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Conventional patellar-tendon-bearing (PTB) socket/stump interface dynamic pressure distributions recorded during the prosthetic stance phase of gait of a trans-tibial amputee.

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Abstract

Force sensing resistors (FSR) have been used to measure dynamic stump/socket interface pressures during the gait of a trans-tibial amputee. A total of 350 pressure sensor cells were attached to the inner wall of a patellar-tendon-bearing (PTB) socket. Data was sampled at 150 Hz during the approximate 0.8 seconds of prosthetic stance of gait. A total of 42,000 pressures were recorded during a single prosthetic stance. This paper describes the distribution of the pressure patterns monitored during the prosthetic stance phase of gait.

Introduction

Several researchers have reported on stump/socket interface pressures using a limited number of individual transducers. Studies such as those reported by Hulshof (1995) provide accurate pressure data for a particular local site within the socket. An overall impression of the stump/socket pressure distribution is not possible with the type of pressure transducer used by previous investigators.

Inaccuracies have been reported using FSR technology (Cavanagh *et al.*, 1992; Ferguson-Pell and Cardi, 1992; Rose *et al.*, 1992; Schaff 1993; Young 1993; Hayda *et al.*, 1994; Cobb and Claremont 1995; McPoil *et al.*, 1995; Sanders, 1995; Brown *et al.*, 1996; Pitei *et al.*, 1996; Woodburn and Helliwell, 1996). The 0.017 mm thick mylar/resistive ink (9810) F-socket transducer developed by Tekscan Inc. in Boston provides a stump/socket pressure distribution during gait. The characteristics of this transducer, which incorporates 96 sensor cells, have been previously reported by Buis and Convery (1997).

Method

The transducers were calibrated *in situ*, while attached to the inner socket wall of the trans-tibial socket. The calibration rig, illustrated in Figure 1, consists of a frame, a socket brim

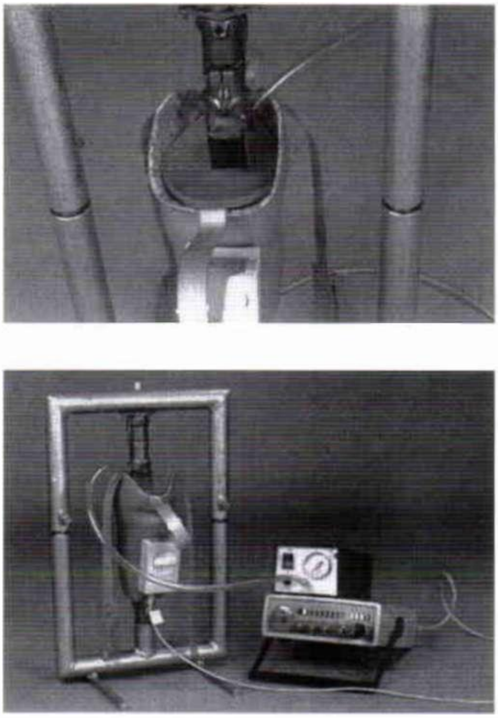

Fig. 1. Transducer calibration

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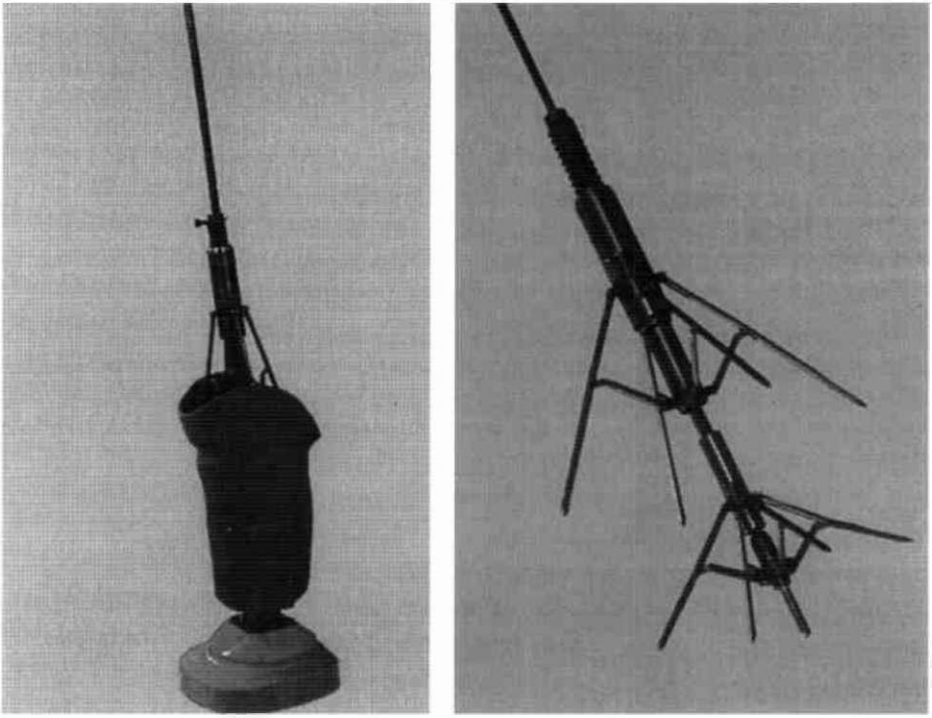

