SOCKET PRESSURE AS A FUNCTION OF PRESSURE TRANSDUCER PROTRUSION [a]

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I. INTRODUCTION

Local pressure, developed between the socket of a prosthetic device and the accompanying body segment, reflects such matters as comfort, stability, and proprioceptive sense. Recent interest in these areas has led to the development of a number of devices to measure pressure. Most such devices, intended for clinical use (temporary mounting in the finished prosthesis), necessarily protrude from the inner wall of the socket, resulting in the physical displacement of flesh. The best of recent models of such devices are roughly the diameter of a pencil and the thickness of a nickel (the coin).

Our concern is with the influence of the sensor protrusion from the socket wall into the flesh on the results obtained, i.e., to what extent the pressure readings, presumably reflecting stump-socket values, are altered by the presence of a protruding clinical-type pressure transducer. An associated issue is the following: The sockets of amputees whose femurs are inadequately padded laterodistally are usually relieved in this region. If the relief is not properly faired into the adjacent wall, local irregularities are produced. It would be of interest to determine to what extent such irregularities alter local pressure.

These issues have been studied experimentally employing four subjects, all vigorous above-knee amputees, equipped with quadrilateral, to-

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tal contact suction sockets. The outputs from both a simulated and a commercially available protruding pressure gage have been compared with a flush gage in terms of local perpendicular pressure.

II. INSTRUMENTATION AND TEST PROCEDURE

A. Equipment

1. Flush Gages and Simulated Clinical Protruding Gage

The apparatus consisted of pressure sensors capable of being mounted in either a flush or protruding configuration when inserted in an especially prepared replica of the subject's socket. Details of the sensor (N.Y.U. Pressure Transducer) and the replica fabrication technique have been given elsewhere (*1*). In brief outline, the transducer, employing a piston impinging against a stiff spring restraint, senses pressure as spring deflection. This motion is transposed into an electrical signal through a network of strain gages.

A second flush transducer, based on the Microsystems Model No. 1003–0046, was employed as an independent checking means. This gage has been described in detail elsewhere (*1*). In brief, it consists of a diaphragm-type transducer whose characteristics and sensitivity are similar to those of the true clinical gage. Smaller than the standard N.Y.U. pressure transducer, it has the advantage of ready insertion at certain sampling sites (brim and proximal medial wall) possessing limited access.

As each replica is equipped with a series of transverse tubular mounts extending through the socket wall, it is possible to position the transducer at any desired depth perpendicular to the wall (Fig. 1). Once positioned, the transducer is clamped. In practice, accurate positioning of the transducer is assured through the use of fixed shims.

2. True Clinical Gage

The clinical gage used for these tests is manufactured by the Sensotec [b] Division of Scientific Advances, Inc. (Model SA-SA M-7BW). The basic transducer is a thin capsule (0.020 in. thick by 0.25 in. outside diameter) one side of which is the pressure sensing diaphragm. Four semiconductor strain gages, wired in a full Wheatstone bridge, are mounted on the underside of the diaphragm.

Because the basic unit produced erratic dynamic results, it was encapsulated in a droplet of Silastic rubber to comply with VAPC specifications. Extensive testing at the VAPC Bioengineering Research Service

[b] Trademark.

