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Pressure sensor calibration for measuring stud-player impacts

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Abstract

In rugby union, laceration injuries can occur from players stamping on opponents in the ruck. To measure the stud-skin interaction during stamping movements, pressure sensors can be used. Pressure sensor calibration techniques have highlighted the need to perform calibrations using appropriate impact dynamics. A pilot study with seven rugby players informed the expected peak forces and loading rates of rugby stamps. Subsequently, a custom calibration procedure was developed, using a drop hammer and force platform to replicate the experimentally observed forces and loading rates. The conventional calibration of the pressure sensor system, supplied by the manufacturer, overestimated total force by 132%. The method described in this paper resulted in a mean error of 7.5%. This study describes a simple and effective calibration procedure for using pressure sensors when measuring the peak force from stud-player impacts. The method has potential to be used as an improved calibration protocol when the expected peak force range of the measured event is between 1800 and 3000 N. The calibrated pressure sensors will be used to obtain kinetic data from stamping events in the ruck in rugby union.

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Keywords: shoe-skin interaction; pressure sensors; calibration; laceration injury; rugby ruck; peak force

1. Introduction

Lacerations account for approximately 6% of the professional match injuries in rugby union [1–3]. Laceration injuries in rugby union can be caused by a number of factors, one of them being studs on players' boots. Studs are regulated by World Rugby (the world governing body for rugby union). Regulation 12 [4] describes 'performance tests' for assessing laceration injury risk of new stud designs. Compliance with Regulation 12 is currently optional for manufacturers. The performance tests aim to simulate stamping - a perpendicular movement of the foot onto a player on the ground; and raking - a similar movement which also includes a horizontal component. Stamping has been previously identified as the most common mechanism causing stud laceration injuries in rugby union [5]. The recommended impact energy stated in the regulation for a stamp test is 4.2 J (50mm, 1m/s, with 8.5 kg). There is no recommended impact energy for the raking test. The British Standards for football shin guards (BS EN 13061:2009) require 14.6 J impact energy (1.0 kg impactor at 5.4 m/s) for testing stud impacts. Payne *et al.* (2013) [6] reviewed the design of human surrogates for the study of biomechanical injury and used an estimate of the lower leg and foot mass (4.58 kg) and in-play impact velocities for a football tackle (1.2-2.5 m/s) to calculate stud-player impact energy (3.3-14.3 J). The actual impact energy of foot-player contact is rarely measured and research using impact tests typically use estimates of body segment mass and inbound speed [7,8]. Ankrah and Mills (2003) [9] reviewed multiple shin guard test methods for their stud-impact specific test and found no other studies had considered stud impacts before. They estimated the stud impact energy at 10-13 J based on an effective foot mass of 0.62 kg and inbound speed of 6 m/s.

The wide variety of impact parameters used in previous research suggests a need for accurate measurements of foot-player contacts if test methods are to be representative and repeatable. The two main variables required for a simulated stamping impact are the inbound speed and impact force. Previously, other sports impacts have been quantified using pressure sensor technology [10–12]. Resistance-based force distribution sensors, such as the piezo-resistive pressure sensors made by Tekscan Inc (Boston, USA), are thin, flexible and give time-based results. Some problems with commercially available pressure sensors exist; mainly the influence of the calibration method on measurement accuracy [10,13,14]. First, the sensors are resistive and their response

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over their total capable measuring range is non-linear. When testing over a smaller loading range, sensor response within this range can appear linear [14]. Calibrating for the expected loading range is therefore important. Second, the rate at which the force is applied to the sensor, i.e. the loading rate, changes the behaviour of the sensor. When testing sports impacts which are dynamic in nature, it follows that a dynamic calibration procedure is recommended [10,15]. Finally, when applying constant force, piezo-resistive pressure sensors exhibit positive logarithmic drift [13]. When measuring pressure of force after initial impact, the output of the sensors needs to be corrected for this drift. After comparing standard calibrations from Tekscan Inc to custom calibrations, Brimacombe *et al.* (2009) [14] recommend user-defined calibration protocols to improve the measurement accuracy of the sensors. They also recommend to calibrate each sensor individually, since calibration equations can differ.

Obtaining kinetic and kinematic data from stud-player impact scenarios is non-trivial. It needs a lightweight, flexible system which is able to measure force and will be safe for participants to impact. Previous studies have successfully used pressure sensors for measuring in-play impact force in basketball [11] and rugby [12], but custom calibration methods need to be developed in order to optimise the accuracy of the sensors. This paper reports on an effective and simple calibration method for pressure sensors to measure peak impact force of the magnitude likely to be experienced during stud-player impacts in rugby union. The method is also applicable to other sport impact events.

