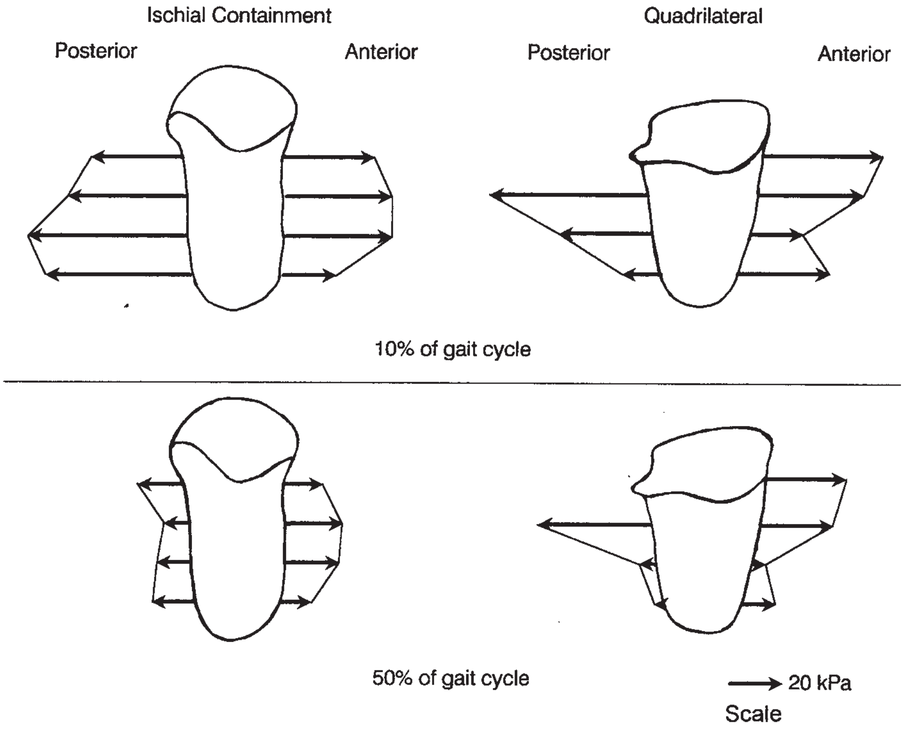


Fig. 10 Interface pressure distribution for subject PU at 10 and 50 per cent of the gait cycle in the AP plane

necessary before such in-depth analysis of the data can be undertaken. Further experiments are being planned.

4.6 Ischial tuberosity loading

Table 3 shows the pressure recorded on the IT for both subjects wearing both types of sockets. It was noted that on subject PU the pressure recorded on the IC socket was lower than that found in the quad. This was expected as the quad socket provides a definite ischial shelf to transmit the vertical load whereas the IC socket has a sloping surface. Subject MM differed: at 10 per cent of the gait cycle the quad socket displayed a lower pressure than the IC. However, from subjective comments received from the latter patient, it would seem that he cannot tolerate high pressures on the IT and in order to avoid pressure tenses his muscles within the socket, thus off-loading the IT.

As seen in Table 3, in both subjects when using the quad socket the pressure on the IT was higher in late stance than in early stance, i.e. showing that the IT was not fully loaded in early stance. This state of loading/unloading of the tuberosity has been noted previously by Lehneis (**26**). Referring to Fig. 11, the distance from the axis of rotation of the hip joint to the ischial seat on the socket changes throughout the stance phase. On the other hand, the distance from the hip joint to the IT remains constant. Thus, flexion of the femur causes separation of the IT from the ischial seat and conversely, extension of the femur creates a high pressure between the IT and ischial seat.