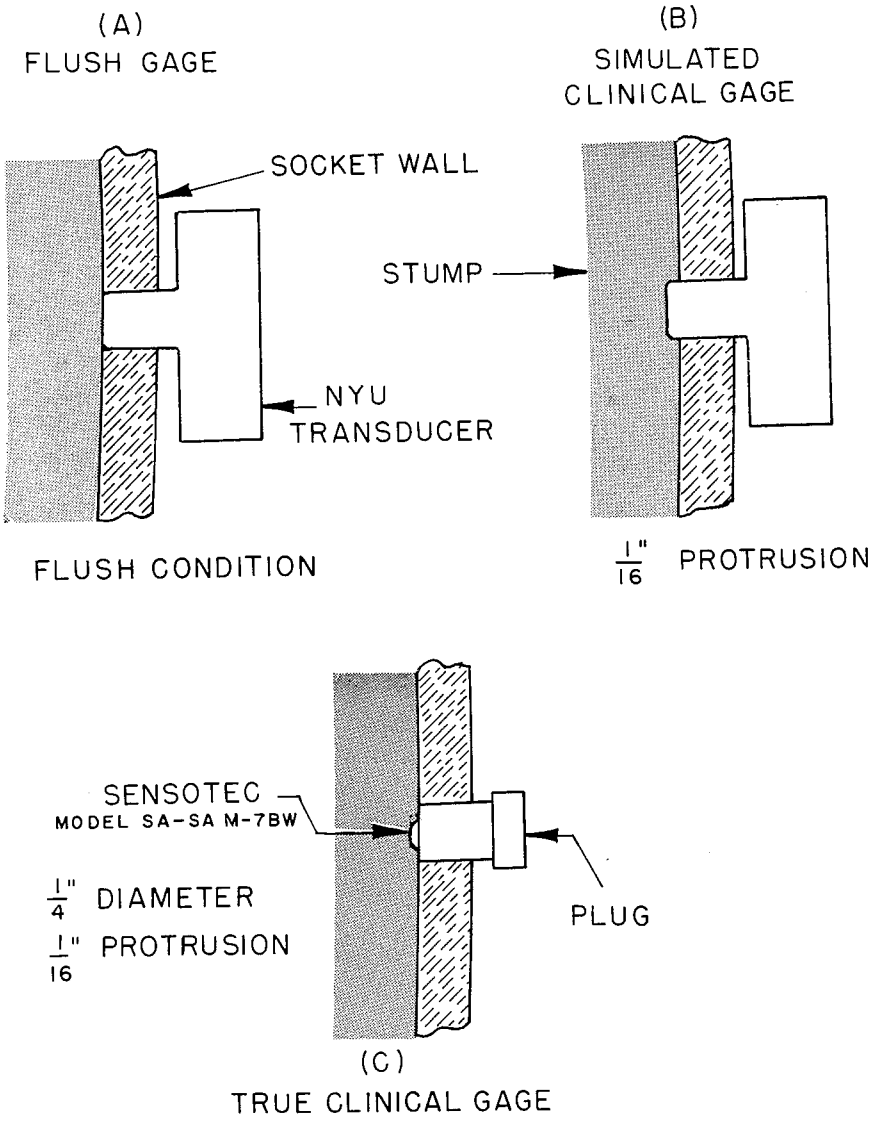

FIGURE 1.—Experimental arrangement. The N.Y.U. transducer of 7/16 in. diameter, was placed sequentially (A) in a flush position with respect to the socket wall, (B) in a protruding position (1/16 in.) with respect to the socket wall to simulate a clinical gage. A true clinical gage was tested as shown in (C).

laboratory indicated that the convex surface of the droplet produced linear and repeatable results. The modification increases the thickness to 1/16th in.

The pressure range of this transducer is 0–30 p.s.i.a., but it will withstand a 50 percent overpressure.

B. Test Procedure

1. Flush Gage and Simulated Clinical (protruding) Gage Tests

The test prosthesis, containing the transducer mounts at numerous socket locations (*1*), was donned by the subject. A short trial period (minutes) followed in which the subject and the observer checked the prosthesis for fit, comfort, alignment, proper knee friction, and maintenance of suction. When both the subject and observer were satisfied with the performance, the transducers were inserted in the mounts and the test was started. Serial duplicate runs were conducted in which a given position was sampled with the pressure transducer mounted flush with the socket wall followed immediately by a run in which the transducer protruded into the socket by $\frac{1}{16}$th in. The total elapsed time was small (minutes) and no further changes in the subject-socket configuration were permitted; for example, the subject was not allowed to doff the prosthesis until all runs were completed. Each run consisted of 12 to 16 strides (depending on the subject).

