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Stephen Tiernan
Technological University Dublin, stephen.tiernan@tudublin.ie

Gary Byrne
Technological University Dublin

David Michael O'Sullivan
Division of Sport Science, Pusan National University, Busan, Republic of Korea,
davidosullivan@pusan.ac.kr

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Evaluation of skin-mounted sensor for head impact measurement

Stephen Tiernan[1] [iD], Gary Byrne[1] and David Michael O'Sullivan[2]

Abstract

The requirement to measure the number and severity of head impacts in sports has led to the development of many wearable sensors. The objective of this study was to determine the reliability and accuracy of a wearable head impact sensor: xPatch, X2Biosystems, Inc. The skin-mounted sensor, xPatch, was fixed onto a Hybrid III headform and dropped using an impact test rig. A total of 400 impacts were performed, ranging from 20g to 200g linear acceleration, and impact velocities of 1.2 - 3.9 m/s. During each impact, the peak linear acceleration, angular velocity and angular acceleration were recorded and compared to the reference calibrated data. Impacts were also recorded using a high-speed video camera. The results show that the linear acceleration recorded by the xPatch during frontal and side impacts had errors of up to 24% when compared to the referenced data. The angular velocity and angular acceleration had substantially larger errors of up to 47.5% and 57%, respectively. The location of the impact had a significant effect on the results: if the impact was to the side of the head, the device on that side may have an error of up to 71%, thus highlighting the importance of device location. All impacts were recorded using two separate xPatches and, in certain cases, the difference in angular velocity between the devices was 43%. In conclusion, the xPatch can be useful for identifying impacts and recording linear accelerations during front and side impacts, but the rotational velocity and acceleration data need to be interpreted with caution.

Introduction

Concussion in sport is very prevalent, with between 1.6 and 3.8 million sports-related concussions in the United States each year.[1] The diagnosis of concussion is particularly difficult with many studies reporting that approximately 50% of concussions go unreported.[2,3] The 5th international conference on concussion in sport defined concussion as a complex pathophysiological process affecting the brain, induced by biomechanical forces.[4] These biomechanical forces may be induced from a combination of direct and indirect head impacts, causing both linear and rotational motions.[5] Abel et al.[6] conducted research in 1978, using monkeys, to investigate the effects of head and brain motion during impacts; they concluded that rotational acceleration in particular was linked to concussive injuries. Furthermore, they stated that, following an impact, rotational motion is the primary cause of strain in brain tissue. Research has since validated this theory in terms of human injuries.[7–9] In addition, the magnitude of strain, which the brain undergoes during an impact, has been determined to be dependent on both the magnitude of the impact and the impact location.[10–13]

In 2003, the first wireless impact sensor was developed to measure the severity of impacts in American football.[14] The Head Impact Telemetry System (HITS) sensor, developed by Simbex, Inc., is an array of six or nine accelerometers embedded in a football helmet. Its accuracy has been investigated by various groups and determined to be dependent on the fit of the helmet to the head.[15,16] It has been used in numerous American football studies[17,18] and also in boxing.[19] Due to the fact that not all contact sports utilise a helmet for protection, other wireless sensors have been developed,

[1]Technological University Dublin, Dublin, Ireland
[2]Division of Sport Science, Pusan National University, Busan, Republic of Korea

Corresponding author:
David Michael O'Sullivan, Division of Sport Science, Pusan National University, 2, Busandaehak-ro 63 beon-gil, Geumjeong-gu, Busan 46241, Republic of Korea.
Email: davidosullivan@pusan.ac.kr

such as instrumented mouthguards (X2Biosystems, Inc.), headbands (Sim-G; Triax Technologies, Inc.)[20] and skin patches (xPatch; X2Biosystems, Inc.). These have been used in studies of head impacts in unhelmeted sports such as soccer[21,22] and rugby.[23]

To date, the majority of studies on the accuracy of head impact sensors have used a Hybrid III headform[24,25] fitted with a reference a triaxial linear accelerometer and a triaxial gyroscope positioned at the centre of gravity. The Hybrid III dummy headform has a viscoelastic skin, the response of which is strain independent up to strains of 20%.[26] In a recently published study, helmet-mounted and head-mounted acceleration sensors were tested.[25] The study used a Hybrid III headform fitted with a Riddell helmet, and data were collected from a number of sensors, including the HITS and the xPatch. The results found that the xPatch peak linear acceleration (PLA) errors ranged from 7.7% to 57.9%, while peak angular acceleration (PAA) errors ranged from 9.5% to 245.6%. This study utilised an impulse hammer and impacted the head in seven locations, where the majority of impacts were below 80g (PLA). A study by Schussler et al.[27] in 2017 on the accuracy of the xPatch found PLA errors of up to 31% and PAA errors up to 23.4%; this study impacted a Hybrid III head fitted with a lacrosse helmet. Despite these errors and unlike other studies, they concluded that the xPatch device measurements highly correlated with their reference device.

