A STUDY OF INTERFACE PRESSURES IN THE
BELOW-KNEE PROSTHESIS
(PHYSIOLOGICAL SUSPENSION: AN INTERIM REPORT*)

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INTRODUCTION

Since its inception, the Prosthetics Research Study has attempted to maximize retention and stabilization of residual limb musculature in the below-knee amputation. Combined with myoplastic technique, Immediate Postoperative Prosthetic fitting, training of residual limb muscles, and an appropriate definitive prosthesis, an effective, functional end organ is achieved.

Clinical observation has shown that certain below-knee amputees are able to utilize their prostheses without built-in suspension (such as the PTS) or auxiliary suspension. It was hypothesized that strength and muscle development in the residual limb would facilitate prosthetic suspension.

The present report provides a detailed investigation of certain parameters of muscle activity and pressure relationships within prosthetic sockets; a preliminary report has been previously published (1). A

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study of five below-knee amputees, undertaken to determine socket interface pressures and the feasibility of “physiological suspension,” is reported here.

METHODS AND MATERIALS

Patient Selection

The following criteria were established for patient selection:
1. The study was limited to unilateral below-knee amputees who had undergone amputation because of trauma.
2. The surgical technique was myoplastic with long posterior skin flap and an anterior suture line.
3. Postsurgical management was either Immediate Postoperative Prosthetic fitting (IPOP) or Controlled Environment Treatment (followed by some elements of IPOP).
4. The length of the residual limb was 6 to 8 in, which was considered adequate for sufficient gastrocnemius length below the bifurcation of the gastrocnemius heads.
5. Patients were at least 6 months postamputation and they were using their definitive prostheses effectively.

Patient Evaluation

Initially, the patients were interviewed individually, at which time the study parameters were explained. A clinical subjective evaluation by a prosthodontist, an engineer and a physical therapist was performed. Physical examinations of the residual limb included:
1. Visual inspection and palpation of residual limb for tender areas and for degree of muscle activity.
2. Evaluation of type, condition, and fit of present prosthesis.
3. Analysis of gait with present prosthesis.
4. Routine X-rays of prosthetic fit.

Photogrammetry

It was assumed and subsequently shown that peak muscle motion or rise would indicate the point of highest pressure at the residual limb socket interface when the muscles were contracted. In order to locate such areas of highest pressure, each patient underwent a photogrammetric study of his residual limb. Photogrammetry is a three-dimensional photographic technique commonly used for making contour maps of land. The patient was photographed standing without his prosthesis. Anterior, lateral, and posterior views of his residual limb were taken, in both relaxed and contracted muscle positions.
Resulting photographs, processed into direct contour maps through a Balplex plotter, were enlarged to full scale and transferred to clear acetate sheets. These transparencies were used as overlays to compare the residual limb contour in relaxed and contracted positions, illustrating physical surface changes which occurred on the residual limb (Fig. 1). The overlays assured correct and repeatable positioning of pressure transducers in the areas of gross muscular changes; i.e., posterior gastrocnemius bulge.

Prostheses

To ensure similarity in the prosthetic technique used, the same prosthetist fabricated and fitted all prosthetic appliances. The type of suspension used in the patient’s previous prosthesis was incorporated into a new prosthesis for each patient.

Four patients had PTB sockets with soft liners: of these, two used cuff suspension (Patients No. 1 and No. 2) and two had no auxiliary suspension (Patients No. 3 and No. 4). Patient No. 5 had a PTS socket with a soft liner and a built-in wedge. Each patient wore his new prosthesis (weight approximately 4 lb including the shoe) for not less than 1 week before further testing was done.

Additional instrumentation was used on one patient’s prosthesis (No. 4) to determine the amount of displacement which occurred

![Figure 1](image-url)
between the distal portion of the residual limb and the bottom of the socket while walking. A displacement sensor was designed to give continuous readout of the resulting separation (Fig. 2).

