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Traveling-Load Calibration of Grid-Array Transient Contact Stress Sensors

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Abstract

Thin, pliant transducers with grid arrays of sensing elements (sensors) have been widely used for transient measurements of intra-articular contact stresses. Conventional calibration procedures for this class of sensors are based upon spatially uniform scaling of sensel output values so as to recover two known fiducial loads, physically applied with the sensor either compressed between platens or mounted *in situ*. Because of the nonlinearities involved, it is desirable to have the highest of those two calibration loadings be such that all individual sensors are engaged at/near the peak of their expected functional range. However, for many situations of practical interest, impracticably large total calibration forces would be required. We report development of a novel pneumatically actuated wringer-like calibration device, and companion iterative post-processing software, that bypasses this longstanding difficulty. Sensors passed through the rollers of this device experience constant-distribution traveling fiducial loads propagating across their surface, thus allowing efficient calibration of all sensors individually to contact stress levels that would be impracticably high to simultaneously apply to all sensors. Sensel-specific calibration curves are rapidly and easily generated using this new approach, and compare favorably to those obtained with less expeditious conventional platen-based protocols.

Keywords

Sensor array; Calibration; Transient pressure measurement

INTRODUCTION

Many techniques have been devised for quantifying articular contact stress distributions, an important class of measurements in the field of orthopaedic biomechanics (Brand, 2005). In situations where the need for transient recording has been paramount, the approach of preference has involved multiplexed grid-array transducers. These types of sensors consist of an array of a large number of discrete local sampling sites, termed sensels (usually, arranged in a row-and-column grid layout), at each of which positions the instantaneous local contact stress modulates an electronically recoverable signal. The leading manufacturer

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of piezo-resistive array sensors, Tekscan, uses a lithography/photo-etching process to produce a wide range of sensel layouts (Tekscan, 2007) to accommodate various contact surface geometries, spatial resolutions, and pressure ranges.

Regardless of design specifics, grid-array sensors cannot practicably be manufactured such that all of their sensels respond identically. Therefore, the task of calibrating such a sensor ideally involves registering and suitably scaling each individual sensel's response to known levels of local contact stress. This poses various practical difficulties. Direct platen loadings are easy to apply, but have difficulty in delivering suitably precisely homogeneous stress distributions. And, platen loading is normally restricted to relatively small areas, thus requiring tedious repetition to calibrate an entire sensor face. Homogeneous loadings over much broader areas can be achieved using hydrostatically pressurized bladder arrangements, but for contact stress magnitudes in the range of interest orthopaedically, these involve high-pressure loading systems that are unduly cumbersome for routine use experimentally (Otto et al., 1999).

We here report a new approach to array-based contact stress sensor calibration, using a novel wringer-like calibration device. The basic idea is to propagate a wave of regional compression across the surface of the sensor, such that each individual sensel experiences a range of contact stress modulated gradually from zero up to (or beyond) the peak level of interest experimentally, and then back to zero. Since the resultant load magnitude of the traveling compressive wave is known and constant, the contact stresses of all sensels engaged at any given instant can be iteratively scaled in post-processing software so as to recover that known loading. In this manner, sensel-specific contact stress calibrations can be quickly and easily regressed. An experiment was conducted to test the hypothesis that sensel calibration curves obtained using this new wringer-based technique would be consistent with those obtained using conventional localized two-level platen loadings, wherein the higher of the two platen loads involves pressures comparable to the peak pressures from roller apparatus.

MATERIALS AND METHODS

The calibration process is illustrated for the case of a Tekscan 5033 sensor, which we earlier had custom-designed (Brown et al., 2004) for use in the human ankle. In principle, this essential approach to calibration can be applied more generally to other types/designs of grid-array sensors, provided that the sensels are in a row-column rectangular layout. The active area (25.8×37.5 mm) of the 5033 consists of a 32 by 46 array of piezo-resistive sensels, on 0.83 mm centers. Resistance values from all 1472 sensels are multiplexed by means of the vendor's proprietary hardware/software interface, which samples the entire sensor at 132 Hz, and writes the resulting data in the form of 8-bit raw integer values (0-255). Those raw values are subsequently converted to pressure magnitudes (0-25.5 MPa, for the 5033) by means of a user-generated calibration curve.

Conventionally, that calibration curve is generated by applying two specific levels of static fiducial loading (Tekscan, 2001). Given the respective numbers of sensels engaged at each of these two loadings, two specific data points of average pressure versus average sensel output are identified, from which the coefficients of a power law calibration curve passing through those two data points are then computed. Limitations of conventional calibration include that only average rather than individual sensel behavior is reflected, and that the nonlinear nature of the piezoresistive response predicates that the uppermost of these two fiducial loads should involve sensel pressures in the range of those expected in the actual experiment, in order to minimize extrapolation error. Unfortunately, subjecting an entire

sensor to pressures at or above the physiologic range would involve impracticably high global loading magnitudes.