Rowson et al.[18] used the xPatch to record 8999 head impacts in women's collegiate soccer, and only 1703 of these could be confirmed by video analysis, thus resulting in a positive prediction rate of only 16.3%. One of the few studies on the accuracy of the xPatch using an unhelmeted headform was undertaken by Nevins et al. in 2015. Their study was limited in that they only impacted the head in two frontal locations using three types of soft balls; they found that the xPatch had errors of approximately 25% for PLA and underpredicted PAA by 25%–35%.[28]

Unhelmeted impacts are quite different to helmeted impacts as the acceleration pulses are of a short duration and contain higher frequency components. This study addresses a number of issues not addressed in the other studies: how does the xPatch sensor perform in unhelmeted impacts above 80g; how does it perform during impacts to the side and rear of the headform; how does the device's output compare when fitted to the left-hand side (LHS) and right-hand side (RHS) of the head. Unlike other investigations, this study investigated the accuracy of the device over its full range (20g–200g) following impacts in four directions to an unhelmeted head.

Methods

This study tested the accuracy and repeatability of the xPatch sensor developed by X2Biosystems. The sensor is a six-degree-of-freedom measurement device, consisting of three single-axis accelerometers and three angular rate sensors. The device measures 37 mm by 14 mm and is designed to attach to the skin over the mastoid process (behind the ear) of the athlete. During an impact, linear acceleration in x, y and z is recorded, as well as rotational velocity about the three axes. Data are recorded by the device for 100 ms with the sampling rates of 1000 and 800 Hz for linear acceleration and angular velocity, respectively. The acceleration data are transformed to calculate linear acceleration at the centre of gravity of the head. Rotational acceleration is calculated from rotational velocity using five-point differentiation. Both the transformation and differentiation were carried using the software supplied by X2Biosystems. The equations for the transformation and differentiation are unavailable to the user, as they are embedded in the software. The transformation is based on equation (1) (below), where a_{CG} is the linear acceleration at the centre of gravity of the head, a_P is the linear acceleration recorded by the device, ω and α are the angular velocity and acceleration of the head, respectively, and r_{p-CG} is the geometric relationship between the device and the centre of gravity of the head[27]

$$a_{CG} = a_P + \left(\alpha \times r_{p-CG}\right) + \omega\left(\omega \times r_{p-CG}\right) \tag{1}$$

Two xPatches were fixed according to the manufacturer's instructions, to a 50th percentile Hybrid III dummy headform. The xPatches were attached using the manufacturer's adhesive patches, to the left and right sides of the head, in the area of the mastoid part of the temporal bone as recommended by X2Biosystems, Inc.: 72 mm from the head's centre of gravity to the inside edge of the xPatch (Figure 1).

Reference devices consisting of a triaxial linear accelerometer (Kistler 8688A) and three angular rate sensors (DTS ARS12K) were mounted at the centre of gravity of the headform on a block supplied by the manufacturer (Humanetics, Inc.). The reference data were sampled at 10,000 Hz, and 200 ms of data were recorded per impact. Linear acceleration was filtered at 1000 Hz and rotational velocity was filtered at 300 Hz. Fast Fourier transformation within LabVIEW (National Instruments)[29] was used to calculate the amplitude spectrum and verify these as suitable frequencies, that is, no loss of data. A forward finite difference method was computed to determine rotational acceleration (equation (2)). All reference data were recorded using a customised LabVIEW 2015 program

$$f'(x) = \frac{f(x + 5h) - f(x)}{5h} \tag{2}$$

Impacts were created by allowing the headform to drop in a purpose-built drop test rig and impact a steel hemispherical anvil of 0.12 m diameter (Figure 1). As skull fracture is not being investigated, the diameter of this impactor is not considered significant. A wide variety
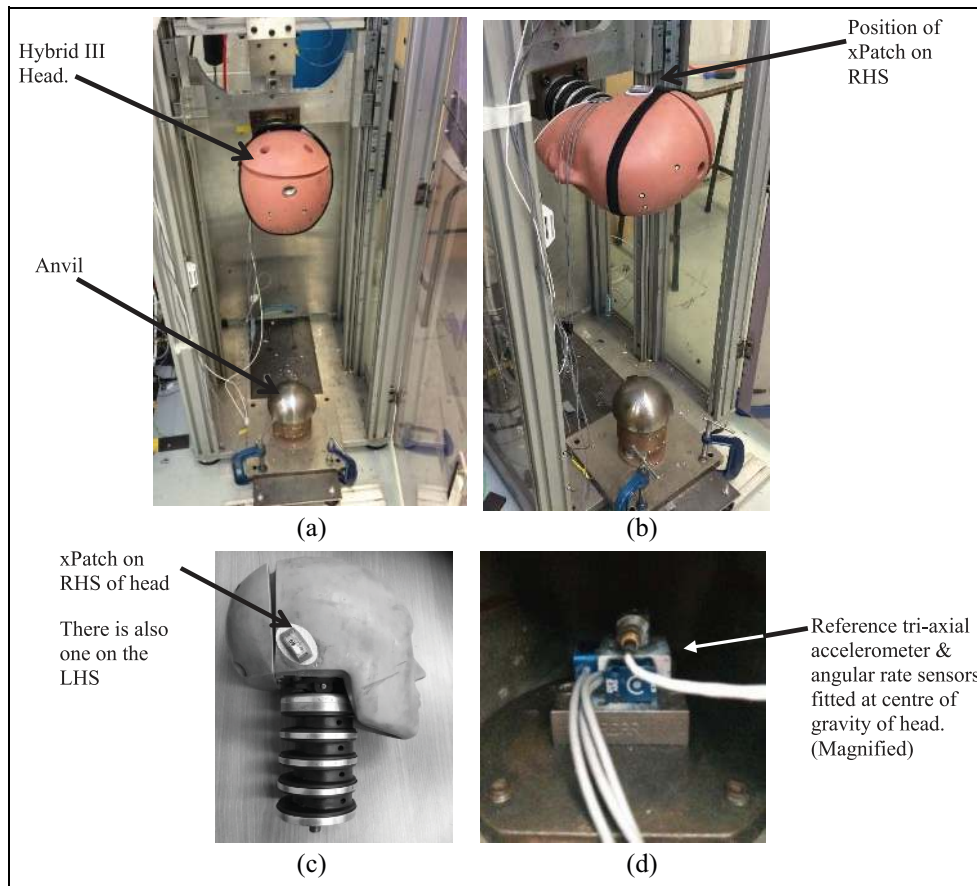
Figure 1. (a) Drop test rig (view 1), (b) drop test rig (view 2), (c) drop Hybrid III head with xPatch attached and (d) reference sensors.

