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Short communication

Accuracy of circular contact area measurements with thin-film pressure sensors

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Abstract

Contact area is often used to characterize the biomechanical properties of joints, especially in testing of injury and joint replacement. Several methods have been developed to measure contact area, including piezo-resistive thin-film arrays. The purpose of this study was to determine the accuracy with which one of these systems (Tekscan, Inc., South Boston, MA) could measure the contact area of flat-ended circular indenters of varying known sizes. Static loads ranging from 1000 to 7000 N were applied to four flat, circular indenters (1140, 2027, 3167, and 4560 mm^2) and the contact areas were recorded with Tekscan 5076 sensor. Similar testing was carried out on a 4000 sensor. I-scan software (Tekscan Inc., South Boston, MA) was used to analyze the Tekscan-recorded area measurements. The Tekscan data were also post-processed to filter out sensel signal intensity values that were at least two standard deviations from the average sensel signal intensity values of the sensor matrix. Unprocessed Tekscan measurements with the 5076 sensor had area percent errors ranging from 5% to 27%. The filtering algorithm reduced most errors to less than 1%. Similar trends of improved accuracy with post-filtering were found with the 4000 sensor. While this method of thresholding out the sensels with the lowest signal intensity values may not work for all surfaces and indenter shapes, it provides a new approach to improve the accuracy of contact area measurements collected with the Tekscan system.

Keywords: Contact area; Pressure; Sensor; Accuracy

1. Introduction

To better understand the biomechanics of joint injury, wear, and replacement, methods to measure contact force, pressure, and area have been developed (Fregly et al., 2003; Greis et al., 2002; Harris et al., 1999; Heino Brechter et al., 2003; Matsuda et al., 1997). The thin-film based Tekscan system (Tekscan, Inc., South Boston, MA), which consists of a matrix of patented semi-conductive ink coating that creates an electrical resistance at intersection points called sensels, is frequently used.

Many studies evaluating Tekscan highlight advantages over Fuji film (DeMarco et al., 2000; Harris et al., 1999; Matsuda et al., 1995; Wilson et al., 2003; Bachus et al., 2006), including a lower profile, real-time continuous data collection, and its ability to be reused and withstand sterilization (Wilson et al., 2003; Agins et al., 2003). Although the sensors pose calibration challenges for the direct measurement of load (Baer et al., 2005; Brimacombe et al., 2005), the accuracy of the contact area measurement has not been assessed. The purpose of this study was to investigate the accuracy of contact area measurements using Tekscan sensors and evaluate a new approach to improve accuracy.

2. Methods

Four flat-ended aluminum circular indenters were used to apply loads to a Tekscan 5076 sensor (Tekscan, Inc., South Boston, MA), which had an 84 mm × 84 mm matrix consisting of 1936 sensels with areas of 3.629 mm^2. This sensor had a pressure saturation rating (P_{sat}) of 3.45 MPa. The indenter contact areas chosen for testing were 1140, 2027, 3167, and 4560 mm^2, a range of sizes covering 15% to 65% of the sensor. Loads ranging from 1000 to 7000 N in 1000 N increments were

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applied to investigate the accuracy of the contact area producing pressures below and above the P_{sat}. According to the manufacturer, exceeding the P_{sat} of the sensor should not affect the contact area measurements. Quasi-static loads were applied using a servo hydraulic material tester (model 8521-S; Instron Corp., Canton, MA). The actuating piston applied a compressive load to a ball bearing centered on the top of a flat circular indenter. The indenter was placed on top of the senor and a 1.85-mm-thick foam-rubber pad (cut to the same diameter as the indenter), with a modulus of elasticity of approximately 1 MPa, was inserted between the indenter and the sensor (Fig. 1). This pad was chosen because its modulus was similar to documented values of modulus of elasticity for human and bovine cartilage, 0.70 and 0.89 MPa respectively (Mow and Huiskes, 2005).

A new 5076 sensor was conditioned according to the manufacturer's recommendations. The contact area measurements were performed by applying a preload of 100 N that was ramped up to the desired load at a rate of 800 N/s. Test loads were held for 1 min while data were collected at a rate of 25 Hz. The amount of time was selected to ensure that the sensor reached equilibrium during this static test. Each indenter was tested three times at each load while the sensor remained in place. Sensors were allowed to unload for 1 min.

A Tekscan 4000 sensor was also used. This sensor had a 28 mm × 33 mm matrix, made up of 572 sensels, with areas of 1.613 mm^2 each, and P_{sat} of 10.3 MPa. Two circular indenters (126.7, 506.7 mm^2), which approximated the percentages of the sensel matrix that was activated for the 5076 sensor when using the smallest and largest indenters, were used. Loads ranging from 500 to 3500 N in 500N increments were chosen so maximum loads for the large indenter were below the P_{sat} of the 4000 sensor, while four of the loads applied to the smaller indenter were above the P_{sat}, as was the case for the 5076 sensor. Testing followed the same protocol as described above for the 5076 sensor.

