TANGENTIAL PRESSURE MEASUREMENTS IN ABOVE-KNEE SUCTION SOCKETS [a]

Francis A. Appoldt, B.A.E.
Research Scientist

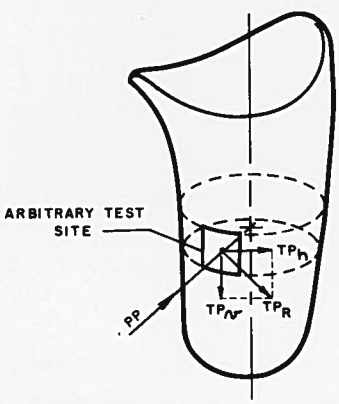
Leon Bennett, M.A.E.
Senior Research Scientist

Renato Contini, B.S.M.E.
Senior Research Scientist

Research Division
School of Engineering and Science
New York University
University Heights Center
Bronx, New York 10453

I. INTRODUCTION

Tangential pressure (TP), as defined in this study, is that pressure parallel to and located at the socket inner face. The tangential pressure resultant (TP_R) will possess a horizontal component (TP_h) directed along an axis perpendicular to the main socket axis and a vertical component (TP_v) directed along the main socket axis (see Fig. 1). The plane in which all tangential pressures exist is at right angles to the perpendicular pressure (PP), i.e., squeeze pressure developed between the socket and the stump.



ABOVE-KNEE SUCTION SOCKET

FIGURE 1.—Definition of terms:
Perpendicular Pressure: PP
Horizontal Component of Tangential Pressure: TP_h
Vertical Component of Tangential Pressure: TP_v
Vector Resultant of TP_h and $TP_v = TP_R$

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

In the literature, tangential pressure is generally referred to as the friction pressure or the shear pressure. From a rigorous point of view, friction and shear factors are separate variables and both are likely active. As we are uncertain concerning the relative portion of shear and frictional stresses in the resulting pressures developed at the socket face, the term tangential as employed here is all-inclusive.

Prior workers have long ascribed stump pathology to "mechanical shearing forces produced by the socket on the skin." Thus, Allende, Levy, and Barnes (1) suggest the use of a buffer between the skin and socket "to reduce the detrimental effects of shear," and conclude "improvement in prosthetic fit, with reduction of shearing forces, appears to be the most promising approach to the problem" (of cyst formation). While much of the interest of Allende et al. is directed to the formation of cysts in that roll of flesh immediately above the socket, they note that "rough surfaces that sometimes develop in areas of increased contact pressure in the socket, particularly the suction socket, tend to catch the skin and adhere to it, increasing the shearing forces. For this reason, the lining of the socket should be smooth and kept smooth." In the above and other works (2, 3) citing the physiological significance of tangential pressure effects, no actual measurements were undertaken. Thus, the influence of tangential pressure factors has been based on simple physical reasoning and conjecture.

We have been concerned with establishing the sense and magnitude of those biomechanical factors deemed significant to the comfort and employment of above-knee suction sockets. In particular, we have concentrated upon mechanical measurements of those conditions at the stump-socket interface. Perpendicular pressures obtained with flush mounted pressure gages (4) and protruding clinical pressure gages (5) have been investigated previously. The free motion or slip within the tangential plane (6) also has been studied. In what follows, the tangential pressures (TP_R, TP_v, and TP_h) developed by two ambulating above-knee subjects equipped with suction sockets are given. Insofar as we know, no prior data of this type exist.

II. INSTRUMENTATION AND TEST PROCEDURE

A. Sockets

The sockets employed in these tests are duplicates of those normally worn by the subjects with the exception of tubular inserts extending through the wall and so located on the socket as to form a network of test locations. The location and arrangement of the test site network are given in Figure 2. The tubular inserts were so fashioned that either a perpendicular pressure transducer or a tangential pressure transducer could be placed within the insert. Pressure gage exchange took a

matter of minutes. When not housing a pressure gage, each insert was plugged, thus maintaining the necessary pressure vacuum. The method of pressure preparation has been given elsewhere (4) in some detail.

B. Tangential Transducer (see Fig. 3)

Four strain gages, cemented to thin steel (shim stock) bending beams, were arranged electrically to respond to the application of a load along the load sensitive axis, while canceling an on-axis compressive load.