of impactors have been used in previous studies.[25,27,28,30] The Hybrid III head was rigidly attached to the cross bar of the apparatus, and this cross bar was constrained so as to allow only vertical movement. This constraint ensured consistency in the repeatability of the tests (sample results in Table 1). Following an impact, the rotation of the head is a function of the stiffness of the neck, as the base of the neck is rigidly constrained in the vertical direction.

The test conditions were designed to cover the sensors' full linear acceleration range of $20g$–$200g$; this corresponded to the drop heights of 160–610 mm. The testing procedure consisted of a total of 10 drop heights, and each test was repeated 10 times. Impacts were to four locations: left side, right side, front and rear of the head (Figure 2). Thus, a total of 400 tests were conducted. A sample of the linear acceleration results from a drop of 360 mm is shown in Figure 3, and the duration of the impact in this case is 12.5 ms.

A sample of the results from a front drop height of 360 mm is shown in Table 1, the PLA average was $62.83g$ (standard deviation (SD) = 1.80), rotational velocity is 20.07 rad/s (SD = 1.62) and the average calculated rotational acceleration was 5135.82 rad/s (SD = 1062).

This study was exempt from institutional review board (IRB) approval as it did not involve human participants as outlined by the code of federal regulations (45 CFR 46.102(f)).

Results

Linear acceleration

An analysis of the data found that all the impacts were recorded by the xPatch, that is, no missing impacts (Table 2). Pearson's correlation coefficient and predicted residual error sum of squares (PRESS) statistic were calculated to investigate the reliability of the data and to provide a summary measure of fit of the model to the data.

The correct location (left, right, front and rear) of the impact was also recorded by both xPatches. When impacted in the front, the linear acceleration of the xPatch device correlated well with the reference accelerometer: $R^2 = 0.9527$; PRESS statistic = 5403 for the LHS and $R^2 = 0.9471$; PRESS statistic = 5403 for the RHS (see Figure 4).

The xPatch overestimated the linear acceleration during a frontal impact. This overestimation was on average 16.9% for the LHS xPatch and 23.7% for the RHS xPatch (Figure 5).

The linear acceleration for the RHS and LHS impacts had a poorer correlation than the frontal impacts. The xPatch device on the side that was being

Table 1. Sample results from 10 repeated impacts to the front (forehead) of the headform.

No.	Test time	Reference sensors			xPatch LHS			xPatch RHS		
		Linear Accel. (g)	Rot. Velocity (rad/s)	Rot. Accel. (rad/s)	Linear Accel. (g)	Rot. Velocity (rad/s)	Rot. Accel. (rad/s)	Linear Accel. (g)	Rot. Velocity (rad/s)	Rot. Accel. (rad/s)
1.0	14:30	65.58	19.42	4866.1	79.45	23.64	4395.0	79.33	17.33	4008.0
2.0	14:33	63.74	22.08	4028.0	77.00	23.80	4356.9	77.44	17.69	4151.5
3.0	14:36	61.70	19.80	3668.2	79.88	24.14	4629.7	85.00	27.41	4242.7
4.0	14:39	61.23	21.46	5653.6	75.00	23.85	4435.6	77.95	21.45	4060.0
5.0	14:42	67.03	21.20	6106.2	77.04	23.49	4445.7	82.03	18.29	3943.8
6.0	14:45	60.37	19.08	4724.1	77.43	24.35	4609.0	84.48	28.54	4330.4
7.0	14:48	60.71	20.16	7026.2	78.62	24.57	4667.9	82.38	26.30	4319.6
8.0	14:51	62.44	19.37	6496.6	80.71	24.36	4601.4	83.49	25.22	4256.4
9.0	14:54	62.84	16.28	4366.2	77.70	23.26	4243.0	85.23	26.27	3879.2
10.0	14:59	62.70	21.84	4423.0	78.02	24.52	4636.1	82.72	24.20	4369.3
Standard deviation		2.01	1.63	1065.8	1.57	0.43	137.9	2.70	4.03	165.25
Average		62.83	20.07	5135.8	78.08	24.00	4502.0	82.01	23.27	4156.1