5 CONCLUSION

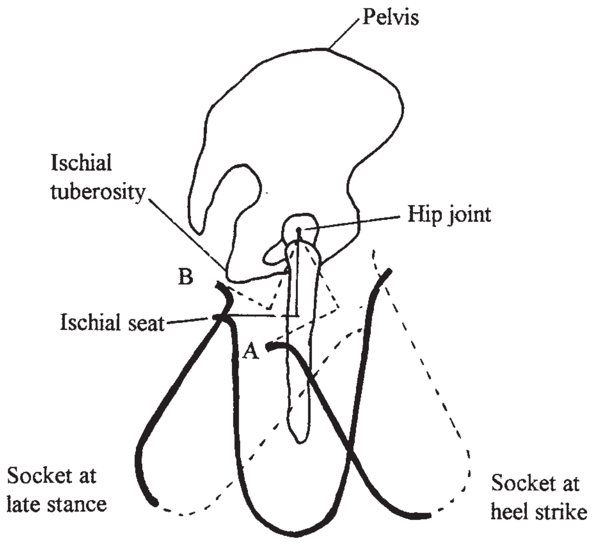
The specially designed and constructed transducers are capable of recording stump–socket interface pressure during standing and walking without disturbing the pressure distribution being measured. The transducer system has an error of ±1.4 kPa up to the calibrated pressure of 200 kPa. It measures the average pressure over a relatively small area (24.8 mm^2).

From the experimental data obtained for the two types of sockets, differences in the pressure distribution were noted. In the quad socket, higher pressures were found at the proximal medial and proximal posterior walls than at the distal areas of the socket. The IC socket displayed a more even pressure distribution. In a subjective evaluation both patients showed a preference for the IC socket. However, further work is required before the biomechanical behaviour of the two sockets is fully understood.

The dynamic pressure distribution in the ML plane was similar for both types of sockets and followed the predicted pattern. However, the pressure distribution on the anterior and posterior walls did not follow the anticipated patterns. Analysis of the results of the pressure distribution in these walls is complex and further work is required in this area.

Table 3 Interface pressure at the IT at 10 and 40 per cent of the gait cycle

	Ischial containment		Quadrilateral	
Subjects	10%	40%	10%	40%
PU	55.67 kPa	48.85 kPa	70.97 kPa	92 kPa
MM	20.82 kPa	29.81 kPa	9.26 kPa	39.03 kPa



(A) At heel strike seat leaves ischial tuberosity
(B) At late stance seat presses hard against ischial tuberosity

Fig. 11 Position of seat relative to the IT in a quad socket at various instants of stance phase

ACKNOWLEDGEMENT

This research was supported by the Engineering and Physical Sciences Research Council.

REFERENCES

1 **Radcliffe, C. W.** Functional considerations in the fitting of above-knee prostheses. *Artificial Limbs*, 1955, **2**(1), 35–60.
2 **Radcliffe, C. W.** A short history of the quadrilateral above-knee socket. In *Report of ISPO workshops* (Eds R. Donovan, C. Pritham and A. B. Wilson Jr), 1989, pp. 4–12 (ISPO, Copenhagen).
3 **Long, I. A.** Allowing normal adduction of femur in above-knee amputations. Technical note. *J. Orthotics and Prosthetics*, 1975, **29**(4), 53–54.
4 **Long, I. A.** Normal shape-normal alignment (NSNA) above-knee prosthesis. *Clin. Prosthetics and Orthotics*, 1985, **9**(4), 9–14.

5 **Sabolich, J.** Contoured adducted trochanteric—controlled alignment method (CAT-CAM): Introduction and basic principles. *Clin. Prosthetics and Orthotics*, 1985, **9**(4), 15–26.

6 **Hoyt, C. Littig, D. Lundt, J.** and **Staats, T. B.** The UCLA CAT-CAM above-knee prosthesis. *UCLA Prosthetic Education and Research Program*, 3rd edition, 1987, Los Angeles, California.

7 **Schuch, C. M.** Report from: International workshop on above-knee fitting and alignment techniques. *Clin. Prosthetics and Orthotics*, 1988, **12**(2), 81–98.

8 **Pritham, C. H.** Biomechanics and shape of the above-knee socket considered in light of the ischial containment concept. *Prosthetics and Orthotics Int.*, 1990, **14**, 9–21.

9 **Flandry, F., Beskin, J., Chambers, R. B., Perry, J., Waters, R. L.** and **Charez, R. C.** The effect of the CAT-CAM above knee prosthesis on functional rehabilitation. *Clin. Orthop. Res.*, 1989, **239**, 249–262.

