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Original research

An assessment of the utility and functionality of wearable head impact sensors in Australian Football

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ABSTRACT

Objectives: To assess the utility and functionality of the X-Patch® as a measurement tool to study head impact exposure in Australian Football. Accuracy, precision, reliability and validity were examined.
Designs: Laboratory tests and prospective observational study.
Methods: Laboratory tests on X-Patch® were undertaken using an instrumented Hybrid III head and neck and linear impactor. Differences between X-Patch® and reference data were analysed. Australian Football players wore the X-Patch® devices and games were video-recorded. Video recordings were analysed qualitatively for head impact events and these were correlated with X-Patch® head acceleration events. Wearability of the X-Patch® was assessed using the Comfort Rating Scale for Wearable Computers.
Results: Laboratory head impacts, performed at multiple impact sites and velocities, identified significant correlations between headform-measured and device-measured kinematic parameters ($p < 0.05$ for all). On average, the X-Patch®-recorded peak linear acceleration (PLA) was 17% greater than the reference PLA, 28% less for peak rotational acceleration (PRA) and 101% greater for the Head Injury Criterion (HIC). For video analysis, 118 head acceleration events (HAE) were included with PLA $\geq$30 g across 53 players. Video recordings of X-Patch®-measured HAEs (PLA $\geq$30 g) determined that 31.4% were direct head impacts, 9.3% were indirect impacts, 44.1% were unknown or unclear and 15.3% were neither direct nor indirect head impacts. The X-Patch® system was deemed wearable by 95–100% of respondents.
Conclusions: This study reinforces evidence that use of the current X-Patch® devices should be limited to research only and in conjunction with video analysis.

Practical implications

- Comprehensive evaluation of wearable sensors is required prior to their implementation as a research, sports science or clinical tool.
- The X-Patch® has many limitations. At present the optimal use of this device would be in combination with video analysis.
- Small head worn sensors are considered to be wearable by adult athletes in a contact sport

1. Introduction

Technology developments in the last decade have resulted in the availability and application of wearable sensor systems, including helmet mounted systems, to measure head impact events in sport.[1–3] There are multiple objectives of measuring head impact

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events, including the clinical management of concussion and to understand the mechanisms of concussion. A frequent application of the new technology has been in instrumented helmets,[3,6,7] such as the HIT™ system. Instrumented helmet systems, however, are not suitable for other forms of contact sport, such as Australian Football and Soccer/Football, where helmets, if worn, are shell-less padded headgear.[8]

Previous research has been conducted on wearable head accelerometer systems that can be worn without a helmet. The current study reports on a protocol to assess the utility and functionality of wearable head accelerometers and applies the protocol in a pilot study of the first generation X2 Biosystems X-Patch® accelerometer device. The study applied a methodology that can be adapted to many potential wearable head accelerometer devices.

The X-Patch® purports to measure a range of head impact characteristics, such as peak resultant linear acceleration (PLA) of the head's centre of mass, Head Injury Criterion (HIC) and peak resultant rotational acceleration (PRA) of the head. These are arguably a comprehensive set of head impact parameters relevant to concussion and brain injury.[9,10] It is often stated that these types of devices measure impact force, although they only measure the kinematic responses of the head during an impact. This means that the sensor is unable to provide information about the impact location on the body that results in the head's kinematic responses, and whether a direct head impact has occurred.

A thorough assessment of wearable head accelerometer systems should be a prerequisite for their application in research and practice. An appropriate assessment protocol should involve independent laboratory and field-testing of the system. Our protocol was developed to assess the X-Patch® in laboratory impact tests, field usability aspects and basic correlations between visually observed head impacts and in-game X-Patch®-recorded head acceleration events.

