COMPLIANCE-DEPENDENT LOAD ALLOCATION BETWEEN SENSING VERSUS NON-SENSING PORTIONS OF A SHEET-ARRAY CONTACT STRESS SENSOR

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ABSTRACT

Piezoresistive array pressure sensors are widely used in orthopaedic research to determine contact stress distributions across articular joint surfaces. Experience with such sensors has shown there can be inaccuracies in how the sensor perceives applied load, depending on the material stiffnesses between which it is compressed experimentally, versus in calibration. A study was undertaken to quantify the relationship between load perception of one such sensor design (Tekscan) and the stiffness of the materials between which it is compressed. A three-dimensional finite element model of a 3x3 sensel portion of the sensing matrix was formulated, along with a layer of compression test material on each side of the sensor. The elastic modulus of the test material was varied across the range representative of cartilage (12 MPa) to hard plastic (10 GPa). Using the computed contact pressure results between contacting surfaces of the sensor layers, the percentage of load passing through the active conductor intersections was determined. The results revealed that with increase of the elastic modulus of the material between which the sensor was compressed, the percentage of load on the active conductor intersections increased monotonically. The highest sensitivity of perceived loading to test material modulus (0.1%/MPa) was seen at the low end of the modulus range. The more compliant the test material, the more the sensor layers conformed around each other's geometric incongruities, the larger the true contact areas, and the higher the fraction of the total load that passed through the intermediate (non-sensing) regions between the conductors.

INTRODUCTION

Piezoresistive array pressure sensors are commonly used in orthopaedic research, to determine contact stress distributions across articular joint surfaces. The physical layout of the (periodic) sensing elements of these transducers is such that differing fractions of the regionally applied loading can potentially pass through non-load-sensing portions between sensing elements of the transducer, depending on the stiffnesses of the test material surfaces between which the transducer is compressed. It is often impractical to calibrate the transducer between loading platens whose stiffnesses identically match those of the actual compression test material surfaces of interest experimentally. Moreover, in some experiments (e.g., osteochondral defect repair studies[1]) sites of greatly differing stiffness come into and out of contact. Need therefore exists to appreciate the influence of compression material surface stiffness on the load perceived by the sensing elements of the transducer.

In the widely-utilized form manufactured by Tekscan (Boston, MA), these sensors can be as thin as 0.1 mm, and consist of a matrix of conductive strips in rows and columns, printed on separate layers of Mylar film. Lines of piezoresistive ink are applied over each conductive strip in the sensing area, leaving visibly ink-free spaces between them. Two such Mylar layers are adhered together around the edges, so that the piezoresistive ink-coated conductors face each other perpendicularly. The entire sensing area can be viewed as divided into squares centered on the intersections between ink covered conductors. Each of these squares is referred to as a sensel, of which as little as 10% of whose area is occupied by the intersection of the orthogonal conductors. When the sensor is positioned between contacting surfaces, each conductor intersection acts as a variable resistor, whose resistance is dependent on the instantaneous local compression of that sensel. Lead wires connect each row and column to a computer that records resistance values for all conductor intersections in the sensor.

To allow conversion of sensel resistance to load or pressure, calibration is necessary. Typically, the sensor is placed between two flat platens made of synthetic materials, such as rubber, plastic, or metal. Then, various known loads are applied across the sensor. Intui-

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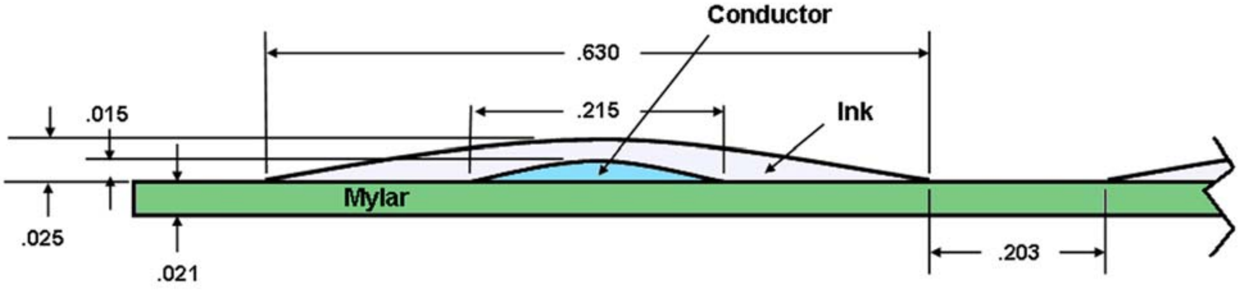

Figure 1. Cross-sectional dimensions (mm) of one ink-covered conductor strip, printed periodically on Mylar substrate.