FIGURE 2.—Sensor designed to determine amount of displacement which occurred between distal portion of the residual limb and the bottom of the socket while walking.
The device consists of two Teflon cylinders arranged one inside the other. The outer cylinder is 1 in. in diameter and 2 in. long; the inner one ½ in. in diameter and 1¾ in. long. The lower half of the inner cylinder is wrapped with resistance wire. The outer cylinder has a small, spring-loaded ball bearing which makes contact with the resistance wire, forming a potentiometer.

A spring ensures that, without load, the inner cylinder extends ¾ in beyond the outer one. As the limb is inserted into the socket, the inner cylinder is retracted into the outer, changing the electrical resistance of the device. In this way, a correlation between the resistance and the cylinder extended height can be made; this also relates to the distal separation between the residual limb and the bottom of the socket.

The sensor was recessed into the bottom of two sockets (one hard socket and one socket filled with a soft liner). There was no difference in the amount of displacement seen, regardless of whether the patient wore a hard or soft socket. Because the patient felt most comfortable in the soft liner, test prostheses for all patients were made with this feature.

Interface Pressure Evaluation

Six thin pressure transducers (Kulite LQ-125), which were zeroed at atmospheric pressure, were affixed directly to the patient’s skin with Micropore (3M) tape. Placement of the transducers (Fig. 3) along the posterior portion of the patient’s residual limb was along a vertical line as follows:

One placed at the center of peak muscle activity (as determined by the photogrammetric overlays);

Two 2 cm and 4 cm proximal from the center; two 2 cm and 4 cm distal from the center; and one at the most distal portion of the residual limb (Fig. 4). To ensure accurate placement of the sensors for repeated study, the transducer placement was then charted on the patient’s photogrammetric overlays.

Muscle Activity

Surface EMG electrodes were also taped over the gastrocnemius and tibialis anterior muscles of both lower limbs. Placement was selected to record maximum muscle activity (4) of both the residual limb and the “normal” limb of all patients, as it occurred during specific phases of gait cycle. No attempt was made to correlate the amount of muscle firing by each patient with other patients or test runs. Of greater interest was to determine when the residual limb musculature fired during the gait cycle.
In order to correlate the cycles of the residual and contralateral limbs' muscle activity, foot switches were taped under the heel, and 2 in from the tip, of each shoe. This switching information was translated into a Visicorder grapher by Medtronic, Inc., signal conditioner, and represented the following phases of gait: heel strike (HS), foot flat (FF), heel rise (HR), and toe off (TO).
Dynamic Evaluation

After all electrodes and transducers were secured, a nylon stocking was carefully pulled over the residual limb to keep all lead wires flat against the patient's skin. The patient then donned his prosthesis in the routine manner (Fig. 5).

All wire leads were connected to a small control box which the patient wore on a waist belt. The information was fed through an "umbilical cord" to a 13 channel Honeywell 1912 Visicorder. Four EMG channels, six pressure channels, and two foot switch channels were used. The thirteenth channel was used for the displacement sensor.

All patients were then instructed to walk along a 60 ft walkway. Each patient traversed the course eight times using his normal mode of suspension. With the two patients who used cuff suspension, ambulation was then repeated without auxiliary suspension.

The patients were observed to build up speed at the beginning and decrease near the end of the walkway; therefore, for graphing purposes, one gait cycle was selected at random from the middle of each
FIGURE 5.—Patient with EMG, pressure transducers, and foot switch leads in place; he is now ready for dynamic evaluation.
of the eight runs, and averaged, to produce the graphs used for evaluation.

Observations

The pressures recorded for each patient’s residual limb during the swing phase showed the same pattern (Fig. 6). This similarity held true when the two patients with cuff suspension ambulated without their cuffs.

Studies conducted by Appoldt, et al. (5) have indicated that pressure gages which are not flush with the socket wall will give inaccurate readings at higher pressure, while at the lower pressures, readings are more likely to be correct. Since this study concentrated on swing phase pressures, which are reasonably low, pressure readings were considered accurate.

