TEKSCAN PRESSURE SENSOR EQUILLIBRATION AND CONDITIONING

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Abstract: An equilibration and calibration approach of the Tekscan sensor system is presented. The response of individual sensels from two 5315 Tekscan sensors for quasi-static and repeated constant loading was investigated with the use of two methods, namely the "Bladder Method" and the "Pin Method". In the first method, uniform pressure was applied by a bladder-equilibrator, whereas in the second loads were applied in a sensel-by-sensel fashion by means of a pin attached to a frame installed on a material testing machine. It was found that the "Bladder Method" provided with a poorer match between the applied load and the pressure output than the "Pin Method". When test conditions resulted in some of the sensels being saturating due to high pressure, the loss of load data from the sensor mat can be estimated using the sensel output.

Introduction

Validation of new design concepts involving contact stress distributions between two adjacent surfaces requires measuring of the interface pressure. Typical applications include human-machine interfaces and orthopaedic Orthotic and Prosthetic devices. Also, in natural joints, characterization of contact stress distributions is very important for understanding the underlying mechanisms of degenerative joint diseases, such as osteoarthritis. Reduction of long-term failure, static and dynamic load limitations as well as evaluation of design improvements require accurate and precise pressure measurement devices. Such devices should be flexible and appropriately thin so that the natural positioning of the sensor and congruency of the contacting members to be optimized. Since many human machine interfaces (e.g., wheelchair seating systems, driver's seats, etc.), furniture (bed mattresses, chairs etc.) and human joints are incongruent, the sensor should operate in a wide range (contact stresses can range from a few Pa for localized buttocks pressure in supine bed-rest to 50 MPa for localized contact in prosthetic joints). In addition, the sensor should demonstrate high spatial resolution and be able to accurately and repeatedly measure both static and dynamic loads.

Many pressure sensors and techniques exist in the assessment of human-machine interface and intra-articular contact stress distributions. However, the pressure assessment appears problematic and appropriate sensors are yet to be developed. Some systems include casting techniques [1], dye exclusion [2], roentgenograms [3] and various mathematical models [4,5]. Alternative techniques, implementing transducers inserted retrograde though holes drilled in subchondral bone, do not interfere with joint congruity in the manner of diaphragmatic fluid pressure transducers but are still difficult to install and require access from the back-side of the contact surface [6]. Ahmed et al. [7] was one of the first researchers to develop flexible viscoelastic pressure sheets, which however presented extensive calibration problems that eventually limited their use. Larger pressure sensor mats have also been implemented in various ergonomic applications, such as the assessment of human-machine interface pressure during the performance of certain tasks, e.g. driving, prolonged seating in wheelchairs etc. [8]. Fuji processor film and Tekscan sensors have become the standard modality for intra-articular contact stress but both present certain limitations. The former applies only to static loading, while the latter is handicapped by drift of sensor output after an applied load.

Multiplexed array piezoresistive sensor systems, such as the Tekscan sensors (Tekscan Inc., Boston, MA) were first introduced in 1987 and have been used to record the pressure distribution within an area of contact between two bodies. Sensor mats have found numerous applications in biomechanics, rehabilitation [1], industry [2], etc. Applications include sensors measuring forces during mouth occlusion, assessment of stress under the foot during gait (F-scan) and joint-specific pressure sensors, such as the knee sensor (K-scan). In addition to the drift of sensor output after prolonged load application, there is no standard protocol provided by the manufacturer for the characterization of the sensor accuracy and repeatability for both static and dynamic response.

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Tekscan pressure sensors are comprised of two thin, flexible sheets (mats) that carry pressure-sensitive ink applied in rows and columns between them. The intersections of rows and columns form small area sensing elements which are called sensels. Each sensel is a “load-type” cell, meaning that the sensels should not be considered as being actual load cells. Rather a response of a sensor and the total force it carries can be obtained through a “calibration” process. It has been reported that the performance of the sensors was altered when the measuring conditions were different than the calibration condition [9]. “Equilibration” is another important aspect of sensor conditioning that refers to the minimization of the inherent output variations between individual sensels in a sensor.

The above class of sensors performs almost ideally in the assessment of platen/indentor static forces under well controlled loading conditions. In such cases, accuracy has been reported to vary from 2% to 10% [10]. In more realistic conditions, in which forces are applied below the thresholds used for calibration, quasi-static sensor drift has been reported to affect significantly the accuracy [11]. Errors can exceed 50% margins if loading is applied statically for more than two hours [12]. However, the dynamic response has not been extensively investigated. Pavlovic et al. [11] reported that a sensor is more accurate during loading than unloading. After studying several loading protocols, Pavlovic et al. concluded that the sensor underestimated the actual load by an average of 22 % during predefined ramp loading.