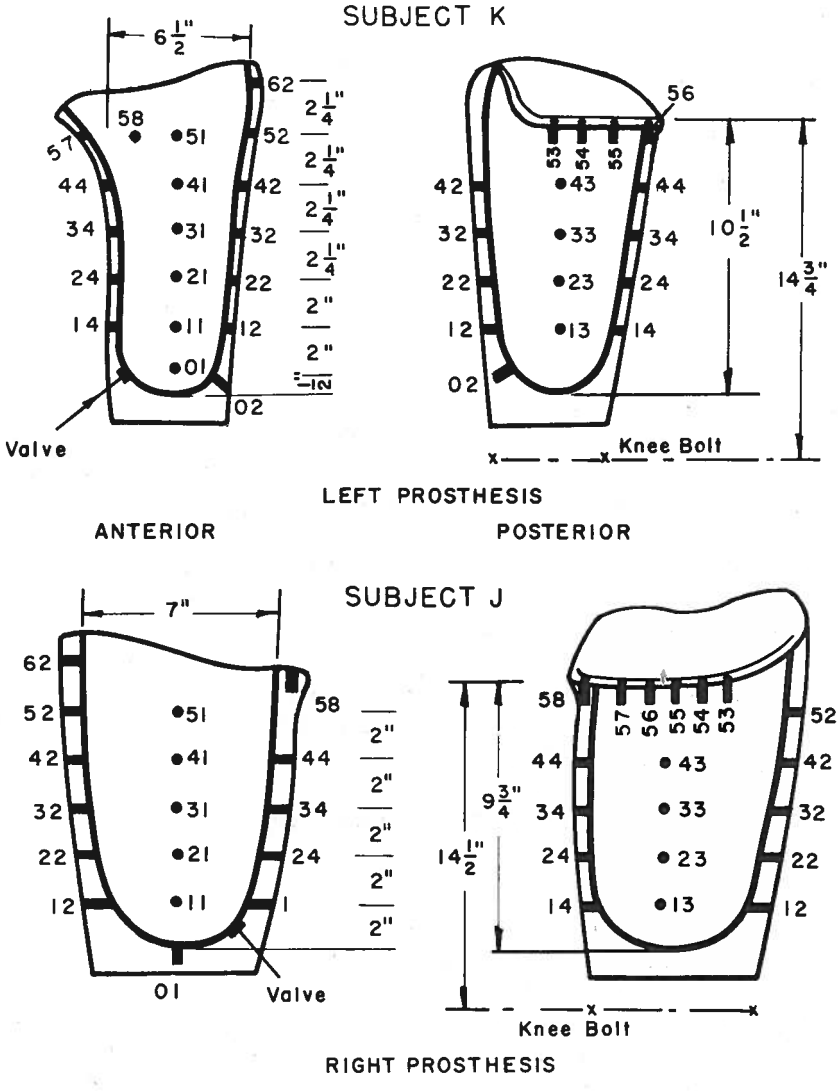


FIGURE 2.—Test site network, subjects J and K.

Load is applied at the bar, a small (7/16 in. x 1/16 in., or 0.274 in.^{2} cross section) and properly centered brass member. Wires were led to an amplifier, power supply, and oscillograph through a hole in the base,

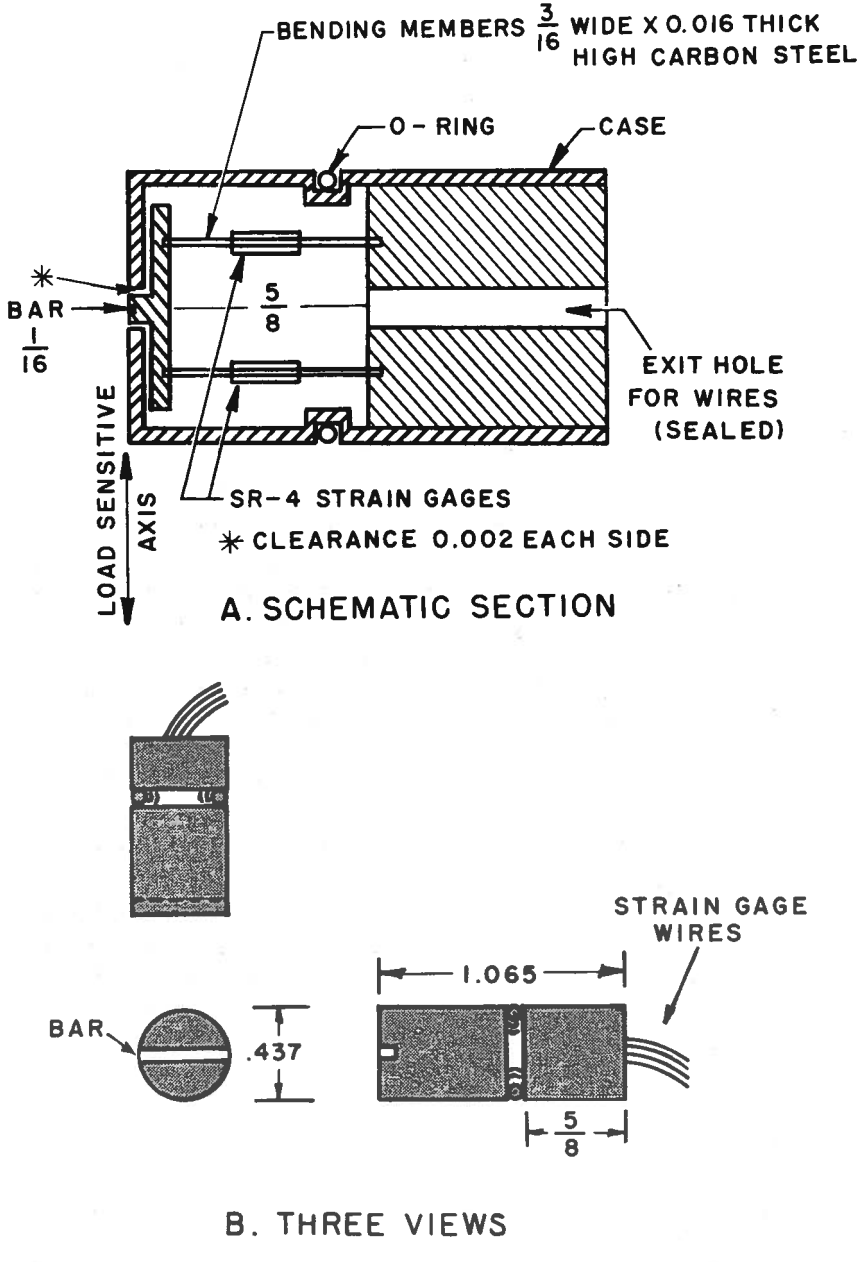


FIGURE 3.—Tangential pressure transducer.

which was then sealed. An O-ring gripped the case, sealing the socket against air leaks.