LHS: left-hand side; RHS: right-hand side.
Drop height was 360 mm. Linear acceleration, rotational velocity and calculated rotational accelerations are given for the reference sensors and the xPatches fixed to the LHS and RHS of the headform.
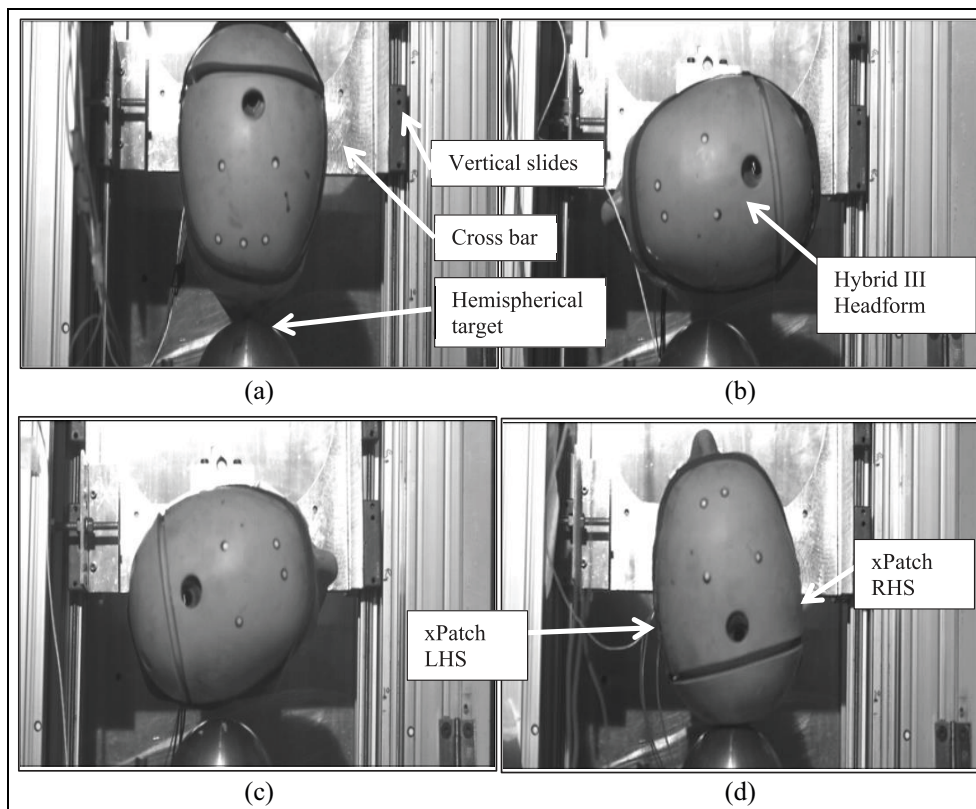

Figure 2. Sample drop from 360 mm to (a) front, (b) left, (c) right and (d) rear. Images were taken from high-speed video of impacts.

impacted overestimated impacts over 110g by 9% and underestimated impacts under 90g by 16%. The device on the opposite side to the impact overestimated impacts over 110g by 14.5% and underestimated impacts under 90g by 13%. Figures 6–8 show box plots of the median and interquartile range of the linear acceleration recorded by Kistler reference accelerometer and the xPatch devices on the LHS and RHS of the head.

The results recorded from the rear impact tests had a poor correlation to the reference data (R^2 for LHS = 0.7311, R^2 for RHS = 0.7021).

Similar to the side impacts, the xPatch overestimated the more severe impacts. The xPatch applied to the
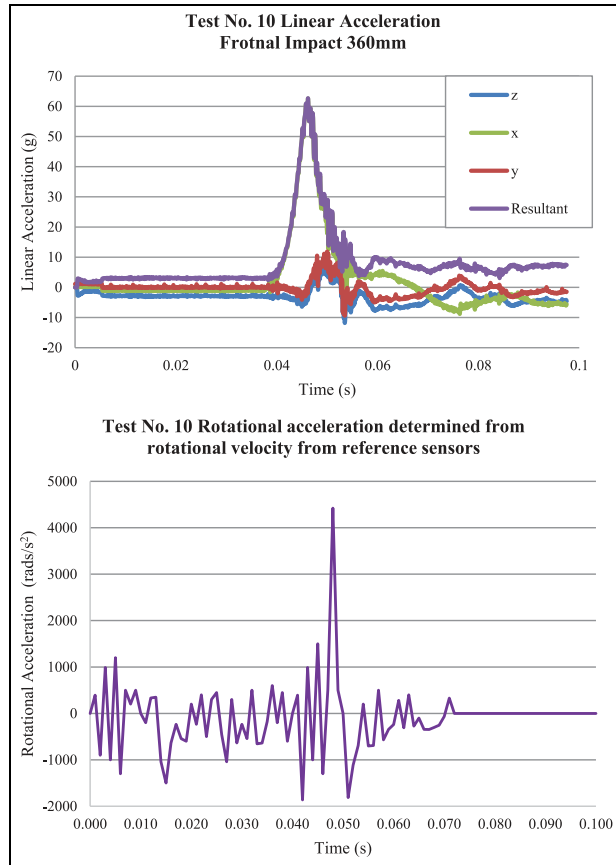
Figure 3. Linear and rotational acceleration following a frontal impact from a drop height of 360 mm (test no. 10).