The topology of the output drift can be characterized locally at the individual sensing sites within the arrays. This is a very important step in all studies involving large pressure arrays and prolonged dynamic assessment of pressure.

When the calibration and equilibration procedures use platen/indentor loading configurations, the results depend on heavily inhomogeneous contact stresses. This fact handicaps the accuracy of these studies in assessing total force. In orthopaedic applications, and particularly in ergonomic applications that involve large size sensor arrays, assessment of the response at the local sensing level may prove more appropriate.

In this study, we present two methods for sensor equilibration and conditioning, namely the “Bladder Method” and the “Pin Method”. To overcome platen/indentor limitations, a custom-made testing frame was developed for the “Pin Method” allowing for homogeneous contact–force application. The methods were tested and evaluated on two sensor mats.

Materials and Methods

Two sensor mats (Tekscan model 5315) were used in the present study (Fig. 1), denoted as “C” and “E”. The multiplexed-array piezo-resistive contact stress sensor comprises of one element containing several columns and rows of conducting strips photo-etched onto a separate layer of green Mylar. Piezo-resistive ink is contained between the rows and columns. The crossing and overlap of a column and a row (Fig. 1(b)) defines a sensel with 1.61 mm^2 resolution (1.27 mm × 1.27 mm in size). The thickness of each element is approximately 0.10 mm. The Tekscan mat 5315 sensor (487 × 427 mm^2, 1 sensel/cm^2) has operating range up to 30 PSI.

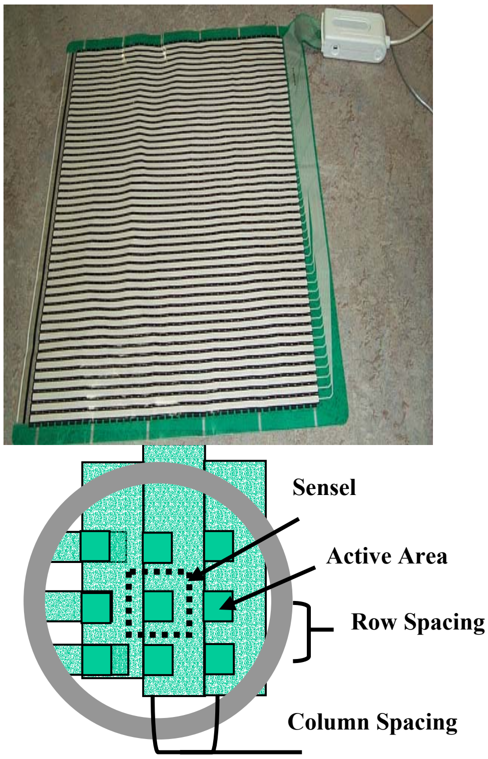

Fig. 1: Large size TECSCAN pressure sensor mat along with a close-up drawing of the sensel configuration.

Tekscan provides a turnkey solution with data conditioning and software (I-Scan software) to control real-time data collection and display. A series of experiments was performed to describe the range of typical load magnitudes that correspond to each sensor type during normal activity (imitating seating loads at the buttocks or maximum loads during prolonged bedrest with movement). The experiment included static, non-static and cyclical loads up to 30 MPa and loading periods up to 1 hour. The experiments were designed to simulate real sensor application during typical biomechanics or ergonomics conditions, such as loading the sensor soon after or long after the calibration procedure.

Prior to each characterization procedure the manufacturer’s static calibration was performed. In this process, each sensor was subjected to contact stress levels of 20% and 80% of the maximum anticipated during actual service, with an auto calibration procedure applied thereafter. The sensel contact stress distributions were saved in ASCII format and were post-processed. The mean of all the sensel recordings was then determined and was used as a single contact stress value that could be compared to the actual stress being applied to the sensor. Inter-sensel standard deviation was also computed.