Considerable development proved necessary to prepare a satisfactory unit, a reflection of the numerous and, in some instances, opposed design objectives. For example, great stiffness of the strain gage bending beams is desirable to simulate the restraint offered by the socket wall; indeed if the resistance to deflection is small the gage becomes a skin deflection measuring device and not a force gage. Conversely, sensitivity requirements favor a soft restraint, so as to produce a large signal from the tangential pressures which are typically small. The final model was so constructed that deflection at the bar was less than 0.002 in. for the largest pressure recorded; a compromise favoring stiffness at the expense of sensitivity.

The avoidance of interaction has been a serious problem. Interaction occurs, for example, when a load directed at an angle α (Fig. 4B) or at two angles α and β (Fig. 4C) measured relative to the load sensitive axis is registered improperly. We avoided this by careful alignment of the load bar and bending beams. Employing large values of bending beam stiffness and cancellation circuitry proved useful steps in reducing such effects. The worst case of interaction occurs when perpendicular loads PP (Fig. 4A) tend to influence tangential pressure results. This occurs because if a deflection δ takes place due to TP, the resulting bending moment PP x δ cannot be distinguished from a bending moment due to tangential pressures TP x A. The latter form of interaction moment is particularly difficult to deal with as it represents an inherent system error as contrasted with, say, a spurious value of moment due to misalignment. Noting that perpendicular loads may be relatively large (perhaps an order of magnitude larger than tangential loads), it follows that only by severely restricting deflection, i.e., employing stiff beams, can the interaction be made small.

Typical calibration and interaction test results are given in Figure 5. Curve A represents the galvanometer response (inches of deflection observed at the oscillograph) to tangential pressures directed along the sensitive axis. The open symbols represent the increasing load cycle and the closed symbols, the decreasing load cycle. The deflection difference between increasing and decreasing loads reflect the hysteresis characteristic of the device. There is an indication from Figure 5, that no deviation from a correct value is greater than 0.2 p.s.i., and in many cases is less than this.

Interaction testing of loads applied within the plane tangent to the socket wall is given in Figure 5, Curve B. In principle, a load applied within the tangent plane and at some angle α to the sensitive axis (see Fig. 4B) should produce the instrument response, load x cos α ; i.e., the sensor should supply the directional cosine component of any

in-plane load. In practice, experimentally observed deflections (Curve B, Fig. 5) obtained for the condition α = 45 deg. are fairly close to a line constructed according to the expression, slope B = slope A x cos 45 deg. Therefore, we regard the in-plane interaction response of the sensor as satisfactory.

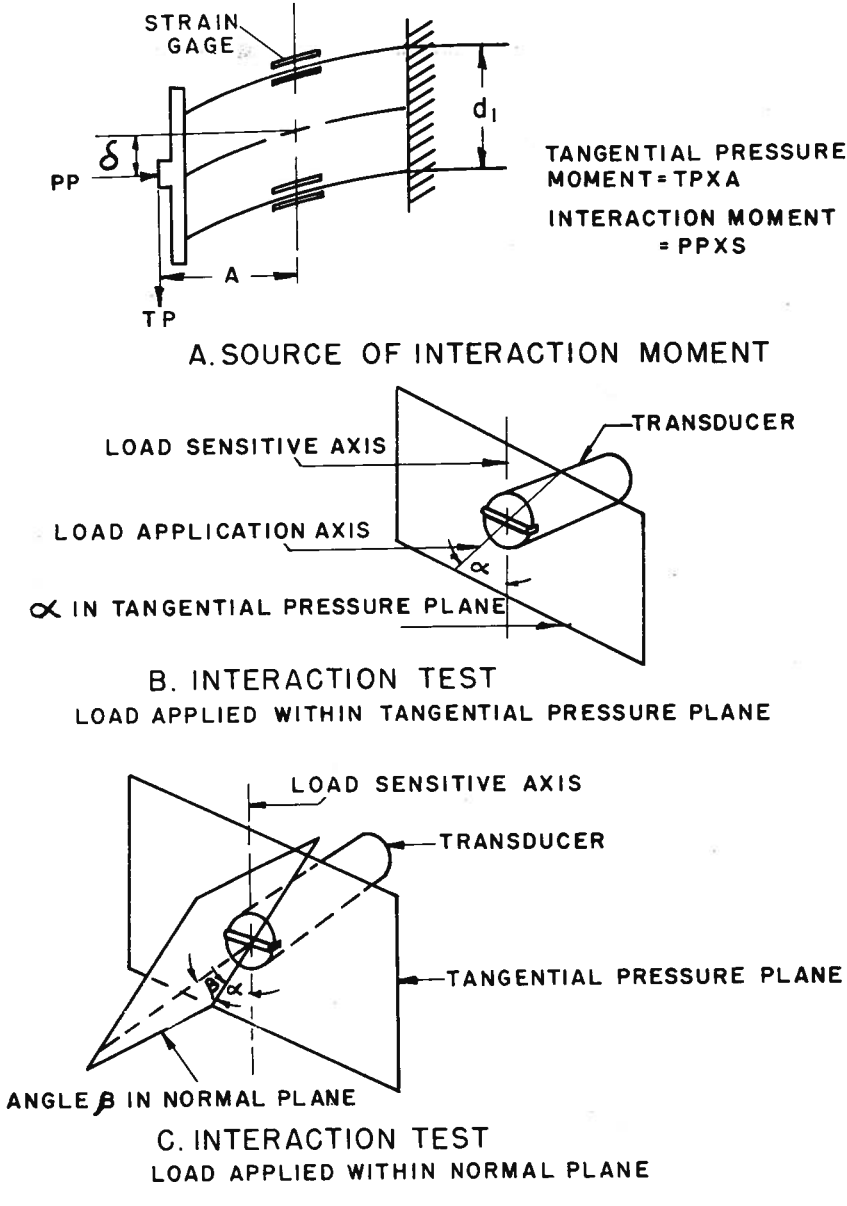


FIGURE 4.—Interaction tests.