Fig. 2. Socket axis locator

template and a dynamic loading input generator. An accurate pre-selected pressure was applied to the inner socket wall via a pressurised gel filled sheath. The socket was perforated at the bottom to avoid air being trapped between the sheath and the inner socket wall during the loading cycles. By adopting a developed calibration technique and following a strict test protocol, the inaccuracies have been minimized to acceptable levels. When subjected to repeat pressures of 100 kPa the variation of the "average" pressure of a transducer was ± 2% with a maximum variation of ± 10% for any individual cell in the 96 sensor array.

A patient was fitted with a trans-tibial prosthesis incorporating an acrylic resin laminated PTB socket. The stump was hand cast and rectification of the cast was typical of that practised in the authors' department. The prosthesis was aligned to the satisfaction of the patient and two prosthetists. The alignment was measured using the socket axis locator illustrated in Figure 2. A duplicate prosthesis was fabricated so that the prosthesis which incorporated the transducers was used only during the pressure studies. The alignment, measured in Figure 2, was duplicated on the instrumented prosthesis. Figure 3 illustrates the alignment of both prostheses. No socket liners were supplied with either prosthesis. A silicone sleeve was supplied for suspension of the prostheses.

A sensor reference grid was established for positioning transducers, using the socket axis locator. Four longitudinal reference lines were used to centre the four transducers.

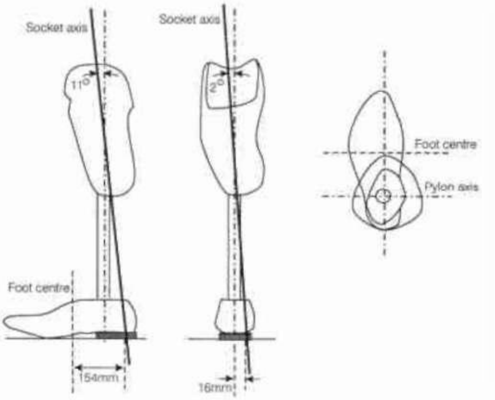

Fig. 3. Alignment of PTB prosthesis.

Circumferential lines using the bottom centre of the socket as a reference were used to locate the four transducers axially. The four transducers, with a total of approximately 350 sensor cells, were attached to the inner socket wall using non-aggressive spray adhesive. Individual cells may be positioned with an accuracy of ± 0.75 mm. The transducers were attached to the anterior, posterior, medial and lateral walls of a trans-tibial socket as shown in Figure 4. The lower posterior socket brim permitted some sensor cells from the posterior transducer to be located at the distal end of the socket.

Initial gait studies investigated the consistency of the subject's walking. This was essential because software limitations dictated that only two transducers per socket could be recorded for a particular walk. In order to obtain an overall pressure distribution using all 4 transducers, pressure data from two similar steps had to be combined. The consistency of the patient's preferred gait, with his existing prosthesis, was verified with respect to walking speed and ground reaction force (GRF). The GRF data was obtained from a force plate located in the middle of a 9 metre walkway. The statistical analysis of 15 walks, with and without a metronome, indicated that the patient demonstrated a very consistent gait with the prescribed PTB prosthesis. The patient's preference for assistance from the metronome supported the recommendation that all pressure study comparisons be undertaken at a pre-determined, metronome assisted, walking speed. This would permit future pressure studies of other socket designs to provide valid comparable data.

Fig. 4. Socket/sensor array.

A strict test protocol was adopted. The patient was allocated the morning to become accustomed to the non-instrumented prosthesis. The pressure study with the prosthesis incorporating the transducers was undertaken that afternoon. A pre-conditioning sequence of taking approximately 30 steps was adopted before simultaneously recording data of walking velocity, pressure and the force plate outputs. The patient was seated for at least 3 minutes to allow the pressure sensors to recover before repeating the exercise. This procedure was repeated 15 times monitoring the two transducers attached to the anterior/posterior aspects of the socket and then 15 times monitoring the two transducers attached to the medial/lateral aspects of the socket.