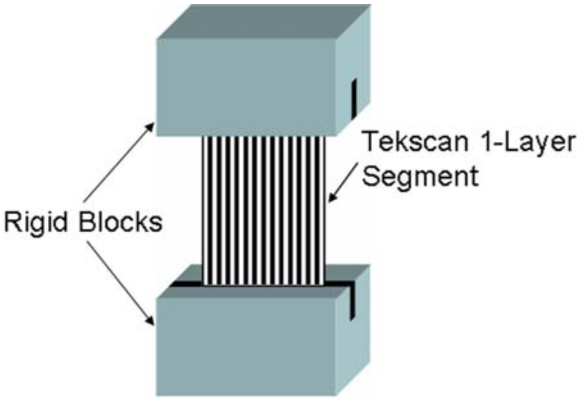

Figure 2. Setup for tensile test used to determine material properties, showing one layer of the sensor bonded to rigid blocks to be clamped in an MTS machine.

tively, the load perceived by the sensor should depend on the properties of the test material compressing it. This is an important relationship to quantify, since final results from the experiment (e.g., cartilage-on-cartilage compression) depend heavily on sensor calibration accuracy. In this study, a finite element (FE) analysis was undertaken to determine the force distribution within a Tekscan sensor, as a function of the stiffness of the surface between which it is compressed.

METHODS

An FE model of a (repeating) section of a Tekscan ankle sensor (Model 5033) was created and analyzed using ABAQUS software. Geometry (Figure 1) was determined from a single layer of a Tekscan sensel matrix, assessed using a measuring microscope. Material properties were found by performing staged tensile tests, parallel to the conductors, on one layer of the sensor matrix from five different sensors, using an MTS machine. To do this, a segment from one layer of each sensor matrix was removed and bonded on each end to two metal blocks (Figure 2) in turn clamped into the MTS machine. A first tensile test determined the elastic modulus of the intact layer. Then, the piezoresistive ink was dissolved with acetone, while preserving the conductors intact, at which point a second tensile test was performed on the remaining segment (i.e., Mylar + conductor). Lastly, after subsequently removing the conductive strips the Mylar film was tested alone. This tensile test sequence was repeated for all five specimens. All (tangent) modulus evaluations were at a strain level of 2%. Since one layer of the sensor array can be considered as a unidirectional fiber-reinforced composite, the rule of mixtures[2]

$$E_{Composite} = E_1 V_1 + E_2 V_2 + \ldots + E_n V_n$$

was used to estimate each component material's modulus, where E_i and V_i represent the elastic modulus and volumetric fraction of each i'th component of the composite. With this approach, the moduli of Mylar, piezoresistive ink, and conductive strips were found to be 2.9 GPa, 3.68 GPa, and 0.77 GPa, respectively. Poisson's ratio was assumed to be 0.35 for all three materials.

The FE model consisted of three units of a (periodic) section of the Tekscan sensor, with three ink-covered conductors attached to a Mylar strip on bottom and three lying perpendicular on top (Figure 3). A layer of compression test material 1.5 mm thick (nominal articular cartilage thickness) backed each side of the Tekscan segment. The model was formulated as a contact problem, with frictionless interaction between the contacting layers. The outermost surfaces of the test material layers were constrained in all directions except for the top surface, which was free to move vertically. The model was driven by a vertical load of 16 N (1.78 N/sensel) applied to the top-most rigid surface, causing compression of the sensor. This load was based on the 80th percentile stress (2.55 MPa) from a recent study where six cadaver ankles at 0° flexion had been subjected to a 600 N axial load, representing one body weight.[3] The test material properties were varied from representative of cartilage (12 MPa modulus,[4] 0.42 Poisson's ratio[5]) up to representative of hard plastic (10 GPa).