Wearable devices (e.g., the X-Patch®) and helmet-mounted devices have been assessed in the laboratory, in sport specific training sessions and in competitive sports situations. Table A.1 in Appendix A (online supplementary material) provides a list of relevant studies that have evaluated methods for wearable devices, including HIT™, mouthguards and skin mounted devices (i.e., the X-Patch®). All laboratory evaluations mounted the device on the head of an instrumented Hybrid III anthropomorphic test device (ATD), which was used to provide the kinematic reference values. The Hybrid III's head was impacted directly. Nevins et al.'s[11] evaluation with X-Patch® in the laboratory using ball impacts reported 'generally good agreement' between the reference and X-Patch® peak headform linear acceleration measurements, but less agreement with peak angular acceleration. Cummiskey et al.[12] used an impulse hammer to strike a Hybrid III headform wearing an American football helmet and several instrumented devices, including the X-Patch®. The X-Patch® was found to outperform most other devices in terms of root-mean-square error and mean absolute value error. Cummiskey et al.[12] also observed large differences in the number of 'impacts' greater than 10 g recorded by the HIT™ system and X-Patch® on a selection of players in a single competitive game of American football. Of the 224 HIT™ system-recorded 'impacts', only 5 were greater than 80 g, compared to 24 from the 231 X-Patch®-recorded 'impacts'. They did not verify with video that a head impact occurred.

Two studies used video to verify head 'impacts' recorded by the X-Patch® device and HIT™ system.[13,14] King and colleagues[4,5,15] reported on mouthguard and X-Patch®-measured head impact exposures, but did not verify whether the impacts occurred and/or whether they were direct or indirect. In contrast, Cortes et al.[13] verified only 32% of the 180 X-Patch®-measured game time head 'impacts' on video. In women's soccer, Press and Rowson[17] recorded 8999 X-Patch®-measured impacts, with only 1703 verified on video. For the video verified impacts, accuracy for identifying true positive events was tenuous, and positive predictive value was maximised at 34 g at which 65.8% of positive recorded impacts were true-positives. Few studies have reported on a comprehensive analysis including laboratory and field assessment.

The aim of the current study was to assess the utility, functionality and wearability of the X-Patch® as a measurement tool to study head impact exposure in sports without helmets, using Australian Football as an exemplar sport. The accuracy, precision, reliability and validity of the X-Patch® were addressed.

2. Methods

During the laboratory assessment, the X-Patch® was attached to a Hybrid III headform during a selection of impacts delivered to a Hybrid III head and neck system via a linear impactor.[27] The Hybrid III headform has a deformable skin and is not rigid. An X-Patch® was secured on the Hybrid III headform at the approximate position of the mastoid process consistent with instructions for use and was not exposed to a direct impact. Hybrid III measurements were considered reference values. After a set of four to five impacts, the X-Patch® was removed and data uploaded through X2's proprietary Integrated Monitoring System (IMS). The X-Patch® has a sample rate of 1000 Hz. The IMS software provides a summary file that reports on time-stamped parameters including: PLA, HIC and PRA.

All reference data from internally mounted sensors on the Hybrid III headform were acquired at 20 kHz with a TDAS™ data acquisition system. Linear accelerometers and angular velocity transducers were mounted at the centre of mass of the Hybrid III headform. Linear head acceleration data ($a_{Hdx,y,z}$) were filtered with an SAE CFC 1000 filter.[28] Component angular head velocity data ($\omega_{Hdx,y,z}$) were filtered with a SAE CFC 180 filter and differentiated to derive headform angular acceleration component time histories and resultant angular acceleration ($\alpha_{Hdx,y,z}$). PLA, HIC_{15} and PRA were derived.

Tests were conducted at four head locations (centre front forehead, left lateral, 45° to mid sagittal plane and lateral chin) and at two speeds (6.85 m/s and 8.34 m/s).[27] Test speeds correspond with the mean closing speed of 7 m/s (standard deviation = 3 m/s) measured in Australian Football in 68 head impacts resulting in medically verified concussion cases analysed on video.[29] The impact severity (force and impact duration) was varied as a result of tests being performed to the headform with or without a headguard. The head impact durations in the tests varied around the median (12.4 ms) observed in computer simulated impact reconstructions of concussion cases in Australian Football[30] and corresponded with post mortem test object impacts, where head impact duration in padded and unpadded head impacts was in the range of 5 to 13 ms.[31]

Correlations between the reference and X-Patch® measurements were assessed. To estimate the X-Patch® accuracy, the random error was calculated by dividing the standard deviation of the mean difference between the X-Patch® and the HIII reference by the square root of the number of measurements (n = 2). This value was then divided by the mean of the combined measurements and expressed as a percentage. The systematic error was calculated as the mean difference between the X-Patch® and reference, divided by the mean reference value.

