

## Review Article

# A Review of Instrumented Equipment to Investigate Head Impacts in Sport

Declan A. Patton<sup>1,2</sup>

<sup>1</sup>Australian Collaboration for Research into Injury in Sport and Its Prevention (ACRISP), Federation University Australia, Ballarat, VIC, Australia

<sup>2</sup>Sports Injury Prevention Research Centre (SIPRC), Faculty of Kinesiology, University of Calgary, Calgary, AB, Canada

Correspondence should be addressed to Declan A. Patton; [declan@unswalumni.com](mailto:declan@unswalumni.com)

Received 7 April 2016; Accepted 23 June 2016

Academic Editor: Justin Keogh

Copyright © 2016 Declan A. Patton. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Contact, collision, and combat sports have more head impacts as compared to noncontact sports; therefore, such sports are uniquely suited to the investigation of head impact biomechanics. Recent advances in technology have enabled the development of instrumented equipment, which can estimate the head impact kinematics of human subjects *in vivo*. Literature pertaining to head impact measurement devices was reviewed and usage, in terms of validation and field studies, of such devices was discussed. Over the past decade, instrumented equipment has recorded millions of impacts in the laboratory, on the field, in the ring, and on the ice. Instrumented equipment is not without limitations; however, *in vivo* head impact data is crucial to investigate head injury mechanisms and further the understanding of concussion.

## 1. Introduction

The potential for concussion is related to the number of opportunities within a sport for events that cause contact to the head of an athlete; therefore, relatively higher incidence rates of concussion are expected in contact, collision, and combat sports compared to noncontact sports. This renders such sports uniquely suited to the investigation of head impact biomechanics. For over half a century, researchers have attempted to use instrumented sporting equipment to measure the loading of the head experienced by athletes during impacts. However, only in the last decade has instrumented equipment been used to collect large amounts of data for full sporting teams over entire seasons. Instrumented helmets and skullcaps have been used in American football and ice hockey, whilst instrumented headgear and headbands have been used in boxing and soccer. Instrumented mouthguards and skin patches have been developed for use in contact and collision sports that do not require wearing helmets or headgear such as soccer, rugby league, rugby union, and Australian football. The main advantage of using instrumented equipment is the ability to estimate the head impact kinematics of human subjects *in vivo*.

The objective of the current study is to discuss the development, validity, and potential of different instrumented equipment: helmets, headgear, headbands, skullcaps, skin patches, and mouthguards.

## 2. Development of Instrumented Equipment

In 1961, the Committee on the Medical Aspects of Sports of the American Medical Association was concerned with the incidence of head injuries in American football and suggested the gathering of head impact data [1]. In response, Aagaard and Du Bois [2] instrumented a suspension helmet with a triaxial accelerometer, which was able to telemeter impact data for a linebacker during a professional American football game. Reid et al. [3] further developed the telemetry system and collected head impact data for an American football player during collegiate games over several seasons. Similarly, Moon et al. [4] developed an instrumented headband, which was worn underneath the helmet. However, both studies recorded peak linear accelerations in excess of 1000 g [3, 4], which were much greater than contemporaneous head injury tolerance limits [5, 6]. Reid

et al. [7–10] revised the instrumented helmet system by mounting the accelerometers on the suspension system in an attempt to obtain more representative data; however, no-injury impacts of up to 400 g were still being recorded, which is higher than the pass criteria of a modern American football helmet standard [11]. One instrumented helmet captured a concussion, which had a peak linear acceleration of 188 g, and another instrumented player reported feeling “fuzzy,” which may have been considered a concussion under the current sports-related consensus definition [12], from an impact with unremarkable peak linear acceleration. Early attempts to collect data during American football games using instrumented helmets were considered largely unsuccessful due to the technical difficulties associated with safely obtaining accurate measurements [13]. Concomitantly, instrumented mouthpieces were used to measure kinematic data in early human volunteer sled test studies investigating injury tolerance limits for automotive and aerospace applications [14–27].

A decade later, Morrison [28] attempted to use instrumented helmets to investigate head impacts in American football; however, similarly to previous studies [3, 4, 7–10], unreasonably high peak linear accelerations in excess of 500 g were recorded. Instrumented helmets were not used to gather head impact data again until Naunheim et al. [29] recorded the peak linear head accelerations of American football and ice hockey players during high school games. Peak linear head accelerations of up to 120 g and 150 g were measured for the American football and ice hockey players, respectively; however, no concussions were reported.

