TIME-BASED CALIBRATIONS OF PRESSURE SENSORS IMPROVE THE ESTIMATION OF FORCE SIGNALS CONTAINING IMPULSIVE EVENTS

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ABSTRACT

Piezoresitive pressure sensors are widely used in biomechanics application involving both static and dynamic loading conditions. The overall accuracy of these sensors has been reported previously in the literature, and multiple linear or polynomial custom calibrations have been proposed to enhance sensors performance mainly in low dynamic conditions. The aim of this technical note was to propose a 'point-to-point' time-based method to improve Tekscan F-Scan sensor calibration procedures in reconstructing a force signal with variable dynamic content and duration, using an application-specific loading pattern, characterised by an initial impact followed by a slow-dynamics phase. The performance of the proposed calibration procedure was compared with four methods divided into time-based calibrations ('point-to-point', 'log time-based', and Tekscan 'step') and linear calibrations ('drop-ball' and Tekscan 'single-point'). The 'point-to-point' calibration was the only method providing accurate force estimation over the entire duration, showing an inaccuracy of about10% both in impact and slow dynamic phase. Tekscan default calibrations ('step' and 'single point') underestimated the criterion force by ~60% over the impact phase but performed better in the slow-dynamics phase (~20% of inaccuracy). 'Log time-based' and 'drop-ball' performed well during the impact phase (~11%) but overestimated the slow-dynamics phase by ~170%. For this reason, we recommend 'point-to-point' calibration for estimation of forces

which are characterised by an initial impulsive event and a subsequent slow-changing load. These findings highlight the importance of selecting the most appropriate calibration with respect to signal dynamics, in terms of loading range, loading pattern and impact duration.

1 INTRODUCTION

Thin-film piezoresistive sensors are widely used in biomechanics to measure pressure distribution and forces[1-4] in applications involving both static[5-7] and dynamic[8-11] loading conditions. Although this type of sensors offer good flexibility and high temporal and spatial resolution, the accuracy of their measures may greatly depend on the calibration procedure chosen[6,12,13]. Comparisons between standard calibration procedures suggested by the manufacturers and customised calibrations have shown that the interface materials[14], sensor type[15], magnitude of the load range[6,15,16] and loading profile[3,14,15] play an influential role on the quality of measures. Additionally, only a few of the proposed calibration procedures have been focussed on highly-dynamic conditions[10], which are particularly critical for biomechanical investigations of events containing an impact.

In previous studies, user-defined calibrations were often implemented by mimicking the signal collected in the tests both in terms of loading range and impact dynamics. Linear[10] or polynomial[6] regression methods have been carried out by defining the calibration line/curve as passing through a single point or a set of points of known force (e.g. the peak value) and the origin of the axes. Although this approach provides suitable results in peak force estimation during single impacts[10], the presence of sensor drift over time may generate a poorer outcome when force estimation has to include an initial peak (impact) followed by a less dynamic phase, such as in the case of rugby scrummaging[17,18] (Figure 1). In fact, Tekscan pressure sensors are subjected to a positive logarithmic drift when constant force is applied, due to the non-linear response of pressure sensels[12,15,19].

We propose a novel time-based calibration method aiming to improve F-Scan sensor (Tekscan Inc., MA, USA) calibration procedures for applications with variable dynamical content. We compared the performance of the proposed calibration procedure with other methods presented in the literature[10] and the standard calibration options provided by the manufacturer[15].

2 METHODS

2.1 Experimental set up

One pair of new Tekscan F-Scan pressure sensors (model 3005E VersaTek-XL size) were used to test force reconstruction accuracy between five different calibration methods. All the calibration trials were based on comparison of simultaneous measurements of a) the vertical reaction force recorded by a floor mounted force platform (Kistler 9287BA, Kistler Instruments, Switzerland) sampling at 2000 Hz, and b) the Tekscan system signal sampled at 500 Hz and expressed in arbitrary units prior to reconstruction with the selected calibration method. Time synchronisation was achieved by sending analogue triggers to initiate acquisition from both systems simultaneously. During all calibration methods, Tekscan sensors were inserted in-between two layers of thin neoprene sheet, and a rigid foot-last, previously shaped to fit with the pressure sensor area, was used to exert a uniform pressure on the sensor. In this way the contact interfaces did not change between loading conditions.

2.2 Calibration Methods

2.2.1 Tekscan single-point

The Tekscan 'single-point' linear calibration[15] is based on the recording of a known force value (e.g. body weight) after 1 sec from the start and a linear scaling ($y=mx$) of transducers' output (Figure 2). The Tekscan 'single-point' calibration was executed 3 times for each sensor, and the average value used as the calibration coefficient.