2. Methods

Ethical approval for this study was obtained from the Health and Wellbeing ethical committee of Sheffield Hallam University.

2.1. Obtaining loading range parameters

To ensure the sensors were calibrated within a representative loading range, a pilot test was initially undertaken in which seven rugby players were asked to replicate stamping another player in the ruck. Participants were between 19 and 28 years old, weighed 80 ± 8 kg and had at least two years of experience playing rugby. The impact force of participants stamping directly onto the force plate was collected by a floor mounted force plate (9281CA, Kistler Instrument Corp, Winterthur, Switzerland; sample frequency 1000 Hz). Each participant repeated the stamp three times, giving a total of 21 stamps. Peak force was identified for each trial. The mean derivative of the loading phase (start impact to peak force) of the force trace was defined as 'loading rate', reported in N/ms. A 95% confidence interval (CI) of peak force was calculated for all stamps, as to define a range of forces for which the pressure sensors needed to be calibrated. This provides three impact energies; 95% CI lower bound, 95% CI upper bound and the mean.

2.2. Experimental set-up

Eight unused Tekscan F-scan 3000E 'Sport' flexible pressure sensors were used for evaluating the accuracy of force reconstruction after a custom calibration procedure within selected force ranges. An unmodified version of the Tekscan F-scan system was used in this research. Each sensor consisted of 954 force sensing elements called 'sensels'. Each sensel measures 2.5 by 2.5 mm giving a density of 3.9 sensels / cm^2. Each sensor was mounted on top of a portable force plate (9286AA, Kistler Instrument Corp, Winterthur, Switzerland) and protected by a 40mm thick sample of Silastic 3483 (Dow Corning Ltd, Michigan, United States). The loading rate response of various materials were analysed during pilot testing, and the silicone material Silastic 3483 was found most similar to loading rates observed in the initial stamping study. The material has also previously been found similar to *in-vivo* human tissue response by Hrysomallis (2009) [7]. The pressure sensor - force plate combination was impacted with a hemispherical head of 1.68 kg. Drop height was set at 58, 71 and 84 cm to replicate peak forces within the 95% CI range that was found in the stamping study. Raw pressure sensor data and vertical force was concurrently recorded by the pressure sensor system at 750 Hz and force plate at 3000 Hz.

2.3. Calibration procedure

Raw pressure sensor data was first resampled to 3000 Hz (matching the force plate sample rate) using spline interpolation with Matlab (R2014a, the Mathworks Inc, Massachusetts, United States). Pressure sensor and force plate signals were synchronised based on the peak pressure and peak force. For each trial, the time of peak force was identified and the sample time of the preceding three data points was also recorded (Figure 1). Force plate values and raw pressure sensor values at the four data points were extracted for the first four repeats only. This resulted in 16 pressure sensor and force plate data points for each test condition. The correlation between force and pressure sensor values were assessed using a polynomial fit. The coefficients for first, second and third order polynomials were calculated by minimising the sum of the squares of the error (Gauss's least squares approach). The polynomial with the lowest error was selected as the calibration relationship. One repeat for each test condition, and thus four data points per test condition, was not used for obtaining polynomial coefficients. These four data points were considered 'blind' and subsequently used to estimate the error of the custom calibration by applying the resulting calibration relationship to the raw pressure sensor data. The estimated peak force derived from the calibration of the blind pressure data was then compared to the measured peak force and the percentage error calculated.

Two pressure sensors were also calibrated with the manufacturer's recommended 'step' calibration procedure for dynamic testing [16] and both raw and calibrated data was obtained for these sensors. This made possible a comparison between the new custom calibration technique and the conventional technique.

3. Results

3.1. Loading range parameters

Seven participants repeated the stamp three times. Mean peak force of 21 stamps was 2328 N, with 95% CI [1834 N, 2821 N]. Mean loading rate over 21 trials was 254 N/ms with 95% CI [201 N/ms, 307 N/ms].

3.2. Test conditions

The corresponding drop hammer test conditions to replicate the loading parameters identified in the pilot study are shown in Table 1.

Table 1. Overview of test conditions of each sensor. Peak forces match those found in the initial stamping study.

	Drop mass (*kg*)	Drop height (*cm*)	Resulting peak force (*N*) and corresponding stamp force loading parameter
Condition 1	1.68	58	1834 *lower bound 95% CI*
Condition 2	1.68	71	2328 *mean peak stamp force*
Condition 3	1.68	84	2821 *upper bound 95% CI*

3.3. Sensor calibration

Eight different sensors were tested five times at conditions 1 - 3 (Table 1). Figure 1 shows an example force trace and corresponding raw pressure values. For each test condition 4 data points were recorded for each repeat (total n = 16). Using the Gaussian least squares method, a first order polynomial was identified as the best fit of the correlation between force and raw pressure values. This indicated that the calibration relationship was linear. Figure 2 (a - h) show the resulting linear calibration factor for each sensor.

