A PRELIMINARY REPORT ON DYNAMIC SOCKET PRESSURES [a]

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I. INTRODUCTION

The quadrilateral suction socket, in either of two forms, open-end or total contact, is currently the most advanced type of suspension with which above-knee amputees may be fitted. Several of the more important advantages of the open-end type are the elimination of the pelvic belt and hinge joint, improved control and position sense, and the development of the stump muscles which are used rather than allowed to atrophy (1). The total contact socket has several additional advantages (2). The slight pressure on the distal tissue helps to support and stabilize this portion of the stump. This additional contact area increases control and contributes in a small way to body support, but more importantly it allows for a looser fit in the critical proximal area where sealing is thought to take place.

There are little actual data concerning the static and dynamic pressures exerted by stumps on these sockets; the only known dynamic results, published by Müller, Hettinger, and Himmelmann, are based on pneumatic transducers sampling relatively large areas (25 sq. cm.) (3, 4).

Therefore, the Veterans Administration, as sponsor of this program, proposed that the project ". . . at New York University should work with the VAPC Bioengineering Laboratory in performing studies of above-knee and below-knee sockets, particularly total contact. The studies should try to discern the effects of total contact on socket pressure distribution and how the pressure distribution achieved by modern sockets affect: 1. the biomechanics of socket design, and 2. the physiology of the stump."

The initial results of a program to measure instantaneous stump socket pressure are described in this paper. The pressure profiles developed at 25

[a] Based on work performed under VA Contract V1005M–1917.

points in the wall and brim of the test socket of a single above-knee amputee were recorded and analyzed. The effects of parametric variations such as alignment and time (diurnal changes) are detailed (Fig. 1 and 2).

II. INSTRUMENTATION

A. Sockets

A well-fitted socket is a primary requirement in a study such as this, if meaningful data are to be collected. Since two of the criteria used in selecting subjects were the possession of a comfortable socket and a healthy stump, it was decided to duplicate the subjects' sockets rather than fabricate entirely new sockets for these tests. In this way, it was felt, the fitting problems often associated with a new socket would be avoided.

Coalginate and a tapered plaster plug were used to take a male impression of the socket; this impression was used to make a plaster-of-paris bandage

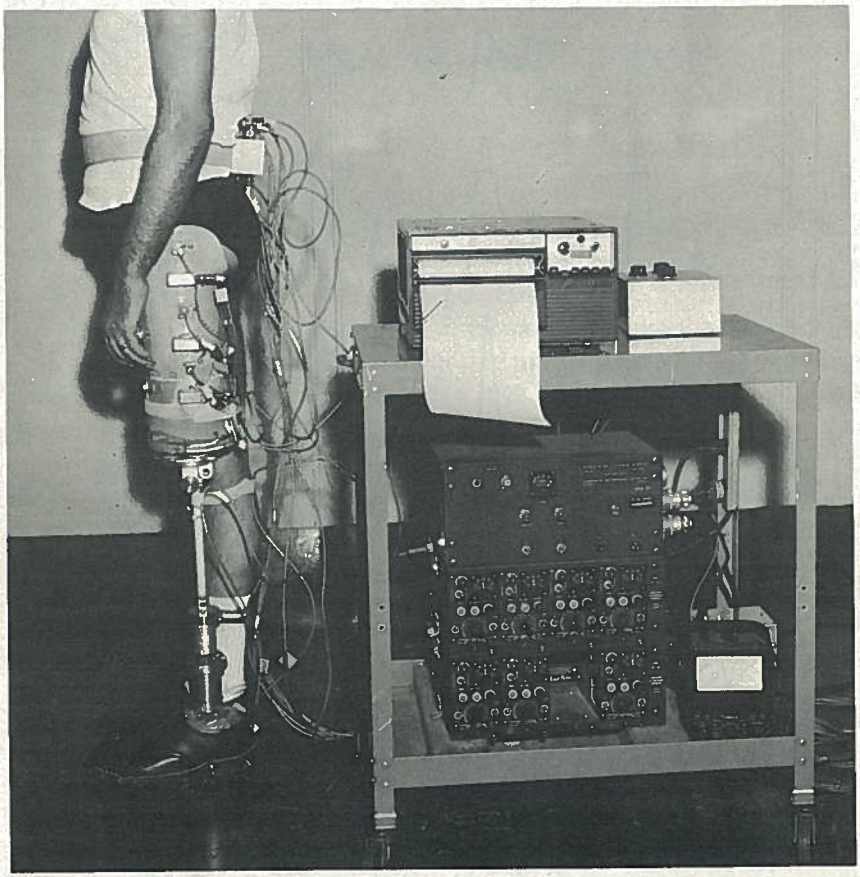

FIGURE 1.—A subject and the complete test setup.

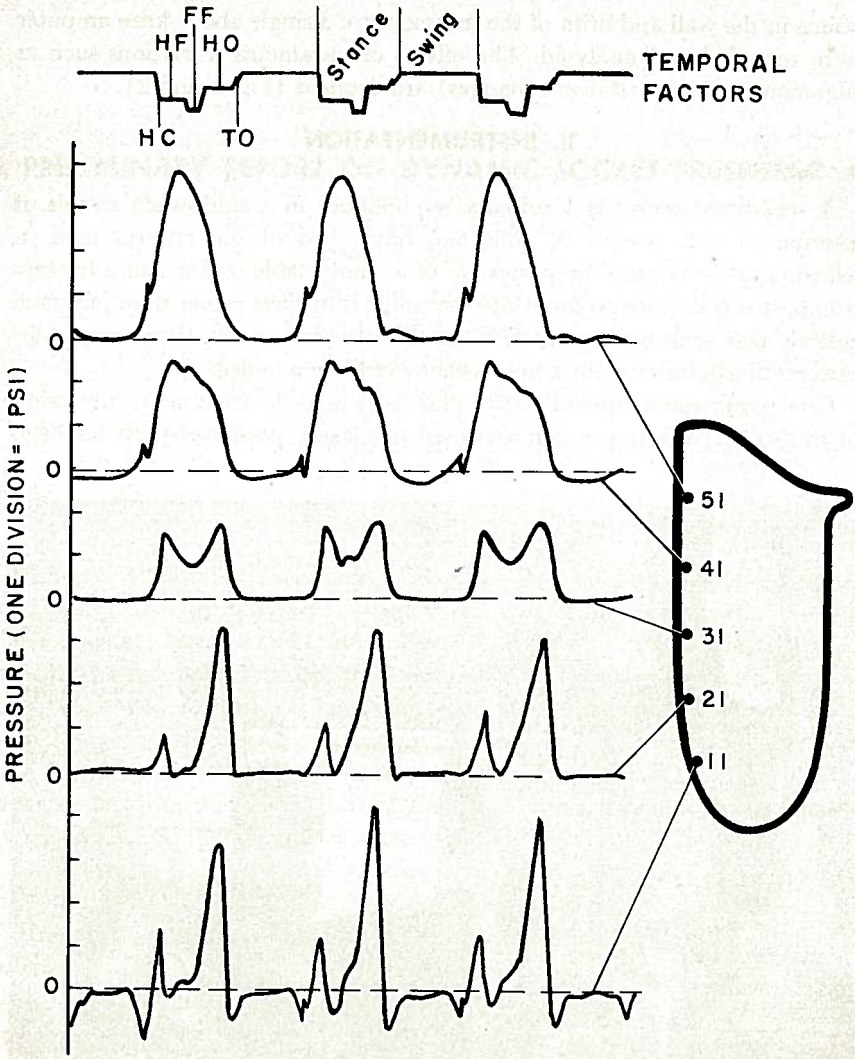

FIGURE 2.—Typical recordings of socket pressures—transducers inserted in anterior wall.

cast. The master model was produced in the usual fashion by pouring plaster into the female bandage cast.

Fabrication of the socket follows normal procedures excepting the placement of the transducer mount inserts. This modification is described in the next section. Upon completion, the socket is glued to a roughly shaped knee block. This assembly is mounted on a Hosmer adjustable above-knee pylon. Lastly, the prosthesis is fitted with the type of foot normally used by the amputee.

B. Transducer Mounts

The transducer mount currently being used required a certain amount of design and development because the special application and overall test program had to be considered. Since a large number of sampling locations were planned, the mount had to be simple to fabricate. Installation should be accomplished with relative ease and without the use of jigs and machine tools, if at all possible. Alignment of the transducer should be automatic and the sensing head of the transducer should always be flush with the inner surface of the socket. The design should allow access to the transducers while the prosthesis is being worn and should include a provision to seal the hole in the socket wall when a location is not being used. The inside face of the sealing device should match the inner surface of the socket.

At a very early stage in the program the transducer mounts were flanged and were attached to the outside of the socket wall with machine screws. This system was discarded owing to the complex jigging required for accurate alignment of the mount.

Another design avoided these problems by incorporating all of the alignment adjustments in the mount itself. However, this design was quite bulky and could not be used on the medial wall of the socket as it would have interfered with the subject's gait.

The system finally adopted integrates the transducer mounts and the test socket into one unit. Although it complicates the prosthetist's task, it is perhaps the easiest way to locate a large number of transducer mounts in a socket, and it is at the same time quite accurate.

The transducer mount consists of four pieces: 1. the insert, a flanged tube with a knurled outer face; 2. the mounting tube, slit for one quarter of its length; 3. the split clamp ring; and 4. a metal plug for sealing the mount when it is not being used (Fig. 3).

The prosthetist starts to fabricate the socket in the usual manner by drawing a polyvinyl alcohol (PVA) bag over the plaster model of the stump. The bores of the inserts are filled with wax (to prevent seepage of the polyester resin) and the inserts are cemented on the PVA bag at the proper locations. A stockinet is drawn over the model, followed by the outer PVA bag. The usual fabrication technique is then followed. After curing and removal of the plaster model, the laminate which covers the inserts is ground off and the wax plugs are removed.

The insert bores are enlarged slightly with a hand reamer and the mounting tubes are cemented in place. The assembly is completed by cementing the clamp rings on the mounting tubes. As a final step, the bore of each tube is tested with a "go, no-go" plug gage and enlarged if necessary. A complete assembly is shown in Figure 4.

On several occasions, when transducer mounts have been installed at new locations after the test socket has been in use, the following technique has

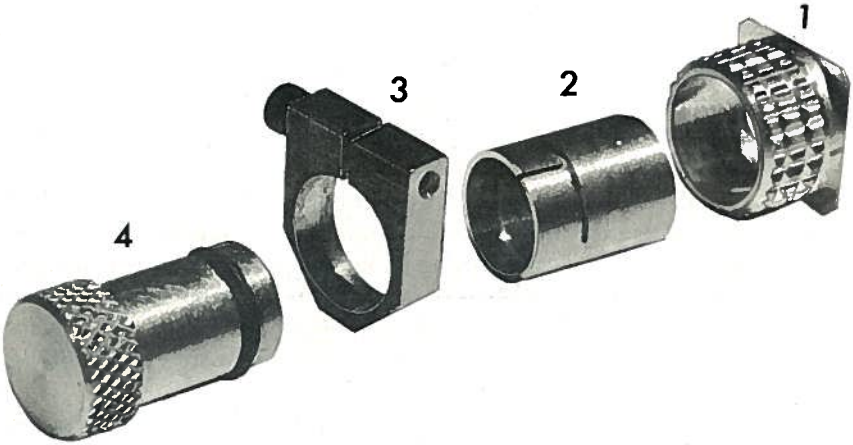

FIGURE 3.—Transducer mount parts.