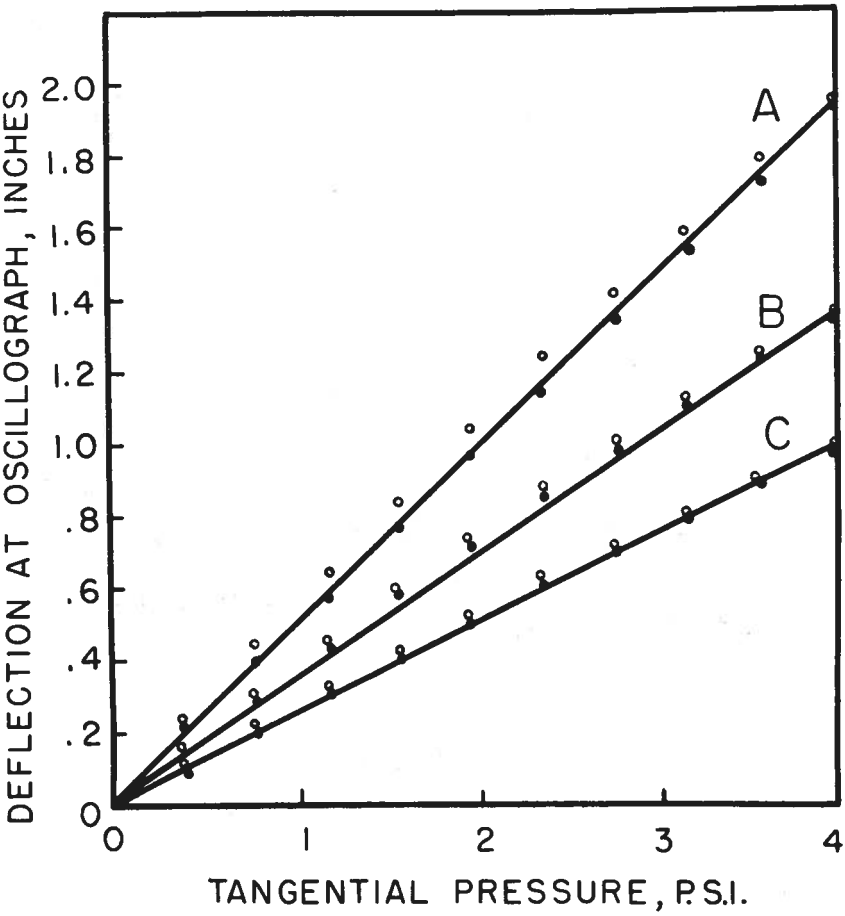


FIGURE 5.—Calibration and interaction tests, tangential pressure gage:
Open symbols increasing load; closed symbols decreasing load.
Curve A. Load applied along sensitive axis
Curve B. Load applied as in Figure 4B, $\alpha = 45$ deg.
Curve C. Load applied as in Figure 4C, $\alpha = 45$ deg., $\beta = 45$ deg.

A combined plane interaction test, performed as sketched in Figure 4C, simulated simultaneous perpendicular and tangential pressure loadings. For zero interaction, the load projected onto the load sensitive axis is load x cos α x cos β. In the test performed, both α and β were set equal to 45 deg., leading to a value of 0.5 for the product of the cosines. A plot of the term, 0.5 slope A, is given as Curve C, Figure 5. It is seen that the fit of the data to the curve is good, and it is concluded that combined plane interaction is negligible. Additional tests (not given) were α and β were set at 90 deg. indicated essential zero output, as one would expect.

Thus, the tangential pressure gage has been shown to register the directional cosine component along the sensitive axis—no matter how the load is applied. It follows that placement of the sensitive axis in a direction of interest, say horizontally or vertically, will yield the appropriate component in the respective direction. Finally, the resultant load may be determined by vector addition.

Even though the largest error derived from such instrumentation problems as linearity, hysteresis, and interaction acting individually or together is everywhere less than 0.2 p.s.i., when the pressure itself is small, a large percent error is possible. Consequently, a cutoff was established (at 0.4 p.s.i.) below which quantitative results, deemed unreliable, are not given. Fortunately, the region cut off is one of small physiological interest (one tending towards zero load). A qualitative comment on this region is given in the results. The possible error decreases proportionately as the absolute pressure value increases, and fortunately in the areas of interest the possible percentage error is small enough to give credence to the values measured. By adopting the cutoff procedure only the relatively accurate readings of large tangential pressures are given explicitly.

C. Test Procedure

The subject first dons the experimental prosthesis with all the inserts plugged. He then walks about to be sure that his stump is inserted properly and that there is no loss of suction. Thin rubber diaphragms are used to seal those sampling sites at which the maintenance of suction is critical. Sealing plugs are then removed from the location to be sampled, transducers are inserted and the test runs started.

The test walkway allows an average of 16 steps in one direction, termed a pass. When the subject turns at the end of the runway and returns to the start he completes another pass. Four consecutive passes, termed a run, complete the test. After a run, pressure gages are moved to a fresh location and the tests continued. During a series of tests, the subjects had to remove their prosthesis several times to permit sealing diaphragms to be mounted or removed. Such halts take place, if at all, between runs, not between passes. Total testing time was divided into sessions limited to about 2½ hours including short rest periods taken about every 30 min. Cadence was entirely the choice of the subject, who was instructed to walk at a comfortable pace.