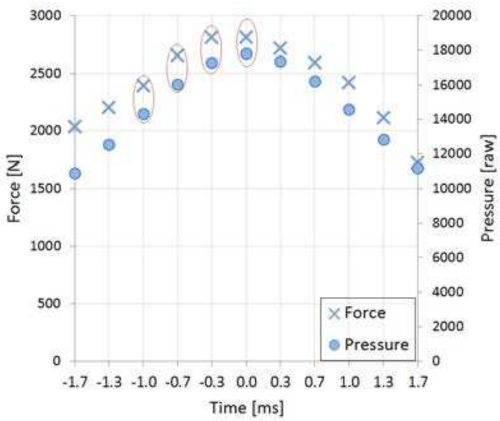

Fig. 1. Example force trace and raw pressure values. Peak force and three values leading up to peak force are highlighted in red circles

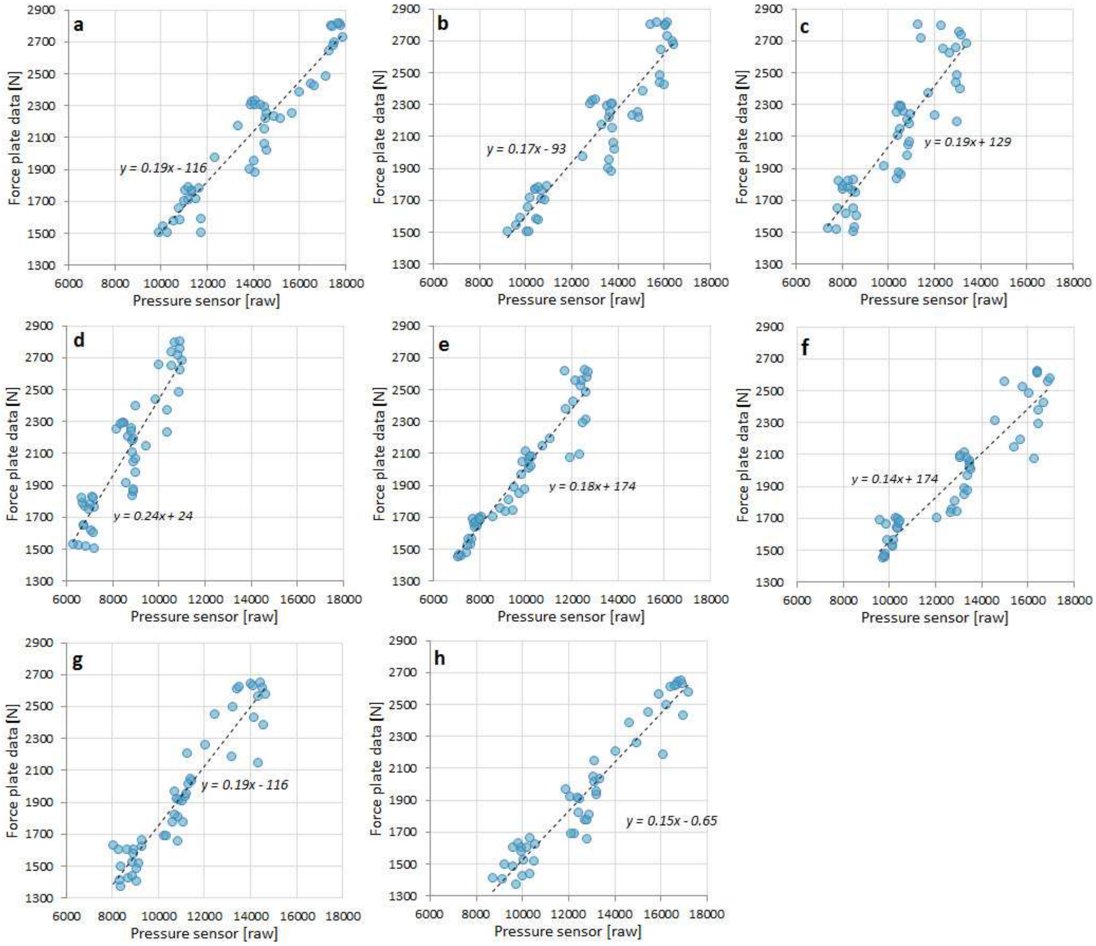

Fig. 2. Linear calibration within expected peak force range for (a) sensor 1; (b) sensor 2; (c) sensor 3; (d) sensor 4; (e) sensor 5; (f) sensor 6; (g) sensor 7; (h) sensor 8.

