PROSTHETIC SOCKET INTERFACE PRESSURES: CUSTOMIZED CALIBRATION TECHNIQUE FOR THE TEKSCAN F-SOCKET SYSTEM.

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INTRODUCTION:

Pressures between the residual limb and the prosthetic socket for below knee amputees (BKA) are speculated to play a critical role in socket fit and comfort, as well as residual limb tissue condition. Appropriate pressure measurement systems to quantify these interface socket pressure distributions during static and dynamic loading are limited [1]. The F-socket system (Tekscan Inc.,South Boston, MA, USA) was used to evaluate dynamic pressure distribution in different socket types for a below knee amputee [2]. Each sensor is comprised of two thin, flexible polyester sheets deposited with patterns of conductive electrodes comprising individual cells. Sensor calibration defined the relation between applied force and current flow at each cell. Limitations of the sensors related to hysteresis, drift, and sensitivity to loading rates were reported [2]. Buis and Convery [2] reported a custom iterative calibration procedure to accommodate sensor accuracy errors of ±10 %. The purpose of this study was to evaluate the F-socket system, as part of a larger project investigating relations amongst BKA socket pressure, tissue sensation, comfort and gait characteristics during standing and locomotion. Errors associated with sensor drift, surface curvature, cell scatter and loading rate were assessed. A custom calibration procedure using the I-Scan software was developed, and associated improvements in sensor accuracy were assessed in comparison to the basic F-Scan procedure.

METHODS:

Tekscan F-socket sensors were used for this study. Each sensor consisted of 96 individual cells (16 rows by 6 columns) and measured 0.017 mm in thickness. The total sensing area covered 154.8 cm^2, providing a resolution of 0.62 cells per cm^2.

Sensor Drift:

Testing of sensor drift was evaluated with the F-Scan calibration and software program. The calibration procedure involved application of a static load for a given duration for sensor equilibration, followed by a measurement recording for calibration at an applied load. The resulting calibration curve was a linear interpolation through zero and the applied load. Two pre-load duration and load magnitude conditions were investigated: (i) pre-load and calibration load of 106 kPa, 60 s pre-loading; and (ii) pre-load and calibration load of 89 kPa, 120 s pre-loading. The accuracy of the calibration was assessed by applying the static calibration load to 16 cells of the sensor (4 by 4 cell area). Three repeat trials were obtained for each condition. For the first condition, the output of the sensor was observed over time, by unloading the sensor region, initiating the measurement, and applying the load for 120 s. The average sensor output over the 16 cells was analyzed at 1, 5, 10, 20, 30, 60 and 120 s after load application. To evaluate the cell output over a longer duration of static loading, in the second condition the sensor region was pre-loaded at 89 kPa for 120 s, followed by a 60 s measurement. The average pressure recorded over the 16-cell region was analyzed at 120 and 180 s after load application. The variables of interest included: load magnitude, pre-load and load duration, timing of calibration measurement and sensor output.

Surface Curvature:

Accuracy of pressure recordings on a curved surface similar to the residual limb using a flat-surface calibration was evaluated. The residual limb was approximated as a cylindrical surface created with half of a cylindrical PVC pipe (ID = 6.7 cm). Both the flat and cylindrical surfaces were lined with a pelite material to simulate a typical prosthetic socket liner. For sensor calibration with the F-Scan procedure, following sensor equilibration, sensors were pre-loaded on a flat surface with 117 kPa for 120 s, followed by a calibration measurement. This calibration was applied to subsequent measurements on a 6-cell region (a 2 by 3 cell area) for both the flat and curved surfaces. Five repeat trials were obtained for both surface conditions. Vertical loads of 117 kPa and 115 kPA were applied to the cell regions for the flat and curved surfaces, respectively. As the sensors detect normal forces only, the force normal to each cell was then calculated as

$$F_{normal} = F_{applied} * \cos\theta \qquad \text{for } \theta = \frac{S}{R}$$

where θ is the angle between the vertical force applied and the vector normal to the midpoint of the cell, S is the distance along the circumference of the cylindrical surface, and R is the radius of the cylinder.

Cell Scatter:

An equilibration procedure is recommended by Tekscan to minimize the variation in individual cell output within a given sensor. The equilibration procedure involves applying a uniform load with a flat pressure bladder over the entire 96-cell sensor. Cell scatter was evaluated with 4 combinations of two equilibration conditions (without and with), and two load conditions (200 kPa, 300 kPa). One trial was recorded at each combination. For conditions with equilibration, the sensor was equilibrated at 200 kPa. Variables held constant across conditions include: (a) sensor calibration at 200 kPa, (b) 120 s preload for calibration, and (c) sensor evaluation at 120 s after load application. Cell scatter was assessed by analyzing the maximal and minimal pressures recorded by any individual cell, and the standard deviation in the output among the 96 cells at the point of evaluation.

Custom Calibration:

To improve sensor accuracy, a custom calibration procedure was developed utilizing the I-Scan software with an Instron testing machine (Model 1122, Instron Corporation, Canton, MA, USA), and custom double plates for providing a uniform load distribution during sensor equilibration. The applied load was accurately recorded using LabVIEW software (National Instruments Corp., Austin, TX, USA). Sensors were conditioned with cyclic loading for 30 cycles prior to calibration. Peak socket pressures during locomotion of 250 kPa were estimated [2]. A 9 point equilibration enabled by the I-Scan software was performed every 25 kPa, over a range of 25 kPa to 225 kPa. The sensors were calibrated using two points that corresponded to 20% and 80% of the maximal load. For static trial calibration variables were selected to mimic the experimental BKA standing trials of 120s duration. The sensor pre-load was 45 kPa (60s). Calibration was performed at 2 loads: 45 kPa for 60s, and 180 kPa for 70s. For dynamic calibration, the sensors were loaded cyclically at 0.75Hz rate with a maximum and minimum loads of 200kPa and 50kPa for 7 cycles, based on the experimental pre-loading protocol for the prosthetic limb with sensors in place prior to each walking trial.