D. Data Handling

Because of limitations indicated previously, tangential pressures below a value of 0.4 p.s.i. have not been evaluated quantitatively. Typical tangential pressure records are unimodal in nature and indicate but a single peak in the course of a step. Unless otherwise stated, the pres-

sure value supplied in this work is that peak value obtained by averaging the peaks of 12 random steps obtained in a run.

The sign conventions employed are positive in an action sense rather than a reaction sense. Thus, the pressures described are those delivered to the socket by the flesh. The horizontal component of tangential pressure is positive in a counterclockwise direction when viewed from above. The vertical component is positive when directed distally (downwards). Figure 6 shows the sign conventions for both a left- and right-legged prosthesis.

E. Subjects

Two subjects were tested. Both were above-knee amputees, equipped with total-contact suction sockets. Additional characteristics of the subjects are given in Table 1.

TABLE 1.—*Subject Description*

Designation	J	K
Age	49	48
Height, in.	76	72
Weight, lb.	220	165
Date of amputation	1952	1954
Cause of amputation	Trauma	Trauma
Perineum to bone, in.	6	10½
Perineum to flesh, in.	8	10½
Prosthesis usually worn	Mechanical friction knee	Henschke-Mauch
Amputated side	Right	Left
Type of suction socket	Total contact	Total contact
Comment on gait	Poor	Very good
Natural cadence steps/min.	75	98

These men were chosen solely on the grounds of availability and demonstrated perseverance. They are not represented as typical prosthesis wearers; indeed one of the subjects (J) is unusually tall and heavy. Results from so small a sample are presented for information purposes only; drawing sweeping conclusions from such a sample should be avoided.

III. RESULTS

Of the two subjects tested, both displayed a preponderance of small tangential pressures, i.e., values smaller than the cutoff value of 0.4 p.s.i. Subject J peak values, in some 19 tested locations, were less than 0.4 p.s.i. at 15 locales. Subject K peak values were less than 0.4 p.s.i. at 5 out of 10 tested locations. Thus, to the limited extent that one may generalize from a two-subject sample, tangential pressures are generally

small. Those larger than the cutoff value (see Table 2) remain small when compared to perpendicular pressure at the same location (4). The maximum tangential pressures encountered in this work are roughly 3 p.s.i. in value.

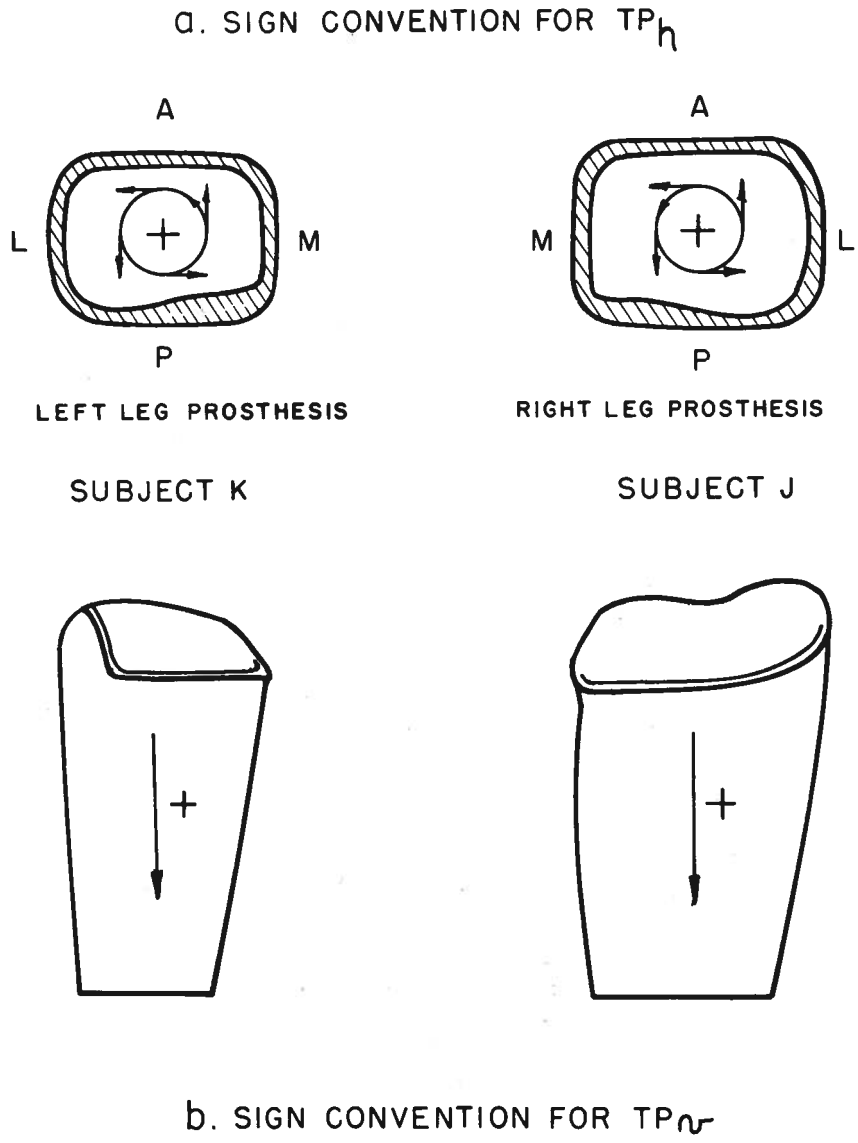


FIGURE 6.—Pressure loading sign conventions:
A. TP_h left- and right-legged prosthesis as viewed from the top. A counterclockwise pressure delivered by the stump to the socket is always considered positive.
B. TP_v left- and right-legged prosthesis as viewed from the back. A downward pressure delivered by the stump to the socket is always considered positive.