Field testing was undertaken using a prospective observational study to assess associations between X-Patch® head acceleration events and head impacts observed on match video in which the X-Patch® devices were worn. The study setting was amateur level adult Australian Football.

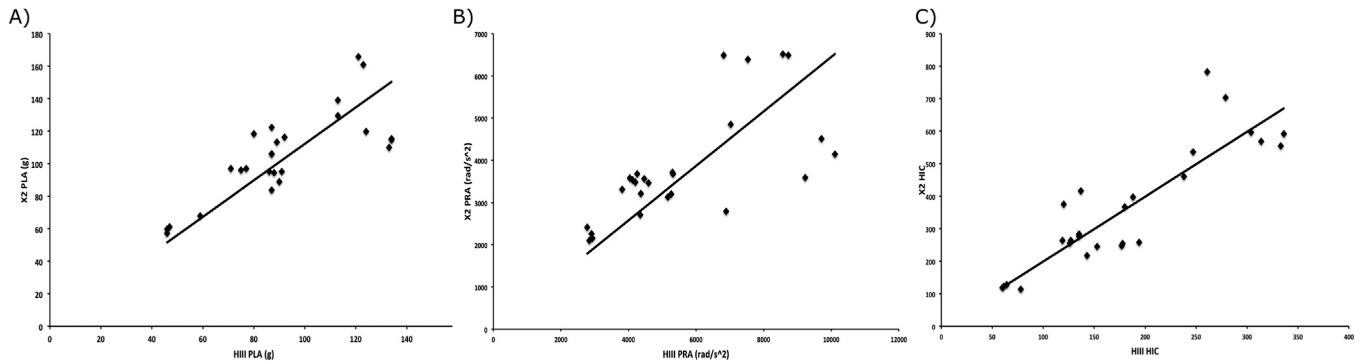

Fig. 1. Correlations of X-Patch measured parameters with reference values: (a) Peak resultant headform linear acceleration (g), HIII Reference PLA to X2 PLA, Pearson's r = 0.783 ($p < 0.05$), where $PLA_{X2} = 1.122\ PLA_{HIII}$; (b) Peak resultant angular acceleration (rad/s^2), HIII Reference PRA to X2 PRA, Pearson's r = 0.689 ($p < 0.05$), where $PRA_{X2} = 0.6449\ PRA_{HIII}$; (c) HIII Reference HIC_{15} to X2 HIC_{15}, Pearson's r = 0.877 ($p < 0.05$), where $HIC_{X2} = 1.994\ HIC_{HIII}$.

The study protocol was approved by Monash University Human Research Ethics Committee (CF15/1267–2015000599). All participants were aged above 16 years and provided written informed consent. Ninety-seven players from four teams – two from a male club (Division 2, Victorian Amateur Football Association) and two from a female club (Division 1, Victorian Women's Football league) – were recruited. The study involved monitoring eight games of Australian Football, two for each team. All participants were required to wear the X-Patch® device during their participation in at least one game.

Prior to the game, all X-Patch® devices were assigned to a player and fully charged. All patches were deemed functional prior to use. On game day, the X-Patch® was applied to each participant within one hour of the game commencing. The player's skin was cleaned with a SKIN-PREP Protective Barrier Wipe to ensure adherence. The X-Patch® devices were placed over the mastoid process and secured according to the X2 Biosystems protocol and supplied double-sided adhesive. In some cases, extra elastic-cotton tape was placed over the X-Patch®. Devices were worn for the entire game and during all game breaks. Each game was videoed from three fixed positions and time-stamped.

A video review session was conducted first (Phase 1) to identify and code selected observable head impact characteristics for all X-Patch® recorded head impact events where PLA ≥30 g; and second (Phase 2) to identify on video all head impacts to X-Patch®-wearing players and code selected observable impact characteristics. The PLA ≥30 g criterion was applied for the following reasons: consideration that impacts less than 30 g may not be easily identified on video and may be confounded by non-head impact events that occur in AFL, such as jumping and landing; and consideration for a broad range of head impact severities commencing with a low likelihood of concussion. In terms of likelihood of concussion and PLA, 30 g is associated with a 7% likelihood of concussion.[32]

The video review session was held with six trained video coders. The coders reviewed the video and entered standard descriptors or free text. Any questions regarding specific video cases were referred to the first author and a consensus was reached on the coding. The primary outcome measure was verification of a head impact using the following descriptors: definite head impact, possible head impact, no head impact, body contact, and unclear/unknown. In Phase 2, coders watched the video from the start of the game and coded any head impacts that had been missed during the first phase because they were not recorded by the X-Patch®. No inter-rater reliability assessment was performed.