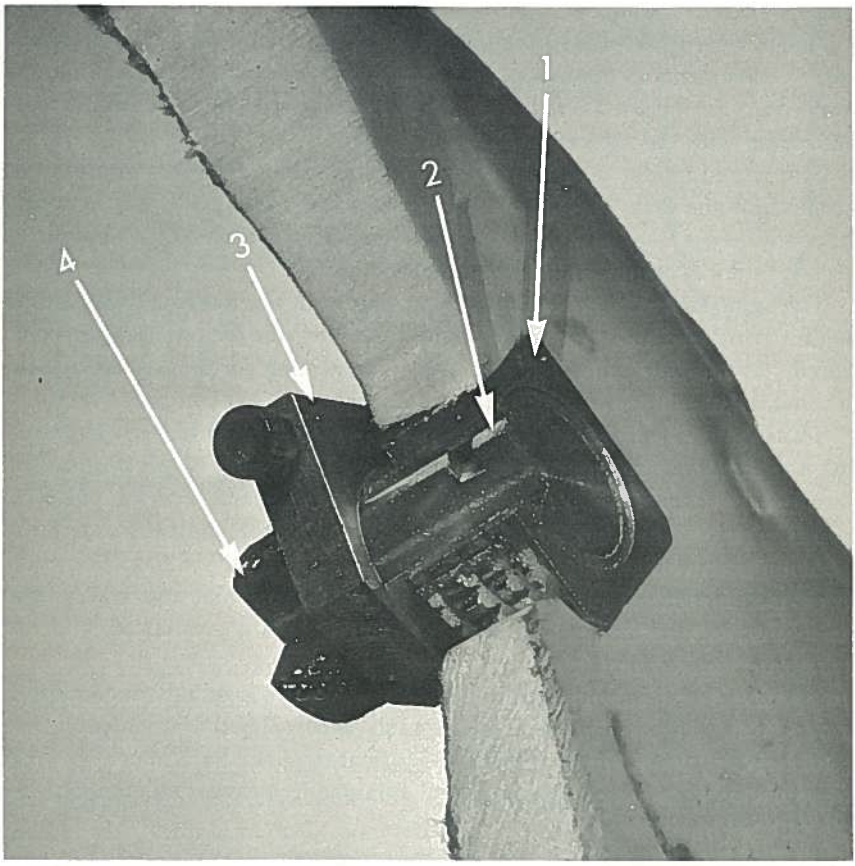

FIGURE 4.—Cutaway of socket and transducer mount.

been employed. The socket is set on the drill press table and blocked or clamped with the socket wall approximately perpendicular to the drill. The hole which is drilled through the socket wall should provide a snug fit for the transducer mounting tube. (The knurled insert is not used.)

In all probability the transducer mounting tube, when inserted, will not be perpendicular to the inside surface of the socket. If the hole is enlarged by redrilling or reaming, holding the tube in proper alignment until the adhesive sets can become a problem, requiring a jig. A simpler and more workable solution has been devised—countersink the hole from outside the socket wall. The material which has been removed by the countersink allows the tube to be aligned properly while being held in place by what remains of the original snug hole. This is a trial-and-error solution, since it is not possible to specify the final diameter of countersinking due to variations in the thickness of socket wall. Unless jigs [b] are to be used this system should be limited to the number of mounts one wishes to locate on one wall.

When not being used as an active sampling location, a metal plug (Part No. 4, Fig. 1 and 2) seals the mount. Since the portion of the plug which is inserted is the same length as the mounting tube, the inner surface of the socket is smooth.

C. Pressure Sampling Locations

There are two basic plans which may be used to locate the sampling sites on a socket. The first would be based on anatomical considerations, sampling pressures at the various critical points or areas on the stump such as the ischium, the ramus, the distal end of the stump, and the belly of a muscle. The second would systematically divide the socket into equal areas or equally spaced sampling sites so that an isobaric chart may be drawn.

The latter plan was employed by Müller and Hettinger when they determined static socket pressures. However, they divided the socket walls into small areas of equal pressure rather than plot isobars.

A hybrid plan was adopted for this program. The pressure transducer mounts are arranged in four columns located on the anterior, lateral, posterior, and medial walls of the socket. The mounts are spaced vertically approximately 2 in. on center. In addition, four to seven mounts are located in the brim (the number being dependent on the length of the brim), and one is located in the region bounded by Scarpa's Triangle. If the subject's stump is not too long, an access hole is placed in the wall of the knee block and a transducer mount is provided at the distal end of the socket.

A two digit numbering system is used to code the locations of the transducer mounts: the first digit (in the tens column) is the row, starting at the distal

[b] It has been our practice to use an epoxy cement which cures in 8 hours at room temperature; thus a jig would be required to accurately position and hold the mounting tube for this period of time. Curing at elevated temperatures for shorter periods of time (1 hour at 200 deg. F.) will still require a jig since the uncured epoxy is not viscous enough to support the mounting tube.

end with #0; the second digit (in the units column) is the column: #1—anterior, #2—lateral, #3—posterior, and #4—medial; for example, location #22 is in the lateral wall in the mid-stump region. The exceptions are the mounts located in the brim which are numbered consecutively starting at the lateral side of the posterior brim. The number of the closest row is used as the first digit, and is fixed; the second digit is changed, starting with the next consecutive column number. This system gives the reader an indication of the approximate length of the subject's stump from the ischium to the distal end since, as mentioned earlier, the mounts are spaced approximately 2 in. apart. Two views of a completed socket are shown in Figure 5.

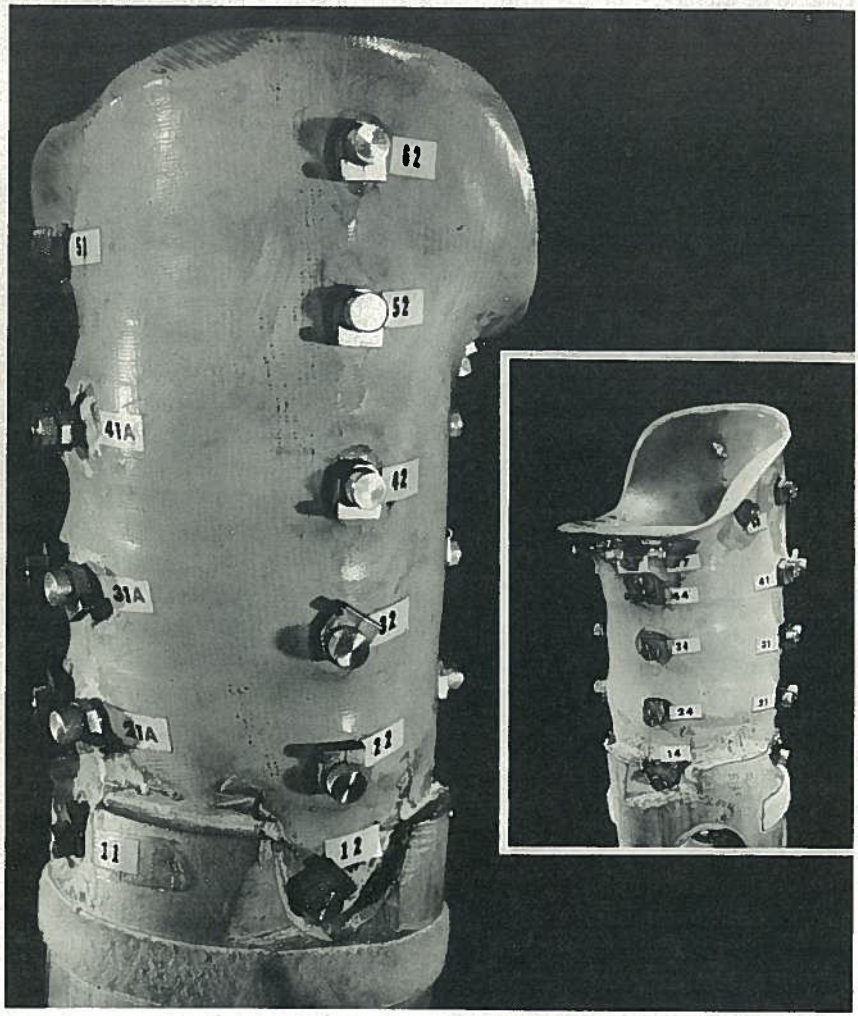

FIGURE 5.—Two views of the test socket.

D. Transducers

1. Background

When this program was initiated, the first task undertaken was a survey of commercially available pressure transducers. The following are the more important criteria which were used: sensitivity, size of the unit and of the sampling area, weight, compatibility with recording system, frequency response, accuracy, stability, and price.

It became clear early in the program that despite the number of pressure transducers manufactured, the majority are of the type designed to measure fluid pressures. This type of transducer is mounted in the system using pipe or tubing fittings, and the pressure sensing element is submerged in the transducer body. This program required that the transducer would, 1. have a configuration which allowed the sensing head or element to be mounted flush with the inner surface of the socket or 2. be small enough to permit mounting the unit in or on the inner surface of the socket.

The latter type of transducer, mounted on the inner surface, would be ideal for this project since the fabrication of the test sockets would be greatly simplified by obviating special transducer mounts. It would allow a large number of amputees to be tested using their regular prostheses, once the most critical or indicative pressure areas had been determined by prior and extensive tests of a select few.

This type of transducer could be used readily as a laboratory-clinical tool in many instances to determine quantitatively why certain and often used corrections are effective. Edema, for example, is caused by strangulation of the distal end of the stump and can be cured by reshaping the socket so as to reduce the pressure. The transducers could be used to map the pressure gradients before and after the socket is reshaped.

2. Principles of Operation

Generally speaking, one of the following principles is employed to detect pressure: piezoelectric effect, capacitance change, differential transformers, and resistance change.

The piezoelectric transducers are usually the least expensive and the smallest but were rejected because, as purchased, they were not compatible with the amplifying equipment on hand. The additional circuitry required to effect compatibility will increase the cost to that of a strain gage unit. In addition these units require dynamic calibration. Since the piezoelectric effect is dynamic, the units cannot read static pressure nor can they be calibrated statically.

The capacitance change transducers are typified by the Franklin Institute Laboratories Pressure Indicating Patch (FILPIP) developed by The Franklin Institute. Prior experience with these units led to their rejection.

They do not respond linearly to pressure change, hysteresis cannot be eliminated, and bending the units will change their characteristics.

Differential transformers, which are capable of measuring very small displacements, could be used to measure force or pressure when connected to a beam or diaphragm. As in the case of the FILPIP, prior experience with such units indicated that they are very sensitive to small alignment changes (they require very rigid mounts), require a complex calibration procedure, and do not respond linearly.

The last principle, resistance change, is the most commonly used for this application, and the most common forms are the wire or foil strain gage (SR–4) and the newer, high sensitivity, semiconductor strain gage. These gages are usually arranged in a Wheatstone Bridge configuration with four active arms for maximum sensitivity. Both of the transducers currently used in this program utilize this principle and configuration.

Two other devices which were tested and which operate on the resistance change principle are the solid state pressure cell and the mercury column strain gage.

The solid state pressure cell is a very attractive unit at first glance because of the very low cost, the simplicity of both the unit and of the recording equipment required, and the sensitivity claimed by the manufacturer. Unfortunately, the cells which have been tested have exhibited the following characteristics—nonlinearity, nonrepeatability and high hysteresis. The manufacturer of these cells also markets a pressure sensitive paint which was thoroughly tested by the VAPC Bioengineering Laboratory with the same disappointing results.