TABLE 2.—*Maximum Tangential Pressures in Level Walking*

Subject J		Subject K	
Test site	Tangential pressure p.s.i.	Test site	Tangential pressure p.s.i.
[a]31A H,V	<0.4	43 H,V	<0.4
[a]41A H,V	"	22 H,V	"
14 H,V	"	12 H,V	"
13 H,V	"	31 H,V	"
23 H,V	"	42 H,V	"
33 H,V	"	02 H	−2.1
43 H,V	"	02 V	−2.4
[a]31B H,V	"	01 H	−2.1
[a]41B H,V	"	01 V	−2.6
[a]41A H,V	"	11 H	−3.6
32 H,V	"	11 V	<0.4
42 H,V	"	[a]21A H	+1.1
52 H,V	"	[a]21A V	+0.8
62 H,V	"	21 H	−0.6
51 H,V	"	21 V	+2.1
61 H	0.6		
61 V	1.2		
21 H	0.6		
21 V	−1.0		
22 H	0.7		
22 V	0.2		
12 H	0.7		
12 V	0.4		

[a]"A" and "B" readings are within a 1-in. circle in the general area of the number shown in Figure 2.

A tangential pressure trace (Subject J, test site 61V) typical of those sites offering large values is given in Figure 7. The curve is essentially raw data as observed at the oscillograph, with the difference that each coordinate axis is marked with an appropriate calibration value. Six steps are shown, involving three complete loading cycles on the prosthesis. Note that the pressure pattern is not perfectly duplicated from one cycle to the next, a characteristic of all pressure results (perpendicular and tangential) obtained in our test work. Implicit in this spread is a combination of human variability and instrumentation error. As the mean instrumentation error is approximately 0.1 p.s.i., it would appear that the human variability factor accounts for much of the amplitude spread. Note that the pressure becomes sizable (> 0.4 p.s.i.) immediately before heel-contact and remains so throughout the stance phase. The direction of the pressure application is largely positive; i.e., the flesh is pressing downward on the socket. It is generally true

that pressures in the swing phase are small; in no instance is a pressure peak developed in the swing phase.

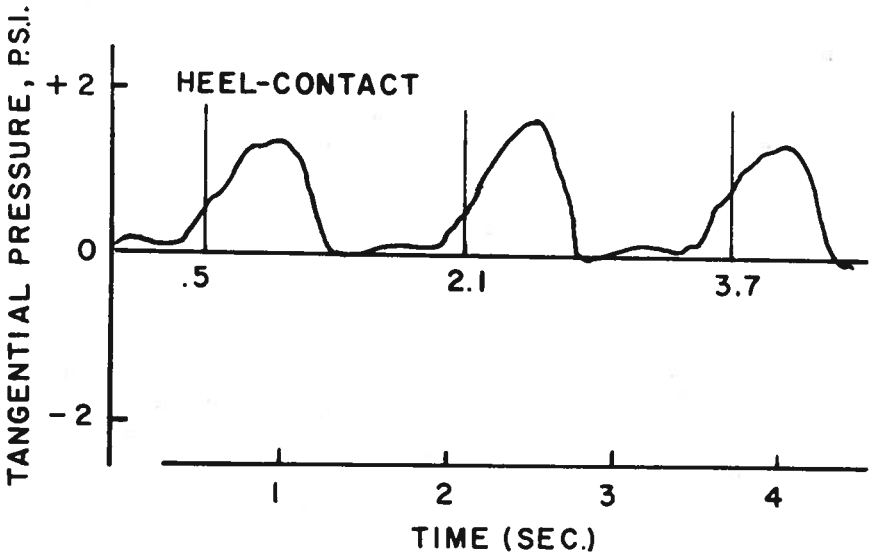


FIGURE 7.—Tangential pressure raw data. Subject J., test site 61V. Chosen as a typical example of large pressure test site output.

It is well known that the basic vertical load upon the prosthesis in gait is directed downward. Therefore, one might expect the maximum vertical tangential socket pressure to be directed downward, or positively within the sign conventions of this work. However, inspection of the results (Table 2) indicates this to be true in only five out of eight non-negligible test sites. Thus, it appears that powerful upward tangential pressures are frequently generated and as noted above, the timing of the peak is such that they invariably occur within the stance phase; the upward loading is unrelated to swing-phase events. This unexpected finding (upward socket loading) is considered in the Discussion section of this report.

The horizontal component of tangential pressure reflects shear flow due to horizontal torsion at the stump. For level walking it has been shown (7) that the essential torsion mode acts to toe-in the planted leg. More sophisticated studies (8), utilizing an instrumented pylon, indicate that while the dominant externally applied torque upon the planted leg is directed in a toe-in sense, a small reversal may occur at the very end of stance phase. Thus, with a right leg planted (Subject J) the dominant external torque is counterclockwise in direction looking down. Such a loading corresponds to a positive horizontal tangential pressure within the sign conventions of this work. Inspection

of Table 2 (Subject J) shows all non-negligible values of TP_h to be positive. Therefore, Subject J values of TP_h are in accord with the dominant external torque. The same line of reasoning applied to Subject K produces the same final result: all TP_h values obtained in this work correspond to a toe-in torque.

