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Development of a test methodology for the assessment of human impacts in sport

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Abstract

The study described in this paper aims to develop a suitable method for the measurement of contact forces, pressures and velocities of simulated human-on-human impacts typical of those experienced within American Football. A thin-film pressure sensor system was chosen to enable the impacts to be quantified, however, initial testing suggested that the measured impact forces were underestimated by circa 30% with the system calibrated in the standard, static pressure manner. A two-stage, dynamic calibration was therefore developed, in which the sensors were subsequently dynamically loaded in a manner more representative of the impacts, allowing an appropriate dynamic calibration factor to be derived. To determine the typical impact force levels experienced in a shoulder-on-thigh impact event, eight subjects were required to perform three “good” tackles at two different velocities. The processed results identified a peak, transmitted force of 1.1 (0.4) and 1.7 (0.5) kN for “low” and “medium” velocities respectively, with corresponding effective areas of application of 70 (22) cm^2 and 85 (25) cm^2 and contact times of 0.257 (0.098) s and 0.245 (0.112) s respectively.

Keywords: American football; impacts; contusions; forces; pressures; velocities

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1. Introduction

American Football (AF) is a full contact sport involving multiple high-speed/high-energy collisions between players. Despite the significant level of sports Personal Protective Equipment (PPE) worn, injury incidence is very high, with Ramirez *et al.* [1] reporting that high school players sustained 25.5 injuries per 100 players over two seasons, with 9.3 injuries per 10000 player-hours, and 8.4 injuries per 100

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session-hours. There are multiple classifications of injuries sustained within AF varying in severity from the less severe skin abrasions to the more severe nerve damage. Skin contusions and sprains/stains have been identified as the two most common types of injury, representing over 60% of all those reported [1]. To reduce the incidence rate of injury, particularly contusions, sports equipment manufacturers have recently developed multi-sport protective apparel which aims to protect vulnerable areas such as the thigh, hips, ribs and shoulders.

While the emergence of such protective equipment is clearly a positive development in terms of reducing both the probability of injury occurring and the severity of injury should it occur [2], it is clearly important to evaluate the effectiveness of such equipment for the prevention of injuries in the sports for which the equipment is intended [3,4]. The importance of incorporating representative materials into PPE testing was demonstrated by Milburn *et al.* [3] when they used a medicine ball, instead of the much stiffer striker used in standard hammer and anvil certification tests, since it was believed to be more representative of the characteristics of the human body. Pain *et al.* [5] also recognised this and incorporated compliance into their sensor calibration procedure. In order to develop more representative test methods, a greater understanding of the nature of the impacts that are to be protected against is required [6]. In this paper the development of a suitable methodology to measure such quantities in simulated human-human AF impacts is presented, with a shoulder-thigh impact case study described.

2. Methodology

2.1. System & sensor selection

Prior to testing it was important to determine which type of pressure sensor was most appropriate for the human-on-human impact testing. Commercially available sensors such as those of XSENSOR, novel and Tekscan were evaluated [7], with the strengths and weaknesses (including the cost) of each being considered. The evaluation determined that, although the XSENSOR option has a more reliable calibration, sampling rates were too low for this application since, in accordance with previous studies [5], the anticipated contact time in this human-on-human impact study was approximately 0.2 s. If using the XSENSOR, therefore, a maximum of 12 data points (i.e. 60 Hz) would be captured during the impact event, compared to 150 (i.e. 750 Hz) if using the Tekscan system.

In terms of the sensor itself, the Tekscan 3001E Sport, as shown in Fig. 1a, was selected for a number of reasons including: i) the density of individual “sensels” (**sen**se **el**ement**s**) is, at 3.9 cm^{-2}, the greatest of any of the off-the-shelf options, and ii) the additional tab length of 335.3 mm over the 182.6 mm 3000E would enable the “cuff” (interface to system electronics) to be located a reasonable distance away from the impact zone. A non-standard choice of dynamic range of 75 PSi (517.1 kPa) was chosen over the typical 125 PSi (861.8 kPa) since it was envisaged that the simulated impacts, purposefully designed for participant safety reasons to be of a lower level than those that occur in play, would result in such levels.