2.2.2 Tekscan step

The Tekscan 'step' calibration uses a loading/unloading procedure and combines fast and slow factors[15], with the purpose of reducing trial-to-trial variation due to rapid dynamic changes and compensating for slower time-related changes in sensor output. The Tekscan step calibration was performed 3 times for each pressure sensor, and force traces were estimated from each calibration.

2.2.3 Drop-ball

During 'drop-ball' calibration[10], a 9-kg medicine ball was dropped from 4 different heights (0.4, 0.6, 0.8, and 1.0 m), executing 3 repetitions for each height. The loading range on the sensor (0 to 6.5 kN) encompassed the maximum expected force range of rugby scrummaging[17]. The 'drop-ball' calibration consisted of a linear regression of Kistler peak force (in N) against F-Scan peak raw output (sum of all sensels) from each trial (n=12 calibration points). The coefficient of the regression line was used as the calibration coefficient for the Tekscan data (Figure 2).

2.2.4 Logarithmic time-based drop-ball ('log time-based')

The 'log time-based' approach was implemented to evaluate the Tekscan F-Scan sensor output as a function of impact duration, that is the time between initial contact and the peak value. For all data points used in drop-ball calibrations (12 points with their respective impact durations ranging from 0.003 s to 0.01 s) the scale factor k_{log} was calculated as the ratio between the measured force peak, $F(t_{peak})$, and the pressure sensor raw output peak (a.u.). The computed scale factor data were logarithmically regressed against their impact duration (Figure 3). Force was estimated by multiplying the logarithmic regression curve $\mathbf{y_{log}(t)}$ by the pressure sensor raw output (s(t)): $F(t) = y_{log}(t) \cdot s(t)$.

2.2.5 Time-based point-to-point

Six drop-landing trials (i.e. an individual of ~80 kg jumping with one leg on a sensor and then standing on it for a few seconds) were performed for each pressure sensor. The novel 'point-to-point' time-based calibration was based on the calculation of a time-dependent scale factor $k_{exp}=k_{exp}(t)$ given by the point-to-point (sample-by-sample) ratio (Figure 3) between the downsampled force platform signal, F(t), and the pressure sensor raw output, s(t). The 'point-to-point' calibration curve $y_{exp}(t)$ (Figure 3), used to reconstruct the force, was computed by using a 2nd order exponential fitting ($y=Ae^{bx}+Ce^{dx}$) of the k_{exp} scale factor. Forces were estimated by multiplying the calibration curve by the pressure sensor raw output: $F(t) = y_{exp}(t) \cdot s(t)$.

To avoid any ‘correlation’ bias in force estimation, a specific $k_{exp}(t)$ scale factor was calculated for each drop-landing force reconstruction, each one containing data from the other five drop-landing trials.

2.3 Statistical Analysis

All calibration methods were evaluated on the basis of reconstructing the forces from ‘drop-landing’. This type of signal was chosen to evaluate each method because it effectively mimics the magnitude (~3.5 kN) and shape of individual force acting on the player’s shoulder during rugby scrummaging[17]. This procedure was repeated six times on each sensor, with at least 120 s unloading time between repetitions. A total of twelve different trials were used to estimate mean values for i) root mean square error (RMSE) as a force offset index related to long period loading, ii) intraclass correlation coefficient (ICC) to quantify curve correlation over the entire signal duration, and iii) delta force peak value (ΔFP), to evaluate peak force discrepancies between force platform measurement and pressure sensor force estimation (Figure 4).

3 RESULTS

The ‘point-to-point’ time-based calibration performed better both during the impact phase, showing the lowest ΔFP value (320 ± 228 N), and the extended constant loading periods, exhibiting the lowest RMSE value (88 ± 27 N - ~10%) (Figure 4). Over the entire signal, the ‘point-to-point’ calibration showed the best force estimation in terms of signal dynamics and pattern mimicking (Figure 1). Additionally, time-based calibrations (‘point-to-point’, ‘log time-based’, and ‘step’) yielded higher correlation values **(r≅0.6)** between measured and estimated force traces over the constant loading period, whereas linear calibrations (drop-ball and single-point) produced the lowest correlation value (r≅0.1) of all calibration methods (Figure 4).

4 DISCUSSION

We have compared five different calibration methods aimed at reconstructing a force signal characterised by initial impact followed by a slow dynamics phase. Methods were divided into time-based calibrations (point-to-point, log time-based, and Tekscan step) and linear calibrations (drop-ball and single-point). The proposed ‘point-to-point’ calibration was the only method that provided accurate force estimation over the entire duration, whereas all the other calibrations performed well only over either the impact or the slow-dynamics phase.