LHS of the headform underestimated impacts over 130*g* on average by 5% and overestimated impacts under 120*g* by 30%, on average. The xPatch applied to the RHS overestimated impacts over 100*g* by 20% on average and underestimated impacts under 90*g* by an average of 30%.
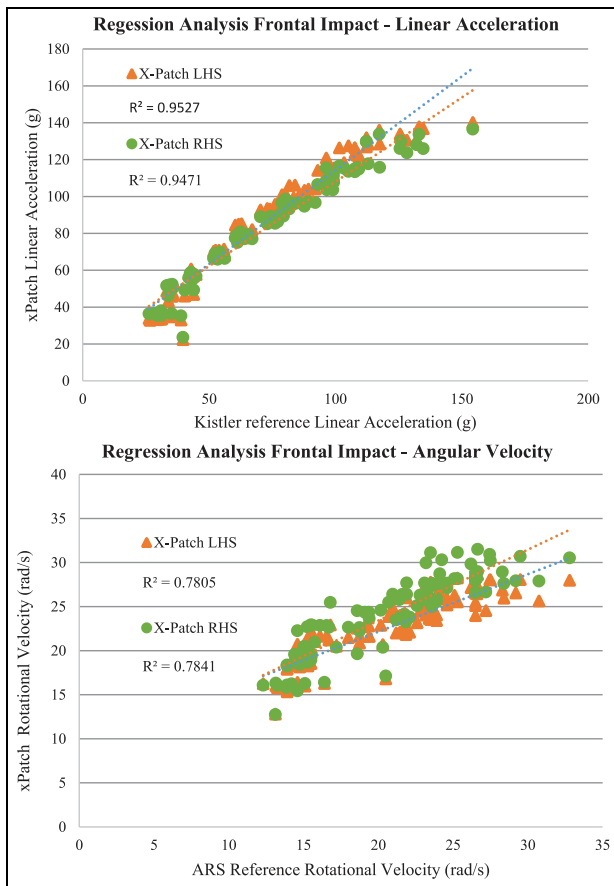
Rotational velocity

It was found that the rotational velocity correlation with the reference device was not as good as that for linear accelerations (R^2 for LHS = 0.7841; PRESS statistic = 566.5, R^2 for RHS = 0.7805; PRESS statistic = 549.3). The xPatch overestimated the rotational velocity on average by 17.4% for the sensor on the LHS of the headform and 13.9% for the RHS of the headform (see Table 3).

The side impact results revealed a significant difference between the xPatches on the RHS and LHS of the headform, with the device on the opposite side to the impact performing better than the device on the impact side. The device on the side of the impact overestimated the velocity by an average of 47.5%, while the device on the opposite side of the impact overestimated the velocity by 23%.

It can also be found from the xPatch results from the rear impacts that the devices overestimated the angular velocity on average by 20% for the device on the left of the headform and 33% for the device on the right. Rear impacts provided the best rotational velocity correlation, with the referenced data (R^2 for LHS = 0.8896, PRESS statistic = 68×10^6 and R^2 = 0.7919 for RHS, PRESS statistic = 72×10^6).

Rotational acceleration

Rotational acceleration produced results that had a poor to medium correlation (R^2 = 0.28–0.88) with the reference data. The error in the results from the xPatch varied depending on head orientation, xPatch location and impact magnitude. The xPatch underestimated the angular acceleration during frontal impacts with an average error of 14.3% for the LHS device and 19.6% for the RHS device; the errors were substantially higher

Table 2. Summary of linear acceleration results for frontal impacts.