While pressures smaller than 0.4 p.s.i. have not been quantified, the following qualitative observation has been made repeatedly. The resting value of tangential pressure is not fixed. Shift in baseline values of $\pm$ 0.2 p.s.i. is common. Presumably the flesh accommodates itself to the socket wall through a series of continuing minor motions and deflections as gait continues.

An unusual load alteration pattern, with respect to time and number of steps taken, is apparent in the distal region of the Subject K stump. Figure 8 is a plot of perpendicular and tangential pressures (h and v) at locations 01 (anterodistal) and 02 (laterodistal) for Subject K as a function of pass number. Each plotted point represents the average value of the peak pressure obtained in 12 steps of a given pass. As time (the number of passes) increases there is a monotonic decrease in all pressure values at location 01, a corresponding increase in all pressure values at location 02. Other test sites, examined in the same fashion, reveal but small order changes of pressure magnitude as time increases. Therefore, it would appear that the stump shifts locally within the socket as ambulation continues, transferring the load at the socket interface from one location to another (about 2¼ in. center to center along the circumference). A temporal factor within the cycle is also involved; the peak loading at the anterodistal location occurs at approximately 0.5 seconds after heel-contact while that at the laterodistal location takes place 0.25 seconds after heel-contact. Large load shifts are not presented as typical; the given instance reflects a test subject whose stump is long and muscular. Examination of the other subject (J) reveals no major shift with time.

Figure 8 also illustrates the dependency of the local tangential pressure upon the value of perpendicular pressure; they clearly rise and fall together. A sense of the "coefficient of friction" may be obtained by taking the ratio

$$f = \frac{\sqrt{(TP_h)^2 + (TP_v)^2}}{PP} = \frac{TP_R}{PP}$$

where the resultant tangential pressure TP_R is simply the vector sum of TP_h and TP_v. Values of f corresponding to the tangential and perpendicular pressures given in Figure 8 have been determined, and are shown in Figure 9. The mean value of f is approximately 0.3. There is a slight tendency towards a reduction of f as PP becomes larger; however, the data are too limited to specify the trend.

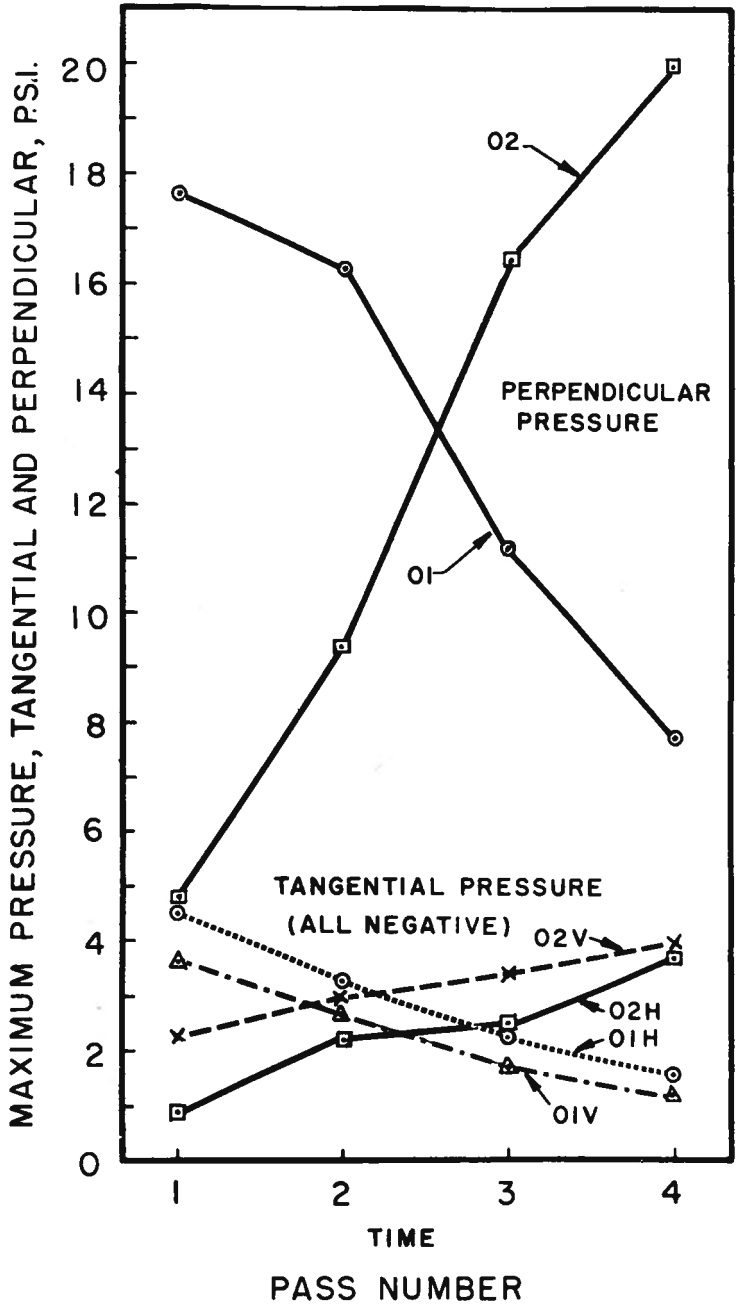


FIGURE 8.—Shift of perpendicular and tangential pressure with increasing walking time. Subject J. The scale for tangential pressure is negative.