Data from Phase 1 and Phase 2 facilitated an analysis of some components of sensitivity and specificity with respect to the X-Patch®-measured head impact events (PLA ≥30 g). A subsequent review of the 118 impact events was performed with regards to the X2 Biosystems 'clack' proprietary algorithm that purports to identify real from false impacts.

To assess wearability of the X-Patch®, the validated Comfort Rating Scale for Wearable Computers was applied.[33] All players were asked to complete the questionnaire within 30 min of completion of the game. Wearability categories and level of effect descriptors are presented in Tables A.2 and A.3 of Appendix A (online). Descriptive statistics were calculated for this sample.

3. Results

Laboratory assessment provided potentially usable X-Patch® data from 26 tests in total. Additional tests were conducted but no data were recorded, which might have reflected user error. Impact duration range was 8 ms to 23 ms with a median of 15 ms. Reference PLA ranged from 46 g to 134 g. Test results by condition are summarised in Appendix A – Table A.4 (online). The X2 system identified the general impact location successfully in 100% of cases. X-Patch®-measured PLA, PRA and HIC_{15} correlations with reference values are shown in Fig. 1.

Regarding accuracy, the mean of the differences between the X-Patch®-measured and reference parameters as a percentage of the reference values were 17.3% (95% CI [10.5%, 24.2%]), 101.4% (95% CI [82.9%, 119.8%]) and −28.4% (95% CI [−22.4%, −34.4%]) for PLA, HIC_{15} and PRA, respectively. Random error was calculated as 12.7%, 31.3% and 24.6%, for PLA, HIC_{15} and PRA, respectively. Systematic error was calculated as 14.8%, 100.6% and −31.9%, for PLA, HIC_{15} and PRA, respectively.

Table 1 presents the available baseline data (demographic, injury history and anthropometry) on the athletes who participated in the video analysis.

Across eight games there was a total of 5160 head acceleration events (HAE) recorded on 90 players by the X-Patch® devices with PLA (≥10 g). Seven players initially recruited did not play in these matches. One game could not be included in the video analysis as the time stamp function was not correctly applied. Data from four X-Patch® devices were excluded because the patches fell off during the game. Therefore, a resultant 3980 HAEs ≥10 g sustained by 82 players across 7 games were recorded (see Fig. 2).

There were 118 HAEs included in the analysis with PLA ≥30 g recorded on 53 players: four players with five impact events, six players with four impact events, ten with three impact events, eleven with two impact events and 22 with one impact event. The 118 HAEs were distributed across all four groups: male senior grade (n = 24), male reserve grade (n = 38), female senior grade (n = 33) and female reserve grade (n = 23). There were 37 (31.4%) of the X-Patch®-coded HAEs (PLA ≥30 g) verified as definite direct head impacts on video, 11 (9.3%) were identified as being related to body

Table 1
Participant demographic, injury history and anthropometry data collected at baseline.

Gender N = 53	
Male	24
Female	29
Age (in years) N = 38	
Mean (SD)	25.97 (4.16)
Range	20.00–34.00
Education (in years) N = 37	
Mean (SD)	16.76 (2.01)
Range	13.00–21.00
Height (cm) N = 36	
Mean (SD)	175.47 (13.06)
Range	147.32–193.04
Weight (kg) N = 36	
Mean (SD)	75.47 (15.94)
Range	45.36–115.67
Ethnicity N = 53	
Caucasian	50
Asian	3
Number of players with previous concussions N = 21	
Mean (SD)	2.43 (1.99)
Median	2.00
Range	0.00–8.00
Interquartile range	2.00

SD = standard deviation.