Drop height (mm)	Reference sensors			xPatch LHS				xPatch RHS			
	Average (*g*)	Std. Dev.	Standard error of mean	Average (*g*)	Std. Dev.	Standard error of mean	%Error	Average (*g*)	Std. Dev.	Standard error of mean	%Error
610	127.57	11.84	3.95	129.72	5.86	1.75	1.69	133.73	0.41	1.25	4.83
560	108.81	4.23	1.83	115.34	3.55	0.40	6.00	125.34	0.32	0.90	15.19
510	97.67	2.57	0.86	108.41	1.64	1.00	10.99	115.04	0.28	0.71	17.78
460	85.16	3.96	1.32	96.14	4.27	0.44	12.89	102.51	0.26	0.64	20.37
410	75.41	2.56	0.85	87.71	2.98	0.54	16.31	93.49	0.48	0.37	23.98
360	62.83	1.80	0.60	78.08	2.48	0.50	24.27	82.01	3.51	0.85	30.51
310	53.41	1.15	0.47	67.41	2.07	0.39	26.21	69.99	0.26	0.37	31.03
260	42.85	0.41	0.17	57.02	1.68	0.40	33.06	58.24	0.36	0.42	35.91
210	36.42	3.08	0.00	46.87	7.14	0.45	28.70	50.85	0.23	0.58	39.64
160	30.86	3.64	1.50	33.51	11.11	1.14	8.59	36.17	0.28	1.29	17.22

LHS: left-hand side; RHS: right-hand side.
Results for reference sensors and LHS and RHS xPatches are given as well as percentage errors between the xPatch devices and the reference devices.

Figure 4. Linear acceleration and rotational velocity – regression analysis for frontal impacts. Reference device data are compared to xPatch LHS and RHS data.

Figure 5. Linear and rotational acceleration following a frontal impact; LHS and RHS xPatch and reference data are shown.
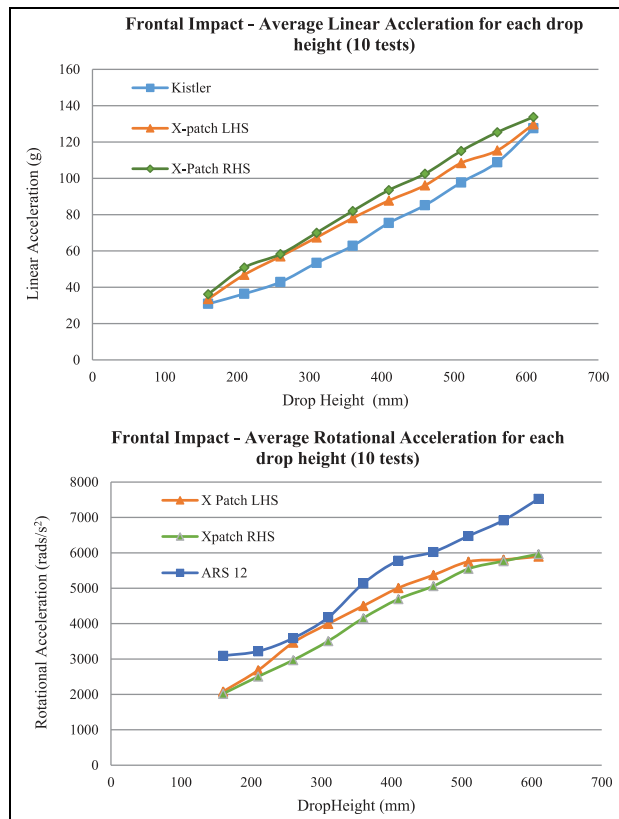
for impacts to the side and rear of the headform (see Table 4).

Impacts to the side of the head had an overestimation error of 46.5% for the device on the impact side and an average underestimation error of 52% for the device on the opposite side to the impact.
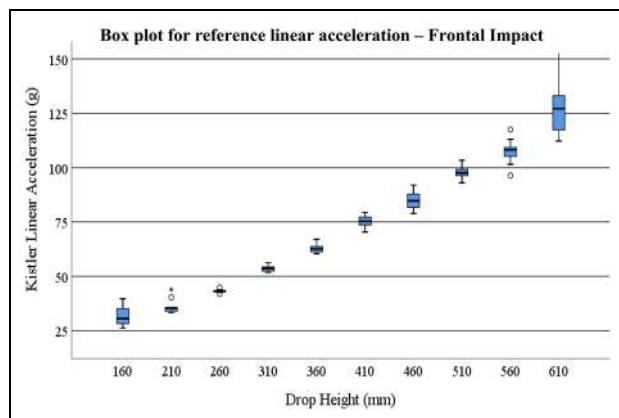
Rear impacts had an error of −57% for the LHS xPatch and 12% for the RHS xPatch. The rotational acceleration from the xPatch had very poor accuracy and consistency when the headform was impacted to the side and rear. The largest error was a 71% underestimation compared to the reference sensor; this was recorded during impacts to the right side of the headform. The errors for all impacts are summarised in Table 5.

Discussion

This study assessed the performance of the xPatch sensor in laboratory conditions by comparing the recorded measurements with calibrated reference devices. The results illustrate that the xPatch provides a reasonable indication of linear acceleration during frontal impacts, but with a possible overestimation of up to 18%. This overestimation error was in keeping with Wu et al.'s[31] study of low-speed impacts (overestimation of 15g) and
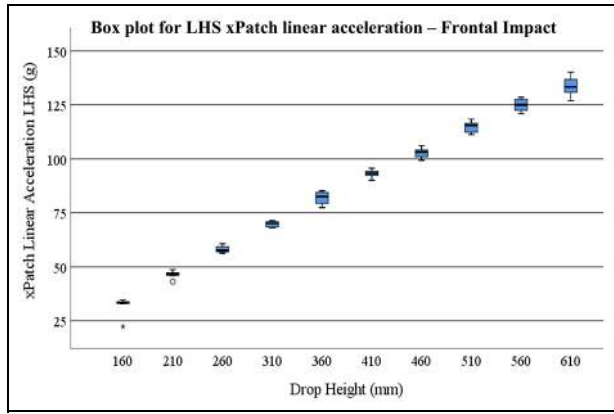

Figure 6. Box plot of median and interquartile range for the linear acceleration recorded by the reference Kistler accelerometer for each drop height.