IV. DISCUSSION

Tangential pressure may be viewed as a form of friction arising from the application of a perpendicular pressure to the socket wall and simultaneously causing a motion or incipient motion of the flesh with respect to the wall. Tangential pressure may also be visualized within a fluid mechanics framework, where the shear stress at a wall reflects the shear modulus of the "fluid" (flesh in this case) and is insensitive to perpendicular pressure.

The results tend to support the former view, i.e., the mechanical friction analogy. The normalized "coefficient of friction" results given in Figure 9, depicting a reasonably constant f value, imply a direct dependence of tangential pressure upon perpendicular pressure throughout the pressure range. The f value itself is fairly close to friction values measured directly (9) on human legs.

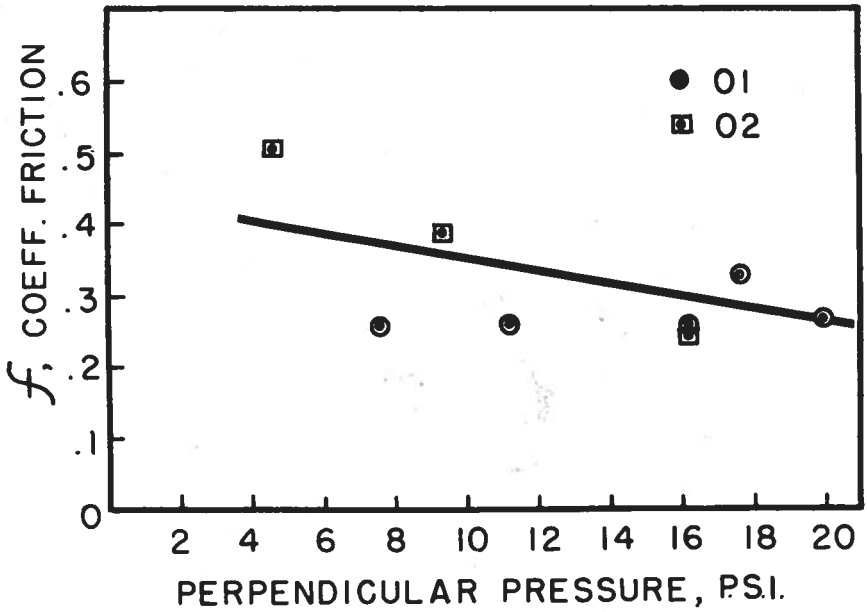


FIGURE 9.—Coefficient of friction vs. perpendicular pressure. Subject J.

In those frequent cases where little or no tangential pressure was obtained, it is suspected that either the local f value was unusually low due to the presence of a lubricant (sweat or body oils), or that the local perpendicular pressure was low, or both. For example, should the local perpendicular pressure peak be as low as 1 p.s.i. (a common socket value in those areas not heavily engaged in load bearing) and the local f value, say 0.3, the product (0.3) would be lower than the

quantitative cutoff value (0.4). Such a result, under the data processing instrumental error limitations of this work, would be classified as small or negligible.

The tendency of local TP_h always to reflect the essential whole body torque (relative toe-in of the planted leg) is not surprising and requires no comment. However, the tendency of TP_v frequently to act oppositely to whole body weight was unexpected (see Table 2, Subject J, 21V; Subject K, 01V and 02V). One may speculate that in the case of upward vertical loading the femur may act as a piston. When driven into the socket during the stance phase, such a piston action might force sections of flesh remote from the femur to rise, reflecting conservation of mass considerations.

Another explanation would suggest that certain gages are sufficiently far from the vertical (Fig. 2, Subject J, 01 and 02) by virtue of positions on the sloping socket wall sections, such that the designation of "horizontal" and "vertical" components is inaccurate. There is sufficient merit in this argument to have motivated additional tests of a fragmentary nature upon a fresh subject, Y. A clearly negative and sizable TP_v was obtained at a mid-stump location at which the socket walls were near vertical. This evidence, taken with that supplied by Subject Y, 21V, leads us to conclude that the occurrence of localized upward loading in the stance phase is real.

Such a loading may also arise when the femur is at a large angle to the socket centerline. In this condition, off-loading from the femur may create a local upload. It would be interesting to inspect X-ray movies of the femur, in this connection.

From our results, there are indications that oppositely loaded portions of the stump flesh are possible within a span of 2 in. The implication is that skin tensile stresses are higher than conventional expectations based on smooth and continuous perpendicular pressure profiles. It is conceivable that such stresses may be significant to such areas as pain and dermatology.

V. CONCLUSIONS

Measurements of that pressure developed at the stump-socket interface, tangential to the socket wall, have been obtained for two above-knee suction socket amputees in level walking. Examination of the data indicates:

1. In general, tangential pressure components (horizontal or vertical) are small ranging from 0 to 3.6 p.s.i. At 20 out of 29 tested locations, the maximum tangential pressure component was less than 0.4 p.s.i.

2. In those instances where the horizontal component of tangential pressure exceeded 0.4 p.s.i., the orientation of the pressure vector was in

accordance with established body torque characteristics (relative toe-in of the planted leg).

3. In those instances where the vertical component of tangential pressure exceeded 0.4 p.s.i., the vector orientation was generally along the line of action of body weight (relative downward loading of socket by stump). Occasional test sites indicated a reverse loading.

4. The perpendicular and tangential pressures developed at a given site are capable of major load redistribution as walking time increases. One subject shifted the bulk of his socket pressure loading (both compressive and tangential pressure loading) at the distal end of his stump through a circumferential distance greater than 2 in.

5. Tangential pressure may be viewed as a form of friction arising from the application of a perpendicular pressure and a coefficient of dynamic friction of typical value 0.3.

VI. ACKNOWLEDGMENTS

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