Calibration problems encountered while monitoring stump/socket interface pressures with force sensing resistors: techniques adopted to minimise inaccuracies

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Abstract

Force sensing resistors (FSR) have been used to measure dynamic pressures at the interface between appliance and patient. Inaccuracies using FSRs have been reported. This paper summarises both the calibration problems encountered and the techniques adopted to minimise inaccuracies.

It is considered that, by calibrating the transducers attached to the socket, and by adopting a strict test protocol, FSRs may provide a guide to the dynamic pressure distribution applied to the trans-tibial stump during gait.

Introduction

The mylar/resistive ink (9810) F-socket transducer, developed by TEKSCAN Inc. in Boston, was selected for this study. The 0.017mm thick transducer incorporates 96 individual cells, displayed in an array of 16 rows and 6 columns, covering a total sensing area of 15,500 mm^2. It is illustrated in Figure 1. This sensor was considered to be suitable for monitoring the pressure distribution during gait, between the stump tissue of a trans-tibial amputee and the prosthetic socket.

The FSR transducer detects forces applied to a cell. Pressure is force/area, and the output signal from an array of FSRs uses a common cell area to estimate the pressure of an individual cell in an array. The "threshold" load, which triggers the initial cell output, varies between the 96 FSR cells. A Tekscan equilibrium software programme balances the cell outputs at at given instant. The sensor has a maximum range of 520kPa. A 486 PC, with a 4Mb RAM, enables 750 frames to be recorded at a maximum sample rate of 165Hz. A colour coded graphic display provides an excellent illustration of pressure gradients

The advantages of the Tekscan sensor are thickness, size, sensitivity, resolution and frequency response. The disadvantages are hysteresis, drift and temperature sensitivity (Cavanagh *et al*, 1992; Cobb and Claremont, 1995; Ferguson-Pell and Cardi, 1992; Sanders, 1995; Schaff, 1993). FSR insoles have been investigated by a number of researches (Brown *et al.*, 1996; Hayda *et al*, 1994, Rose *et al*, 1992; McPoil *et al*, 1995; Woodburn and Helliwell, 1996; Young, 1993) with doubts

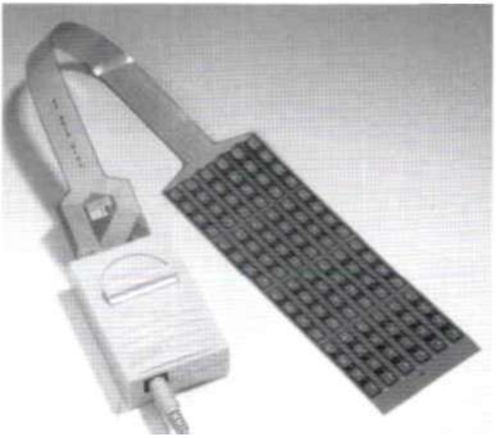

Fig 1. TEKSCAN 9810 transducer.

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being cast on the repeatability and accuracy of FSRs. This may be influenced by both the flexibility of shoes and the compliance of the material supporting the FSR insole.

Test method

Compressive loads were applied to individual cells of the sensor, using a dynamic Instron compressive testing machine. Signal drift was investigated by applying a constant compressive load and measuring the output signal over a period of time. Flat, cylindrical and spherical matching contact surfaces were studied. Incremental compressive loads were applied to monitor the response of the FSR to the applied load. Each loading cycle lasted 10 seconds, followed immediately by 10 seconds unloaded. Individual cells were subjected to a cyclic load to investigate whether the dynamic response of the sensor output matched that of the applied load. A constant triangular wave load input was applied at various frequencies. The difference in the loading and unloading characteristics displayed the hysteresis characteristics. Cyclic drift was also studied.

A pressure rig was developed, so that all 96 sensors could be simultaneously loaded and calibrated. Figure 2 illustrates the design of a two part pressure rig. The sensor was placed on the top surface of the base plate. The small chamber, in the top plate, was pressurised with air. A 0.02mm thick mylar membrane was attached to the undersurface of the top plate and used as the loading medium. Air was introduced to the upper chamber at eight locations to ensure uniformity of loading.