2. True Clinical Gage Test Procedure

For the tests with the clinical gage the subject removed the test prosthesis after each run to permit the placement of the VA Sensotec Transducer within the socket or on the brim. After the Sensotec transducer was located at a specified sampling site, it was taped in place with double-backed tape. The transducer and its leads were then secured with vinyl tape.

The subject donned the prosthesis and the N.Y.U. transducer and the Microsystems transducer were inserted. The proper amplifier attenuator settings were determined for each of the transducers by having the subject take several steps. This was followed by a run which consisted of two passes, back and forth. Prior to the next run, the whole procedure was repeated and the clinical gage was interchanged with one of the other two flush-mounted units.

C. Data Reduction

Each pressure trace demonstrates a temporal variation containing one to three peaks (depending on the subject and location within the socket) during stance phase. In this paper peak pressure magnitudes are employed as a final result. Whenever pressure values are compared, in either the flush or protruding mode, the values are gathered on the same

subject at the same anatomical location on the same day. Should the pressure-time record display more than one outstanding peak, comparisons are made on a peak to respective peak basis, i.e., first to first and second to second. All pressures under discussion are those acting perpendicular to the socket at the stump-transducer interface. Compression at the transducer (or at the stump) is taken as positive. General calibration and conversion procedures have been given elsewhere (*1*). Recent studies (*2*) concerning possible interaction effects on the transducer when subjected to simultaneous compression and shear have shown the effects of the latter to be negligible.

D. Test Subjects

Four male above-knee amputees have been tested extensively with both the flush and simulated clinical gage. Certain of their characteristics are given in Table 1. The test group (randomly arranged) is not represented as typical of the entire amputee population; age (average 42) and height (average 72 in.) factors are obviously biased. Such bias arose by chance; indeed the only qualification demanded of the subjects, beyond unilateral above-knee status, was a willingness to undergo lengthy experiments and possession of well-fitting, comfortable sockets. The true clinical gage has been tested only with subject J.

TABLE 1.—*Subject Description*

Designation	G	J	K	Y
Age	28	48	47	47
Height, in.	70	76	72	69
Weight, lb.	168	220	165	175
Date of amputation	1962	1952	1954	1944
Cause of amputation	Malignancy	Trauma	Trauma	Trauma
Perineum to bone, in.	11	6	10½	5
Perineum to flesh, in.	11	8	10½	5
Prosthesis usually worn	Henschke-Mauch A	Mechanical knee	Henschke-Mauch B	Henschke-Mauch A
Amputated side	Left	Right	Left	Left
Type of suction socket	Total contact quadrilateral	Total contact quadrilateral	Total contact quadrilateral	Total contact quadrilateral
Comment on gait	Very good	Poor	Very good	Good
Natural cadence steps/min.	104	75	98	95

III. RESULTS

A comparison of the peak pressures as measured by flush and protruding transducers (simulated clinical) is given in Figure 2. For a given socket location and subject, the protruding sensor pressure reading is plotted against that value obtained with a flush sensor. The points, essentially raw data, are sorted by subject only. Every available point of magnitude greater than 1.0 p.s.i. is given without discrimination. This policy produces an unbalance in the representation of the subjects (subject G points/subject Y points = 5.6).