The contact area data were collected using I-scan software. A MATLAB (The Mathworks, Inc., Natick, MA) program calculated the area recorded with the Tekscan sensor. The program also filtered out sensels with the lowest signal intensity values that generally lay outside the periphery of the recorded areas. The program determined the mean signal intensity value of the sensels, filtered out sensels that recorded signal intensity values that were greater than two standard deviations from the mean, and calculated an adjusted area. The data were plotted as functions of applied load and percent error between the actual area of the indenter and the unfiltered and filtered Tekscan areas.

Percent errors in contact area measured with the Tekscan system and those values computed after implementation of the filtering program were compared using a Mann–Whitney rank sum test (SigmaStat3.1, Systat Software, Inc., Point Richmond, CA). The significance value of $P<0.05$ was set a priori.

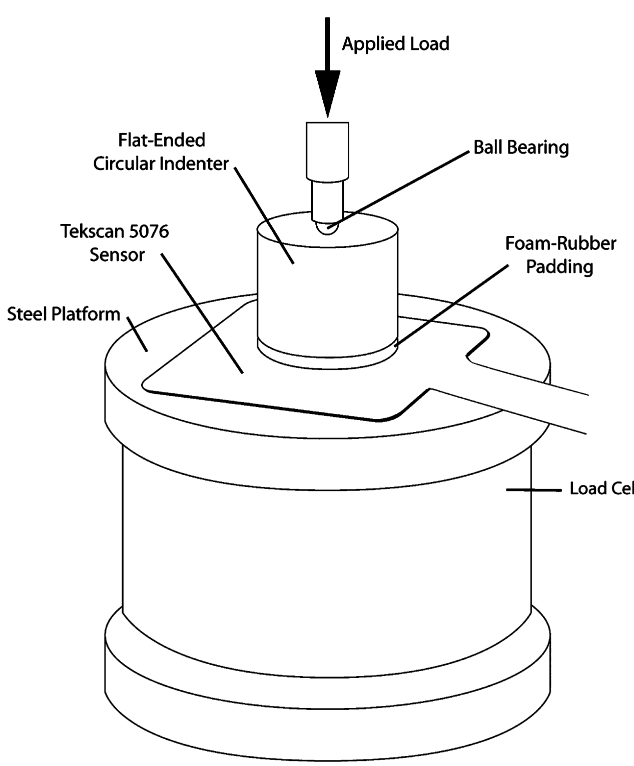

Fig. 1. Experimental test setup. Flat-ended circular indenter placed on top of Tekscan sensor, with foam rubber pad inserted between the indenter and the sensor sitting on a rigid steel plate and load cell.

3. Results

For the 5076 sensor, percent errors in the contact area ranged from 5% for the largest indenter at the lowest applied load to 27% for the smallest indenter at the highest applied load (Fig. 2). At all loads, decreasing the indenter size increased the contact area percent error. An unexpected finding was the trend of a greater percent error in contact area with an increase in the applied load (Fig. 2). No curling up of the sensor around the periphery of the indenter was observed during any of the tests.

Filtering the data before calculating contact area significantly ($P<0.001$) reduced percent errors in contact area for all forces and areas using the 5076 sensor. After filtering the data, the percent error in contact area was reduced to less than 1% when using the three largest indenters. The smallest indenter, however, had area percent error ranging from approximately 2% for the lowest applied force to 14.3% for the highest applied load (Fig. 3). The majority of the tests demonstrated normal distributions for their signal values. At applied loads of 4000 N and greater, the smallest indenter produced a very narrow distribution of signal intensity values that reduced the effectiveness of the filtering method.

Filtering the signal intensity values before calculating contact area significantly ($P<0.001$) reduced percent errors

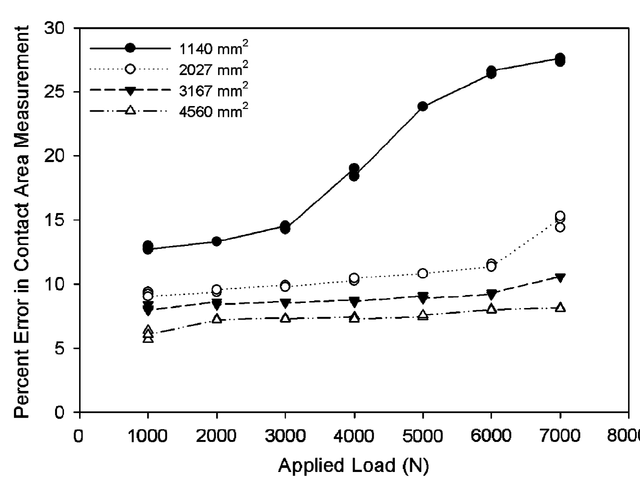

Fig. 2. Area percent error between the actual areas of the indenters and the areas recorded with Tekscan 5076 sensor as a function of applied load for the four circular indenters at loads ranging from 1000 to 7000 N. The percent error in contact area increased with increasing applied load and decreasing indenter size.

