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Short communication

Tekscan pressure sensor output changes in the presence of liquid exposure

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ABSTRACT

The purpose of the study was to evaluate the load output of a pressure sensor in the presence of liquid saturation in a controlled environment. We hypothesized that a calibrated pressure sensor would provide diminishing load outputs over time in controlled environments of both humidified air and while submerged in saline and the sensors would reach a steady state output once saturated. A consistent compressive load was repeatedly applied to pressure sensors over time (Model 4000, Tekscan, Inc., South Boston, MA) with a tensile testing machine (Instron ElectroPuls E10000, Norwood, MA). All sensors were initially calibrated in a dry environment and were tested in three groups: humid air, submerged in 0.9% saline solution, and dry. Linear regression of load output over time for the pressure sensors exposed to humidity and submerged showed a 4.6% and 4.7% decline in load output each hour for the initial 6 h, respectively ($\beta=-0.046$, 95% CI: $[-0.053$ to $-0.039]$; $p<0.001$) ($\beta=-0.047$, 95% CI: $[-0.053$ to -0.042; $p<0.001$). Tests after 72 h of exposure had linear regression decline in load output over time of 0.40% and 0.47% per hour for humidified and submerged sensors, respectively ($\beta=-0.004$, 95% CI: $[-0.006$ to $-0.003]$; $p<0.001$) ($\beta=-0.047$, 95% CI: $[-0.053$ to $-0.042]$; $p<0.001$). Because outcomes in biomedical research can affect clinical practices and treatments, the diminishing load output of the sensor in the presence of liquids should be accounted for. We recommend soaking sensors for more than 48 h prior to testing in a moist environment.

1. Introduction

Real-time pressure sensing film has become increasingly used to quantify contact area, pressure, and forces in biomedical studies (Becher et al., 2008; Elguizaoui et al., 2012; Flanigan et al., 2010; Hofer et al., 2012; Kock et al., 2008; Lee et al., 2006; Ode et al., 2012; Ostermeier et al., 2007; Prisk et al., 2010; Seo et al., 2009; Verlinden et al., 2010; von Lewinski et al., 2006). It is important to properly utilize this technology, as outcomes in biomedical research can affect clinical practice and patient care. This study reviews a new technique to properly utilize a pressure sensing film for use in moist environments, such as in cadaveric joints.

In a recent in-house study examining cadaveric tibiofemoral contact mechanics, loads were transmitted within the knee and measured with pressure sensors. The pressure sensors were implanted on the tibial plateau and underwent consistent and repeatable axial loading over 6 h. During testing, the sensors were exposed to fluids from the cadaveric specimens and sprayed with saline to prevent tissue desiccation. It was observed over time that the cumulative load output from the sensors was diminishing in the presence of the same load. Due to the open-cell material of the flexible sensors, the manufacturer states that they are susceptible to absorbing moisture which can alter the electrical output signal.

The purpose of this study was to evaluate the load output of a pressure sensor in controlled environments similar to those found in cadaveric testing. We hypothesized that the load output of a calibrated, non-vented pressure sensor would diminish over time when enclosed in humid air and when submerged in saline. These load outputs would reach a steady-state saturation limit and stabilize in a manner similar to testing in a dry environment.

2. Materials and methods

A test protocol was created to mimic the loading, timing, and environment for the aforementioned cadaveric knee testing. The pressure sensors were calibrated with a single point method mimicking our test setup, as recommended by the manufacturer's applications engineer for this test protocol (Model 4000, Tekscan, South Boston, MA). The calibrations were performed by ramping a compressive load for 12 s up to 450 N and maintaining this for 30 s. Compressive loads were applied to the sensors with a tensile testing machine in a custom jig designed with size and material mimicking human knee cartilage stiffness and thickness (ElectroPuls E10000, Instron Systems, Norwood, MA). Data was acquired using I-Scan 6.10 software (Tekscan, South Boston, MA) and analyzed with Microsoft Excel (Microsoft, Redmond, WA).

2.1. Control testing

A single sensor with two separate sencell tabs was used to test if the sensors would have a consistent output over time in a dry environment. Following storage

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and calibration in the dry lab environment, groups of five, single data points were taken by ramping the sensor for 12 s to a compressive load of 500 N and holding this for 30 s. A data point was collected and then the sensors were unloaded for 48 s prior to compressing the sensor for the next data point. This protocol was repeated every 45 min for nine iterations over the course of 6 h. Five data points were measured at 24, 48, and 72 h.