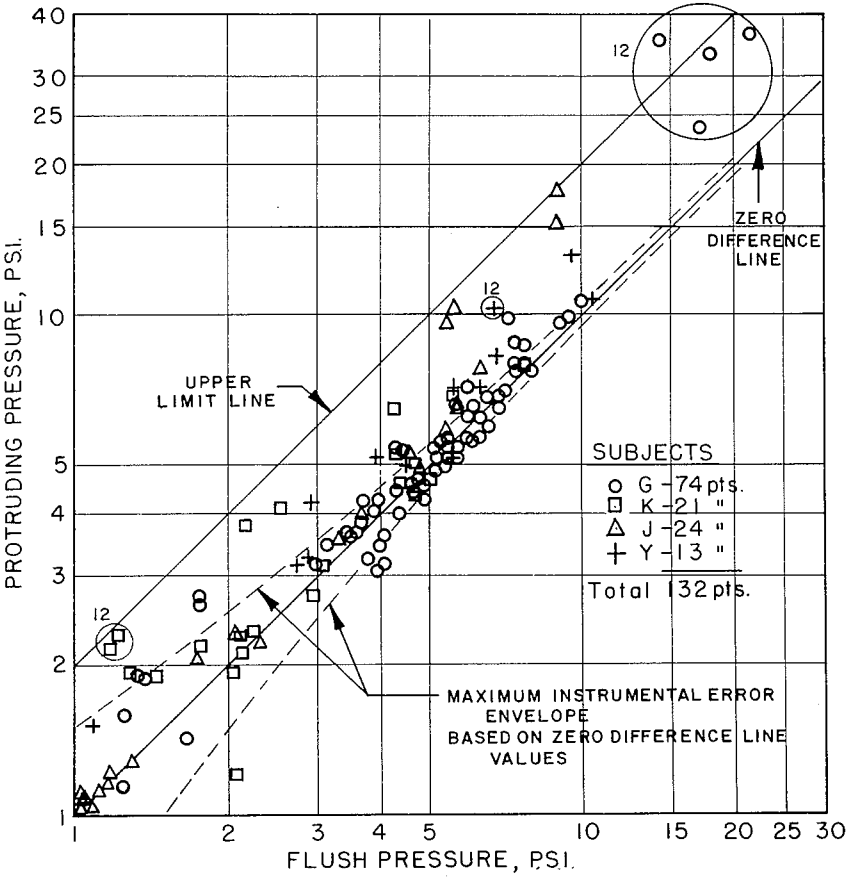

FIGURE 2.—Flush pressure versus protruding pressure (simulated clinical gage) on the same subject at the same location. The zero difference line represents coincidence between flush pressure and protruding pressure. The instrumental error envelope is the expected error amplitude superimposed on the zero difference line. The upper limit line is the observed boundary to all data. Points flagged "12" are located at the lateral distal socket position.

A "zero difference line" is given, representing the case of equality between flush and protruding readings. Straddling the "zero difference line" are two curves representing instrumentation error limits ($\pm$ 0.5 p.s.i. or $\pm$ 3 percent of the reading; whichever is greater) (*3*). Thus, all points reflecting similar flush and protruding readings will fall between the upper and lower points of the error curves. Of the total 132 points, 81 points (about 61 percent) are so bounded.

The results by subject are as follows:

Subject	Percent Data wherein Protrusion Pressure = Flush Pressure
G	47/74 = 63 percent
K	12/21 = 57 percent
J	16/24 = 66 percent
Y	6/13 = 46 percent
	58 percent Average

Note that weighting the subjects equally produces a lower percentage (58 percent) of equal flush and protruding pressures than weighting each point equally without respect to the source (61 percent). Implicit in this difference are the variations in the number of test points from subject to subject. Despite this spread the primary result is not affected, i.e., pressure values obtained from flush mounted sensors, when compared to those obtained from protruding but otherwise identical sensors at the same well-distributed above-knee suction socket locations, are equivalent in about 60 percent of the tries.

As Figure 2 demonstrates, it is possible to construct a realistic upper line to all the data (by eye) with a slope equal to one and an "intercept" of two. By intercept, we mean the ordinate at log abscissa = 0, i.e., the ordinate at flush pressure = 1. Noting that the figure represents log coordinates, it follows that the upper limit represents the line

$$2 \geq \frac{\text{Protruding Pressure}}{\text{Flush Pressure}}$$

For a lower limit, the inspection indicates the zero difference line, corrected for allowable instrumental error to be adequate. Thus the expression

$$2 \geq \frac{\text{Protruding Pressure}}{\text{Flush Pressure}} \geq 1$$

embraces the bulk of the data (97 percent); i.e., protruding pressure (that measured by a protruding gage) is only rarely below pressure measured by a flush gage and rarely more than twice that measured by a flush gage.