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The I-Scan software allows the user to “calibrate” the sensor. Two options are available: a) linear or one point calibration (zero is the second point assumed for the linear calibration), and b) power law or two-point calibration. For both calibration methods the software creates a calibration file containing the points (one or two points) used for calibration and the coefficients of the calibration curves. It should be noted that one and only one calibration curve is obtained and is applied to the individual output of every sensel of the sensor. The calibration curve is an average in a statistical sense since it refers to the average pressure (total load over the total area of contact of the sensor). This is the reason why the sensels were previously characterized as “load cell type” and not as actual load cells. The use of a single calibration curve for all sensels introduces some uncertainty/inaccuracy on the pressure output between individual sensels. However, this variation between the outputs of individual sensels is assumed to be rather small since the calibration constants are obtained from equilibrated data.

The two-point power law calibration is used in the present study because the sensor exhibits nonlinear behavior. The 2-point power law calibration assumes a function as appears in Equation 1:

$$y = a \cdot x^b , \qquad (1)$$

where a and b are calibration coefficients, x is the raw output of the sensor or the sensel (equilibrated raw output) and y is the pressure in units of PSI.

Equilibration was accomplished by applying a uniform pressure level over all sensels. An equilibration matrix was generated containing correction factors that, when multiplied by the actual output of a sensel, they force it to be the same with the output of another sensel under the same pressure. Those matrices are generated for a number of pressure levels so as to span the pressure range of the sensor.

Two equilibration methods were used. The first was the “Bladder Method” in which uniform pressure was applied by a bladder-equilibrator (Fig. 2(a)). An Omega PX236 0-100 PSI capacity pressure transducer was used to record the pressure in the equilibrator. Sensor equilibration was completed using 3-PSI increments for 10 equilibration levels, ranging from 1 to 27 PSI for all sensors.

The “Pin Method” was performed as a different load application scenario in order to test large size mats that the bladder configuration could not fit or where equilibrium produces too many “uneven” spots in the pressure distribution. In the “Pin Method” loads were applied in a sensel-by-sensel fashion by means of a pin (area 0.8 cm^2) attached to a custom-made properly-designed aligning frame. The frame was installed on a materials testing machine (Instron 8871). The testing machine equipped with the application frame and the load pin is shown in Fig. 2 (b). This method overcomes the averaging issue since each sensel is calibrated individually by a point by point application system. The concept is that a waveform is produced by the test rig with a threshold for maximum force that approximates the maximum pressure measurement range of the sensor. When force is the thresholding criterion for the periodic function of the rig, resolution between the rig motion and the pressure sensor maximum loading threshold must be carefully matched so that the sensor is not damaged.

A series of tests were performed with a wide range of thresholds and an example is presented here. The pin-like load was applied to at least 30% of the sensels (i.e., 1100 individual sensels) of each sensor in a standardized way. Sensor equilibration using the “Pin Method” was performed using 1-PSI increments for 10 equilibration levels.

In a third cluster of experiments, drift characterization was also performed by two separate long-term drift protocols. The first was the “quasi-static loading” and the second was the “continuous loading”. Both sets of characterizations were performed with incremental loading ramps (i.e. at 5, 10, 15, and 20 MPa), in each case for a total experimental period of 1 hour.

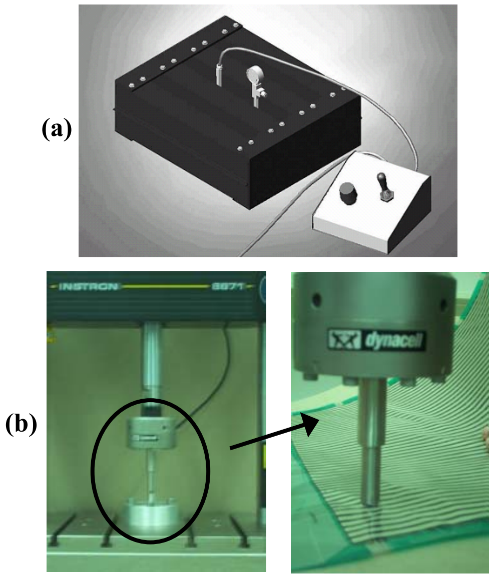

Fig. 2: (a) Calibration bladder from TEKSCAN, and (b) the pin force application mechanism and its application on a pressure sensor mat sensel.

Results

The time history of the bladder pressure as was recorded during the equilibration process of sensor “E” is shown in Fig. 3. Fig. (4a) depicts the calibration points (red points only) and the calibration curve fitted through these points. The two blue points, which corresponded to the pressure levels of 24.15 PSI and 27.47 PSI, were not included in the calibration because of the large number of saturated sensels present. The maximum pressure that sensor “E” can record before saturation is approximately 27.5 PSI. Fig. 4(b) shows the calibration points (red points only) and the calibration curve fitted through these points for the sensor “C”. The two blue points, which correspond to

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pressure levels of 23.03 PSI and 28.58 PSI, were not included in the calibration because of the large number of saturated sensels present. The maximum pressure that sensor "C" can record before saturation is approximately 25 PSI.