Regarding linear calibrations (Figure 2), the ‘single-point’ was carried out with relatively low-magnitude quasi-static load and therefore provided reasonable reconstruction of sustained force, but significant underestimation during the impact phase (Figure 1). Similarly, the ‘drop-ball’ method used a constant scale factor (Figure 2) and yielded accurate force estimations only over a limited loading range and specific impact duration[6,15]. ‘Drop-ball’ calibration was optimised for fast impacts (~6 ms time to peak) so it matched peak forces reasonably well but considerably overestimated force during extended loading (Figure 1).

Time-based calibrations exploited different procedures to estimate time-dependent calibration coefficients. The ‘step’ calibration utilised a ‘slow response factor’[15] that yielded accurate force estimations during the more steady phase but showed an underestimation of peak force similarly to the ‘single-point’ calibration (Figure 1). The ‘log time-based’ calibration provided an accurate force estimation during impact phases, but the number of impacts used in the logarithmic fitting and their short impact duration reduced its accuracy for force estimation over the extended loading situation (Figure 2). The ‘point-to-point’ calibration was inspired by the limitations of the previous methods and was based on a coefficient curve that balanced the sensor drift effect but also matched with signal pattern/dynamics. The ‘point-to-point’ exponential decay compensated for sensor drift more effectively than the ‘log time-based’ coefficient curve, because of the larger number of calibration points and their uniform distribution over all loading periods (Figure 3). It also provided a higher correlation between estimated and measured force traces both during impacts and transient and constant phases (Figure 4). This improvement was a result of using the ‘dynamic landing’ procedure that loaded the Tekscan sensor with a realistic loading force simulation in terms of loading range and duration for our application (Figure 1).

Our results highlight the importance of selecting the most appropriate calibration with respect to signal dynamics, in terms of loading range, loading pattern and impact duration. Time-based calibrations generally achieved higher correlation with measured force, with their measurement accuracy over the entire loading period being dependent on the curve fitting process used and loading pattern chosen. On the other hand, linear calibrations were accurate only for a specific loading range and impact duration.

The ‘point-to-point’ appears to be an effective and low-cost calibration method for pressure sensors being used in situations with variable dynamics, provided that it is possible to validly replicate the loading pattern and magnitude of the event under analysis. We showed its potential in the estimation of forces which are characterised by an initial impact and a subsequent slow-changing load. Different events and loading patterns may need different formulations for the regression curves.

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DECLARATION OF CONFLICTING INTERESTS

None of the authors has competing financial, professional or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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6 FIGURES