Average values of the protruding pressure/flush pressure ratios are given in Figure 3 on a lumped subject and location basis. Protruding pressure values are those obtained with the simulated clinical device. Using geometrically increasing flush pressure values as class boundary values, the average ratio is given for each class in bar graph form. The percentage of all data contained within a given class (and shown as the ordinate) is an index to confidence. All average ratio values are greater than one. The P/F ratio is a minimum in the 2–4 p.s.i. range (protruding pressure/flush pressure = P/F = 1.08) and increases continuously as pressures depart from this range. While the ever higher P/F ratios associated with increasing flush pressures imply the importance of pressure itself as a parameter, it should be noted that the number of readings available decreases as pressure increases. Consequently the confidence to be placed in the higher pressure findings decreases as pressure increases. Therefore, we can report a real, albeit weak, correlation between large pressure and large P/F ratios.

To examine the relationship of P/F with respect to anatomy, a list of unusual (high and low) P/F ratios and locations has been prepared and is given in Table 2. Unfortunately, the extensive remolding of the stump within the socket resultant from donning the prosthesis lends uncertainty to the assignment of a precise stump location. Nonetheless it is our opinion that most high P/F ratios correspond to locations associated with bone or muscle proximity. Thus location 12 (lateral and distal), approximately at the amputated extremity of the femur, produces significantly high P/F ratios in three out of four subjects. These points are flagged with a "12" in Figure 2. Note that the corresponding flush pressures cover the full range of all tested values, implying the sensitivity of P/F to a location factor as distinct from a "pressure alone" factor. Brim location (near the ischium) yields high P/F ratios in two of four subjects. Location over a muscle also produces high P/F ratios in two subjects.

Low P/F ratios are few in number and scattered in location. Noting that of some 132 measured pressure ratios, only the listed four values offer P/F ratios less than 0.90; we are uncertain concerning the significance of these meager results. The two subjects displaying low P/F results are the more muscular and active members of the group.

The results of matching the pressure output of a flush device with that of a typical clinical protruding transducer (Sensotec Model SA-SA, M-7BW) are shown in Figure 4. Small in size and designed for casual mounting to the socket wall, it necessarily protrudes slightly into the stump flesh. As in Figure 2, the plot employs flush pressure values as the abscissa. The ordinate also represents pressure values, gathered at the

same location on the same subject (J). Triangular points are those readings obtained with an independent N.Y.U. flush gage within several hours of the abscissa values. Open symbols are check points, gathered in identical fashion, two weeks after the initial runs. For perfect coincidence, all such flush pressure values should fall within the maximum instrumental error envelope straddling the zero difference line.