### 3. Instrumented Helmets and Headgear

In 2003, Greenwald et al. [30] developed the Head Impact Telemetry (HIT) System, which uses a novel computational algorithm to process data from a nine-accelerometer array incorporated into a helmet, allowing continuous sideline monitoring of head impacts in real-time [31, 32]. Pendulum impact testing using a Hybrid III anthropomorphic test device (ATD) head-neck system was performed to evaluate the accuracy of the HIT System [33], from which the mean error for linear acceleration was 4%; however, angular accelerations had a mean error of 17%. Manoogian et al. [34, 35] investigated 50 helmet-to-helmet impacts using two HIT System helmets mounted on Hybrid III ATD head-neck systems in a pendulum arrangement and found peak linear acceleration of the head to be less than 10% of peak linear acceleration of the helmet, which may explain the high results of early helmet instrumentation studies [3, 4, 7–10, 28]. Manoogian et al. [34, 35] reported a good agreement between the measured accelerations of the HIT System and the Hybrid III ATD headform. Similar validation assessment studies were also performed on HIT Systems, which had been modified for use in boxing [36, 37] and soccer [38].

To address the limitation of angular acceleration estimation accuracy, Chu et al. [109] developed a revised computational algorithm, which iteratively optimised the equations

of motion for a head impact to determine the full head kinematics with six degrees-of-freedom (6DOF). The revised algorithm was implemented in a revised system, which comprised 12 uniaxial accelerometers arranged in orthogonal pairs, tangential to the skull, in six locations within the helmet. In a validation assessment of the 6DOF system, Rowson et al. [94] used a linear impactor to impact an American football helmet mounted on a Hybrid III ATD head-neck system. Mean errors for peak linear and angular acceleration were reportedly 1% and 3%, respectively. Although the revised system offered more accurate data for angular acceleration in comparison to the HIT System, prohibitive costs limited the widespread implementation of the 6DOF system [110].

Beckwith et al. [95] also used a linear impactor to deliver impacts to an American football helmet, which was instrumented with the HIT System, mounted on a Hybrid III ATD head-neck system. The HIT System was found to overestimate linear acceleration and underestimate angular acceleration of the Hybrid III ATD headform by 1% and 6%, respectively.

Allison et al. [96] evaluated the accuracy of the HIT System for ice hockey helmets. A linear impactor was used to impact an instrumented helmet, which was mounted on a Hybrid III ATD head-neck system, at speeds ranging from 1.5 to 5.0 m/s to several sites: front, rear, side, oblique-rear, and oblique-front. Initially, the effect of the interface between the helmet and the ATD headform was investigated using three interface conditions: nylon skull cap to mimic previous validation assessment studies [94, 95], dry human hair wig, and wet human hair wig. The latter was chosen by Allison et al. [96] as the most realistic interface condition. The HIT System algorithm identified almost a fifth (19%) of all impacts as perturbations, especially frontal impacts to the facemask, and removed such data. For the remaining impacts, peak linear and angular accelerations were found to strongly correlate with the reference data recorded by the ATD headform; however, correlations varied with impact location and the error associated with the HIT System data was found to be greater than previously reported for American football helmets [94]. Wilcox et al. [111], which included developers of the HIT System, criticised the protocol used by Allison et al. [96] for not being representative of on-ice conditions; however, Arbogast et al. [112] defended the protocol used by Allison et al. [96], which was chosen to mimic previous HIT System studies for boxing headgear [37] and American football helmets [94, 95].