In the new approach, appropriate levels of contact stress from which to generate these calibration curves can be conveniently delivered in the form of traveling compression wave, using a purpose-designed “wringer” apparatus (Figure 1). This unit consists of a pair of 5.2 cm.-diameter cylindrical rollers (comprised of rubber-cushioned steel rods), pushed together by means of a pneumatic piston. The lower roller is affixed to a mobile yoke (actuated by the pneumatic piston), whereas the axis of the upper roller is fixed relative to the wringer unit’s frame. A meshing pair of spur gears keyed to the respective roller shafts constrains the rollers to rotate at the same rate, in opposite directions. An 18 cm.-long lever affixed to the upper roller’s shaft allows the operator to manually draw the sensor inward between the rollers. Depending on the choice of material for the roller cushioning sleeves and the magnitude of piston actuation force, the longitudinal span of the contact patch (i.e., in the direction of sensor draw-through) can be user-controlled. For purposes of calibrating 5033 sensors, convenient longitudinal patch spans of 4-6 sensel lengths are achieved using polyurethane rubber sleeves of 75D Shore hardness, in combination with (toggle switch) selectable piston forces of 1050 N or 1890 N (confirmed via load cell), delivered by means of regulator-attenuated line air pressure of 345 kPa (50 psi) or 559 kPa (90 psi).

To prepare a sensor for calibration, two 6.4 mm-diameter registration holes are first punched in its non-functional area, using a custom die. These two holes mate with pins on a carrier plate that reproducibly pre-positions the sensor relative to the rollers, and that constrains the (lever-actuated) longitudinal sensor travel to be perpendicular to the roller axes. The handle is used to turn the rollers, advancing the sensor’s active region into the contact patch. Each sensor is pre-conditioned by running it back and forth five times through the rollers, after which a formal data capture pass is made. That data capture results in typically three to five dozen data points being recorded for each sensel during its period of over-passage by the roller contact patch. This provides an ample dataset of discrete samplings of each sensel’s pressure-vs-output behavior, from which a continuous (polynomial) calibration curve can be regressed. While the discrete data points need to substantially populate the pressure range of interest, there is no particular requirement for them to be uniformly spaced either in time or in terms of pressure increments. So, simple manual actuation of the roller-advance lever is adequate.

In typical usage, the entire sensor is advanced through the rollers in nominally four seconds, corresponding to a longitudinal sensor traverse velocity of nominally 10 mm/sec. The corresponding sensel output data are recorded in a file of nominally 777,216 integer values, corresponding 1472 sensels each being sampled nominally 528 (132 Hz $\times$ 4 sec) times. Since the roller contact force is set so as to achieve a contact patch typically spanning only four to six sensels longitudinally, the great majority (~ 80%-90%) of these data points correspond to non-contact conditions.

These raw data are then exported to a purpose-written post-processing algorithm programmed in Matlab® (Mathworks, Inc., Nattick, MA). This algorithm’s output is a continuous (polynomial) calibration curve for each sensel, relating that sensel’s contact stress σ to its raw output ψ . The basis for determining these calibration curves is that the sum F^* of all reported sensel forces (sensel contact stress times sensel area ΔA) at any given instant must equal the piston-applied roller contact load F . Enforcing this condition of equipollence is approached iteratively, based on provisional calibration curves that are used to infer corresponding provisional pressure distributions, which then are spatially integrated and compared to the physically applied (piston) loads. After each such comparison, the pressure distribution for the subset of sensels that are active at that particular instant is then

scaled up/down so as to reduce any undershoot/overshoot in returning the physically applied load. In practice, attempting to abruptly fully eliminate the entire undershoot/overshoot leads to numerically unstable behavior of F^* . Upward/downward scaling of provisional pressures by the 0.1 power of the ratio (F^*/F) empirically affords reasonable compromise between the need to preclude unstable numerical oscillations of F^* , and the need to expeditiously eliminate the force residual $|F^*-F|$. Since any given sensel is active to varying levels of (pressure-dependent) output at three to five dozen independent instants, basis exists to make (independent) upward or downward adjustments of the pressure values provisionally associated with each of its sampled output values. These scalings of the pressure values permit “improved” provisional calibration curves to be generated, a process which is successively repeated until the spatially integrated pressure force F^* at all sampling instants suitably approximates the applied load F . A convergence criterion $\varepsilon = (|F^*-F|/F) = 0.01$ was empirically found to achieve satisfactory algorithm performance.