The last gage to be tested was the mercury strain gage (Whitney Gage). This unit was designed to be used with a plethysmograph designed and manufactured by Parks Electronics Laboratory. The gages are made of a synthetic elastic tube which is filled with mercury. The ends of the mercury column make electrical contact with solid lead wires which also seal the ends of the tubing. As normally configured the tubing is wrapped to form a ring which is slipped over a finger or a toe.

These units showed promise although they were not designed for this application. The units are tension gages and are not designed to be compressed in a direction perpendicular to their length. Since the leads were simply forced into the ends of the tube (not bonded) the compressive load often forced the mercury out of the end of the tube, separating the column end and destroying electrical continuity. Testing was discontinued because it was felt that this sealing problem could become a minor project in itself. In addition, the use of the elastic tube as a container would probably introduce hysteresis effects.

3. Description

Two different transducers are presently being used on this program. Both employ the same electrical principle, that is, four active strain gages arranged as a Wheatstone Bridge, but they differ markedly in physical detail and sensitivity.

The Micro-Systems Pressure Transducer—a flush-diaphragm unit designed to record fluid pressures. (In this application the flesh of the amputee's stump may be considered a highly viscous fluid.) The transducer is basically a hollow cylinder, 1/4 in. in diameter by 5/32 in. long, hermetically sealed at one end by an electrical feed-through terminal plug and at the other end by the pressure-sensing diaphragm. The terminal plug and diaphragm are separated, leaving a small chamber which acts as a pressure reference cavity. The stresses in the diaphragm, produced by externally applied pressures, are sensed by four semiconductor strain gages which are bonded to the inner surface of the diaphragm.

This transducer has a range of 0–85 p.s.i.g., but is routinely calibrated to 27 p.s.i.g. since the pressures encountered rarely exceed this value.

The NYU Pressure Transducer—a plunger or piston-type force gage. Since the area of the head of piston is known it can be used to detect pressure. The head of the piston normally used is 1/4 in. in diameter.

The piston is rigidly fixed to the center of a small steel beam. The ends of the beam are in turn rigidly clamped to the body of the transducer. Four SR–4 foil strain gages are bonded to the beam and detect the bending stresses produced in the beam when it is flexed by pressures applied to the face of the piston.

Extensive calibrations have confirmed that the transducer's response is linear to 30 p.s.i.g.

The sensitivity of this unit is approximately one-tenth that of the Micro-Systems transducer, because the SR–4 gages are much less sensitive than the semiconductor gages used in the latter unit. Sensitivity may be increased by substituting semiconductor gages or by reducing the thickness of the steel beam. The latter solution would decrease the linear range of the transducers. An advantage of this design is the ease with which the sampling area may be changed simply by changing the diameter of the piston head. As presently configured, the diameter may be increased to 7/16 in., without modifying either the transducer or the transducer mount.

The decision to employ two gage types reflected the desire to have a backup system available should one system prove ineffective. The results of extensive testing indicate both systems to be highly effective. The advantage of the Micro-Systems transducer is the greater range and sensitivity; that of the NYU unit is the readily altered pressure sensing area. In a system comparison, such advantages appear as second order factors; there are no first order differences with respect to the task.

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E. Calibration

The Micro-Systems pressure transducers are statically calibrated with a system which uses nitrogen to apply pressure and a differential manometer filled with mercury to determine the gas pressure. Basically, the calibration system (Fig. 6) consists of: 1. a baseplate in which, 2. the transducers are mounted, and 3. a small metal chamber resembling a bell jar which is

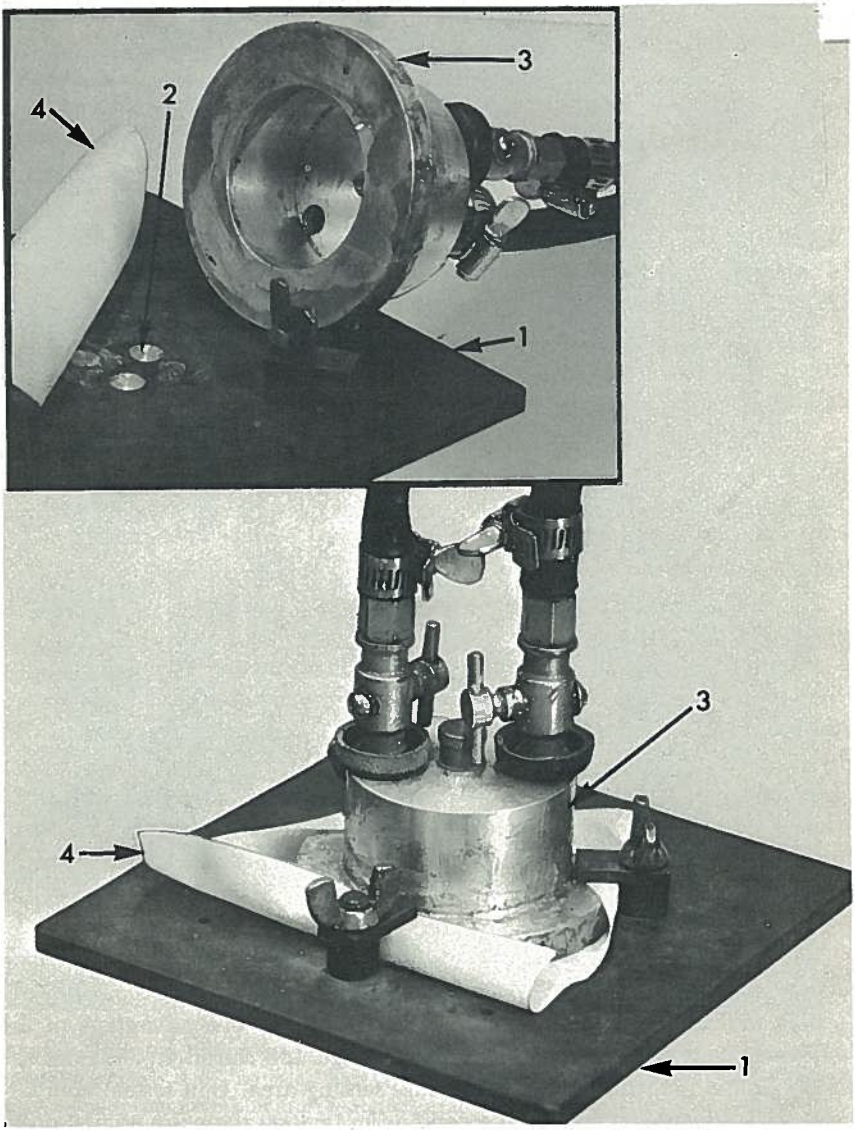


FIGURE 6.—Calibration device for the Micro-Systems pressure transducer.

mounted atop the base. The transducers are mounted so that their sensing heads are flush with the upper surface of the baseplate. A rubber diaphragm, 4., sandwiched between the chamber and the baseplate, both seals the system and applies pressure to the metal diaphragm of the transducer's sensing head.

The NYU transducers are calibrated by direct application of weight or by gas pressure. The equipment used to apply the weights (Fig. 7) consists of: 1. a rigid base in which, 2. the transducer is inserted, and 3. a small weight pan mounted on the plunger.

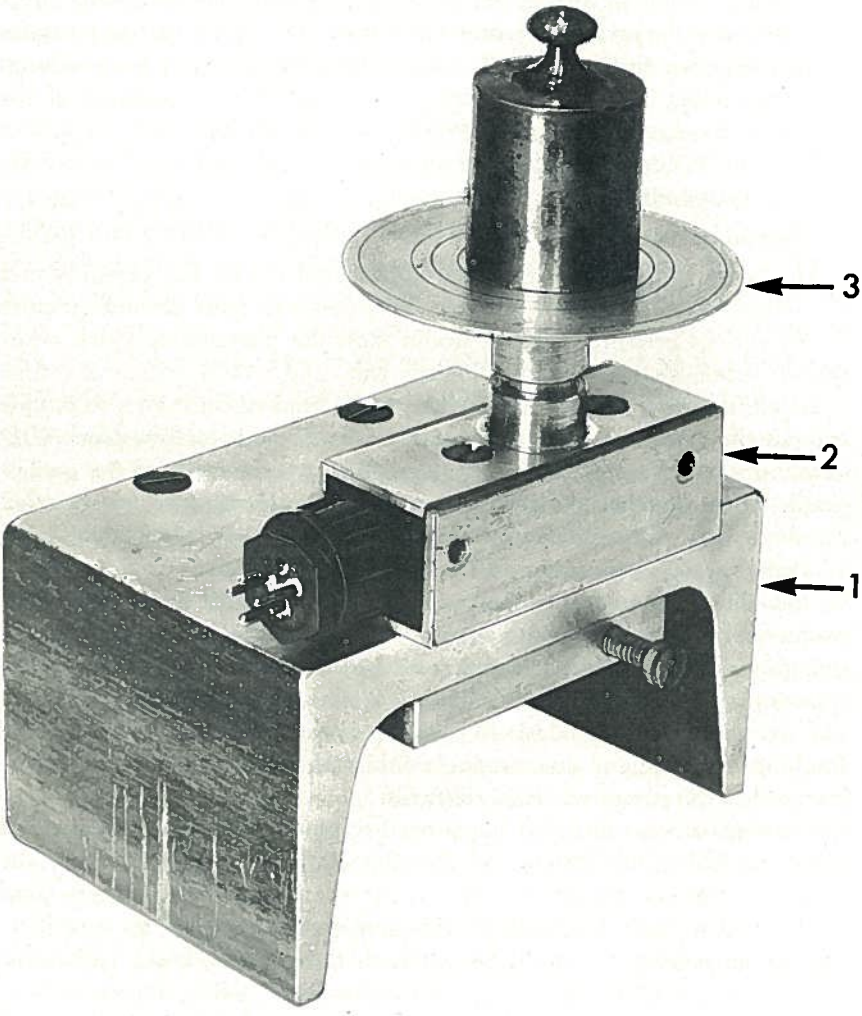


FIGURE 7.—Calibration device for the NYU pressure transducer.

F. Attenuator Settings

The amplifier attenuators are set so that maximum transducer outputs are recorded consistent with the galvanometer beam location on the recorder paper.

The normal procedure has been to determine the attenuator setting for a particular transducer and a particular location on the test socket. This setting is then used throughout all succeeding tests and would only be adjusted if the output signal is either too weak or too strong, e.g., due to a change in alignment.

In many instances this system obviates data reduction, allowing direct comparison of the pressures recorded during several runs at specific locations to determine whether a change in the subject's test prosthesis has produced a corresponding change in pressure. It does not allow comparison of the pressures recorded at several locations during one run since each transducer will respond differently, depending on the individual transducer's sensitivity and attenuator setting.

G. Sampling Technique

The ideal sampling technique would record all of the pressure sites simultaneously. This would produce the truest and most accurate picture of the various pressure patterns, would show the interactions which occur due to subtle changes in the subject's gait, and would reduce the time required for a test. Unfortunately, the system required for such a technique exceeds the capacity of the equipment on hand, both of New York University and the Veterans Administration. The true capacity of the oscillograph is the number of information channels which may be recorded simultaneously without overcrowding the recorder paper. The Consolidated Electrodynamics Corporation (CEC) oscillograph has an 18-channel capacity but only six to eight channels may be used to record the pressures encountered in this program with a reasonable degree of accuracy, i.e., permitting galvanometer deflections of at least 1 in. for peak pressures. Since the recorder paper is 7 in. wide, any additional channels of pressure data would require additional attenuation of the individual signals, otherwise the resulting crowding and intertwining would make data reduction and interpretation of the records extremely difficult.