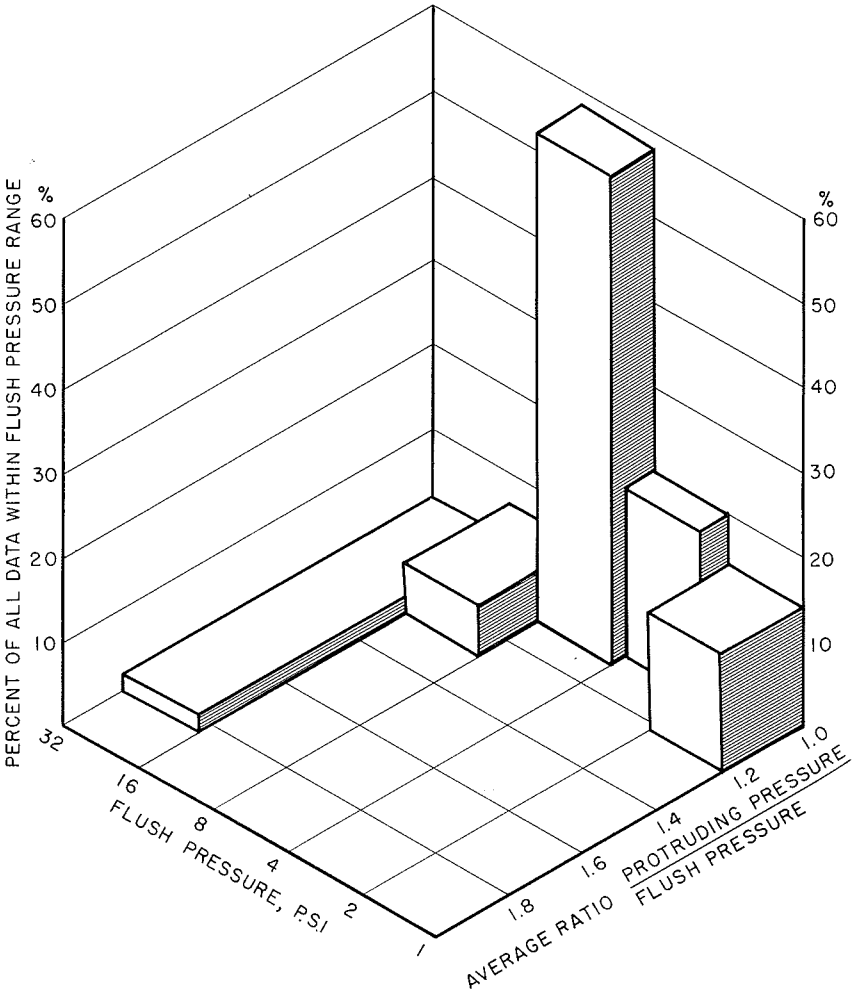

FIGURE 3.—Distribution of the average protruding pressure/flush pressure ratio with respect to flush pressure. All protruding results obtained with simulated clinical device. The vertical axis represents the percentage of all data falling within a given flush pressure range and thus serves as an index to confidence. For example, data collected within the flush pressure range 16→32 p.s.i. has an average P/F ratio greater than 1.8. However, as less than 5 percent of all data collected fell within this range, limited confidence is to be placed in the result.

TABLE 2.—*Unusually High and Low P/F versus Location*

Subject	Location code	Location
	HIGH P/F (>1.35)	
G	12	Lateral and distal
	13	Posterior and distal
	21	Anterior and distal
	54, 52	Near ischium on brim
K	62	Proximal lateral wall (near brim)
	12	Lateral and distal
	23	Posterior and distal
	21A	Anterior and distal (rectus femoris)
Y	34	Lateral side gluteus maximus
	12	Lateral and distal
	22	Anterolateral
J	56	Brim
	55	Brim
	LOW P/F (<.90)	
G	31, 14, 41	Anterior and mid-stump
K	13	Posterior and distal
Y	None	
J	None	

It is evident that the flush pressure values do not offer perfect coincidence. However, note that the means of testing has been altered from that employed previously. The gathering of all data shown in Figure 4 required the removal of the prosthesis and substitution of gages; the data shown in Figure 2 were obtained without removal of the prosthesis or gage change. Thus, the triangular points (Fig. 4) combine the variability to be expected from donning and doffing the leg with the variation resultant from different (flush) gages. The maximum error so produced is about 1.0 p.s.i., or about twice the instrumental error.

The circled points, obtained by removing the prosthesis and mounting the Sensotec unit are, in general, larger in value than corresponding flush pressure readings. The upper limit line, drawn by eye, has an intercept of five. The mean P/F ratio value of all brim points is approximately three. (Brim points are those flagged with a location number. The ischial seat is located near B6. Values for B6 and B7 were not obtained due to concern about overloading the gage.) Thus, the brim pressure readings obtained with a true clinical gage greatly exceed those values obtained with a flush gage. Further, true clinical gage brim values greatly exceed those obtained with a simulated clinical gage.