Results

The selected Tekscan transducers provided a large amount of pressure data. Three hundred and fifty sensor cells sampling at 150 Hz, for approximately 0.8 seconds of the prosthetic stance of gait, resulted in 42,000 recorded pressure readings during a single step. Interpretation and presentation of the data necessitates a means of viewing all of the data to condense the results in manageable format. Particular instants of the prosthetic stance can then be selected to demonstrate pressure distributions.

Statistical analysis of force plate and pressure data for the 15x2 recorded steps revealed that there was no significant difference in the ground reaction force or the "average" pressure of the transducers. The force plate and walking speed data was reviewed and two particular steps were selected which were considered to be most representative of the patient's average gait. The pressure data from these two selected steps were combined to provide a pressure distribution from all four transducers during a "single" prosthetic stance phase of gait.

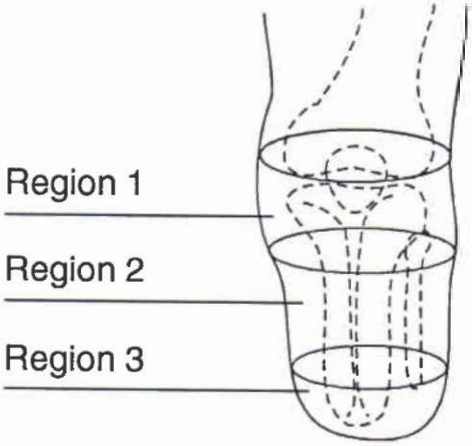

Fig. 5. Stump/socket regions.

This selected pressure and force plate data was used to develop a 3 dimensional computer model of the prosthesis. This 3D computer model permits the observer to view the output from all four transducers and hence the distribution of pressure within the socket. At any instant of gait the pressure distribution may be related to the line of action of the GRF relative to the socket.

Three axial regions within the socket may be identified, as illustrated in Figure 5. Figure 6 illustrates the typical pressure distribution of all 4 transducers displayed in a 2D configuration. The anterior, medial, posterior and lateral pressure data results are illustrated, from left to right, during an instant shortly after mid-stance. Due to the tapering of the distal socket, the medially and laterally positioned transducers have been pruned. The posterior transducer has also been pruned to accommodate the sensor cells which measure distal end bearing. During gait, some areas within the physical boundary of the transducers may be displayed in "white". The white scale merely indicates that the pressures experienced in these areas are below the minimum measurable threshold of 4 kPa. This does not imply that there is no contact between the stump tissue and socket wall in these regions.

Figure 6 demonstrates how the pressure distribution may be represented. The illustrated pressure distributions will vary throughout the stance phase of gait. A sample rate of 150 Hz for 0.8 seconds provides a total of 120 pressure distribution patterns throughout prosthetic stance.

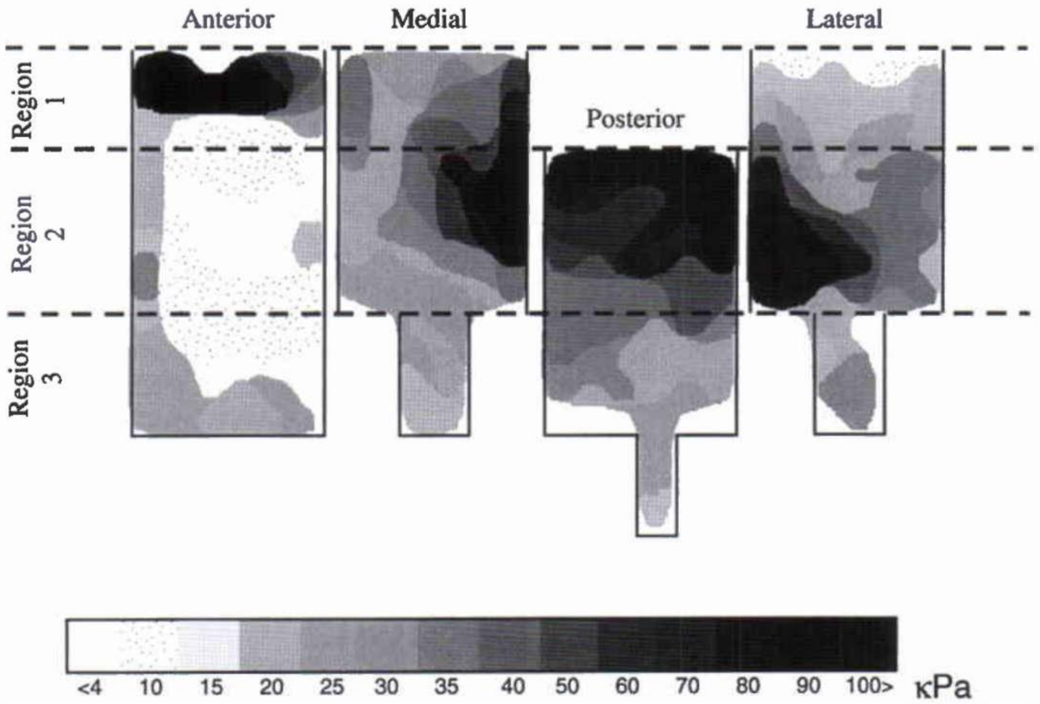

Fig. 6. Stump/socket interface pressure distribution at mid-stance.