2.2. Sensor calibration procedure development

Prior to calibration the sensors were “equilibrated” in Tekscan software in the normal way, i.e. applying a constant, predetermined pressure to the sensor by means of an instrumented air bladder as shown in Fig. 1b. The 2-point software calibration similarly involved using the bladder to create an even pressure of 150 kPa (21.8 PSi) and 500 kPa (72.5 PSi) across the entire sensor. Once the calibration process was complete the sensor was checked for accuracy using the bladder with the pressure varied from 0 to 500 kPa to 0 in 100 kPa increments with a lead-time of 10 sec and a dwell at each incremental pressure of 5 sec; this procedure was repeated five times with the pressure-time profiles being recorded.

The applied pressure levels were compared with those reported by Tekscan and consistency between readings interrogated. The data indicated that the Tekscan pressure readings were consistent across all five repeats and were within 5% of the applied pressure in the case of pressure greater than or equal to

200 kPa as shown in Fig. 2a. The larger errors in readings below 200 kPa, are the result of a known limitation within the sensor: its non-proportional output variation over the first 10-20% of its range. Care must be therefore be taken to correctly specify the sensor range for the anticipated impact pressures.

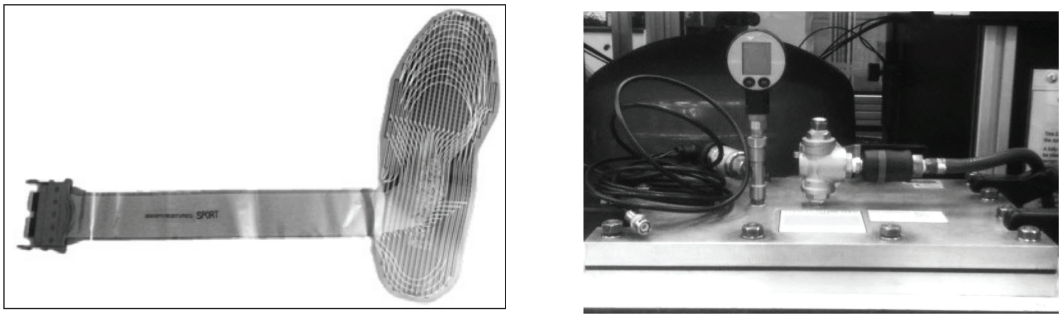

Fig. 1. (a) Tekscan F-Scan 3001E Sport sensor; (b) bladder set up for static sensor calibration & checks

In order to correct for the under-estimation of short duration pressure variations, the performance of the statically calibrated sensors was determined by subjecting a specific region of the sensor to instrumented drop tests as shown in Fig. 2b. Using an Instron Dynatup 9250HV, a flat-faced cylindrical 3kg impactor was used to dynamically load a 51 x 76 mm piece (engaging exactly 150 sensels) of 20 mm thick rubber by dropping it from a number of different heights (20, 30 & 40 mm). Again, five repeats were performed in order that increased confidence could be obtained in the recorded values. Triggered acquisition was used to collect force-time profiles; these were interrogated and the peak force for the first impact extracted. The results, as shown in Table 1 identify that the Tekscan system consistently underestimated the dynamic peak force values by circa 30%.

Table 1. Comparison of Instron load cell and Tekscan peak dynamic force readings for "sensor 0001"

Drop height (mm)	Instron load cell force (N)		Calibrated Tekscan force (N)		Delta (%)
	Mean	St. Dev.	Mean	St. Dev.	
20	2022	16.7	1341	30.5	33.7
30	2520	12.1	1722	58. 1	31.7
40	2867	13.3	1835	16.7	36.0

From this outcome it is apparent that the way in which the force is applied, i.e. the loading rate, plays a significant role in the behaviour of the sensor and, for this reason, a dynamic calibration is required to use the sensors for such data collection. Using the sensor static calibrated force value and the load cell force value, a dynamic calibration factor can be derived and used as a conversion factor for data obtained in impact events, thereby enabling the Tekscan reading to be representative of the actual force experienced. The derivation of this factor is shown in Table 2 as follows; the individual conversion factors for each drop are averaged to give a singular value with which subsequently acquired Tekscan force values can be multiplied. Clearly this is somewhat simplifying the matter but, in the interests of keeping the data processing simple, this was the procedure that was deemed suitable. Further work would look to improve this and, in doing so, better understand the variability in the Tekscan values that are observed.

Each sensor which was to be used for the human-human impact testing was calibrated for the range of forces in which it was to be used. In accordance with the information presented in previous studies [5,6], this range was 900 to 3400 N. Each sensor underwent a full calibration process: firstly the sensors were statically equilibriated and calibrated utilising air bladder; secondly they were dynamically calibrated by performing 12 drop tests, three drops, sufficient to obtain some confidence in consistency, at heights of 20 – 50 mm in 10 mm increments. The average calibration factor for each sensor was used as a conversion factor for the Tekscan data in the human-human testing; this is described in the next section.