In summary, protruding gage results are higher in value than those obtained with a flush gage. Location within the socket and protruding

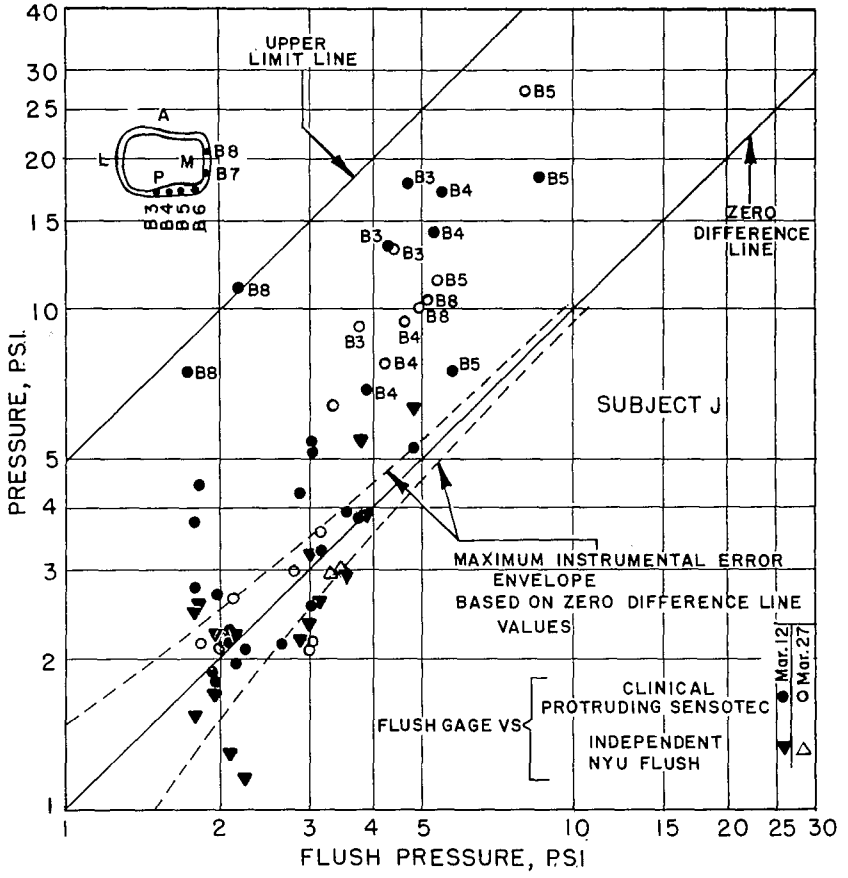

FIGURE 4.—Flush pressure versus true clinical gage pressure, subject J (circle points): Results from a second flush gage are also given (triangle points). Open points are repeat runs taken 2 weeks later. Flagged points indicate protruding clinical gage tests on the brim, located as shown on the top view brim sketch.

gage configuration are variables which powerfully affect the resultant pressure/flush pressure ratio.

IV. DISCUSSION

The results indicate a protruding gage tends to display a larger pressure value than a flush gage. Consider the cause. Imagine a model of the stump which is sufficiently soft and homogeneous to be represented by a membrane enclosing a volume of gas, i.e., a balloon. Consider the model placed within a socket and given a weight-bearing load. The socket pressure will be the same everywhere. This is true no matter how the

socket is shaped. If the membrane is able to accommodate itself to the socket contour, then undercuts and protrusions will not alter the local socket pressure value. In this case, a protruding and flush gage should read the same value.

As the stump model is changed to one of great stiffness, the stump loses its ability to conform to the socket and the load will be carried at "high" points, i.e., areas of stump-socket contact. The protruding gage is such a "high" point and will garner an ever larger share of the local loading as the stump is progressively stiffened. Ultimately, given sufficient stiffness, the slightest protrusion will absorb all of the local loading.