2.2. Submerged, humidified air, and saturation testing

Three sensors were each used to perform the submerged and humidified air saturation test, which followed the same protocol as the control sensor. Sensors were contained in a sealed, custom testing apparatus, with one sensor tab testing in the humid air above the surface of the 0.9% saline solution where the second tab was submerged (Fig. 1). The testing apparatus was covered with airtight plastic wrap to seal in the moisture and maintain humidity in the air. Following the 72 h data points, the sensors were immediately recalibrated and tested according to the 6 h protocol used for the control sensor. A temperature and humidity sensor was calibrated as per the manufacturer's guidelines with an accuracy of $\pm 3\%$ and used to measure the temperature and humidity of the air of the lab and in the jigs used (Model RH300 Digital Psychrometer, Extech Instruments, Nashua, NH).

2.3. Statistical analysis

Simple linear regressions were performed on the data points collected over the first 6 h of the various test conditions. This was performed to quantify the effect of saturation over time on the mean load output for each test. To compare individual load output means at 24, 48, and 72 h, a one-way ANOVA was performed and Tukey post-hoc comparisons were utilized. Statistical analysis was performed using SPSS Statistics, Version 20 (IBM Corporation, Armonk, NY).

3. Results

The load outputs relative to the initial load (mean $\pm$ standard deviation) are shown in Fig. 2. The linear regressions and statistical analysis are shown in Table 1. Following storage, calibration and testing in dry air, linear regression of the load output over time for the pressure sensors demonstrated no significant change in load output between tests ($p > 0.05$). For the sensors stored and calibrated in dry air and tested in humid air and submerged conditions, linear regression of load output over time demonstrated a 4.6% and 4.7% decline in load output each hour for 6 h, respectively. For the long-term testing (24, 48, and 72 h), we did not measure a significant difference in the load output after 48 h in either humid air or submerged conditions ($p > 0.05$). Following the 72 h of saturation and recalibration, the sensors in humid air and submerged conditions both demonstrated a 0.4% decline in load output each hour for 6 h ($p < 0.001$). Temperature and humidity in the lab air environment measured 22 °C and 9% relative humidity. The relative humidity in the humid air testing jig measured 99%.

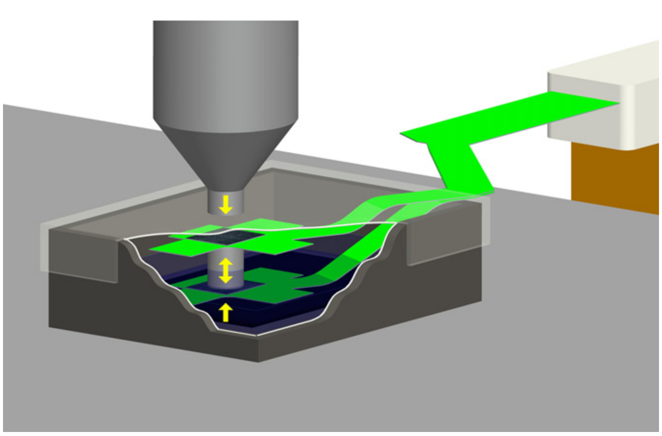

Fig. 1. Illustration demonstrating a cutout view of the test jig used in the testing machine with the sensors in the submerged and humid conditions. Saline solution filled the lower half of the basin in the jig and plastic wrap was used to seal in the air to allow humidity saturation in the top half of the jig. The arrows show the forces translated to the sensors.

4. Discussion

The results of this study confirmed our hypotheses that liquid saturation can diminish the load output of a pressure sensor over time and that testing in a controlled dry environment yielded consistent load output over time. Additionally, the humidified and submerged sensors reached a steady-state output once saturated, and the load output remained consistent when the sensors were recalibrated and retested following saturation. More than 90% of the decline in load was mitigated by the saturation procedure, which entailed sensor exposure to either a saline bath or humidified air for 48 h. Also, since no difference was detected between 48 and 72 h, we recommend submerging the sensors in water or saline for 48 h or more prior to calibrating the pressure sensors and testing them in a moist environment. Pre-saturation of the sensors will improve the accuracy of output recorded over time when testing in moist environments, as well as reduce the likelihood of needing post-hoc data corrections. These environments are found locally during cadaveric testing, when it is crucial to maintain a moist environment to prevent changes in tissue properties due to desiccation, which can occur within 90 min (Pham and Hull, 2007).