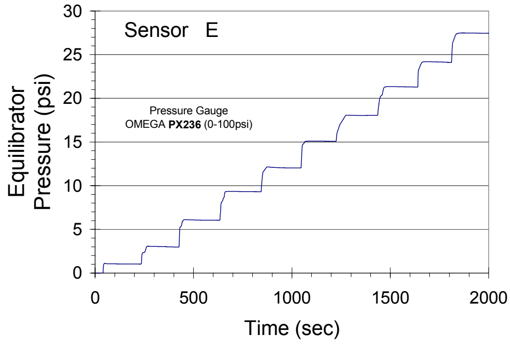

Fig. 3: The time history of the bladder pressure as was recorded during the equilibration process of sensor "E".

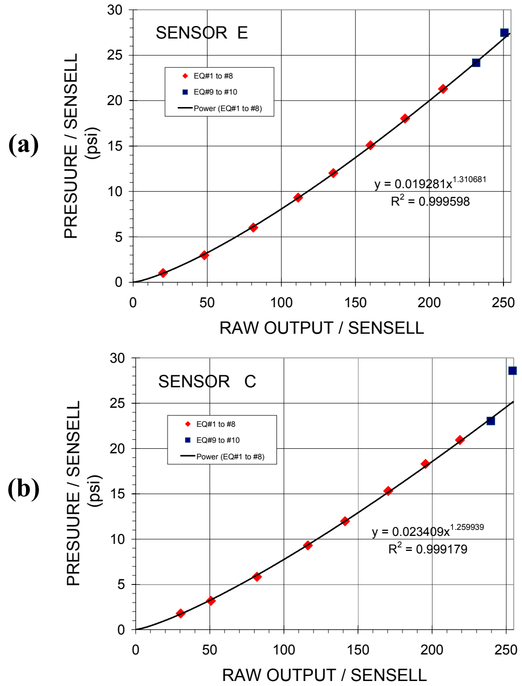

Fig. 4: Calibration curve for (a) Sensor "E" (above) and (b) sensor "C".

Repeatability of a sensor is the sensor's ability to respond similarly to the same stimulus and under the same conditions. The repeatability of the sensor was evaluated at two levels first at the sensel level and second at the sensor level. The repeatability of individual sensels is depicted in Fig. 5. Sensor "E" was placed in the equilibrator bladder and was loaded with a pressure time history as shown by the blue line (6 repetitions of ~4 PSI held for ~100 s and 0 PSI for ~600 s, and 6 repetitions of ~20 PSI held for ~100 s and 0 PSI for ~600 s). The recorded data for two individual sensels (SENSEL#1: row=10 & col=20, SENSEL#2: row=41 & col=46) are shown in Fig. 5 in pink. It

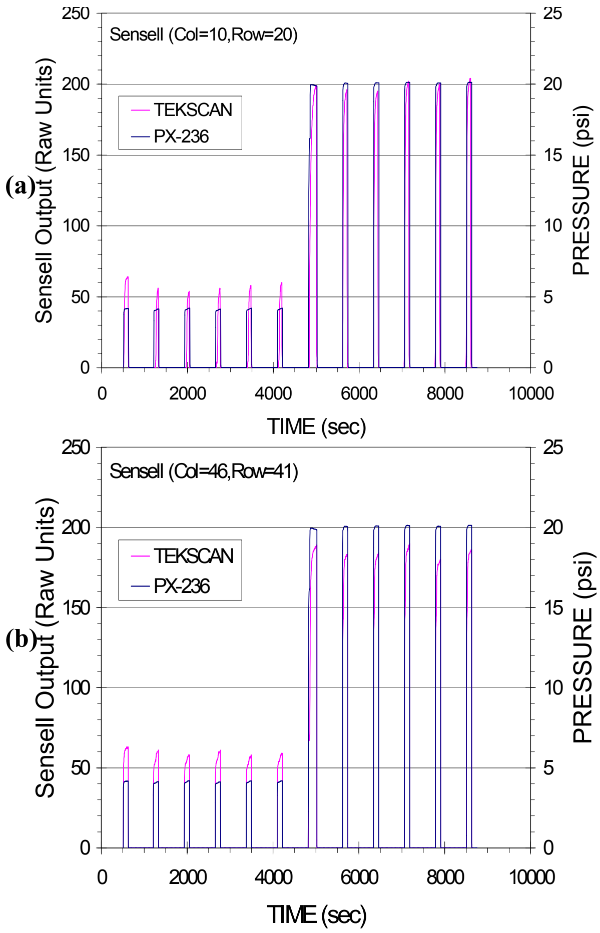

Fig. 5: Individual sensel response for repeated constant pressure loading.