contact (i.e. indirect, inertial or impulsive loading) and 52 (44.1%) could not be verified either as being a definite direct or indirect head impact or no head impact. In 18 cases (15.3%), no direct or indirect head impact occurred. Among the 66 (56.1%) cases with HAEs (PLA $\geq$30 g) that could be verified on video, 48 (72.7%) were true positive for direct or indirect head impact and 18 (27.3%) were false negatives. Table A.5 and Figure A.1 of Appendix A (online) provide a summary of the kinematic responses measured by the X-Patch® devices. The mean PLA for a definite direct head impact (PLA = 47.2 g) was less than the mean PLA for indirect head impacts, i.e. body contact, (PLA = 49.1 g) and definitively no head impact (PLA = 57.1 g). The subsequent review of the 118 impact events regarding 'clack' status identified in total 51.7% of all head acceleration events. There were 37.8% of definite head impact cases, 72.2% of no head impact cases and 27.3% of the body contact cases assigned a positive clack.

A secondary analysis of 11 game quarters was undertaken of direct head impacts not recorded by the X-Patch® (Phase 2). The analysis found 17 definite head impacts and 68 possible head impacts (overall n = 85). Twelve of the 17 definite head impacts were observed impacts between the head and the ground.

One hundred and twenty-three wearability questionnaires were completed, as some players completed it twice. Responses in the six wearability categories were overwhelmingly positive. For the categories of 'emotion', 'harm', 'perceived change', 'movement' and 'anxiety', the X-Patch® system was deemed optimal (WL1) by between 95 and 100% of the respondents. Responses to the category 'attachment' indicated that the system was deemed optimal (WL1) by 85% of the respondents.

4. Discussion

The study identified limitations in the performance of the X-Patch® across two distinct areas: accuracy (laboratory tests) and validity (field tests). Players found the X-Patch® to be wearable, with a small proportion of players identifying sub-optimal attachment of the X-Patch® to the mastoid process.

The laboratory test inputs (velocity and impact site) and outputs (pulse duration and PLA) corresponded with those observed in Australian Football and realistic head impacts in the injury severity range of interest, i.e. no-concussion and concussion.[30,31,33] For example, in an analysis of Australian Football and rugby football the mean PLA in concussion cases was 103 g and non-concussion cases 59 g, which corresponded with the PLA range of 46 g to 134 g in the laboratory tests.[34] The laboratory assessment of the accuracy of the X-Patch® was limited by the number, location and severity of impacts. The accuracy of location for direct head impacts only was good. Within the limits of the testing, the estimated PLA was considered a usable measurement, albeit not 100% accurate. On average, X-Patch®-measured PLA was 17% greater than the reference value and the slope of the correlation (1.122) was similar to the results reported by Siegmund et al. (1.108)[6] and Tyson et al. (1.03 for padded bare NOCSAE headform and 1.12 for helmeted NOCSAE headform).[35] Additional repeat testing could have assessed precision thoroughly and accuracy in more detail. On balance, fur-

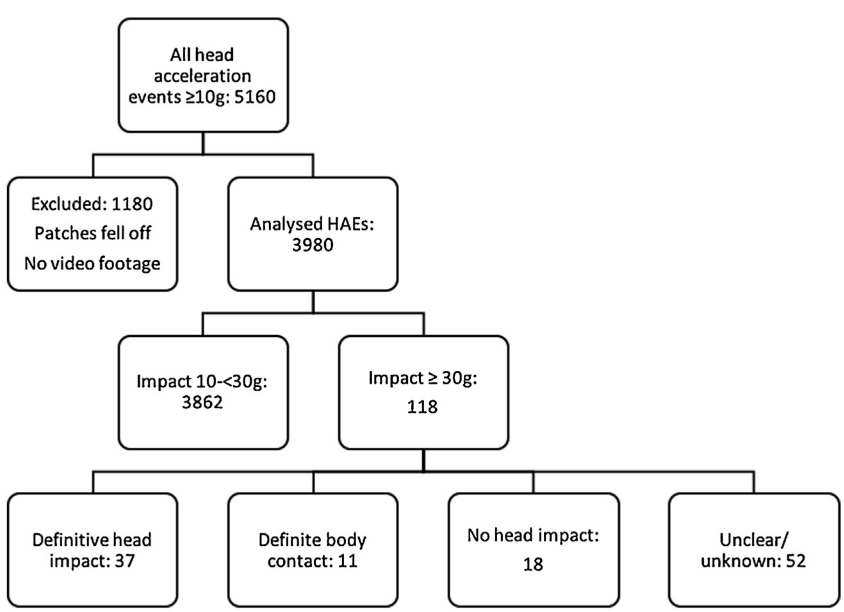

Fig. 2. Video identification status for X-Patch® recorded head acceleration events (HAEs) greater than 30 g (n = 118).

ther testing would have only highlighted measurement variability. X-Patch®-derived angular acceleration and HIC parameters were considered inaccurate.