Several previously published studies which used pressure mapping sensors to report contact pressures in cadaveric models have reported modifications to the data, or a diminished load output over time. In a study by Prisk et al. 2010 similar pressure sensors from the same manufacturer were used to measure contact mechanics of the ankle joint. Deviation of the sensor load output was observed by the authors throughout testing and was immediately corrected by recalibrating the sensor when the load decreased from the calibrated output by more than 10%. Additional cadaveric studies have utilized Teflon tape to isolate the sensors from the surrounding environment (Ostermeier et al., 2007; von Lewinski et al., 2006). While this can prevent output drift by isolating the sensors from the external environment, it can potentially triple the thickness of the originally 0.1 mm thick pressure sensors. Contact mechanics are changed by insertion of tape to pressure sensing film with a thickness of 0.3 mm, which induces an increase in the contact pressure of 10–26%; therefore, modifications that increase the thickness should be avoided (Wu et al., 1998).

The authors recognize that there were limitations to our study. The manufacturer claims an error of up to 3.5% when used for repeated measurements. This error was minimized by calibrating the sensors in the jig used and using consistent loading and timing for each data point measurement. Load drift over time is inherent to the technology, so care was taken to acquire measurements precisely after 30 s of loading because drift of the sensor output changes only 0.05% when captured within ± 1 s. However, these are magnitudes below the accuracy of the sensor. Finally, we discovered our lab environment contains very dry air. If the humidity of other lab environments is higher, it is possible that the sensors will not take as long to reach steady-state saturation in the presence of moisture to reach a consistent load output; however, the phenomena still exists.

In conclusion, the load output of the pressure sensor will diminish over time in the presence of liquids following storage and calibration in a dry environment. We recommend soaking the pressure sensor in a liquid bath for at least 48 h prior to testing in cadaveric specimens. In the event that the pressure output is diminishing over time because the sensor was calibrated in a dry, controlled environment, and then tested in the presence of liquid or a humid environment, normalizing the data to account for these changes is recommended.

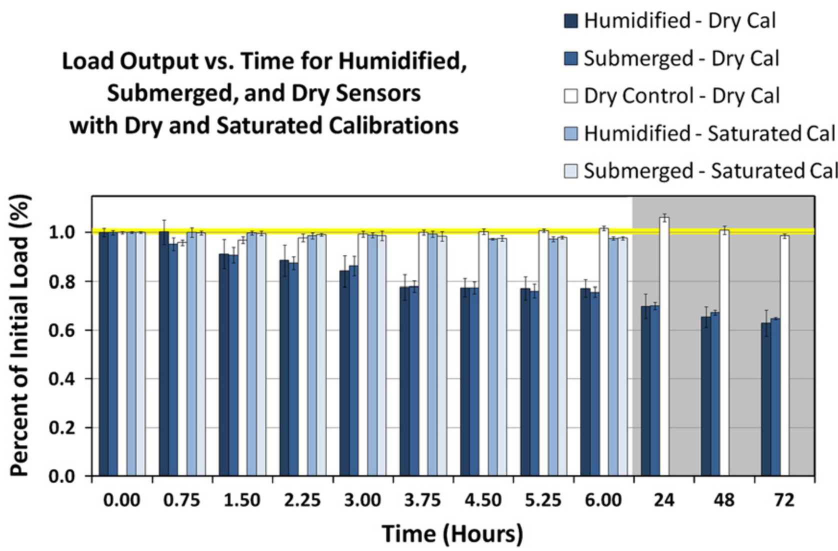

Fig. 2. Load output versus time relative to each condition tested. Mean averages and standard deviations as a percentage of the initial load is reported. The saturated calibration points were data collected upon recalibrating the sensors after 72 h and running the original test protocol again. (Cal=Calibration).

Table 1
Statistical analysis of the linear regressions performed relative to each condition tested for pressure sensors calibrated dry and saturated (cal=calibration, LB=lower bound, UB=upper bound).

Condition	Coefficient	95% CI LB	95% CI UB	Significance (P-value)
Humid–dry cal	−0.046	−0.053	−0.039	<0.001
Submerged–dry cal	−0.047	−0.053	−0.042	<0.001
Dry control–dry cal	0.000	−0.004	0.005	0.936
Humid–saturated cal	−0.004	−0.006	−0.003	<0.001
Submerged–saturated cal	−0.004	−0.005	−0.004	<0.001

Conflict of interest statement

The authors have no conflicts of interest to declare.

Disclosure

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