An interesting observation was made when testing distal displacement. The generally accepted premise is that more than \( \frac{1}{4} \) in of pistoning in swing phase is an indication of a poorly fitting prosthesis. However, the tests with a distal displacement sensor on one patient

![Figure 6](image.png)

**Figure 6.** Average pressures recorded of five patients at transducer (4+ cm).
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(No. 4) revealed ¾ in of pistoning, without disturbing the patient's comfort or gait pattern. This surprising result was confirmed by Grevsten, et al.(6), in their study of skeletal displacement, and by our own X-ray examination (Fig. 7). In all five patients, X-rays of their residual limbs within prostheses in simulated swing phase confirmed a displacement of more than ¼ in.

**Figure 7.** X-rays of patient No. 4: at left, weight-bearing and at right, non-weight-bearing, revealing displacement in contracted position.
EMG studies were done to determine when muscle activity in the gastrocnemius and tibialis anterior muscles occurred. On the non-amputated side, the gastrocnemius fired mid-foot-flat through toe off, and the tibialis anterior fired at heel strike. In the residual limb, the gastrocnemius fired from toe off through mid swing, and the tibialis anterior from swing to mid-heel-strike on that side. It was noted that neither muscle fired during swing on the non-amputated side, while both overlapped in swing on the residual limb (Fig. 8).

Patients No. 1 and No. 2, who normally used cuff suspension, demonstrated no graphic difference between their pressure and gait parameters as they walked with and without their suspension for normal ambulation. (This study did not evaluate any other activities of daily living, e.g., up and down stairs and ramps, and rising from sitting to standing.)

While their pressures, EMG, and gait patterns were similar, patient No. 2 showed a considerable gastrocnemius contour bulge with the photogrammetric pictures, but patient No. 1 did not. In fact, No. 1 did not show any demonstrable differences in either the relaxed or contracted positions. For the above reason, patient No. 1’s pressure transducers were set up on a purely symmetrical basis, corresponding to the positions on the other four patients.

Of the two patients not using auxiliary suspension, patient No. 4 appeared to suspend his limb by muscle contractions alone. With the patient sitting down, and with his residual limb straight or bent (45 deg) and muscles relaxed, a very small amount of force (less than
10 lb) removed his prosthesis. However, with his muscles contracted, it was impossible to remove his prosthesis without exerting a force greater than 45 lb.

Patient No. 3 was also able to ambulate without auxiliary suspension. In his case, however, whether residual limb muscles were contracted or relaxed, it was still difficult to remove the prosthesis. X-rays showed a bony callus at the proximal end of the fibula (Fig. 9).

![Figure 9](image)
which gave the patient minor prosthetic donning problems; however, once the limb was in, it was difficult to remove the prosthesis.

Conclusions

At this interim point, we have accumulated data on the interface pressures of what we consider the key areas for physiological suspension, these being areas of peak muscle motion of the gastrocnemius as shown by photogrammetry. In conjunction with these data we have determined “normal” EMG firing patterns for both lower limbs during the gait cycle, as indicated by the foot switches.

All this information has indicated that there is no basic difference between patients ambulating on a straight level walkway with or without auxiliary suspension. With this in mind, future studies would entail the fabrication of sockets for the three patients still using some type of auxiliary suspension. Their new sockets would not incorporate any type of suspension. Socket modifications could be made along the line of Blevens (7) to enhance physiological suspension capabilities. They would then be trained in the active use of their residual limb muscles through physical therapy and biofeedback training. The tests conducted in this interim report would be repeated at monthly intervals to determine the patient’s progress with their new limbs.

As another consideration, surgical procedures for new below-knee amputees could be modified to augment the ability of the patient’s residual limb to adhere to the socket. On those patients who do not use auxiliary suspension, studies could be made to determine if they have any problems keeping their prosthesis on during other activities of daily living.

REFERENCES