In practice, the flesh portions of a stump resemble the soft model while thinly padded bones correspond to the stiff model. Thus, we expect a greater protrusion effect in proximity to bone (or tough fascia, tendon, or tensed and hardened muscle) than we do in proximity to soft flesh. Partial support of these expectations is given by Table 2, wherein high P/F ratios frequently reflect proximity to bone or muscle. While our knowledge of the dynamic location of the femur is uncertain (X-ray motion pictures of the walking stump would be useful, but are expensive), available results suggest that correspondence between local stiffness and local P/F does exist, albeit with frequent exceptions. For example, the data given in Figure 4 demonstrate the high P/F ratios present in the brim compared to non-brim locations. The ischial seat for this subject (J) is nearest B6. One might reasonably expect the proximity of bone to produce the high P/F values existent at B5, and a combination of bone and tendon to influence the values at B8. The reason for the same phenomenon occurring at B3 is not as obvious. This is in the outer region of the gluteus maximus approximately at its junction with the tensor fasciae latae and the tendinous attachment to the gluteal tuberosity of the femur. In most of the stance phase this muscle group is contracted and as such may act as a stiff model (previously discussed).

As other tested locations reveal high P/F values without as obvious a relationship to local stiffness as in instances already discussed (see presentation of Table 2 in "Results") it is reasonable to consider other factors capable of influencing P/F. One such possibility is the basic value of pressure itself. Consider as a model, not the previously discussed gas bag, but a bag containing soft flesh. The flesh stress-strain curve becomes highly nonlinear at high load conditions, i.e., as one continuously approaches failure a uniform incremental change in strain produces an ever increasing incremental change in stress or load (*4*). In popular terms the bag of flesh may be viewed as possessing a great deal of

"slack." As the "slack" is "taken up" the flesh stiffens, offering greater and greater resistance to further deformation.

Applying such a model to a protrusion gage, one would expect but a slight effect at low pressures. As the basic pressure becomes large, the additional strain imposed by the physical extent of the protrusion should lead to increasing measured pressures (compared to flush gage pressures). Therefore, one would expect P/F to increase continuously with F.

In practice, there is some evidence to support this view (Fig. 3), but the case is uncertain at best. The uncertainty reflects the dearth of high pressure F points and the difficulties of separating the local stiffness variable from the pressure-alone variable. It may be said only that pressure-alone effects appear of lesser importance than local stiffness, but are not to be entirely discounted.

Another possible manner of influencing P/F values is through local interaction at the gage. Consider a large tangential (or shear) loading to exist at the gage face, perhaps due to local slip. The protrusion may act as a miniature cam, converting a portion of the shear load into a compressive load. If this possibility were real, one would expect interaction effects to be, at most, of lesser magnitude than the basic compressive load. As the data contain numerous points of large P/F value, the interaction effect would not seem to offer an adequate explanation. Nonetheless, we may conjecture that some degree of interaction influences certain of the results.

The possibility has been suggested that the relatively sharp corner of the simulated clinical device may create a local skin stress discontinuity, thus contributing to an increase in pressure. It should be noted, however, that the true clinical gage, devoid of such sharp discontinuities and possessing a smaller perimeter, would appear to offer generally higher P/F ratios than the simulated clinical device. The effect of protrusion radius would appear to warrant further investigation.

The significance of these results with respect to clinical measurements of local pressure is clear: high pressure readings obtained with protruding pressure gages are suspect. When employed as a qualitative tool, useful results are obtained. However, the quantitative validity of such measurements is, at least, questionable. Since lower pressures are desirable, it is fortunate that the clinical gage is more likely to be correct at these lower pressures than at higher pressures.

With respect to small irregularities present on the socket inner wall, large order pressure changes may attend their removal or modification. Socket conformity, especially in areas adjacent to slightly padded bone, is of considerable importance in reducing local high pressure.

V. CONCLUSIONS

Four above-knee amputees, equipped with quadrilateral total contact suction sockets were tested with matched flush mounted pressure transducers and simulated clinical pressure transducers protruding into the socket. One amputee was tested with a matched flush gage and a true clinical protruding pressure gage (Sensotec). Analysis of the dynamic stump-socket pressure patterns obtained in level walking indicated the protruding gages to supply generally larger pressure values than those obtained from flush gages. The measured ratio of protruding to flush values was frequently larger than 1.5 and in certain instances larger than 4.0. Factors possibly influencing these values, including anatomical (local stiffness), nonlinear stress-strain characteristics of tissue, and interaction at the gage are discussed.

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