The estimation of HIC and angular acceleration in the X-Patch®/IMS system may be influenced by its relatively low sample rate of 1000 Hz. The HIC algorithm includes time duration. In an impact lasting 10 ms, the X-Patch® records ten samples compared to 200 samples with the reference sample rate of 20,000 Hz. Within our assessments, the X-Patch® peak angular accelerations were not accurate or precise, although they were correlated with the Hybrid III reference. The X-Patch® measures angular velocity directly, which is then differentiated to estimate angular acceleration. The exact filter functions and numerical methods applied in the X-Patch®/IMS system are unknown. Numerical differentiation is affected by noise, especially high frequency noise, a property of each gyroscope sensor, and sample rate. We agree with Cummiskey et al.,[12] that higher sample rates will be beneficial. More recently, Tyson et al.[35] observed better correlation between the NOCSAE headform measured angular acceleration and X-Patch® (slope 1.02 for padded bare NOCSAE headform and slope 0.99 for helmeted NOCSAE headform). Differences in PRA accuracy may reflect technology changes or quality control issues in the production cycle of the X-Patch® sensors and, at least, indicate a need for sensor suppliers or large sporting organisations using specific sensors to maintain quality control checks in the laboratory and field and communicate those to users.

The video study identified and reinforced observations made in the laboratory and by other authors (i.e., Press and Rowson[17]). The X-Patch® recorded spurious head acceleration events; for example head accelerations were measured when there was no perturbation of the head either directly or indirectly. Some of the PLA ≥ 30 g head impact events were spurious and, because of the acceleration magnitude, unlikely to be related to the execution of basic motor skills such as jumping and landing. The X-Patch® also missed events where there were direct and observable head impacts recorded on video. In the laboratory, for each physical test, there were also a number of recorded head impact events that were not associated with any physical perturbation of the HIII.

If the 'clack' filter had been applied to the data, it would have excluded 37.8% of the definite head impacts identified in the video analysis and included approximately 18% of definite no head impact events in the sample. As opined by Cummiskey et al.,[12] a numerical algorithm that identifies legitimate head impact events from the recorded kinematics must also be assessed using at least video. Limitations in the video verification process also exist (e.g., timestamp errors and human error).

Future additions to assessments of wearable head impact sensors might include the following: sensor position variation and sensor placement/replacement variation assessment in laboratory tests and inter-rater reliability studies of video coders.

At present, the X-Patch®/IMS system does not provide for real time monitoring of the athlete. The X-Patch® needs to be removed from the player and the data uploaded for review. Therefore, other events or signs are required to trigger the removal of a player from the game. At that point, hypothetically, data from an 'X-Patch′-like device could be reviewed to assist with sideline player management. The physical application process for the X-Patch® and technical aspects of operating the X-Patch®/IMS system could be learnt by a competent sports trainer or degree-qualified sports scientist.

5. Conclusion

The current study highlights the benefits of comprehensive program of wearable sensor evaluation. In addition, our results strongly suggest that considerable caution is required with the interpretation and application of X-Patch® data. The potential errors in the X-Patch® head kinematic measurements were considerable, especially angular kinematics, and would result in sizable misreporting of the head impact incidence rates.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jsams.2019.02.004.