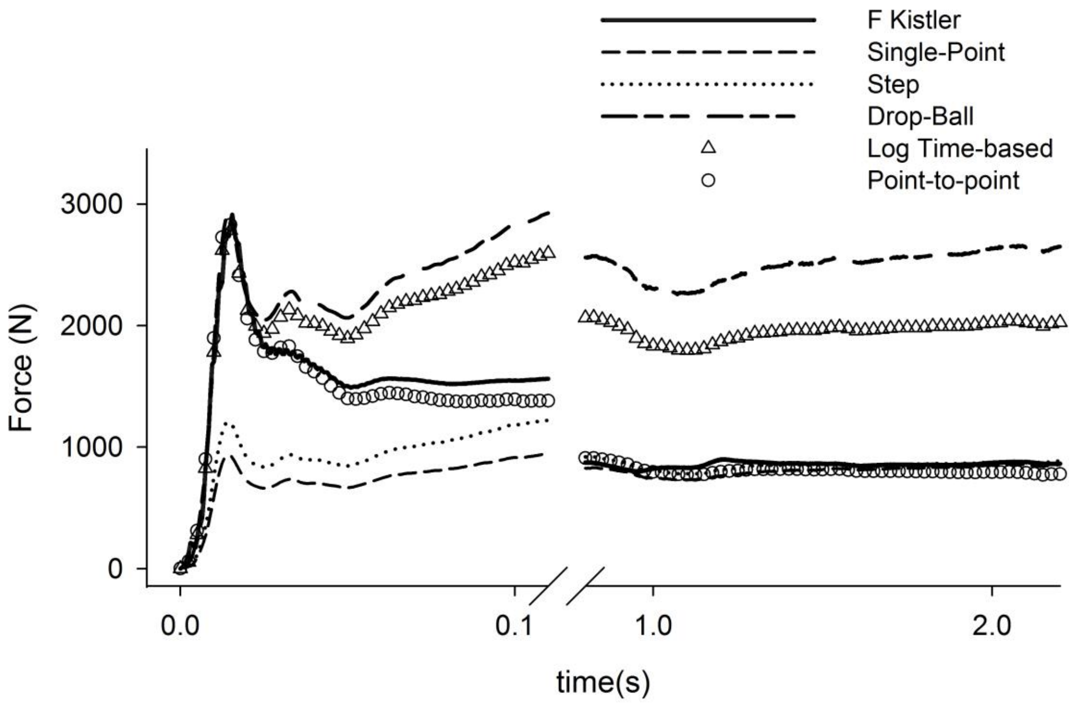

Figure 1: An example curve of the force estimated over time by the five different calibration methods. ‘Drop-ball’ (black long-short-short dashed), ‘log time-based’ (triangles) and ‘point-to-point’ (circles) were the most accurate in impact phase force estimation (~10% of difference), while Tekscan ‘step’ (black dotted) and ‘single-point’ (black dashed) calibrations underestimated force by ~60%. Regarding force estimation over the extended loading period, ‘point-to-point’ calibration reported the best results followed by ‘step’ and ‘single-point’ calibration. Otherwise, ‘log time-based’ and ‘drop-ball’ calibrations largely overestimated force over the more constant force phase respectively by ~150%, and ~190%.

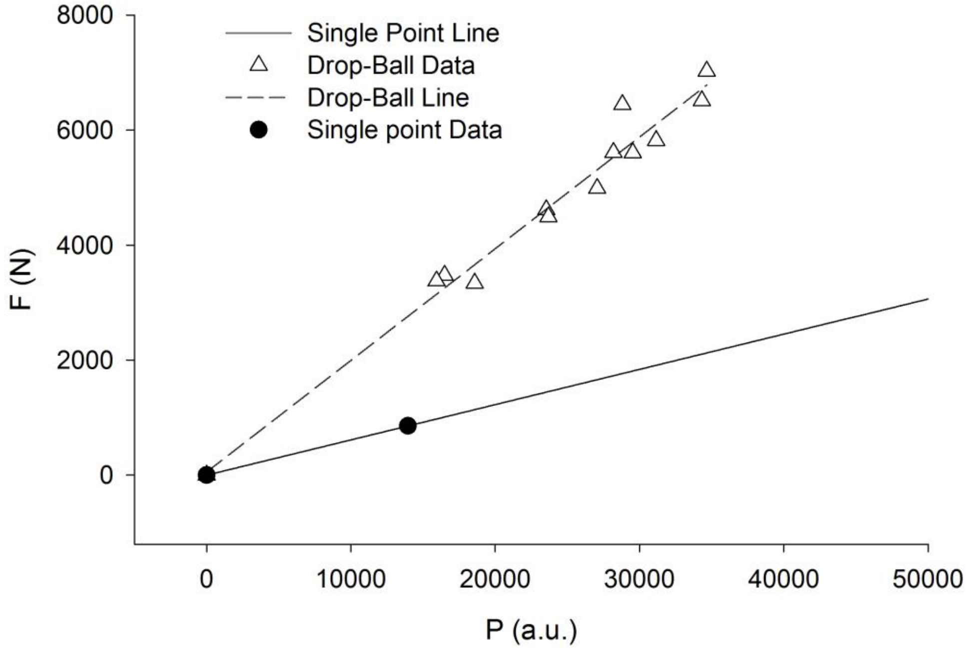

Figure 2: The linear calibrations coefficients are shown. ‘Single point’ calibration line (black solid line) passing through the origin and the single point recorded (circles) is given by the average of 3 ‘single point’ calibration trials. The ‘drop-ball’ calibration coefficient is the coefficient of the line (black dashed line) regressed using 12 ball drops data (triangles).