A system which was tested but proved to be unworkable was sequential sampling. Using this system, all the sites could be sampled during the same run but not simultaneously. If, for example, 18 transducers were used and arranged electrically in six groups of three, only six amplifiers and six galvanometers would be required, this number being within the capacity of the CEC oscillograph. By means of a switch, the outputs of each group would be fed, in sequence, to one amplifier and then to a galvanometer. The sampling time increment could either be fixed by using

a motor-driven rotary switch or synchronized with the subject's cadence by using a stepping switch activated by a switch mounted on the subject's shoe.

In order that this system functions properly, the transducers which are grouped should have identical electrical characteristics and almost identical response characteristics since the amplifier can only be balanced once—before the test. The sites at which the grouped transducers are located would have to be chosen with care since marked differences in the pressures at the sites would result in very poor oscillograph records. As an example, suppose that the peak pressures at sites A, B, and C are 25, 20, and 5 p.s.i. respectively, since only one attenuator setting on the amplifier is possible for the three transducers, the setting for site A would have to be used, at the expense of sensitivity at site C.

To compensate for this and for the differences in the electrical characteristics would require that supplementary circuitry be added—one circuit for each transducer. It was the opinion of the group that the added complexity and expense outweighed any advantages of the system.

Eight channels are currently being used, six for pressure data and two for temporal data. This is, of course, a compromise solution which has worked quite well. The oscillograph record is relatively uncluttered by locating the temporal data traces on either edge of the paper; therefore, almost the full paper width may be occupied by the six pressure data traces.

H. Temporal Factors

In a study such as this, identification of the swing and stance phases of walking is of importance; if the various parts of stance phase can be recognized the analysis of data can be refined.

This, of course, has been recognized by the earliest investigators, who used various methods to determine the locomotion cycle and its component parts. Until recently, the most commonly used systems were interrupted light photography, several types of walkways, and foot contact switches.

The interrupted light camera is usually used in conjunction with the force plates and produces stick pictures of the subject as he approaches, contacts, and departs from the force plates. During stance phase the shank and foot, in essence, rotate about one point, and as a result, the sticks representing the successive positions of the shank and the sole of the foot are crowded together. This makes it much more difficult to distinguish the segments of stance phase.

Because of this, the various temporal factors have been determined by other and usually more simple means. One very successful and simple method, used by NYU and the VA Prosthetics Center, is the metal walkway. The walkway consists of two parellel metal plates upon which the subject walks while wearing aluminum foil soled sandals or aluminum foil fastened to the soles of his shoes.

The plates, isolated from one another electrically, are connected in series with a power supply and an oscillograph. The subject, whose foil soles are connected electrically by a jumper wire, acts as a switch, closing the circuit during double support time and opening it during swing phase. The disadvantages of this system are its inability to detect the constituent parts of stance phase, the need for the metal walkway, and finally, the foil-soled shoes or sandals which could subtly alter the subject's gait as a result of reduced traction.

The system which is currently in use employs an array of switches which are arranged along the foot so that the stance phase can be divided into its constituent parts. This system is new in detail but not in concept—a number of previous investigators have used various types of switches to determine swing and stance phase and to identify the components of stance. What distinguishes this system is its simplicity, reliability, ruggedness, and freedom from fussy adjustments.

The heart of the system is a strip switch [c] which may be cut to any length. Five strips are cemented in the transversely grooved heels and soles of the subject's shoes; wired in two parallel circuits (Fig. 8), they divide stance phase into five discrete segments—heel-contact, heel-flat, foot-flat, heel-off, and toe-off.

III. TEST RESULTS

The experimentally measured stump socket pressures are presented for a single above-knee amputee, believed to be representative of those amputees

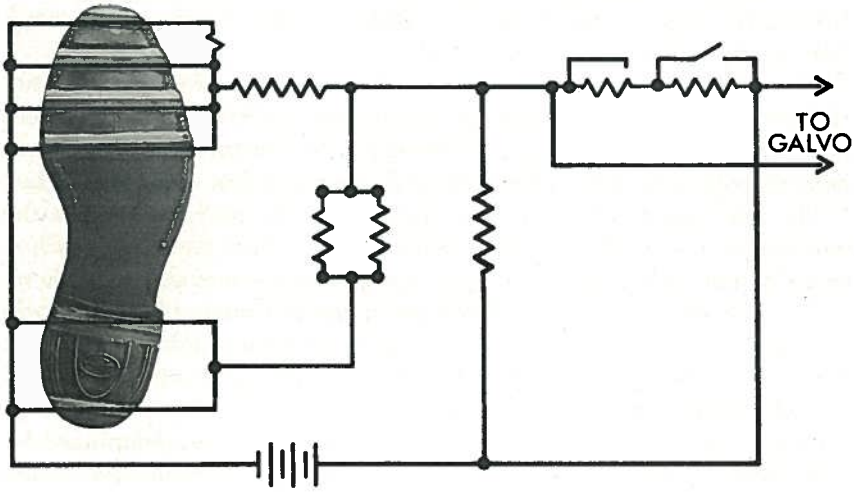


FIGURE 8.—Schematic of the temporal factors circuit.

[c] Controflex Ribbon Switch, manufactured by the Tapeswitch Corporation of America.

possessing a long stump and wearing properly fitted prostheses. Two alignments have been tested—normal and abducted shank.

Four discrete points of stance phase are analysed. They were chosen because peak pressures were recorded at these points at many of the sampling locations. The peaks were recorded at 100, 300, 470, and 540 milliseconds (msec.) after heel-contact. Figure 9 depicts the attitude of the socket at these instances.

The sign convention used in this analysis is one in which the stump is considerd to be acting on the socket.

It should be noted that two assumptions were made in this analysis. They are that:

1. The instantaneous pressures, represented by vectors, act perpendicular to the vertical axis of the socket. In actual practice the transducer is mounted in the socket with the pressure sensor flush with the inner wall at the point of insertion. Figure 10 illustrates the angular deviation of the longitudinal axis of each transducer mount from the transverse plane of the socket. Since large deviations occur only at four positions, the effects of angulation may be neglected.

2. A given pressure value represents the mean value experienced over

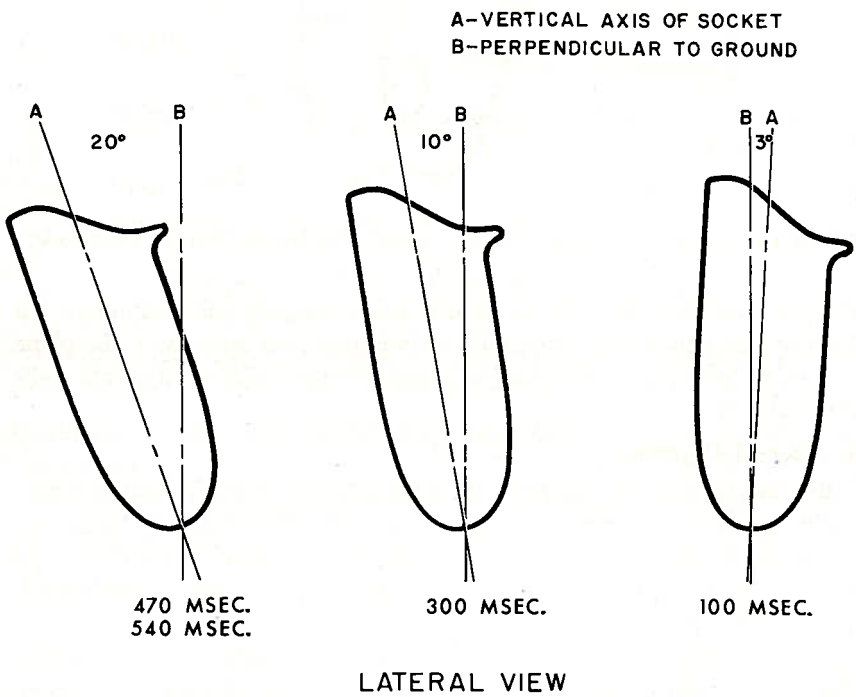


FIGURE 9.—Attitude of socket during stance phase.

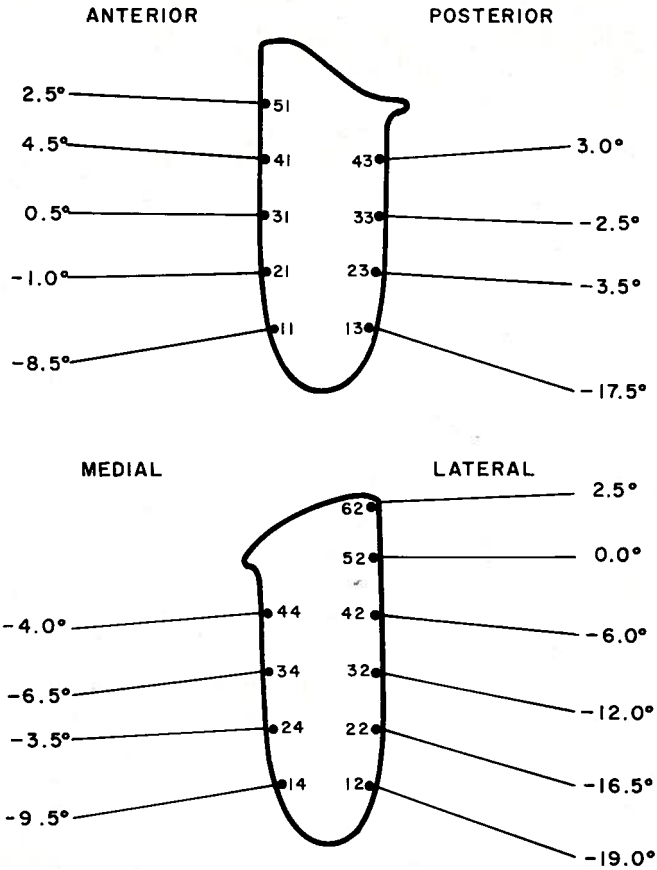


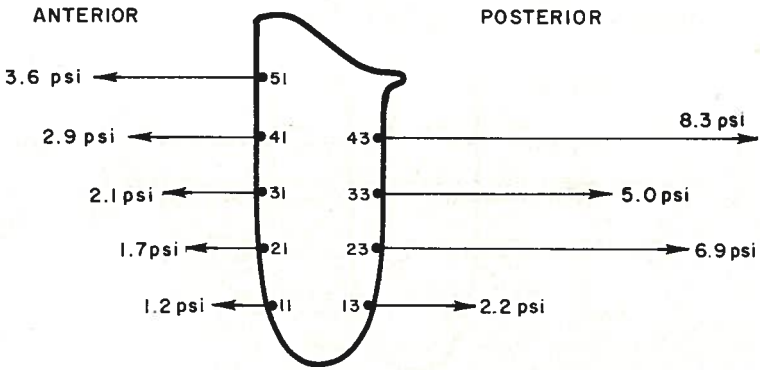
FIGURE 10.—Angular deviation of transducers from the transverse plane of the socket.

1 sq. in., and that the pressure distribution is smooth and continuous. In making this assumption it is possible to determine net loadings in the plane of interest by summing the resulting force vectors acting on opposite walls of the socket.

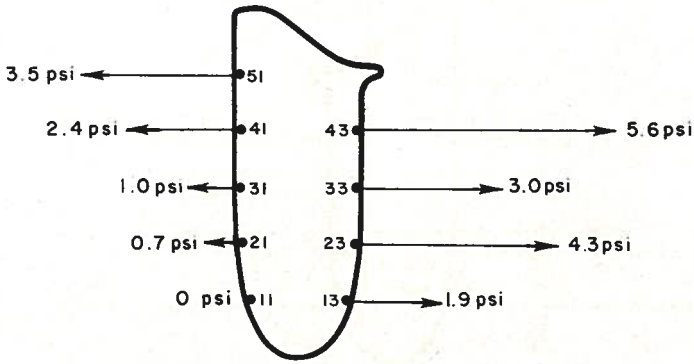
A. Normal Alignment

In what follows, the results of the tests with the subject's prosthesis normally aligned are detailed. Normal alignment is defined as that alignment which would produce the highest overall rating on a gait evaluation. It is the alignment the subject's test prosthesis had when he was originally fitted by the project prosthetist.