Sensor accuracy was assessed at specific sites, by dividing the sensor into 8 regions of 12 cells each (3 by 4 cell area). The average pressure recorded in each region was compared to the applied load.

Pilot gait studies of study participants indicated loading rates ranging from 0.70 to 1.00 Hz. The influence of loading rate on sensor accuracy was assessed by loading sensors at rates ranging between 0.64 Hz to 1.00 Hz. For each loading rate, maximum (206±4kPa) and minimum (49±2kPa) loads were applied over entire sensor and compared to the maximum and minimum pressure recorded.

The accuracy of results obtained using the I-Scan software were compared with those obtained using the F-Scan software with sensors calibrated using three different methods. First, was the same dynamic calibration using I-Scan as described above. Second, using the F-Scan software the sensors were equilibrated at 103 kPa and the dynamic calibration (same as for I-Scan) was performed (F-Scan 1). Third, using the F-Scan software the sensors were again equilibrated at 103 kPa and static calibration at 200 kPa (F-Scan 2). Three dynamic trials were recorded where the load cycled between 203 kPa and 50 kPa at a rate of 0.76 Hz. Each trial was then processed using each of the three calibrations and the average pressures were compared to known applied loads.

RESULTS:

The sensor output showed that, at the 60 s point, the average pressure recorded underestimated the applied pressure by 8.5%, and, at 180 s, overestimated the applied pressure by 5.6% (Table 1).

	Seconds after load applied	*Trial 1 (kPa)*	*Trial 2 (kPa)*	*Trial 3 (kPa)*	*Avg (kPa)*	*Std. Dev (kPa)*
Condition 1:	1	39	33	45	39	6
	5	63	68	73	68	5
	10	81	78	84	81	3
	20	92	86	91	90	3
	30	96	89	93	93	4
	60	101	94	97	97	4
	120	106	98	100	101	4
Condition 2:	120	92	95	90	92	3
	180	93	97	91	94	3

Table 1. Sensor drift up to and after 120s of loading.

The sensor output was overestimated by 8% for both flat and curved surfaces.

The equilibrations procedure was effective in reducing inter-cell variation. The standard deviation in individual cell output decreased from 22 kPa to 6 kPa after the sensor was equilibrated at 200 kPa load, and the same was observed at the 300 kPa load when the standard deviation in individual cell output dropped from 34 kPa to 13 kPa.

The I-Scan software with a 9-point equilibration and 2-point calibration resulted in more accurate pressure recordings. Among the 8 areas examined, pressures were underestimated and overestimated by a maximum of 10.9% and 1.1% respectively. The error was greatest at the 52-kPa load (10.9%), while at the 152-kPa recorded pressure differed from the applied load by only 2.4%. The maximal errors at the 201 kPa and 73 kPa loads were 4.8% and 6.4 % respectively.

Results were most accurate when the loading rate matched the loading rate of 0.76 Hz used in the calibration (Table 2).

Trial	Loading Rate (Hz)	Max Applied (kPa)	Max Recorded (kPa)	% Error	Min Applied (kPa)	Min Recorded (kPa)	% Error
1	0.64	199	211	6.0	52	58	11.5
2	0.68	200	210	5.0	52	57	9.6
3	0.72	202	211	4.5	51	57	11.8
4	0.76	203	201	-1.0	50	49	-2.0
5	0.80	204	214	4.9	50	54	8.0
6	0.84	206	217	5.3	49	53	8.2
7	0.88	207	216	4.4	49	52	6.1
8	0.91	209	219	4.8	48	50	4.2
9	0.93	210	223	6.2	48	52	8.3
10	0.97	211	226	7.1	47	51	8.5
11	1.00	212	229	8.0	46	50	8.7

Table 2. Effect of loading rate on sensor output

Using the I-Scan calibration, pressures recorded at 203 kPa and 50 kPa were within 2% of the applied loads. With the F-Scan 1 calibration, pressures were overestimated by 64 to 116%. The F-Scan 2 calibration produced pressures that were underestimated by 18% at the higher load, and overestimated by 8% at the lower load.

CONCLUSION:

The customized calibration procedure developed for the current study has several benefits over previously used methods. The use of the I-Scan software enabled pre-recorded trials to be used to create calibration curves for each sensor. This minimized the effects of sensor drift, which occurs when a static load is applied to the sensor. The calibration procedure developed for this study did not require an iterative method to compensate for underestimated pressure recordings, as described by previous researchers. It was shown that by using the customized calibration procedure presented here, pressures measured over the range of 50 – 200 kPa should be accurate within 10 kPa (10.9%) of the applied loads. This calibration procedure appears to be necessary if accurate pressure results are required.

REFERENCES:

1. Sanders, J. E., 1995, “Interface mechanics in external prosthetics: review of interface stress measurement techniques,” Med & Biol Eng & Comput, Vol. 33, pp. 509-516.
2. Buis, A. W. P., Convery, P., 1997, “Calibration problems encountered while monitoring stump/socket interface pressures with force sensing resistors: techniques adopted to minimise inaccuracies,” Prosthet Orthot Int, Vol. 21, pp. 179-82.

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