As a practical matter, iterative convergence proceeds more expeditiously when the initially assumed calibration curves are physically plausible. For this purpose, it has proven expedient to start with provisional calibration curves that are consistent with the contact stress distribution between the rollers being identical to that for a pair of parallel homogeneous linearly elastic cylinders in edge contact. (This initially assumed elastic-cylinder contact stress distribution is immediately discarded after the first iteration, and plays no further role in the calibration process.) Using this initial condition and the above numerical parameters, convergence is typically achieved in 10-20 iterations. Details of the post-processing algorithm are set forth in flow chart form in Figure 2.

For purposes of comparison, calibration curves for the same Tekscan 5033 ankle sensors were generated also using the manufacturer’s conventional two-discrete-load calibration protocol. For this purpose, loading was applied using a small rectangular platen (11.9×11.9 mm, covering a patch of 196 sensels), using an upper-end load magnitude of 2832 N, corresponding to upper-end pressures (20 MPa) that were nominally similar to the peak pressures developed in the wringer apparatus.

RESULTS

Raw output signals for a typical instant during roller data capture, and the pressure distribution at this same instant as inferred from the corresponding converged calibration curves, are shown in Figure 3. It can be observed that the iterative calibration process successfully deals with inter-sensel variations of pressure sensitivity. Figure 4 shows individual and group-averaged calibration curves for a representative rectangular region of 14×14 sensels, determined via wringer calibration versus the group average determined by small-platen conventional calibration. It can be appreciated that these two modalities of calibration curves reasonably coincide with one another. However, the platen-based calibration is contingent upon the assumption that all sensels behave identically, and its curve morphology is dependent upon the specific relationship (here, a two-coefficient power law) used to interpolate between just two fiducial input loadings. The roller-based calibrations by contrast are sensel-specific, and their curve morphologies arise from regression best-fits to several dozen discrete data points of pressure-vs-output for each individual sensel, so it seems reasonable to presume that they lie closer to ground truth.

DISCUSSION

Utilizing a traveling wave of contact load for purposes of calibrating a grid-array contact stress sensor in principle is applicable to a wide range of specific sensor designs and transduction modalities. Of this broad class of transducers (Ashruf, 2002), Tekscan is of

particular interest owing to its relative popularity within the biomechanics research community. The present wringer system and post-processing algorithm satisfactorily address the need to base calibrations on the full range of pressures expected experimentally. Both the physical equipment involved and the post-processing routine utilized are tractable to implement in most contemporary biomechanics laboratory settings. Obviously, the specific design parameters of the present wringer embodiment can easily be modified to accommodate other specific sensor geometries or contact surface compliances (Hartmann et al., 2009.) And, various details of the post-processing algorithm can easily be modified in various ways (e.g., different algebraic forms of regressed calibration curves, different iterative strategies to recover the applied physical load, etc.) to accommodate user preferences. Our experience has been that this type of traveling-wave sensor calibration capability, once in place, is simple enough and easy enough to use that it becomes the procedure of choice not only for challenge situations such as articular incongruities, but indeed routinely.

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Figure 1.

Physical appearance of the wringer unit. A Tekscan 5033 sensor is shown pre-positioned on the carrier plate. Depending on the range of pressure interest experimentally, the toggle switch at the top controls a valve that selects between two levels of regulated line air pressure (typically 50 or 90 psi) available to the air cylinder, resulting in corresponding peak contact stresses of typically 15 or 25 MPa between the rollers. The handle (manually actuated) is used to turn the rollers (linked by spur gears), drawing the carrier plate and the sensor through the rollers. With the sensor being sampled at 132 Hz, a sensor draw-through speed of nominally 1 cm/sec results in nominally 3-5 dozen discrete pressure-vs-output samplings per sensel, which form the basis from which to regress sensel-specific continuous calibration curves.

Figure 2.

Flow chart of the iterative post-processing algorithm. The regressed calibration curves use a third-order polynomial curve fit, constrained to pass through the origin (i.e., $\sigma = 0$ at $\psi = 0$) and to have a slope of zero (i.e., $\partial\sigma/\partial\psi = 0$) at that point. (Other specific forms of regression curve fits could of course be invoked, depending on analyst preference.) The basis for iterating the calibration curves is to maximize the fractional load recovered $(1 - |(F^* - F)/F|)$ when summing the reported individual sensel loads.

Figure 3. a) Raw signals, and b) contact stress distribution after calibration curve convergence, for several rows of sensels active at a representative instant during sensor passage through the wringer.

Figure 4. Individual calibration curves, and their ensemble average, for a representative rectangular (14×14) patch of sensels located centrally within the sensor, for calibrations done with the wringer apparatus versus done with a small platen that delivered peak fiducial pressures similar to the peak pressures delivered with the roller.