To assess the error of the resulting linear calibration factor, a blind set of raw pressure data collected during testing was used. The raw pressure values were calibrated using the linear calibration factor found for the corresponding sensor and the peak force values calculated. These were compared to the actual peak force measured on the force plate (Table 2). During the testing of sensor 1 and 2, Tekscan 'step' calibrated pressure sensor data was obtained next to the raw data. When comparing the Tekscan 'step' calibration results to the force plate data, the pressure sensors overestimated the peak force in both sensors (Table 2).

Table 2. Mean and standard deviation of the peak force measured from the force plate and compared to the custom and manufacturers calibration methods.

Condition	Peak force (*N*) from force plate	Loading rate (*N/ms*) from force plate	Error (%) of custom calibration process	Error (%) of manufacturers calibration process
1	1730 ± 75	278 ± 14	5.3 ± 1.7	134 ± 6.6
2	2169 ± 140	361 ± 26	7.5 ± 2.2	129 ± 3.8
3	2701 ± 87	460 ± 17	9.6 ± 7.6	134 ± 5.3
All	2200 (*n = 48*)	360 (*n = 48*)	7.5 ± 5.0 (*n = 96*)	132 ± 5.9 (*n = 30*)

4. Discussion

Piezo-resistive pressure sensor systems, such as Tekscan's F-scan pressure sensor system, are useful in biomechanical applications because they are lightweight, thin, flexible and safe to use. Previous research has highlighted the need for custom calibration methods with similar impact mechanics to its intended use, in order to improve the accuracy of measurement systems [10,13,15]. The expected force range of stamps in rugby was 1834 - 2821 N (95% CI). The 95% CI of the loading rate of simulated stamping was 201 N/ms - 307 N/ms. Conditions 1-3 of the calibration procedure aimed to replicate the range of peak forces found in the stamping test and established 2200N force. Loading rate was on average higher than the 95% CI at 360 N/ms. Lower drop heights were associated with lower loading rates (278 ± 14 N/ms for 58 cm).

The expected error of the measurement system is important for establishing confidence bounds and the interpretation of testing results. When minimising the sum of the squares of the errors with a first order polynomial, the error of the eight sensors was 7.5%. The error of the custom calibration is consistently lower than the error of Tekscan's standard calibration method, the 'step' calibration (mean ± SD: 132 ± 5.9%; $n = 30$).

Over time, pressure sensors can experience signal degradation, i.e., a loss of sensitivity. In dynamic loading situations, the effect of shear loads, loading between curved surfaces and small contact areas can all decrease measurement accuracy of pressure sensors [14] and it is difficult to predict this for future testing. Different types of data fitting were not tested in this study. Cazzola *et al.* (2013) [13] recommends a logarithmic regression to correct for drift when measuring longer contact times, as can be seen during rugby scrum impacts. In our pilot study we have seen that stud-player impact peak force can be expected at the first 40ms of the impact. Therefore no drift correction was applied to the signal. Non-linear fitting could prove itself useful when calibrating over a larger force range than was required for stud-player impact testing; it could be that the conductive response of the sensors is not directly proportional to the applied pressure. Calibrating each individual 'sensel' of the sensor separately has previously been shown to not have an effect on the magnitude of load measured [14].

Potential improvements for this calibration method would be to use a studded impactor instead of a hemispherical head, as to match the intended use more closely. Human-surface interaction is difficult to accurately simulate in a consistent way, and when aiming to match peak force and loading rate in our experimental set-up, a combination of silicone materials and a drop hammer machine presented the best results. Linear calibration methods produced error estimates of less than 10% within expected peak force loading ranges. It is currently unclear of a similar calibration approach would be equally effective for lower or higher force ranges than tested (1800 to 3000 N).

The findings of this study will be used in future experiments exploring the stud-player impacts which are thought to cause laceration injuries in rugby.

5. Conclusion

This study described a simple and effective calibration procedure for using pressure sensors when measuring stud-player impacts. Eight piezo-resistive pressure sensors were impacted with similar peak loads to rugby stamping impacts. The force range of the impacts was 1800 to 3000 N. The expected measurement error of the system after the standard manufacturers calibration was found to be 132 ± 6%; custom calibration reduced this error to 7.5 ± 5%. Linear calibration curves were found suitable for the application. This method shows that a calibration protocol simulating the expected peak force range - in this case 1800 to 3000 N - of the intended measure can reduce the error of a pressure sensor whilst using linear calibration coefficients.

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