Similarly for American football helmets, Jadischke et al. [100] used a linear impactor to investigate the accuracy of the HIT System for two helmet sizes: medium and large. For the large size helmet tests, the front, rear, and sides of the helmet shell were impacted at speeds of approximately 9.3 m/s. For the medium size helmet tests, various helmet shell sites were impacted at speeds ranging from 5.0 to 11.2 m/s. Root-mean-square (RMS) errors of HIT System linear and angular accelerations from the ATD headform data for the large size helmet were 18% and 66%, respectively, and for the medium size helmet were 18% and 20%, respectively. The medium size helmet was also impacted to face mask sites,

for which RMS deviations of HIT System linear and angular accelerations from the ATD headform data were 148% and 71%, respectively. Jadischke et al. [100] also investigated the pressure exerted by an American football helmet on the head of a volunteer high school player using a nylon skull cap. A medium size helmet mounted on a 50th Hybrid III ATD headform was found to exert peak pressures of 93 kPa, which were in excess of the discomfort pressure of 69 kPa reported by volunteer high school players. Previous validation assessment studies had used medium size helmets [94, 95], which Jadischke et al. [100] considered too tight in comparison to comfortable helmet pressures. Similar to the study of Allison et al. [96], the protocol of Jadischke et al. [100] was also criticised for not being representative of on-ice conditions.

Siegmund et al. [108] assessed the validity of the HIT System using a linear impactor to impact a mandibular load-sensing headform (MLSH) [113], which was wearing an American football helmet and mounted on a Hybrid III ATD neck. For peak linear acceleration and peak angular acceleration, the HIT System did not achieve level 1 validity, which was arbitrarily defined as “an average intercept and slope that were not statistically different from zero and one, respectively, for all impact sites combined”.

For over a decade, numerous studies have used the HIT System to collect a large amount of head kinematic data from American football and ice hockey players (Table 1) [114], which have been used to further the understanding of concussion and investigate injury tolerance criteria [115]. The HIT System has also been used to monitor the head impacts of boxers [36, 37, 43] and female ice hockey players [52, 66, 83, 116].

The GForceTracker (GFT) comprises a triaxial accelerometer and gyroscope and, similar to the HIT System, allows continuous collection of head impact data in real-time [117]. In contrast to the HIT System, a GFT unit is attached to the helmet, which allows integration with a helmet of choice across a range of sports. During an impact, the GFT samples linear acceleration and angular velocity at 3000 Hz and 800 Hz, respectively, with the angular velocity signal passing through a low-pass filter with a cut-off frequency of 100 Hz.

Allison et al. [101] evaluated the accuracy of the GFT using a linear impactor, at speeds ranging from 1.5 to 5.0 m/s, to impact a hockey helmet mounted on a Hybrid III ATD head-neck system at various sites: facemask, side, rear-oblique, and rear. Relative to the peak linear acceleration data from the Hybrid III ATD headform, the raw data from the GFT demonstrated large differences of up to 150%, which was attributed to the lack of algorithm to transform the data to the centre of gravity of the head. When logistic regression was used to account for impact direction, mean absolute errors of up to 15% were obtained, which varied by helmet brand, impact direction, and sensor location, but not impact severity. In contrast, relatively small raw data differences of up to 15% were reported for angular velocity and mean absolute errors of less than 10% were obtained after logistic regression was used to account for impact direction. Mean absolute errors for angular velocity did not vary substantially

by helmet brand, impact direction, sensor location, or impact severity. Allison et al. [101] recommended that helmet brand-specific correction algorithms be developed to transform the raw linear acceleration data obtained from the GFT to represent the kinematics of the centre of gravity of the head.

In a similar study, Campbell et al. [104] used a linear impactor to impact an American football helmet mounted on a Hybrid III ATD head-neck system to assess the accuracy of the GFT. Impact speeds ranged from 3.0 to 5.5 m/s and various helmet locations were impacted: facemask, front, front-oblique, side, and rear. A correction algorithm was developed and used to predict the kinematics at the centre of mass of the head. Campbell et al. [104] found a strong correlation ( $R^2 = 0.97$ ) between the peak linear accelerations measured by the GFT with the correction algorithm applied and the Hybrid III ATD headform data. A strong correlation ( $R^2 = 0.94$ ) was also found between raw peak rotational velocity measured by the GFT and the Hybrid III ATD headform data. Campbell et al. [104] supported the conclusions of Allison et al. [101] regarding helmet brand-specific correction algorithms.

Certification of instrumented helmets is a contentious issue [118]. In 2013, National Operating Committee on Standards for Athletic Equipment (NOCSAE) published a press release stating that American football helmets with additional third-party products, such as impact sensors, which were not affixed during standards testing, voided the certification of compliance with the standard [119]. Several months later, NOCSAE published a clarification stating that helmet manufacturers were required to decide whether additional third-party products voided the certification of their helmets [120].