1. Anteroposterior Loading (*Fig. 11a and 11b*). Each pressure diagram represents a scaled construction of the anteroposterior pressures developed on the socket walls along the sagittal plane as time increases after heel-contact. The range of all pressure results falls between 0 and +8 p.s.i.



100 MSEC. AFTER HEEL-CONTACT (HEEL-ON)



300 MSEC. AFTER HEEL-CONTACT (FOOT-FLAT)

DYNAMIC SOCKET PRESSURES
SHANK ALIGNMENT- NORMAL

FIGURE 11a.—Anterior and posterior wall pressures: 100 and 300 msec.

Maximum values are experienced approximately 100 msec. after heel-contact.

Initially, the largest individual pressures are developed at posterior proximal locations. Further, there is a net overall loading in the posterior direction corresponding to the extension moment about the hip. The unbalanced resultant force is what is to be expected as the stump is accelerated into the socket.

By the time mid-stance is reached all of the pressures decrease in magnitude. In particular the distal end of the stump produces small anterior pressures. With the passage of still more time the net load has decreased and then reversed direction, corresponding to a flexion moment about the hip.

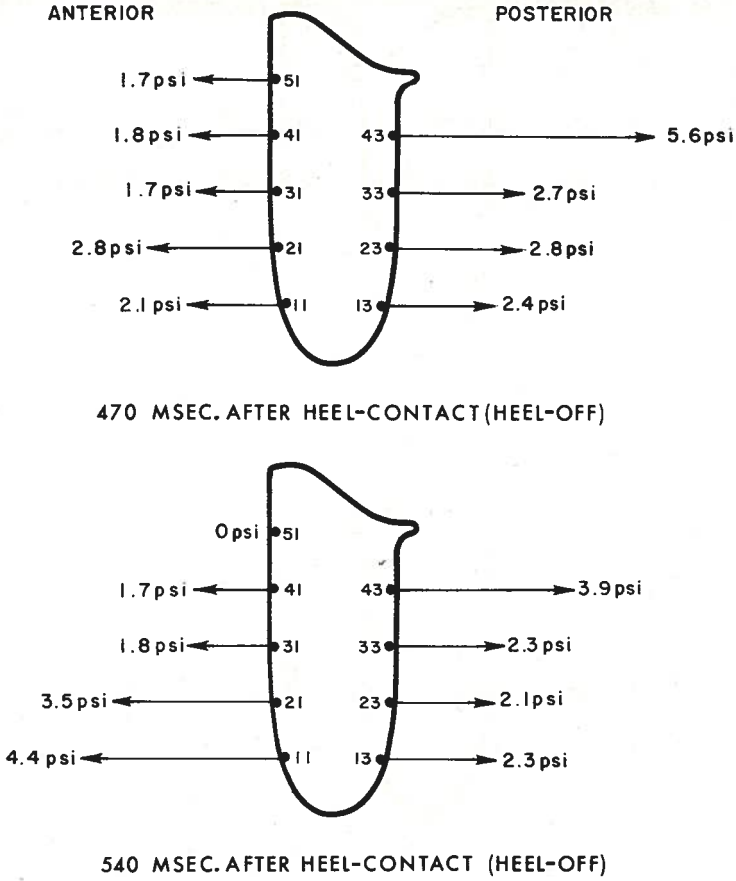
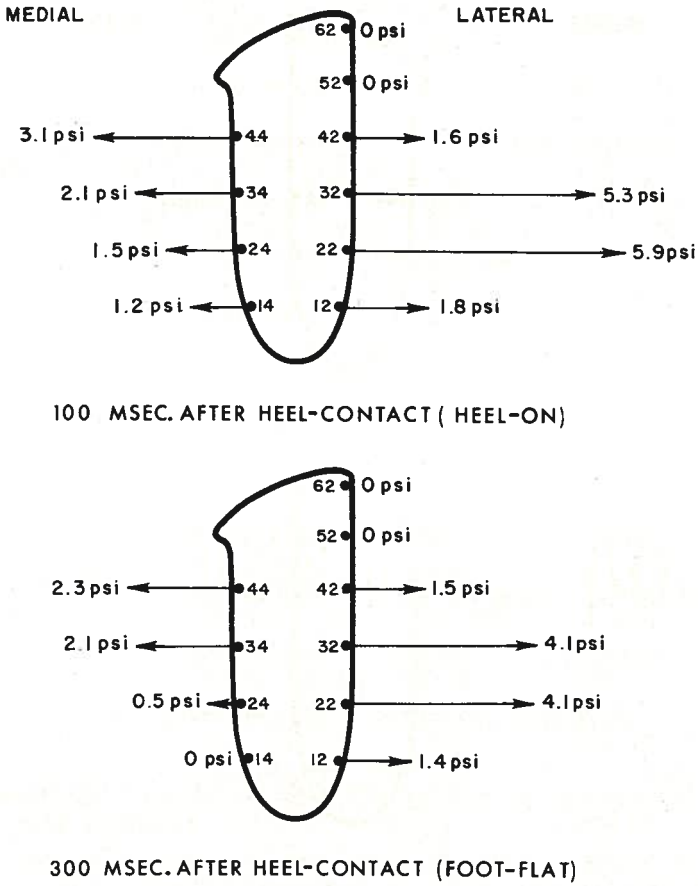


FIGURE 11b.—Anterior and posterior wall pressures: 470 and 540 msec.

Specifically, late in stance, anterior pressures increase with distance from the hip and posterior pressures decrease. The highest pressure region shifts to the distal end of the stump.

2. *Mediolateral Loading.* A corresponding set of pressures for the same subject is given in Figures 12a and 12b. Maximum pressures, developed soon after heel-contact (100 msec.) are experienced distally and are directed laterally with a peak pressure of 6 p.s.i. The net load is directed laterally, suggesting an acceleration of the stump relative to the socket.

As time increases and mid-stance is reached, the pressures are reduced in magnitude but the pattern of pressures is similar. Towards the end of the



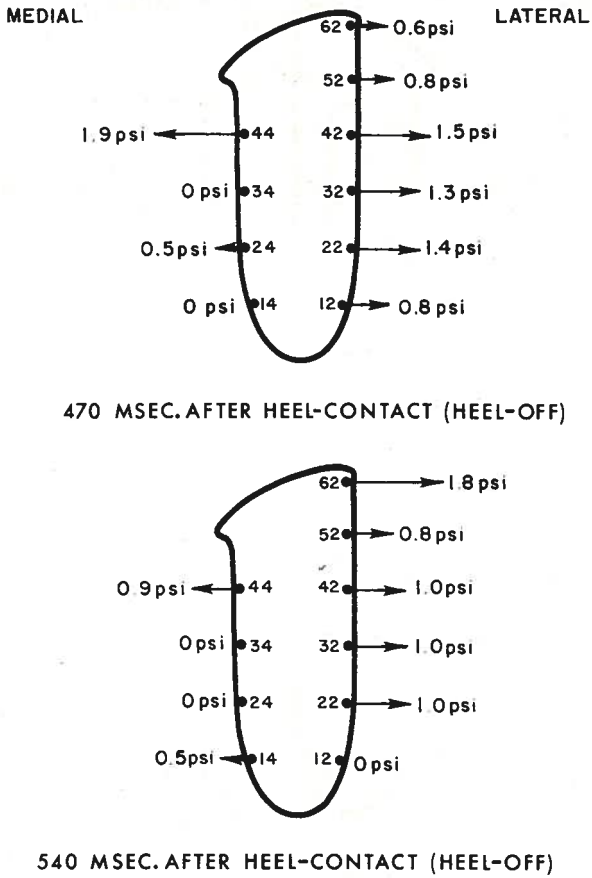
DYNAMIC SOCKET PRESSURES

SHANK ALIGNMENT- NORMAL

FIGURE 12a.—Medial and lateral wall pressures: 100 and 300 msec.

stance phase (Fig. 12b) all pressures tend to vanish; nonetheless, a small net lateral load remains.

3. *Brim.* Those pressures developed on the brim are given for the same subject (normal alignment) in Figure 13. Pressure values are a maximum immediately after heel-contact (100 msec.) and decrease everywhere on the brim as a function of increasing time. Local pressure values are in general large, exceeding maximum values developed elsewhere in the socket by a factor of 2 to 3. For example, position No. 53 realizes a maximum pressure of 24 p.s.i., 100 msec. after heel-contact, by far the largest value obtained at any test location within the socket. By contrast, those values developed in



DYNAMIC SOCKET PRESSURES
SHANK ALIGNMENT - NORMAL

FIGURE 12b.—Medial and lateral wall pressures: 470 and 540 msec.

the anterior locations lower in the socket at the same point in time (same percent stance phase) are an order of magnitude lower in value.

While data at precisely the location of the ischial seat have not been obtained, and interpolation is at best an uncertain affair, the existent data do not suggest the ischial seat as possessing the greatest pressure value.

B. Scatter and Diurnal Variation

1. General. To examine the effects of alignment changes on stump socket pressure values, it is necessary first to examine confidence levels of the data. Should the subject produce large day-to-day variations in output, it is

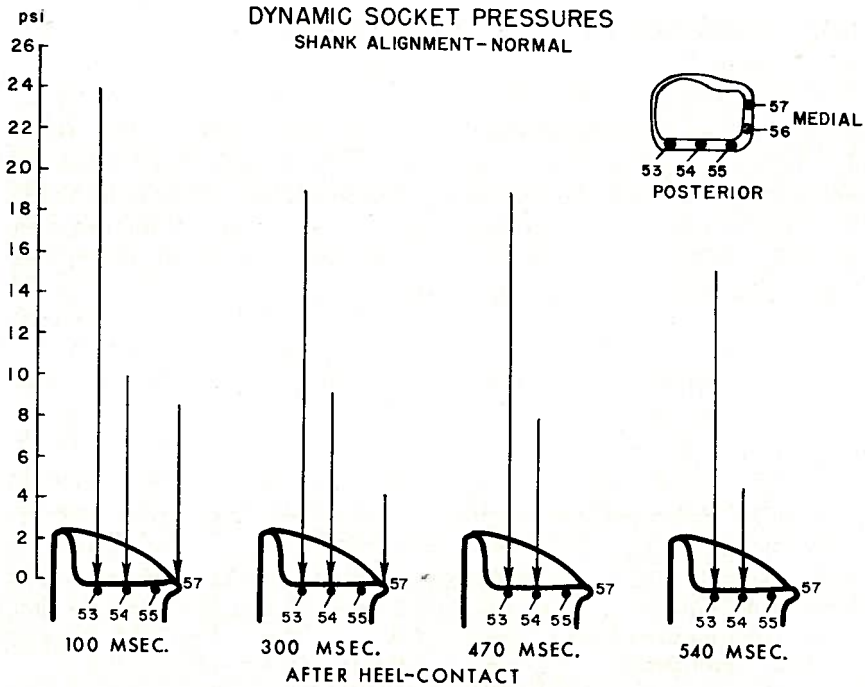


FIGURE 13.—Posterior and medial brim pressures.

conceivable that a small order change in trend due to an alignment change may be hidden in scatter.