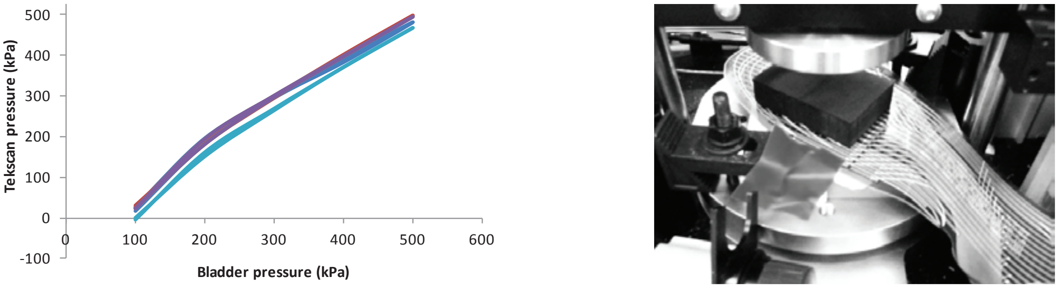

Fig. 2. (a) Accuracy and repeatability check for “sensor 0001”; (b) test setup for dynamic calib. of Tekscan sensors

Table 2. Dynamic calibration results and conversion factor derivation for “sensor 0001”

Drop ht. (mm)	Load cell force (N)	Tekscan raw	Static cal’d (N)	Pressure (PSi)	Conversion factor
20	1574, 1559, 1559	9962, 8790, 7249	1145, 1061, 977	49, 48, 48	1.37, 1.46, 1.59
30	1899, 1899, 1892	13081, 10509, 13079	1340, 1202, 1330	59, 59, 58	1.42, 1.58, 1.42
40	2180, 2194, 2231	14426, 15223, 15584	1396, 1444, 1472	67, 68, 69	1.56, 1.52, 1.52
50	2490, 2513, 2527	15143, 14383, 16049	1462, 1425, 1492	77, 78, 78	1.70, 1.76, 1.69
				Mean	1.55
				St. Dev.	0.12

3. Case study – shoulder-thigh impacts

The following case study details the initial human-human data collection to quantify impacts typical of simulated in-game situations. This case study focused on shoulder-thigh impacts typical of those experienced within AF.

3.1. Equipment set-up

To determine the “striker” velocity at impact, motion data were collected using a Charnwood Dynamics 4x Codamotion cx1 system sampling at 200 Hz. A raised platform (1.22 m x 2.42 m x 0.40 m) was located in the centre of the first half of the data collection area. The “target” was positioned on the edge of this platform in order that, as soon as possible after initial contact, the target would leave the platform thereby minimising complications due to ground-reaction force differences. For the velocity data capture, a marker was placed on each shoulder plate of the striker harness and one on base of the spine as shown in Fig. 3a; the impact velocity achieved was taken as the mean of these. The pressure data were captured using two Tekscan 3001E Sport sensors with a 75 PSi (517.1 kPa) range, sampled at 750 Hz. The sensors, orientated at 180° to one another as shown in Fig. 3b, were mounted directly on the thigh and were positioned to cover the area beneath the protective pad in typical AF protective shorts. The small overlapping region of sensels can be conveniently removed in software during post-processing.

3.2. Trials and subjects

Subjects participated in pairs with each subject performing three low velocity (1.7 ± 0.5 m/s) and three medium velocity (2.2 ± 0.5 m/s) tackles starting from a “3 point stance”. The target was positioned at right angles to the striker, taking the impact on their right hand side. After each tackle both the Coda and Tekscan data were checked to ensure no markers were occluded, that the tackle was performed at an appropriate velocity and that the impact was nominally located towards the centre of the pressure sensor pair. If the impact did not to satisfy on any of these tests, the trial was repeated.