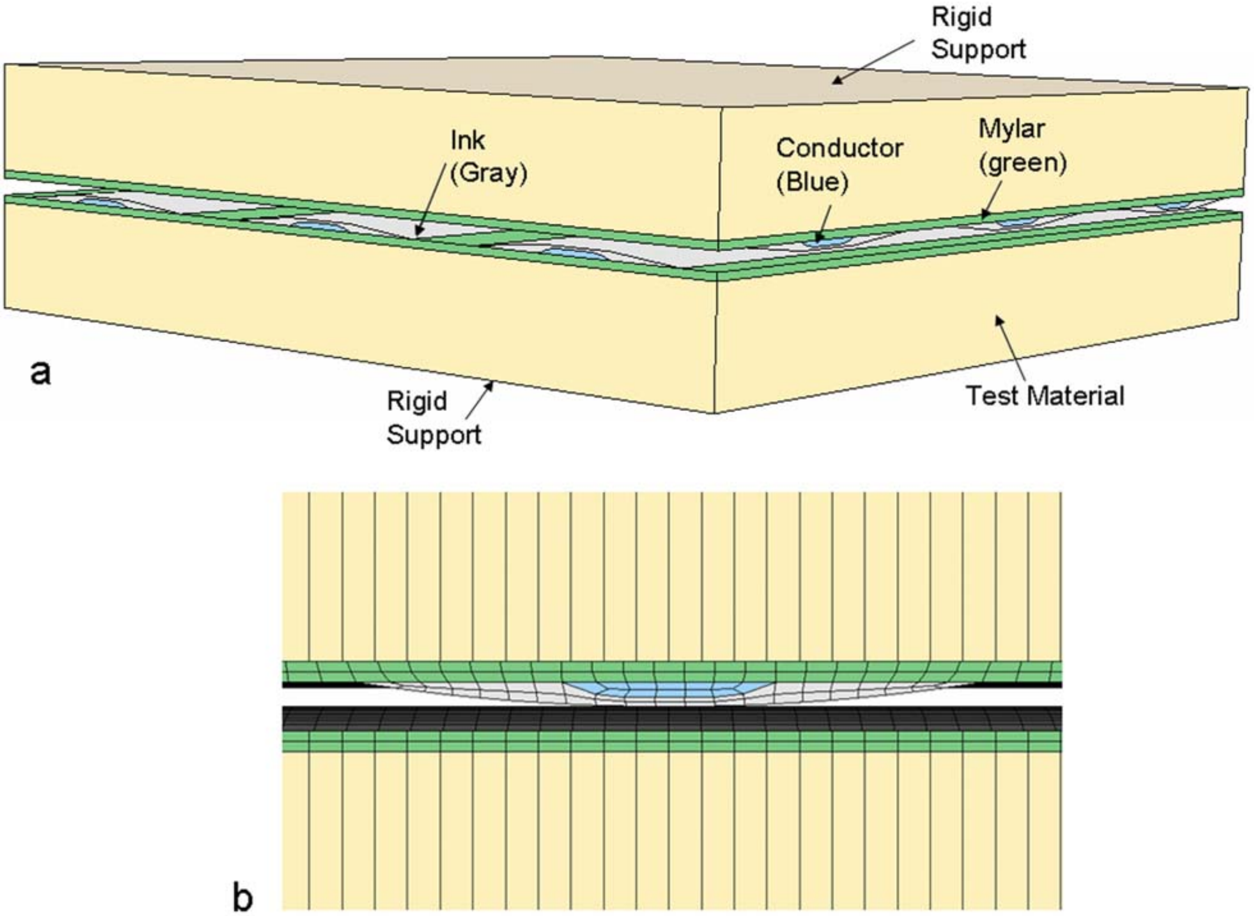

Figure 3. (a) Finite Element model of a segment of a Tekscan ankle sensor showing three ink-covered conductors on bottom, and three lying perpendicular on top, with a test material backing on each side. (Not shown to scale) (b) FE zoning of the cross section for one sensel.