should be noted that the recorded data were obtained without equilibrating the sensor. At the low pressure level ~4 PSI (the actual pressure level on each sensel is assumed to be the same) and for six successive loadings SENSEL #1 response varies between 54 and 64 raw output units and SENSEL #2 response varies between 58 and 63. At the high pressure level ~20 PSI (the actual pressure level on each sensel is assumed to be the same) and for six successive loadings SENSEL #1 response varies between 195 and 204 raw output units and SENSEL #2 response varies between 180 and 190. The variations of the response of each sensel are attributed to a) small differences of the pressure level (pressure amplitude) between successive repetitions of loading, and b) differences on the time the pressure is maintained (~100 s) on the sensor at every loading repetition (the sensel drifts) and c) possible non-uniform load. The large variations (± 10%) the sensels exhibit at low pressures are expected since there was limited control on the pressure amplitude and the time it was maintained on each sensel. The variations were much smaller (± 2.5%) for high pressure loadings. When comparing the response between different sensels, inherent (random) variability between individual sensels contributes to differences in the response in addition to (a) and (b) above, however this can be eliminated by equilibrating the sensor.

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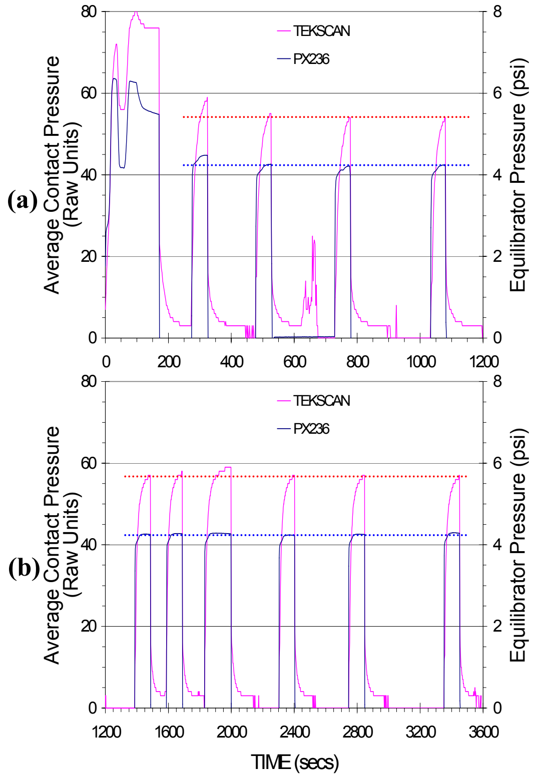

Fig. 6: Sensor "E" response to cyclic loading

Looking at the response of the sensor as a whole in the sensel by sensel (or small group of sensels) loading, Fig. 6 presents the sensor response in terms of the average contact pressure (when it is one sensel only one value is presented). The loading history of the sensor in Fig. 6 is depicted by the blue colour line and the sensor response by the magenta colour line. The dotted straight lines parallel to the time axis are introduced to aid with the evaluation of the response of the sensor. It can be seen at the top and bottom figures that the sensor response was repeatable when the pressure amplitude and duration of application were the same. However, when the duration of the loading changed (increased) the response of the sensor drifted.

Discussion and Conclusions

An equilibration and calibration approach of the Tekscan sensor system was developed and is in the process of being evaluated. The response of individual sensels (from 5315 Tekscan sensors) for quasi-static and repeated constant loading using the bladder equilibrator and the pin method were studied.

The bladder pressure, during the equilibration process, was set using manual controls. The lack of an automatic feedback control mechanism resulted in a slight drop of the bladder pressure between some steps. This can affect significantly the equilibration procedure. It was observed that the "Pin Method" provided with a better match between the applied load and the pressure output measured by the Tekscan. The "Pin Method", although more laborious, is a better method for equilibration and calibration of sensors, particularly when saturation is prevalent.

When test conditions resulted in some of the sensels being saturating due to high pressure, the loss of load data from the mat can be estimated using the sensel output.

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