Schussler et al.'s[27] study of helmeted impacts (PLA error 22%). The rear impacts had errors of up to 30% and perhaps of greatest concern is the underestimation of severe ($>110g$) impacts; this underestimation has not been reported in other studies. Angular velocity errors were large (up to 47.5%) and hence the rotational acceleration errors were also large (57%), as this is derived from the rotational velocity. This study

Figure 7. Box plot of median and interquartile range for the linear acceleration recorded by the xPatch on the left-hand side of the headform for each drop height.
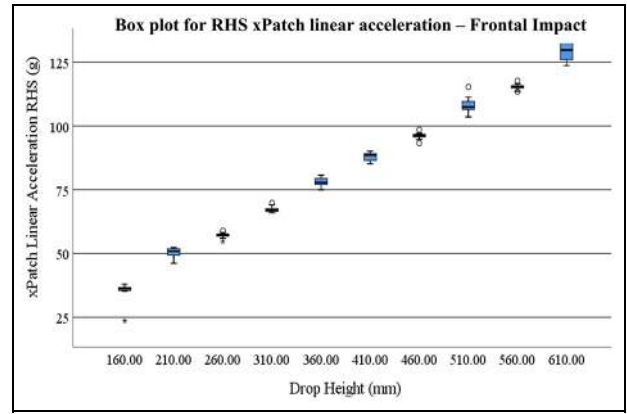
Figure 8. Box plot of median and interquartile range for the linear acceleration recorded by the xPatch on the right-hand side of the headform for each drop height.

found that rotational acceleration was underestimated by the xPatch; this was similar to Nevins et al.'s[28] findings from their study of frontal impacts. Unlike Nevin et al.'s study, this investigation also tested severe frontal, side and rear impacts; these were found to produce substantially higher errors (up to 71%). A study by Siegmund et al.,[32] using the xPatch with a helmeted cadaver, reported much larger errors of PLA (64% ± 41%) and PAA (370% ± 456%); this was not broken down by impact location. The large discrepancy between the xPatch and the reference sensor data in Siegmund et al.'s[32] study may be partly a result of the degree of coupling between the head and the xPatch: when attached to human skin, the device may move up to 4 mm relative to the skull, even during low impacts.

During the data processing, it was found that the sampling rate of both the reference data and the xPatch data was critical in acquiring accurate results. The xPatch is reported to sample linear acceleration at 1000 Hz and angular motion at 800 Hz.[31] The low sampling frequency may be a possible cause for the underprediction of results. Unhelmeted impacts require a higher frequency and bandwidth than helmeted sports, due to the shorter duration of the impact. This requirement will have a greater influence on the accuracy of the angular motion data as it has been found that, for dummy helmeted impacts, gyroscopes require bandwidths of 500 and 740 Hz if numerical differentiation is used to calculate rotational acceleration.[31] The bandwidth of the gyroscopes in the xPatch may be too low as it has been reported that most of these sensors have a bandwidth of 110 Hz.[31] In this study, both the reference and the xPatch rotational acceleration data were computed using a numerical differentiation method. This method amplifies the noise on the signal, and this was particularly apparent on severe impacts where large errors in the rotational acceleration data occurred. In future work, it would be interesting to use a six- or

Table 3. Summary of rotational velocity for frontal impacts.

Drop height (mm)	Reference sensors			xPatch LHS				xPatch RHS			
	Average (rad/s)	Std. Dev.	Standard error of mean	Average (rad/s)	Std. Dev.	Standard error of mean	%Error	Average (rad/s)	Std. Dev.	Standard error of mean	%Error
610	25.49	3.59	1.20	30.62	0.52	0.17	20.14	27.90	0.41	0.14	9.45
560	25.01	2.22	0.71	28.45	0.41	0.15	13.76	26.74	0.32	0.10	6.92
510	23.93	2.31	0.77	27.67	0.28	0.14	15.66	25.62	0.28	0.10	7.06
460	23.37	1.88	0.68	26.56	0.45	0.16	13.68	24.15	0.26	0.10	3.36
410	21.81	2.00	0.67	25.58	0.27	0.10	17.29	23.76	0.48	0.17	8.93
360	20.07	1.62	0.54	19.50	2.94	0.14	2.84	23.27	3.51	0.14	15.95
310	16.96	1.49	0.55	22.70	0.19	0.08	33.82	21.43	0.26	0.12	26.32
260	16.25	1.81	0.63	20.13	0.44	0.17	23.87	20.40	0.36	0.15	25.50
210	15.35	1.22	0.65	18.30	0.25	0.17	19.25	18.63	0.23	0.17	21.43
160	14.07	1.07	0.37	15.97	0.32	0.37	13.46	16.04	0.28	0.34	13.96

LHS: left-hand side; RHS: right-hand side.