The force transmitted through the region directly between the top and bottom intersecting conductors was determined for each case, using the ABAQUS contact pressure results. The middle sensel was analyzed, to minimize end condition effects. The region of elements on the bottom sensor layer directly between the middle column and row conductor intersection was isolated, as shown in Figure 5. The percentage of force on the middle sensel conductor intersection, relative to the force passing through the overall middle sensel, was calculated.

To confirm adequacy of the FE zoning, a preliminary comparison was done versus Hertzian contact stresses. Using similar zoning, homogeneous material properties were assigned to the model. A load of two N per sensel (18 N total) was applied in the same manner as in the Tekscan sensor FE model. The (homogeneous) material elastic modulus was varied from 500 MPa to 5000 MPa. Hertzian contact equations for two perpendicular cylinders[6] were used to determine the theoretical pressure at the center of each contact area. Hertzian analytical vs. ABAQUS-calculated pressure values had discrepancies ranging from 1.6% to 4.3%, with an average of 2.6%.

The FE model was then validated by performing a corresponding physical force vs. displacement compression test on a sensor. In this test, a sensor was compressively loaded between rigid parallel platens in an MTS machine. To simulate this situation, the test material was removed from the total FE model, leaving just the sensor. The outermost surfaces of the sensor-only model were then rigidly constrained. The FE-predicted compressive load/displacement behavior was in very reasonable agreement with the experimental measurements (Figure 4).

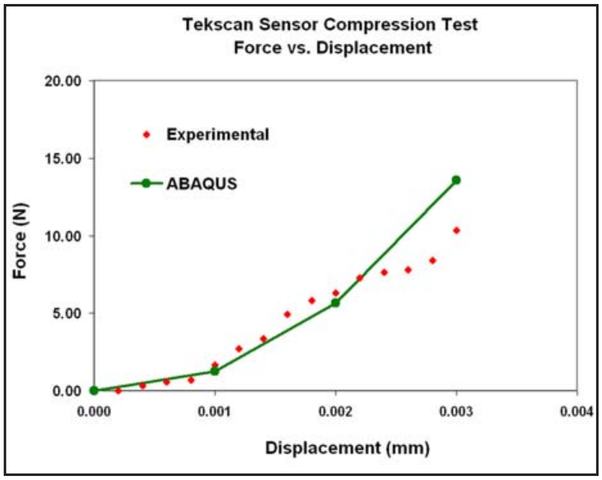

Figure 4. Force vs. displacement relationship comparing the FE model response and experimental response of a Tekscan 5033 sensor in a compression test.

RESULTS

A series of model trials was then run, spanning test material elastic modulus range from 12 MPa to 10 GPa. Figure 5a shows the computed contact pressure distribution on the bottom contact surface of the sensor segment when the test material had a modulus of 10 GPa. The nine contact patches were small in area, and the force transmission was concentrated through the conductor intersections. Figure 5b shows the contact pressure distribution when the test material had a modulus of 12 MPa, in which case the nine contact patches were very large, with diffuse contact pressure, and with substantial load transmission through the regions between the conductor intersections.

Figure 6 shows fractional load transmission changes for test material modulus between 12 MPa and 10 GPa. The percentage of force over the middle sensel active sensing region ranged from 8.5% (for a 12 MPa test material) to 96.4% (for a 10 GPa test material). The relationship reveals that with increase of test material elastic modulus between which the sensor is compressed, the force on the active conductor intersection monotonically increases, with greatest sensitivity (~1% perceived load change per 10 MPa of test material modulus change) occurring at the (cartilage-representative) low end of the range considered.