Variability of results has many potential sources including instrumentation error, the inability of the test subject to repeat his gait precisely throughout a test sequence, the tendency of the subject to don the prosthesis in a slightly different manner at each fitting, the tendency of the test subject to tire when completing a lengthy series of runs, and week-to-week variations in stump size. Each of these conditions has been examined in a preliminary manner utilizing the subject under discussion. While the small sample precludes broad applicability, certain of the resulting trends are of interest. In this section, the maximum pressures developed between socket and stump of a nominally unchanged above-knee socket are examined in terms of variability.

2. *Transducer Error.* Combined nonlinearity and scatter results obtained in static pressure calibration tests indicate the maximum transducer error to be less than the larger of either ± 0.5 p.s.i. or ± 3 percent of the reading. Such values are small when compared to certain of the following sources of variability.

3. *Transducer Mounting Error.* Varied means of sealing the transducers in the socket were tested for repeatability by comparing the results obtained

from successive tests of the subject. No specific sealing error, as distinct from human variability, emerged from an analysis of the results.

4. Step-to-Step Variation. Generally, a run consists of approximately 20 steps. The data presented in this work are generally based on those values determined from a single step chosen as typical through visual inspection unless otherwise noted. To determine the degree of confidence to be placed in so small a sample, standard deviations have been computed for a number of runs in which all step data have been reduced. The results, which vary with the location in the socket, are shown in Table 1.

TABLE 1.—*Variation in Steps*

Transducer		Pressure (p.s.i.)		
Pos.	Location	Mean	Std. dev.	Largest scatter
51	High anterior	5.2	0.5	1.4
54	Brim	15.1	1.6	3.5
55	Brim	7.7	0.7	1.0
58	High anterior[a]	5.9	0.4	0.7
52	Upper lateral	1.6	0.1	0.2

[a]Scarpa's Triangle.

A value (last column) is also given for the largest single departure (worst scatter point) from the mean. If we assume a standard unimodal distribution, some two-thirds of the data will fall less than one standard deviation from the mean. This implies that even a relatively poor choice of a "typical" step on the part of the data reducer will alter the predicted mean value less than 10 percent ($\approx$Std. Dev./Mean). In the unlikely event that the reducer chooses the most atypical step for reduction, an error of roughly 20 percent ($\approx$Largest Scatter/Mean) in predicted values might result. While possible, this occurrence is regarded as improbable; the personnel involved are well trained. It is our opinion, therefore, that single step data presented in this work are representative of a series of steps and offer results within ± 10 percent of the mean obtained from a series of steps.

For those interested in the concept of employing a pressure pickup point as a means of triggering apparatus, the statistical results may be summarized as follows. Over the short run, two-thirds of the steps taken yield values within roughly ± 10 percent of those given; the remainder of the steps taken yield values within roughly ± 20 percent of those given.

5. Donning and Doffing Variation. When the subject removed and then replaced his prosthesis between tests, no significant change in pressure

output was obtained as a specific function of the replacement process. This result applies to but small "leg off" time periods (minutes).

6. *Fatigue.* Towards the end of all day testing periods, with the test subject visibly demonstrating fatigue (subjective evaluation) significant changes occur in the pressure patterns. Step-to-step and run-to-run variability increases; the results become increasingly erratic with time. Further, normally high pressure regions, particularly those in the brim, decrease significantly, approaching a value 10 percent less than the mean value for the day. Regions other than the brim are less influenced; lateral loading appears unchanged by fatigue, anteroposterior loading is but slightly altered.

7. *Day-to-Day Variability.* When the subject is tested repeatedly over many days, weeks, and months under nominally identical conditions, the variations in maximum pressure developed can be large. The results, for different pressure regions, given in Table 2, are in the form of the departure of the mean (of maximum pressure values) either plus or minus obtained on a given day from that obtained not less than 10 days later and not more than one month later. Inspection of the results shows that the departure of the mean for positions remote from the brim is small. On or near the brim, a shift of some 2–3 p.s.i. in mean value does occur as a function of time (weeks).

TABLE 2.—*Short Term Pressure Variation*

Transducer pos.	Pressure level (p.s.i.)	Shift of mean (p.s.i.)
53	18	2.5
55	7	2.5
44	6	1.1
42	3	0.4
23	4	0.0
34	4	0.2

8. *Month-to-Month Variability.* See Section E, part 3.

C. Change in Alignment

The above-knee amputee, whose "normal alignment" stump socket pressures are given in the previous section, was tested on the same day with the shank of the test prosthesis abducted 2 deg. (Valgus). Since this change moves the foot only ½ in. laterally (outset), the SACH foot was not realigned. In all other respects the prosthesis was unchanged. To the observer, the alteration in gait attendant the modified alignment, appeared qualitatively evident; the gait style might be described as a form of inverse circumduction or "skating." The following paragraphs detail a comparison

between "normal alignment" stump socket pressures and corresponding values obtained for the 2 deg. abducted alignment.

1. Anteroposterior Loading (*Fig. 14a and 14b*). The abducted alignment does not change the order of magnitude of pressure loading; the greatest alteration in values is +2.4 to −2.7 p.s.i. relative to normal alignment. However the net loading on the socket is considerably altered. Abduction produces a small posterior net load at the beginning of the stance phase and a large anterior net loading as stance time increases. With normal alignment, while the same basic trend exists, i.e., posterior net load changing to anterior, the time averaged net loading is posterior in direction; with abduction, the time averaged net load is anterior in direction.

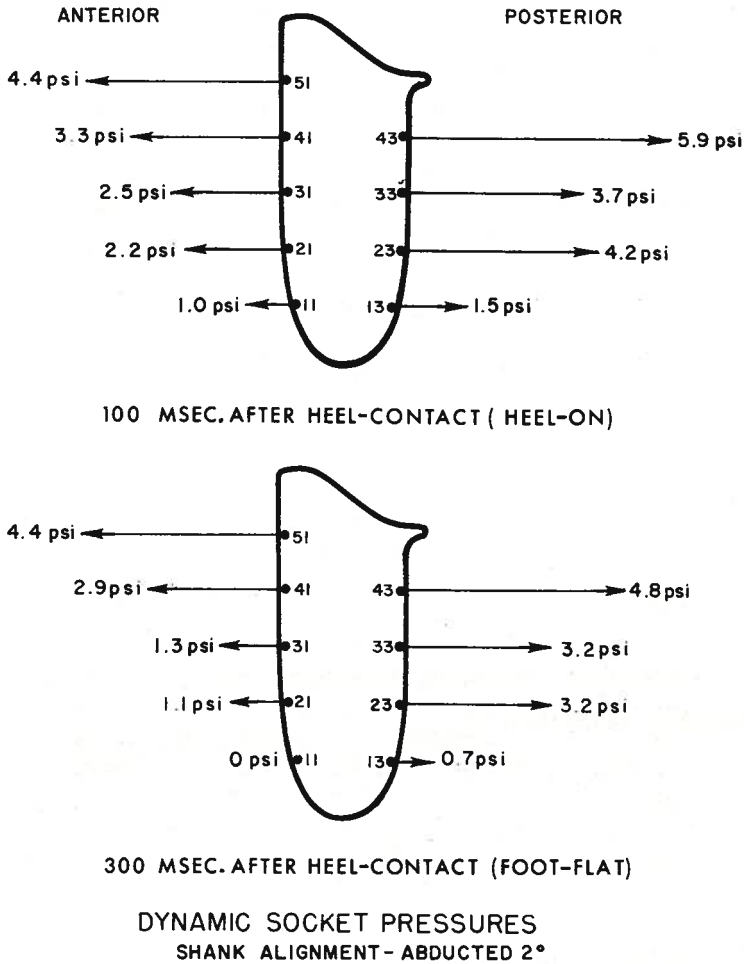


FIGURE 14a.—Anterior and posterior wall pressures: 100 and 300 msec.

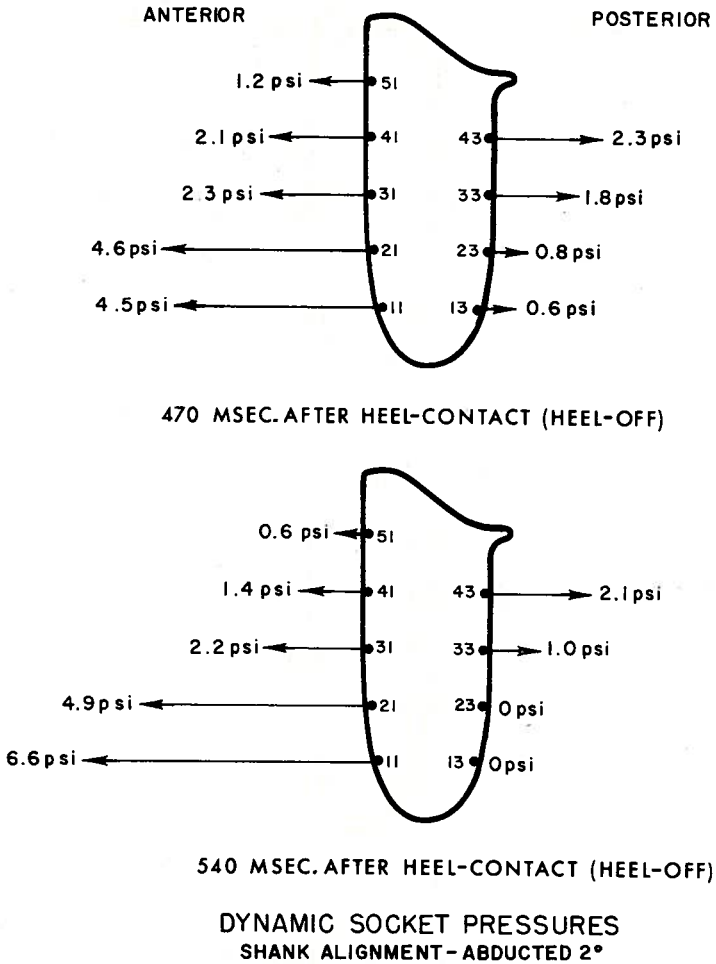


FIGURE 14b.—Anterior and posterior wall pressures: 470 and 540 msec.

2. *Mediolateral Loading* (*Fig. 15a and 15b*). The mean departure of all medio-lateral pressure data (either + or −) obtained in the abducted condition is 0.8 p.s.i. with respect to the normally aligned results. While significant statistically, the difference is small. No basic change in trend of loading with time is apparent.