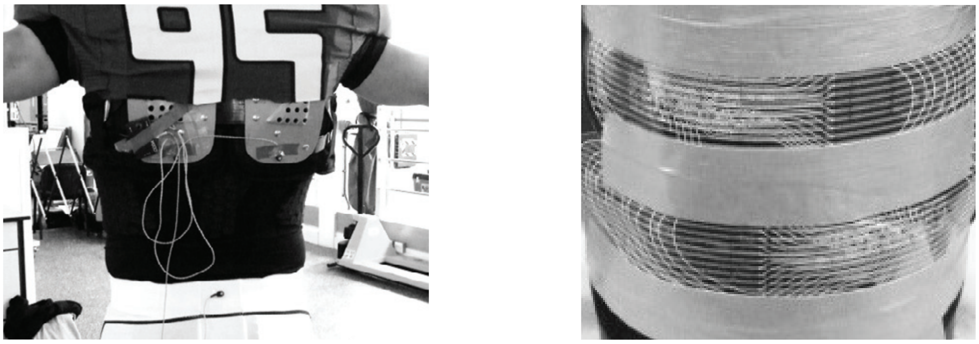

Fig. 3. (a) Marker setup for the striker; (b) pressure sensor setup for the subject

Eight participants were recruited from local Rugby and AF teams. Within the recruitment process, the desired height and mass guidelines were set as follows: 181 - 192 cm and 85 - 135 kg, respectively. All subjects were required to be in training at least twice per week and to be free from injury. Table 3 shows the mean statistics for the subjects.

Table 3. Subject statistics

	Age (years)	Mass (kg)	Height (cm)
Mean	20.5	97.4	183.3
St Dev.	1.9	9.9	5.9

3.3. Results

For all eight subjects, striker velocity was measured to ensure consistency between tackles. Mean impact velocity achieved for the low and medium velocity impacts was 1.74 ± 0.19 m/s and 2.18 ± 0.38 m/s, respectively. Force and pressure data were also measured; an example set of Tekscan force data for “subject 6” is presented in Fig. 4. Figs. 4a & 4b show the nett force-time profile for the impact event as recorded by the Tekscan sensors for an individual trial; Figs. 4c & 4d show the pressure map plot at the peak force level. Table 4 details the means and standard deviations for each of the key measurements for all eight subjects and all 24 repetitions of each impact. It is acknowledged that the variation in the various levels is related to the variation in the subjects’ mass etc. but pointed out that e.g. technique etc. also has an effect.

Table 4. Mean Tekscan and Codamotion data for all low and medium velocity impacts, Mean (St. Dev.)

Condition	Vel. (m/s)	Peak force (N)	Contact time (s)	Contact area (cm^2)
Low vel.	1.72 (0.19)	1178 (420)	0.257 (0.098)	70 (22)
Med. vel.	2.18 (0.38)	1747 (538)	0.245 (0.112)	85 (25)

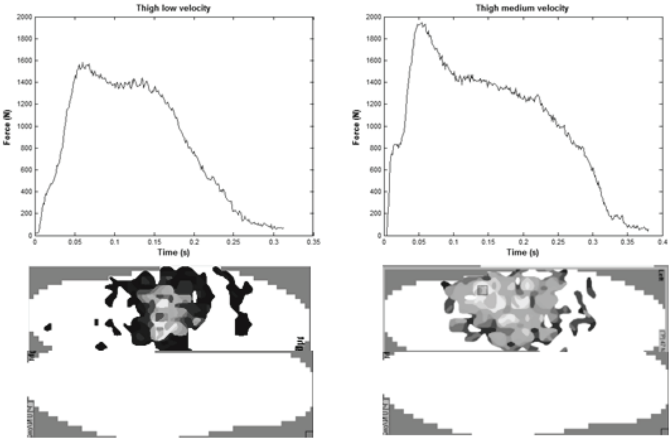

Fig. 4. Example Tekscan data for "subject 6": (a) & (b) force-time profiles; (c) & (d) pressure map plots at peak force

The results show that the mean velocity is reasonably consistent across both conditions with a clear velocity difference between the low and medium velocity impacts. A large increase in the peak force was observed as the impact velocity increased ($p < 0.05$), with peak force reaching a maximum of 1747 N in the medium velocity condition. No significant differences were found in regards to contact time ($p > 0.05$) between the two conditions. The contact area appears to increase with impact velocity, although statistical confidence was not achieved ($p > 0.05$).

4. Discussion and conclusions

The development of a suitable method to determine impact forces within AF tackles has been discussed, with a particular focus on sensor selection and calibration. It was determined that, in order to maximise pressure measurement accuracy, a two-stage calibration process was required. An example case study was discussed in which measurements of thigh impacts at low and medium velocities were taken. The results highlight the importance of identifying the "tackle intensity" experienced within game situations as it has significant affects on the peak force observed. Through the increased understanding of such human-on-human impacts with it is possible to develop more representative mechanical test methods to be used within the product development process as well as for product safety certification.

Acknowledgement

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