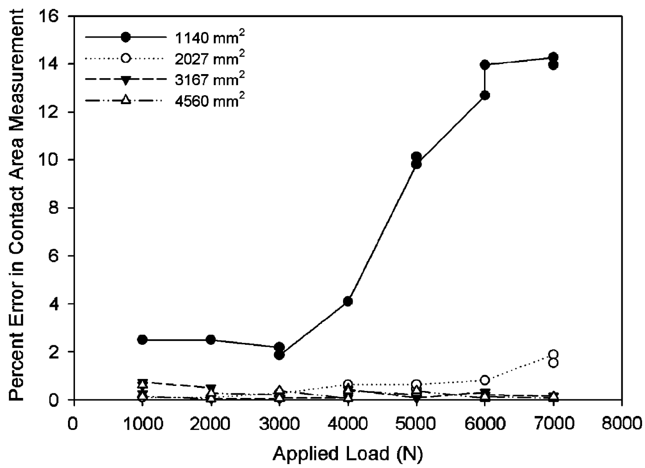

Fig. 3. After the data presented in Fig. 2 was processed by filtering out pressure values lower than two standard deviations from the mean pressure value, the percent error in contact error was significantly ($P<0.001$) reduced.

in contact area for all forces using the larger indenter on the 4000 sensor. The percent errors in contact area for the Tekscan 4000 sensor ranged from 11.7% to 20.0%. After filtering the area percent error ranged from 2.2% to 8.9%. However, for the small indenter the percent errors in contact area ranged from 37.4% to 53.1%. Using the MATLAB code to filter out sensels with signal intensities lower than one standard deviation, rather than two standard deviations, the area percent errors were reduced to 3.1% to 8.2% for the smaller indenter, and 1.0% to 6.7% for the larger indenter.

4. Discussion

The Tekscan system is widely used in biomedical research. However, there appears to be no investigation of the system's ability to accurately measure contact area over a variety of areas and range of applied forces. These data demonstrate that care should be taken when using Tekscan to evaluate contact areas such as joints and joint replacements, especially at pressures close to or above the sensor's P_{sat}, despite the claim that the applied pressure should not affect contact area measurements.

Very few studies have investigated Tekscan accuracy of contact area using an object with a known area. One such example was part of a study comparing the contact area, force, and pressure capabilities of both Tekscan and Fuji Film (Bachus et al., 2006). Using one circular indenter and a 5051 sensor, Bachus et al.'s results showed accuracy ranging from 2% below the actual area to 3% above the actual area. The underestimated percentages correspond with the lowest loads while the overestimated percentages correspond with the highest loads, the same trend reported in this study. They used a steel peg on a steel plate, while this study used a foam-rubber pad between the sensor and the indenter. This difference is important because the pad that we used had a modulus of elasticity much closer to human cartilage. Bachus et al. also used a range of pressure below the P_{sat} of their sensor, and as our data have shown, pressures above the P_{sat} greatly affect that accuracy of contact area measurements. For cases where applied pressures are close to or above the P_{sat} of the sensor, our filtering method helps to improve accuracy.

While our filtering approach improved the accuracy of contact area measurements, it has limitations. When signal intensity distributions had a small range of values, such as the smaller indenter used on the 4000 sensor, the improvement in accuracy was minimal. Additionally, the indenters were circular, so we cannot say if this filtering method would work for other shapes. Measurements taken using indenters with straight edges could potentially over- or underestimate the areas depending on the placement of the indenter on the sensor. Only one 5076 and one 4000 sensor were evaluated. Further testing could investigate the effects of sensor fatigue on accuracy. Also, compliance of the indenter, underlying surface, and speed of load application could affect results.

The Tekscan system also has limitations. Despite the fact that the contact area measurement is a binary function, higher applied loads affected the accuracy of the contact area measurements. One weakness of this system is that if any part of the indenter comes into contact with the sensor, the area for the entire sensel will be added to the total contact area; hence, overestimating contact area. Also, sensors are sensitive to the temperature, the compliance of the indenters and supporting surfaces, and the length of time that an indenter is in contact with the sensor. Variability of these factors could lead to further inaccuracies.

In summary, sensor selection plays a vital role in Tekscan contact area measurement accuracy. Avoid applying pressures that exceed the sensor's P_{sat}. Use sensors with high sensel densities and avoid using indenters that are very small in comparison to the sensel grid. Our results show a degree of inaccuracy in contact area measurements when using the Tekscan system. However, when the data were filtered, accuracy was dramatically improved. This method may have minimized possible edge effects of the sensors where sensels along the perimeter were lit up despite the fact that they were not in direct contact with the indenter. Because the contact area analyses of the Tekscan sensors with I-scan software are prone to errors, it is important to verify that sensors are appropriate for particular applications by testing basic shapes and surfaces before focusing on more complex models such as joints and joint replacements. This study provides a method for improving the accuracy of contact area measurements for a system frequently used in biomedical research.

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