3. *Brim* (*Fig. 16*). Brim pressures are sensitive to alignment. Abduction changes both the manner of loading, with respect to time and location, and the absolute loading values. The position of greatest pressure (No. 53, the most lateral transducer location on the posterior brim) experiences from 14 to 24 p.s.i. as a function of alignment and time (see Fig. 13). The effect of abduction is to decrease the absolute pressure at position No. 53 during

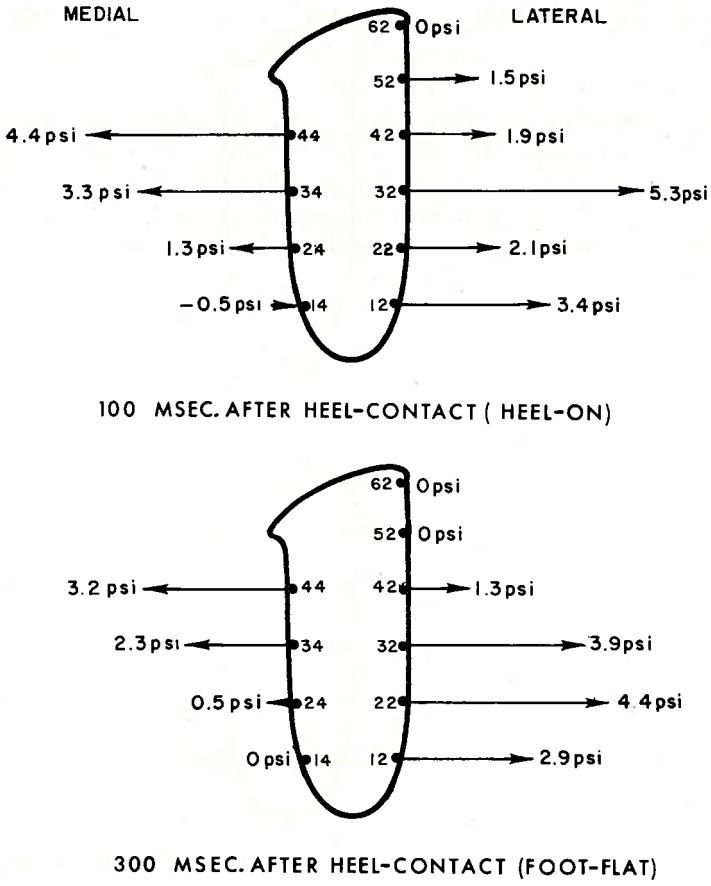


FIGURE 15a.—Medial and lateral wall pressures: 100 and 300 msec.

the initial 300 msec. of stance phase. The pressure at position No. 54 is correspondingly increased, throughout the stance phase, to maintain vertical equilibrium. It is of interest to note that the ischial seat location (roughly midway between No. 54 and No. 55), while not directly measured, would not appear to experience a large pressure with either the normal or abducted alignments.

D. Standing

The maximum pressures developed while standing are in every case smaller than those experienced while walking (Table 3). The subject was instructed to stand quietly, without favoring either leg, while the pressures were recorded.

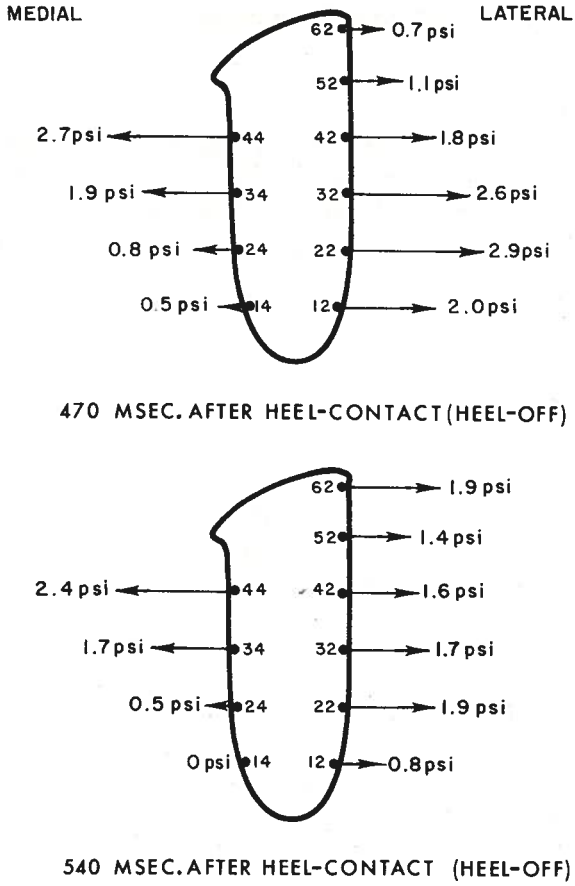


FIGURE 15b.—Medial and lateral wall pressures: 470 and 540 msec.

The mean brim load (proportional to the sum of the brim pressures) is roughly 40 percent of the maximum load developed in walking. Similar reductions occur at other pressure sampling sites.

E. Preliminary Results of Additional Testing

1. Background

Three months after the completion of the tests which have just been discussed, a duplicate set of tests was conducted. The duplication was planned to confirm the findings of the earlier tests, e.g., the pressures are changed when the alignment of the shank is altered. In addition, a new change in alignment was added—adduction of the shank.

TABLE 3.—*Comparison of Dynamic and Standing Pressures*

Transducer		Pressure (p.s.i.)	
Pos.	Location	Dynamic	Standing
53	Brim	15. 3	5. 9
54	"	13. 3	4. 2
55	"	3. 7	2. 1
56	"	3. 1	2. 5
57	"	4. 1	1. 1
12	Lateral wall	2. 7	1. 2
22	" "	2. 4	1. 1
32	" "	3. 0	1. 1
42	" "	1. 2	0. 9
44	Medial wall	4. 3	1. 7

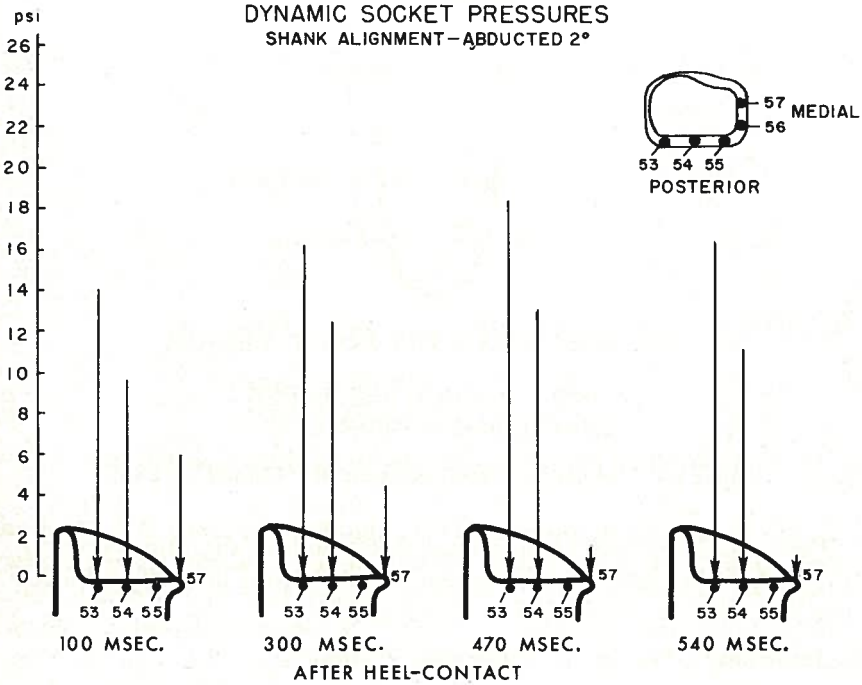


FIGURE 16.—Posterior and medial brim pressures.

Several factors had to be taken into consideration in planning these tests. First, the tests should be completed in one day to be sure that diurnal variations in pressure do not mask the changes in pressure due to altered

alignment. Second, the "test day" should be no more than four hours and should include several rest periods to prevent fatigue. Third, a performance evaluation of the subject, by a qualified person, should be scheduled for the same day.

Because of the conflicting requirements it was decided to reduce the number of pressure sites sampled to shorten the testing time. In general, the sites chosen were those which were most affected by changes in alignment and were picked after a review of the earlier data.

2. Results

A preliminary analysis of the data partially confirmed the results of the earlier tests, i.e., the dynamic pressures were changed and the pressure gradients modified by changes in alignment. However, when both days' results for a given alignment were compared there were marked differences in the values of the pressures recorded.

For example, Figure 17 depicts the pressures on the anterior and posterior walls of the socket, recorded at 100 msec. after heel-contact. The shank alignment is normal in both cases. All of the locations were sampled during the earlier tests (top diagram) while five were sampled during the later tests (lower diagram).

Of the five locations sampled on both days, the only position at which equal pressures were recorded was on the anterior wall (position No. 31). The pressures sampled at the other locations were reduced considerably. The pressures at positions No. 11 and 21, which were 1.7 p.s.i. and 1.2 p.s.i. on the first day, dropped to zero. On the posterior wall the pressures at positions No. 23 and 43, 6.9 p.s.i. and 8.3 p.s.i. originally, decreased to 3.5 p.s.i. and 5.3 p.s.i. respectively, on the second day.

Large changes in the instantaneous pressures sampled on the medial and lateral walls also occurred as shown in Figure 18. Pressures of almost equal magnitude were recorded at only one location, position No. 12. The pressures recorded at the other sites which were sampled were affected.

3. Month-to-Month Variability

Since the paired pressures which were recorded on the two test dates were markedly different in many instances, the corresponding pressure data of three tests performed in the intervening period were also plotted.

These data, shown in Figures 19 and 20, indicate that the pressure values may change considerably over a period of months. While basic trend lines retain validity, inspection of the data shows that a given location, subject to a nominal pressure of 6 p.s.i., may experience a pressure shift as large as 3 p.s.i. Therefore, in evaluating a given variable, it is important to make comparisons over small elapsed time periods (days). The alteration in local pressure does not seem to follow a discernible pattern; simple inspection reveals only a random variation about the mean.

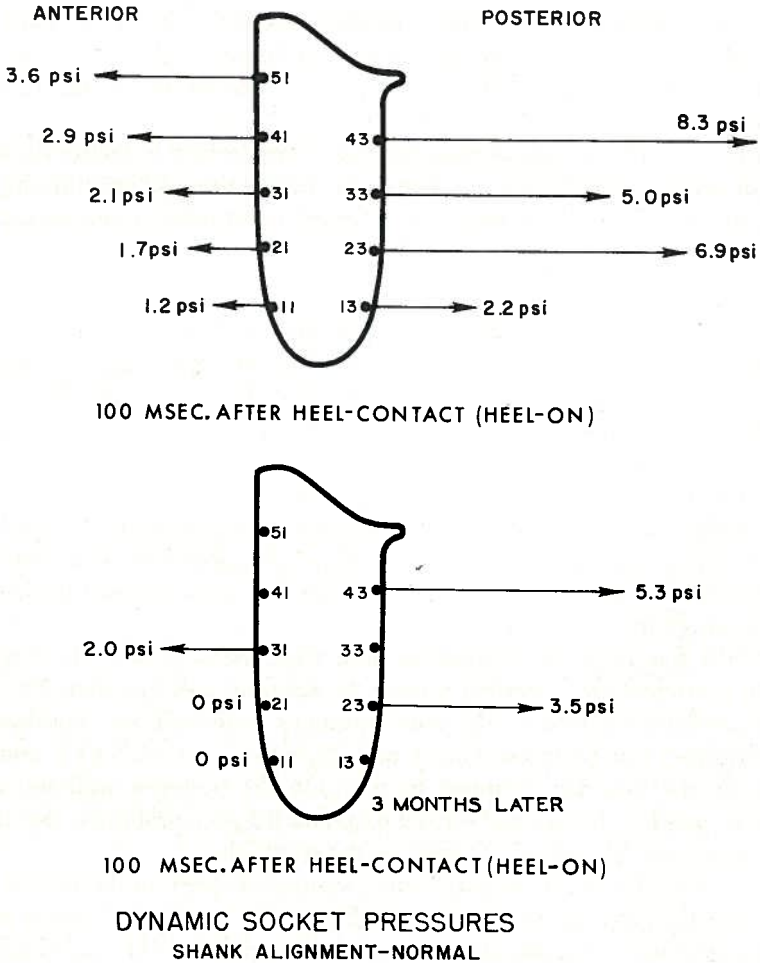


FIGURE 17.—Comparison of anterior and posterior wall pressures—three months apart.

4. Performance Evaluation

The evaluation was scheduled in order to determine whether:

a. The alignment changes affected the subject's gait in any noticeable way.

b. The noticed gait changes were consistent.