References

1. Brennan JH, Mitra B, Synnot A et al. Accelerometers for the assessment of concussion in male athletes: a systematic review and meta-analysis. *Sports Med* 2016; 47(3):469–478.
2. Campbell KR, Warnica MJ, Levine IC et al. Laboratory evaluation of the gForce Tracker™, a head impact kinematic measuring device for use in football helmets. *Ann Biomed Eng* 2016; 44(4):1246–1256.
3. Jadischke R, Viano DC, Dau N et al. On the accuracy of the head impact telemetry (HIT) System used in football helmets. *J Biomech* 2013; 46(13):2310–2315.
4. King D, Hecimovich M, Clark T et al. Measurement of the head impacts in a sub-elite Australian Rules football team with an instrumented patch: an exploratory analysis. *Int J Sports Sci Coach* 2017; 12(3):359–370.
5. King D, Hume PA, Brughelli M et al. Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches. *Am J Sports Med* 2015; 43(3):614–624.
6. Siegmund GP, Guskiewicz KM, Marshall SW et al. Laboratory validation of two wearable sensor systems for measuring head impact severity in football players. *Ann Biomed Eng* 2016; 44(4):1257–1274.
7. Wu LC, Nangia V, Bui K et al. In vivo evaluation of wearable head impact sensors. *Ann Biomed Eng* 2015; 44(4):1234–1245.
8. McIntosh AS, Andersen TE, Bahr R et al. Sports helmets now and in the future. *Br J Sports Med* 2011; 45(16):1258–1265.
9. McIntosh AS. Biomechanical studies of impact and helmet protection, in *Concussions in athletics: from brain to behavior*, Slobounov SM, Sebastianello W, editors, New York, Springer, 2014, p. 167–180.
10. McIntosh AS, Patton DA, Frechede B et al. The biomechanics of concussion in unhelmeted football players in Australia: a case-control study. *BMJ open* 2014; 4(5):e005078.
11. Nevins D, Smith L, Kensrud J. Laboratory evaluation of wireless head impact sensor. *Procedia Eng* 2015; 112:175–179.
12. Cummiskey B, Schiffmiller D, Talavage TM et al. Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. *Proc Inst Mech Eng Pt P: J Sports Eng Tech* 2017; 231(2):144–153.
13. Cortes N, Lincoln AE, Myer GD et al. Video analysis verification of head impact events measured by wearable sensors. *Am J Sports Med* 2017; 45(10):2379–2387.
14. Hanlon EM, Bir CA. Real-time head acceleration measurement in girls' youth soccer. *Med Sci Sport Exerc* 2012; 44(6):1102–1108.
15. King D, Hume P, Gissane C et al. Head impacts in a junior rugby league team measured with a wireless head impact sensor: an exploratory analysis. *J Neurosurg Pediatr* 2017; 19(1):13–23.
17. Press JN, Rowson S. Quantifying head impact exposure in collegiate women's soccer. *Clin J Sports Med* 2017; 27(2):104–110.
27. McIntosh AS, Patton DA. Boxing headguard performance in punch machine tests. *Br J Sports Med* 2015; 49(17):1108–1112.
28. SAE Internationall. *Instrumentation for impact test — Part 1 electronic instrumentation J211/1_201403*, Warrendale, PA, SAE International, 2014.
29. McIntosh AS, McCrory P, Comerford J. The dynamics of concussive head impacts in rugby and Australian rules football. *Med Sci Sports Exerc* 2000; 32:1980–1984.
30. Fréchède B, McIntosh AS. Numerical reconstruction of real-life concussive football impacts. *Med Sci Sports Exerc* 2009; 41:390–396.

31. McIntosh AS, Kallieris D, Mattern R et al. Head and neck injury resulting from low velocity direct impact. *Proceedings of the 37th. STAPP Car Crash Conference* 1993. SAE technical paper 933112.
32. McIntosh AS. Biomechanical considerations in the design of equipment to prevent sports injury. *Proc Inst Mech Eng Pt P: J Sports Eng Tech* 2012; 226(3–4):193–199.
33. Knight JF, Baber C. A tool to assess the comfort of wearable computers. *Hum Factors* 2005; 47(1):77–91.
34. McIntosh AS, Patton DA, Frechede B et al. The biomechanics of concussion in unhelmeted football players in Australia: a case-control study. *BMJ Open* 2014; 4:e005078. http://dx.doi.org/10.1136/bmjopen-2014-005078.
35. Tyson AM, Duma SM, Rowson S. Laboratory evaluation of low-cost wearable sensors for measuring head impacts in sports. *J Appl Biomech* 2018; 34:320–326.