DISCUSSION

The purpose of this study was to quantify how the sensor's perception of applied loading would change due to variation in the stiffness of the surfaces between which it was compressed. With more compliant materials, such as cartilage, the top sensor layer was able to conform to the curvature of the ink/conductor complex on the bottom layer. This resulted in a much larger contact area, with less load passage through the active intersection. By contrast, stiffer test materials resulted in small contact area, with almost all of the load going through the active intersection. Since the pressure sensor reads the electrical resistance only at the sensing sites (i.e., directly between the intersecting conductors), any load passing outside of the intersecting region would not be accounted for in the sensor output data. This makes it evident that the sensor results will be compromised when there is a mismatch between the moduli of the materials between which the sensor is calibrated, versus those between which it is used experimentally. Fortunately, as a practical matter,

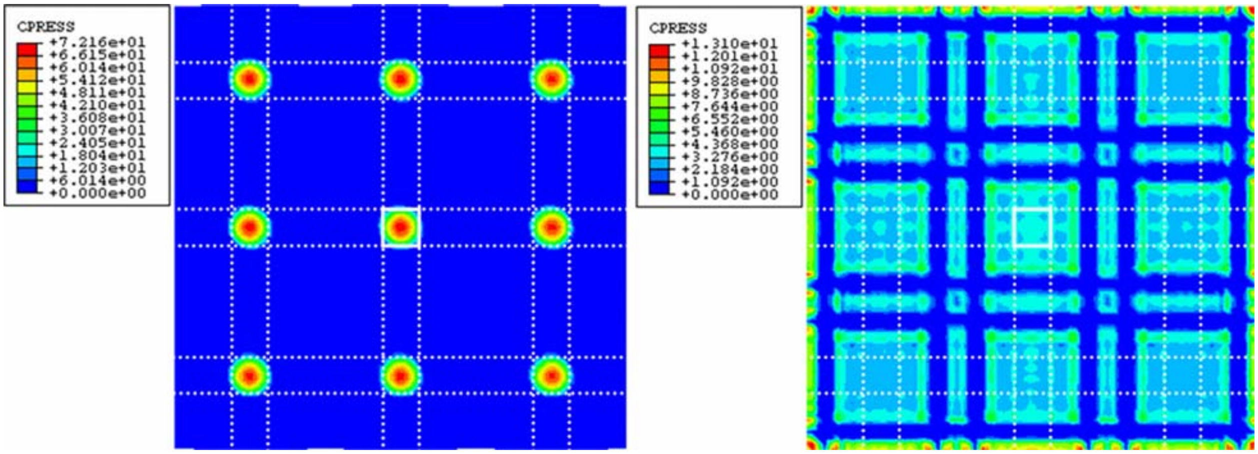

Figure 5. ABAQUS images showing the contact pressure distribution on the top of the bottom layer in the sensor with a regional applied load of 2.56 MPa, for a test material with an elastic modulus of (a) 10 GPa, representing hard plastic and (b) 12 MPa, characteristic of cartilage. (Color scales are different) Dotted lines show the conductor traces. The white square shows the active conductor intersection in the middle sensel that was isolated to determine the force distribution.

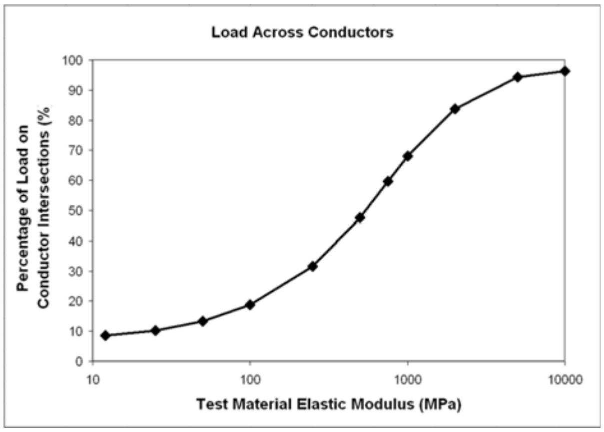

Figure 6. The semi-log relationship between the stiffness of the contact material and the fractional force distribution over the sensel active conductor intersection at an applied load of 16 N (1.78 N/Sensel).

for most usages in orthopaedic research, the magnitude of this compromise does not appear to be severe. In even the most sensitive region (12 MPa, representative of cartilage-on-cartilage contact), an "error" of 1% per 10 MPa of modulus discrepancy would not be problematic, since even for relatively severe levels of cartilage degeneration the effective elastic modulus changes are only on the order of a few MPa.[7] It therefore should suffice for most purposes to have performed calibrations between synthetic surfaces nominally matching cartilage modulus, with a scaling step to register recovery of the aggregate load applied to the specimen.

ACKNOWLEDGMENTS

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