The complete pressure system consists of an accurately calibrated pressure regulator connected to a valve system and hence to the upper chamber of the pressure rig. The valve system incorporates two micro valves controlled by a solenoid, which is activated by a wave input generator. The wave generator frequency controls the rate of cyclic pressure. The accuracy of the pressure rig was verified using a strain gauge pressure transducer, positioned in the air supply to the upper chamber. Alternative strain gauge transducers were positioned at the centre and edges of the pressure chamber base. These strain gauge transducers exhibited a linear calibration, with very little hysteresis. Subsequently, the air supply pressure was compared to pressure applied to the FSR and also to the pressure between the FSR and the pressure rig base. This study concentrated on the 0 - 200kPa range, which was linear for all transducers.

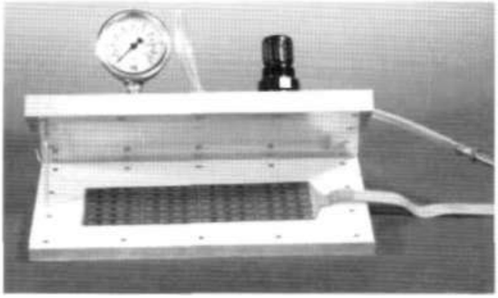


Fig. 2. Pressure rig.

The following calibration procedure was adopted with the pressure rig. After 10 seconds of lOOkPa static pressure, the output of all 96 cells was balanced using the equilibrium software programme. A cyclic pressure of lOOkPa was applied at 0.5Hz, for a period of 60 seconds. (This is equivalent to 30 steps during gait). After a further 5 seconds of lOOkPa static pressure, the FSR was calibrated at lOOkPa. Having calibrated the FSR output at lOOkPa, the sensor output was checked at pressure levels of 50, 75, 100, 125, 150, 200 and lOOkPa.

Results

When subjected to compression tests, each individual cell has its own unique output. Maximum inter-cell variation is of the order of mean output ± 50%. At a selected applied pressure and instant, the use of the equilibrium software programme eliminates this variation.

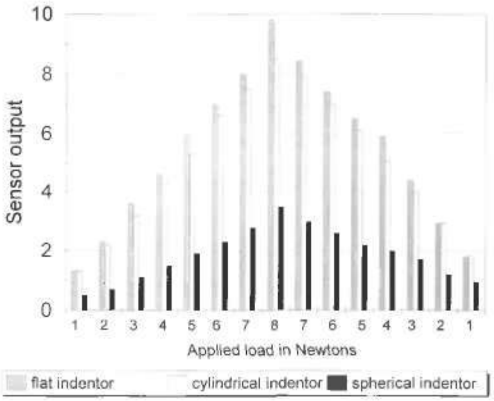


Fig. 3. Incremental loads - curvature effects.

A study of the effect of maintaining a constant load indicated an increase of sensor output with time, which can be classified as drift. Tekscan literature quotes a static drift of 5% after 10 seconds, with additional *5%* increases at 10^2 and 10^3 seconds respectively. The response of the FSR to incremental loads was not satisfactory. The output of a typical cell demonstrated both a lack of repeatability and a difference between loading and unloading. Figure 3 illustrates that, when subjected to incremental loads up to 8N, cylindrical contact surfaces demonstrate these effects marginally. However, spherical or 3 dimensional curvatures will produce significant reductions in the output results.

Cyclic tests on the Instron testing machine indicated a good dynamic response between the applied load and the FSR output. Output stability was demonstrated after approximately 10 cycles. Figure 4 illustrates the FSR output for an individual cell, subjected to a triangular load wave of 1 to 8N at 1.0Hz for 20 loading cycles. Hysteresis varied with respect to the load range and frequency. The greater the load range the greater the hysteresis. A greater cyclic drift was noted at lower frequencies of 0.1 and 0.5Hz.

During pressure rig tests, good correlation was obtained between the strain gauge transducers located at the inlet, and at the centre and edges of the pressure chamber. A single Tekscan cell, positioned at random locations within the pressure chamber, indicated a consistent FSR output. Following a calibration at lOOkPa, Table 1 lists the average Tekscan pressure output of 96 cells for a series of known applied pressures.