10 **Gailey, R. S., Lawrence, D., Burdi, H. C., Spyropoulos, P., Newell, C.** and **Nash M. S.** The CAT-CAM socket and quadrilateral socket: A comparison of energy cost during ambulation. *Prosthetics and Orthotics Int.*, 1993, **17**, 95–100.

11 **Visser-Meily, J. M. A., Cluitmans, J. J. M., Deckers, J. H. M.** and **Ring, S.** Experiences of above-knee amputees with an NML-Socket in comparison with a quadrilateral socket. *J. Rehabil. Sci.*, 1992, **5**(1), 22–25.

12 **Esquenazi, A., Leonard, J. A., Meier, R. H., Hicks, J. E., Fisher, S. V.** and **Nelson, V. S.** Prothetics, orthotics and assistive device: 3. Prosthetics. *Arch. Phys. Med. Rehabil.*, 1989, **70**, S206–S209.

13 **Mitchell, C. A.** and **Versluis, T. L.** Management of an above-knee amputee with complex medical problems using the CAT-CAM prosthesis. *Phys. Therapy*, 1990, **70**, 389-393.

14 **Muller, E. A., Hettinger, T.** and **Himmelmann W.** Druckverlauf am Rand und Trichter eines Oberschenkelschaftes beim Gang (Pressure distribution about the brim and surface of an AK socket in walking). *Orthopadie Technik Heft*, 1956, **6**(June), 132–138.

15 **Muller, E. A.** and **Hettinger, T.** Die Messung der Druckverteilung im Schaft von Prothesen (Measuring the pressure distribution in the socket of prostheses). *Orthopadie Technik Heft*, 1954, **9**(September), 222–225.

16 **Appoldt, F. A.** and **Bennett, L.** A preliminary report on dynamic socket pressures. *Bull. Prosthetics Res.*, 1967, **10**(8), 20–55.

17 **Appoldt, F. A., Bennett, L.** and **Contini, R.** Stump–socket pressure in lower extremity prostheses. *J. Biomechanics*, 1968, **1**(4), 247–257.

18 **Van Pijkeren, T., Naeff, M.** and **Kwee, H. H.** A new method for the measurement of normal pressure between amputation residual limb and socket. *Bull. Prosthetics Res.*, 1980, 10–33, **17**(1), 31–34.

19 **Naeff, M.** and **Van Pijkeren, T.** Dynamic pressure measurements at the interface between residual limb and socket : The relationship between pressure distribution, comfort and brim shape. *Bull. Prosthetics Res.*, 1980, **10**(33), 35–50.

20 **Krouskop, T. A., Brown, J., Goode, B.** and **Winningham, D.** Interface pressures in above-knee sockets. *Arch. Phys. Med. Rehabil.*, 1987, **68**, 713-714.

21 **Steege, J. W., Schnur, D. S.** and **Childress, D. S.** Prediction of pressure at the below-knee socket interface by finite element analysis. ASME Symposium on the *Biomechanics of Normal and Pathological Gait*, Boston, 1987, pp. 39-43.

22 **Wall, M.** Stump descriptors. In *Report of ISPO Consensus Conference on Amputation Surgery* (Eds G. Murdoch, N. A. Jacobs and A. B. Wilson Jr), University of Strathclyde, Scotland, 1–5 October 1990.

23 **Day, H. J. B.** The assessment and description of amputee activity. *Prosthetics and Orthotics Int.*, 1981, **5**, 23-28.

24 **Ferguson-Pell, M. W.** Design criteria for the measurement of pressure at body/support interfaces. *Engng in Medicine*, 1980, **9**(4), 209–214.

25 **Radcliffe, C. W.** The Knud Jansen Lecture: Above knee prosthetics. *Prosthetics and Orthotics Int.*, 1977, **1**, 146-160.

26 **Lehneis, H. R.** Beyond the quadrilateral. *Clin. Prosthetics and Orthotics*, 1985, **9**(4), 6–8.