Results for reference sensors and LHS and RHS xPatches are given as well as the percentage errors between the xPatch devices and the reference devices.

Table 4. Summary of rotational acceleration for frontal impacts.

Drop height (mm)	Reference Sensors			LHS xPatch				RHS xPatch			
	Average (rad/s^2)	Std. Dev.	Standard error of mean	Average (rad/s^2)	Std. Dev.	Standard error of mean	%Error	Average (rad/s^2)	Std. Dev.	Standard error of mean	%Error
610	7526.5	1150.3	517.1	5896.5	290.8	96.9	21.7	5966.0	252.5	84.2	20.7
560	6919.7	724.8	597.2	5806.6	161.0	62.0	16.1	5766.0	127.1	49.7	16.7
510	6477.4	809.5	288.8	5751.6	95.8	33.9	11.2	5547.5	42.5	18.8	14.4
460	6024.7	1311.0	796.6	5372.6	134.3	46.1	10.8	5062.1	132.4	44.6	16.0
410	5780.6	1625.0	541.7	5007.4	47.4	21.2	13.4	4693.3	121.4	40.6	18.8
360	5135.8	1062.0	355.3	4502.0	6.9	46.0	12.3	4156.1	0.3	55.1	19.1
310	4176.9	798.1	565.2	3996.2	91.5	42.1	4.3	3507.5	71.8	29.3	16.0
260	3590.1	262.3	151.0	3465.1	61.9	28.3	3.5	2970.1	38.9	13.1	17.3
210	3218.1	619.8	221.3	2682.7	31.9	16.8	16.6	2504.9	33.8	17.3	22.2
160	3093.1	613.6	431.7	2079.9	30.5	62.8	32.8	2018.0	26.5	60.0	34.8

LHS: left-hand side; RHS: right-hand side.
Results for reference sensors and LHS and RHS xPatches are given as well as the percentage errors between the xPatch devices and the reference devices.

Table 5. Summary of average errors (xPatch on the LHS and RHS relative to the reference device).

	Frontal impact		Side impact		Rear impact	
	LHS xPatch	RHS xPatch	xPatch on the side of impact	xPatch on the opposite side	LHS xPatch	RHS xPatch
Peak linear acceleration	+16.9%	+23.7%	+9% > 110g −16% < 90g	+14.5% > 110g −13% < 90g	+5% > 110g −30% < 90g	+20% > 110g −30% < 90g
Rotational velocity (%)	+17.4	+13.9	+47.5	+23	+20	+33
Peak rotational acceleration (%)	−14.3	−19.6	+46.5	+52	−57	+12

LHS: left-hand side; RHS: right-hand side.

nine-accelerometer array as used in some other studies[33] to eliminate the requirement for numerical differentiation.

This study demonstrates the usefulness of the xPatch for identifying and recording impacts, as all of the impacts tested were recorded, that is, no false positives or negatives. However, it must be noted that our study had a controlled setup and is unlike in-field testing; the study by Press and Rowson[30] which resulted in a positive head impact prediction rate of 16.3% questions the reliability of the sensor on the field and highlights the need for video confirmation of all impacts. Recording all head impacts accurately, without either over- or underprediction, is important in studies of player welfare.[34,35] To date, the xPatch sensor has been used to collect cumulative data in helmeted[31] and unhelmeted sports.[23] King et al.[23] utilised the xPatch to measure the magnitude, frequency and location of head impacts sustained by under 9s Rugby Union players over the course of four consecutive matches. A study indicating the usefulness of such sensors in regard to player's welfare was undertaken by Swartz et al.[36] They conducted a study over the course of an American Football season and used the xPatch with two separate cohorts of players. The objective of the study was to analyse the head impacts of a group who practised unhelmeted drills against those who practised with helmets. It was determined that there was a 28% reduction in head impact frequency recorded by the group that did not use helmets during practices.

Accurately recording the occurrence, magnitude and direction of all impacts is critical in any investigation of head impacts. This study has highlighted that the results from the xPatch device must be treated with caution: frontal impacts are recorded with reasonable accuracy (up to 24%), but rotational velocity and acceleration results from side and rear impacts may have large errors.

Conclusion

This study has shown that the xPatch performs reasonably well in terms of linear acceleration but has highlighted that the rotational velocity and acceleration

measurements recorded by the xPatch have high levels of error and therefore need to be used with caution. This study also found that there is an issue using differentiation to calculate rotational acceleration unless the sampling frequency and bandwidth are suitable. To improve the rotational acceleration measurements, either a higher sampling rate or an array of accelerometers that allows the rotational acceleration to be calculated without differentiation must be used.

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ORCID iD

Stephen Tiernan https://orcid.org/0000-0002-0658-7557

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