Relative to the calibration, the two subsequent studies at lOOkPa indicate an average variation of ± 2%, with a maximum variation of ± 10% for any individual cell within the array. During cyclic tests, good correlation was noted between the calibrated FSR output and the strain gauge transducer output.

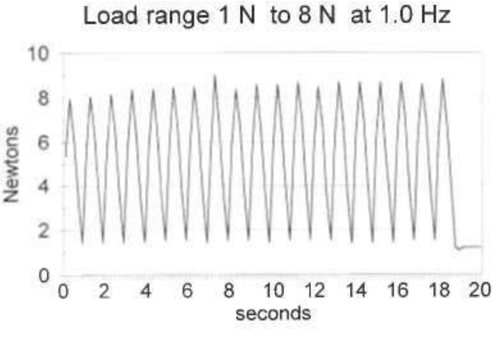
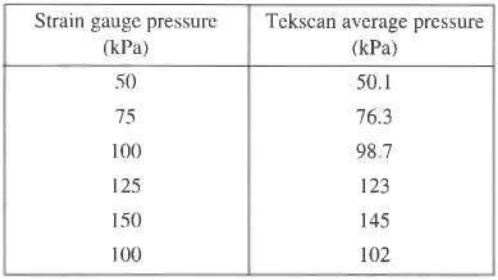


Fig 4 Cyclic drift

Table 1.



Strain gauge pressure (kPa)	Tekscan average pressure (kPa)
50	50.1
75	76.3
100	98.7
125	123
150	145
100	102

Discussion

The Tekscan equilibrium software programme ensures that, for a selected pressure, all 96 cells have the same common output. However, this common output is only valid for that selected pressure and at that particular instant.

In order to calibrate the FSR, the software programme requests the input of an applied load. An iterative method is necessary. The following procedure may be adopted. As a first approximation, multiply the total sensing area of 15,500 mm^2 by the known applied pressure. For example, if the known applied pressure is lOOkPa, a load of 1550N is applied. If after 60 seconds of lOOkPa cyclic pressure, the FSR sensor registers an average pressure of 90kPa, the assumed load of 1550N must be amended. This 10% "error" can be corrected by increasing the requested input load by 10%, i.e. to a value of 1705N, rather than the initial 1550N.

Random checks on a number of Tekscan 9810 sensors revealed that, occasionally, an individual cell in the sensor array may be "defective". Data from this "defective" cell must be ignored in subsequent studies.

Future clinical investigations will assess prosthetic socket fit and different casting techniques. Tekscan FSRs will be used to monitor the stump socket interface pressures. These FSRs are very thin and ideal for positioning at the interface between stump and socket. The Tekscan specification quotes an output data change of 1% per °F. Temperature investigations suggest that there is not a significant temperature variation within a prosthetic socket, during a 10 to 15 minute gait study period.

The 3-dimensional curvatures within a prosthetic socket may introduce significant inaccuracies in FSR output data. This problem can be reduced by bonding the FSRs to the inner wall of a rigid socket and calibrating the sensors *in situ. A* gel filled "condom" is fitted in the socket, the brim of which is sealed, and the gel is pressurised to a pre-determined level. The sensors, when equilibrated and calibrated, demonstrate consistent pressures irrespective of socket curvature. This technique provides repeatable results for a total of approximately 350 cells fitted at pre-selected locations on the inner socket wall.

During socket assessments the amputee must become accustomed to the prescribed prosthesis. This involves walking for a period of time prior to recording data. The pressure sensors if fitted, will also be cyclically loaded during this period. Thus, immediately prior to calibration, the sensors are subjected to a cyclic load for the equivalent of 30 steps.

The amputee's stump tissue characteristics are not uniform. Hence, during load bearing the stump tissue loading rate may vary at different socket locations. The susceptibility of FSRs to loading rate may introduce inaccuracies.

Conclusions

The inaccuracies of FSRs must be recognised, so that the limits of their application may be identified. By selective applications and by adopting strict test protocols, it may be possible to minimise inaccuracies to such a level that a satisfactory impression of the overall pressure distribution may be recorded. However, it must be recognised that the actual pressure levels recorded are not absolute. Sensitivity to loading rates and hysteresis are two problems which still exist. In the future, development of computer software packages may minimize these effects.

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