The evaluation was performed by a qualified member of the VAPC Bioengineering Research Service, who was aware that alignment changes would be made but was not informed as to the nature of the changes. The results are contained in Table 4.

TABLE 4.—*AK Performance Evaluation—Gait During Level Walking*

Rating: 1=Greatest deviation from normal
10=No Deviation from normal

Gait deviation	Rating (& comments)		
	Normal	2° Abd.	2° Add.
Lateral bending of trunk	[a]9	[a]9	10
Abducted gait	[b]8	[c]9	10
Medial whip of foot	10	10	10
Lateral whip of foot	10	10	9
Circumduction	10	10	10
Uneven toe-out	[d]9	[d]9	9
Lumbar lordosis	—	—	—
Uneven arm swing on prosthetic side	[e]8	[e]7	8
Swing phase, forward	[f]8	[f]8	8
Swing phase, rearward	[g]6	[g]7	8
Vaulting	[h]8	[i]7	7
Uneven step lengths	[j]9	[j]9	9
Uneven timing of heel contacts	7	7	[k]8
Others	—	—	—
General performance	8+	8−	8

[a] Slight bending to prosthetic side.
[b] Space of about 3 in. between medial sides of heels. Skates once in a while.
[c] Space of about 2 in. between medial sides of heels. Has a tendency to skate.
[d] Slight toe-out normal side. Prosthesis usually straight, but toes-out occasionally at heel-contact.
[e] Tends to walk with shoulders back. On prosthetic side, holds arm restricted at shoulder, but swings forearm.
[f] Terminal impact minimized by good timing.
[g] About 2 in. difference between prosthetic and normal sides.
[h] Tends to remain on toe of normal foot while waiting for prosthesis.
[i] On toe of normal foot waiting for prosthesis.
[j] Bilaterally long steps.
[k] Slightly shorter on prosthetic side.

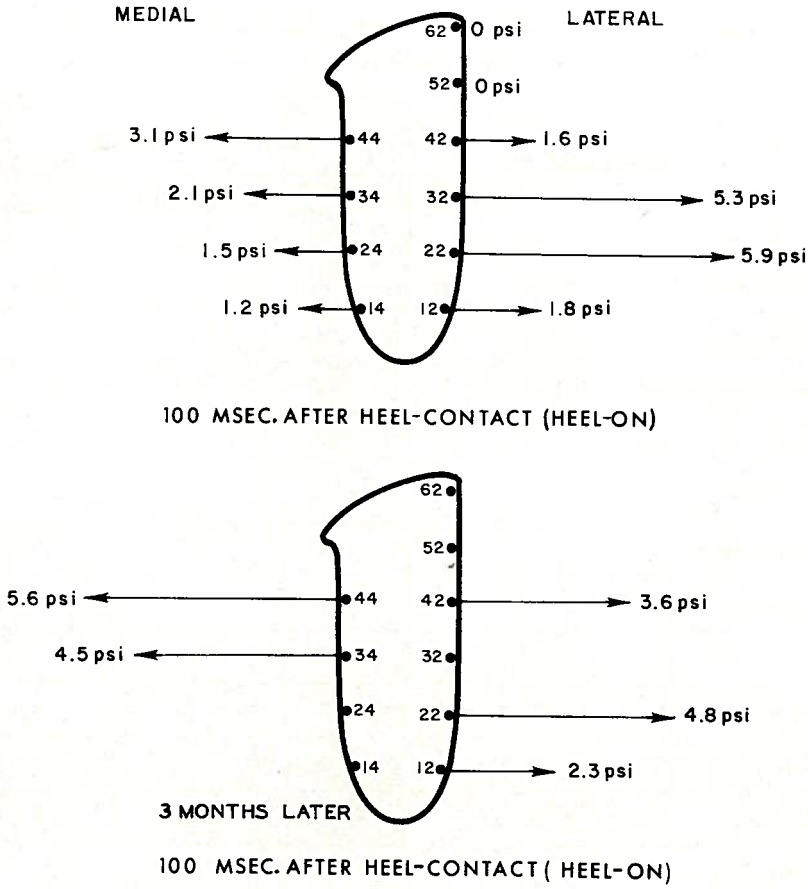


FIGURE 18.—Comparison of medial and lateral wall pressures—three months apart.

IV. SUMMARY AND CONCLUSIONS

1. Socket pressures, developed between stump flesh and socket, have been measured in normal walking, as a function of time.

2. Socket pressures range from −1 p.s.i. gage to 24 p.s.i. gage as a function of location within the socket and phase of walking. In general, maximum positive pressures are developed on the brim (typical range 10–25 p.s.i.); however, the ischial seat is not necessarily the location of maximum pressure. In general, lowest pressures are realized distally on the stump (typical range 0–3 p.s.i.). Mid-stump pressure values (typical range 4–10 p.s.i.) fall between those of the brim and the distal locations.

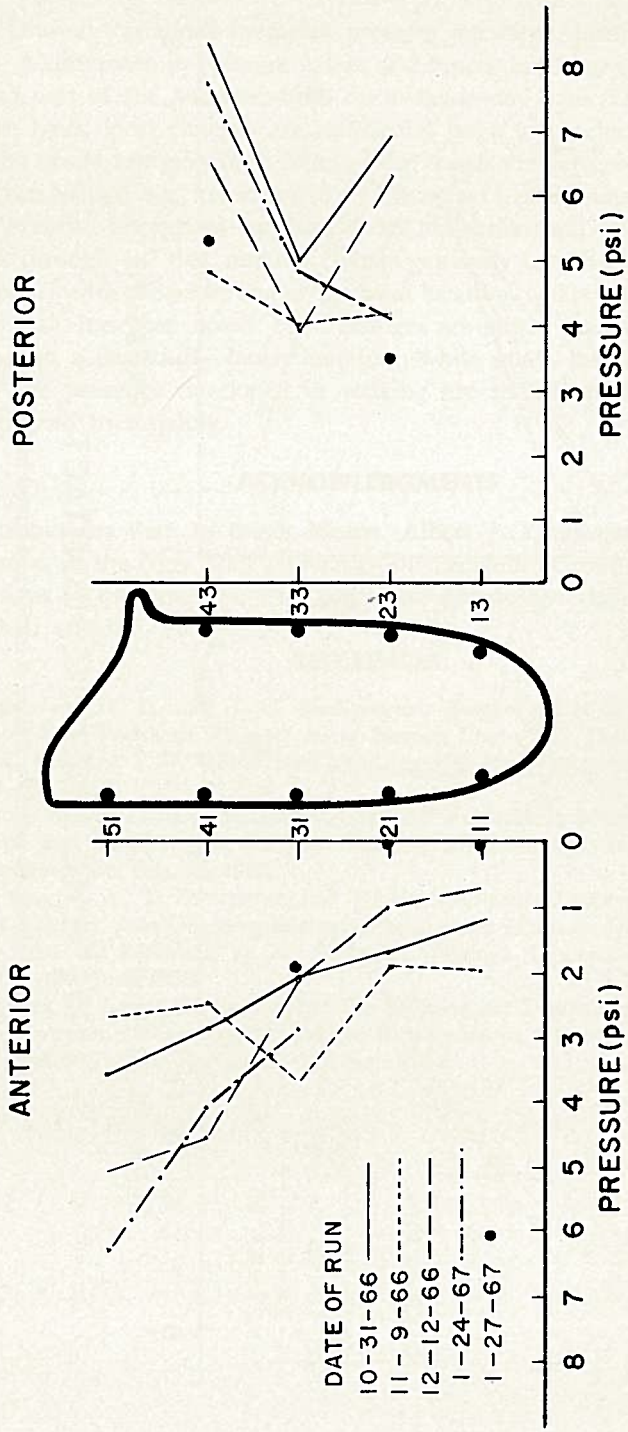


FIGURE 19.—Month-to-month variability of anterior and posterior wall pressures.

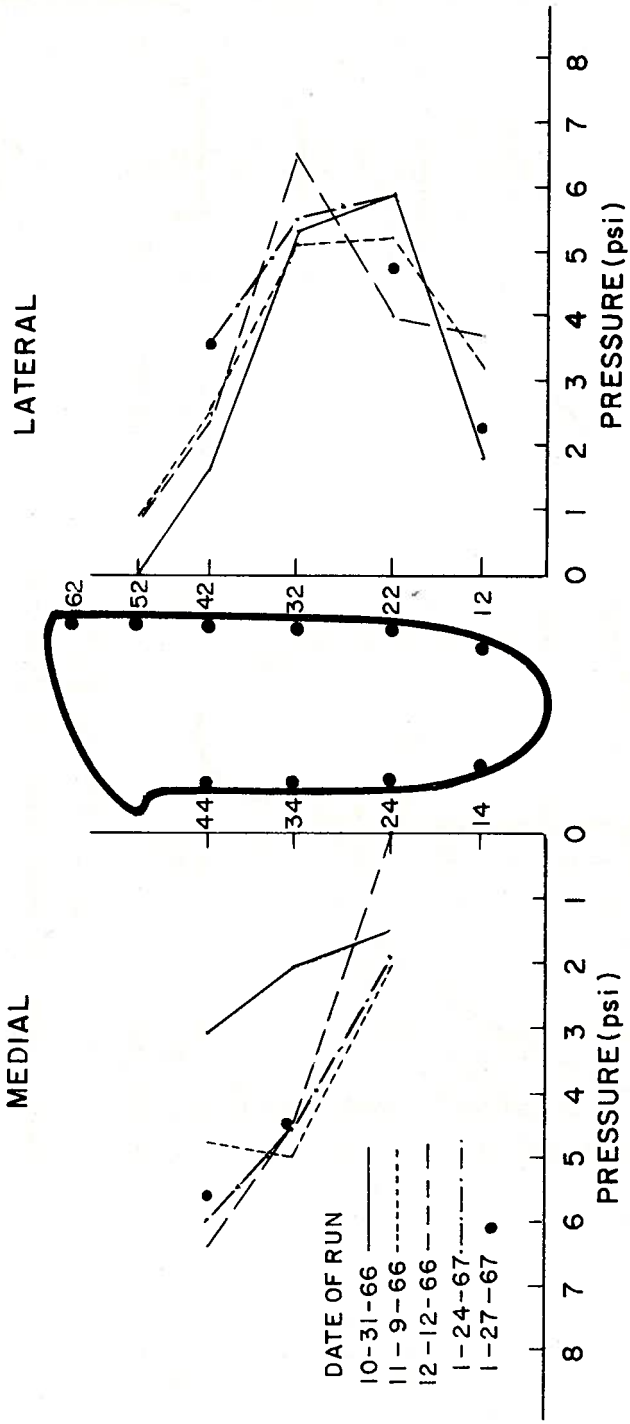


FIGURE 20.—Month-to-month variability of medial and lateral wall pressures.

3. Diurnal variations in socket pressure are large, particularly on the brim. A difference in pressure values of 2.5 p.s.i. has been recorded on the lateral part of the posterior brim on a day-to-day basis. On a month-to-month basis, local changes are sufficiently large to preclude simple comparison of old and new data. While basic trends are preserved, local variations can be high, e.g., in excess of 3 p.s.i. in a 6 p.s.i. environment.

4. Pressure alterations resultant from abduction and adduction of the shank through a 2 deg. angular change generally are small (typical range 0–2 p.s.i.) with the exception of the brim location, where a change as large as 10 p.s.i. has been noted. Such changes are larger than those to be expected on a day-to-day basis; therefore, while small, they are significant.

5. The pressures developed in walking are sharply higher than those experienced in standing.

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