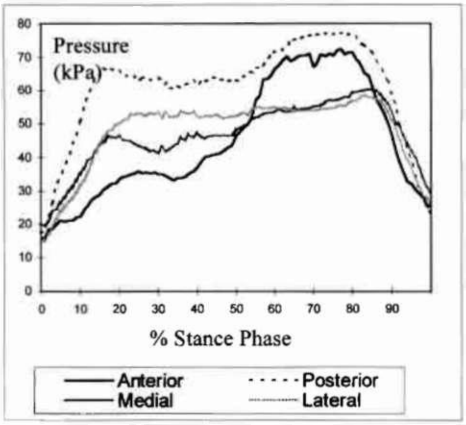

Fig. 7. "Average" pressure per transducer during prosthetic stance.

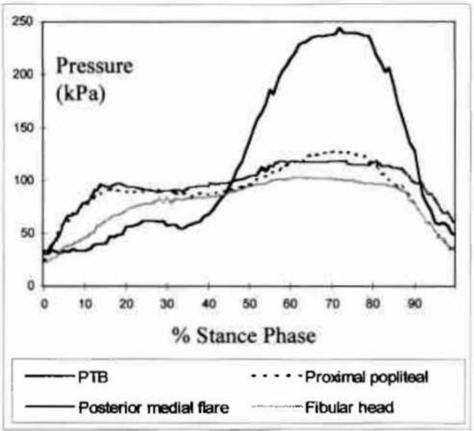

Fig. 8. Maximum "average" pressures in (>100 kPa) areas.

Figure 7 illustrates the variation of the "average" pressure of each of the four transducers during the stance phase of gait. However the "average" pressure reflects the mean of approximately 96 sensor cells and therefore peak pressures within the sensor array are concealed when average values are used.

Discussion

The pressure pattern (Figs. 6 and 7) will be influenced by the relationship of the line of action of the GRF to the socket during the stance phase of gait. Throughout the prosthetic stance phase of gait the line of action of the GRF always passed ahead of the socket, for this particular patient. This is not typical of trans-tibial gait.

A distinct pressure pattern was demonstrated. A ring of pressure at the patella bar level in the PTB socket was noted with no major distal end pressure. Using Tekscan software, four specific socket areas that experienced pressures in excess of 100 kPa were identified. These four areas were the patellar bar (PTB), the proximal popliteal (PP) area, the posterior medial flare (PMF) and the fibula head (FH). The variation of the average pressure in these four limited areas is illustrated in Figure 8. Table 1 highlights the number of sensor cells within these four socket areas, the maximum "average" pressure experienced and the maximum pressure experienced by an individual cell within each area.

This patient demonstrated peak pressures (>100 kPa) just after mid-stance. For example, at the patellar bar a group of 12 sensor cells recorded a maximum average pressure of 244 kPa with an individual sensor cell recording a maximum of 417 kPa. Peak pressures (>100 kPa may be considered potentially dangerous.

Conclusions

This study highlights the capability of FSR to display stump/socket interface pressure distributions during gait. Useful pressure data may be recorded if a strict calibration procedure and test protocol is adopted.

The presentation of pressure data in this paper has been restricted to only one subject fitted with a PTB socket. A future paper will compare the pressure distribution contained in this paper with the same subject fitted with a hydrocast socket.

Table 1. Socket pressures in excess of 100 kPa.

Legend	No. of sensor cells within area	Maximum "average" pressure of all cells within area (kPa)	Maximum pressure of single cell within area (kPa)
Patellar bar (PTB)	12	244	417
Proximal popliteal (PP)	8	128	168
Posterior medial flare (PMF)	10	119	132
Fibular head (FH)	9	103	114

Recommendations

Tekscan have improved their software system such that all four sensors may be recorded simultaneously. A series of different pressure studies may be undertaken using the improved system in the future.

A greater number of subjects must be investigated to confirm the effectiveness of different socket designs. The effect of alignment modifications on stump/socket interface pressure may be re-investigated now that the total pressure distribution within the socket may be studied rather than at "selected" localised sites. The long term variation of socket pressure distributions may be studied in conjunction with intermittently monitored patient stump volumes.

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