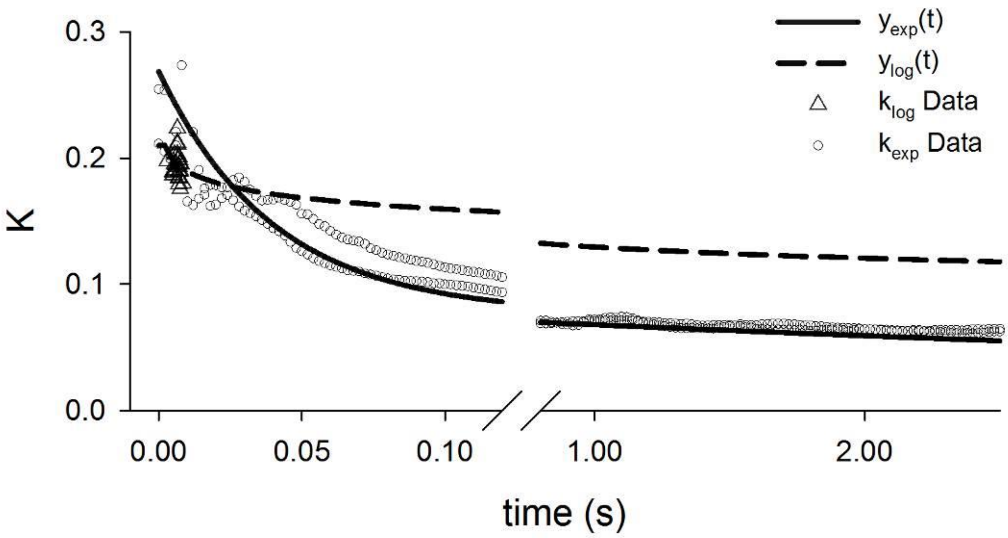

Figure 3: The exponential fitting $\mathbf{y_{exp}(t)}$ (black solid line) of k_{exp} coefficients (circles) and the logarithmic regression $\mathbf{y_{log}(t)}$ (black dashed line) of k_{log} coefficient (triangles), are shown. To facilitate the figure comprehension only two k_{exp} coefficient curves (circles) are shown. The high initial value, the first fast exponential decay and the subsequent low exponential decay of the k_{exp} curve perfectly corresponded with drop-landing loading procedure, which incorporated weighting from rapidly changing components and an extended quasi-static loading period. This was due to the interpolation of all points available (point-to-point ratio between force and pressure curves) rather than using only points relative to signals' peak values (triangles). For this reason, k_{log} regression provided accurate force estimation only during the initial part of the curve (fast loads).

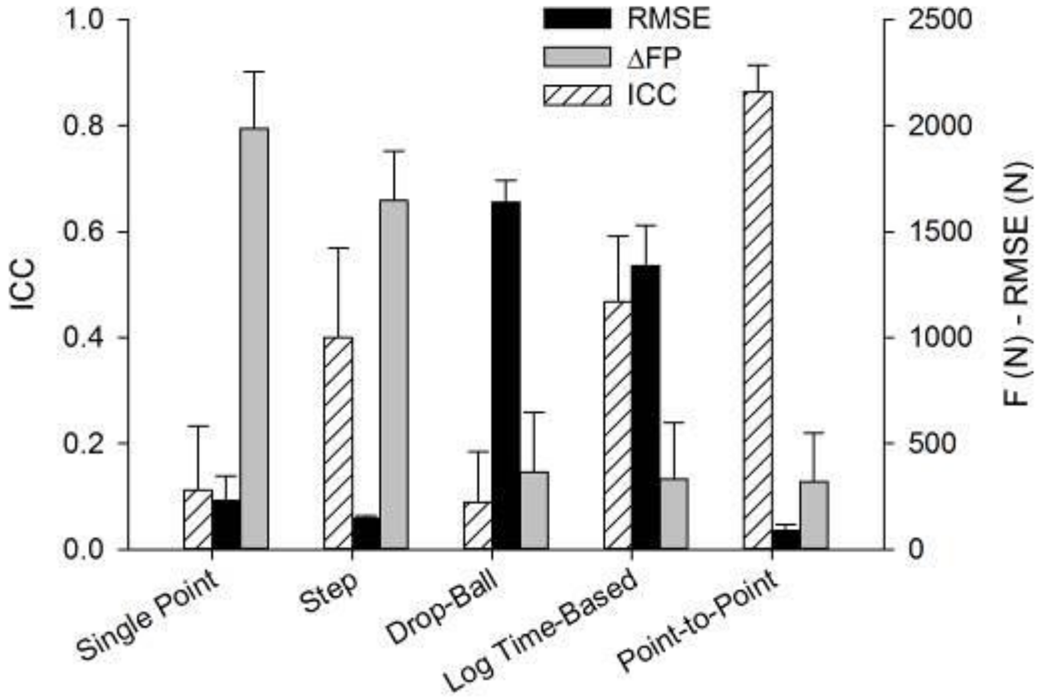

Figure 4: Calibration methods accuracy scores. ICC, ΔFP and RMSE average values and relative standard deviation are shown for each calibration method. The 'point-to-point' calibration provided the best ICC and RMSE values while ΔFP was comparable to 'drop-ball' and 'log time based' calibration methods.