#### 4. Instrumented Mouthguards

Half a century ago, instrumented mouthpieces were used to measure kinematic data in early human volunteer sled test studies [14–27]. More recent studies have used instrumented mouthpieces, which resemble mouthguards used for orofacial protection in sports, to investigate head kinematics during soccer heading with [121–123] and without [124–126] head protection; however, such devices were hardwired and not suitable for in-game situations. Higgins et al. [127] conducted impact drop tests to compare acceleration data from an instrumented mouthpiece and helmet with data from a modified NOCSAE headform. A significant relationship was observed between mouthpiece and headform acceleration; however, helmet acceleration was not significantly associated with headform acceleration.

More recently, Paris et al. [128] instrumented a custom acrylic mouthguard with a single dual-axis accelerometer, which was able to wirelessly transmit linear acceleration data. Kara et al. [129] further developed the instrumented mouthguard design of Paris et al. [128] to incorporate an array of three accelerometers so that angular acceleration, in addition to linear acceleration, was able to be measured. Six heading events were conducted, which all involved the same female subject. The device was suggested as a

TABLE 1: HIT System studies of male athletes during training and games.

Study	Season(s)	Sport	Level (age)	Players	Impacts <sup>a</sup>	Concussions
Duma et al. [39, 40]	2003	American football	Collegiate	38	3312	1
Brolinson et al. [41]	2003-2004	American football	Collegiate	52	11,604	3
Gwin et al. [42]	2005	Ice hockey	Collegiate	4	1875	0
Greenwald et al. [43]	2003-2006	American football	Collegiate	423	249,613	11
	2005	Ice hockey	Collegiate	5	5463	0
Funk et al. [44]	2003-2005	American football	Collegiate	56	22,704	3
Funk et al. [45]	2003-2007	American football	Collegiate	64	27,319	4
Guskiewicz et al. [46]	2004-2006	American football	Collegiate	88	104,714	13
Mihalik et al. [47]	2005-2006	American football	Collegiate	72	57,024	0
Schnebel et al. [48]	2005	American football	High school Collegiate	16 40	8326 54,154	3 3
Greenwald et al. [49]	2004-2006	American football	High school Collegiate	190 259	99,862 190,054	6 11
Mihalik et al. [50]	2006/2007	Ice hockey	Youth (13 years)	14	4543	0
Beckwith et al. [51]	2005-2008	American football	High school, collegiate	52	71,390	55
Brainard et al. [52]	2008-2009	Ice hockey	Collegiate	10	Not reported	0
Broglio et al. [53]	2007	American football	High school	35	19,224	0
Cubos et al. [54]	2006/2007	Ice hockey	Youth (13-14 years)	13	1137	0
Duma and Rowson [55]	2003-2008	American football	Collegiate	64	71,300	6
Gwin et al. [56]	2005-2006	Ice hockey	Collegiate	12	4393	0
Rowson et al. [57]	2007	American football	Collegiate	10	1712	0
Broglio et al. [58]	2005-2008	American football	High school	78	54,247	13
Crisco et al. [59]	2007	American football	Collegiate	188	Not reported	0
Broglio et al. [58]	2007-2010	American football	High school	95	101,994	20
Mihalik et al. [60]	Not reported	Ice hockey	Youth (14 years)	16	Not reported	0
Reed et al. [61]	2006-2007	Ice hockey	Youth (13-14 years)	13	1821	0
Kimpara et al. [62]	2007-2008	American football	Collegiate	19	4709	0
Beckwith et al. [63, 64]						
Beckwith et al. [65]	2005-2010	American football	High school, collegiate	1208	Not reported	105
Brainard et al. [66]	2008/2009-2009/2010	Ice hockey	Collegiate	44	15,281	0
Breedlove et al. [67]	2009-2010	American football	High school	24	Not reported	4
Daniel II et al. [68, 69]	Not reported	American football	Youth (7-8 years)	7	748	0
Duhaime et al. [70]	Not reported	American football, ice hockey	Collegiate	450	486,594	48
Funk et al. [71]	2006-2010	American football	Collegiate	98	37,128	8
Gysland et al. [72]	Not reported	American football	Collegiate	46	Not reported	0

TABLE 1: Continued.

Study	Season(s)	Sport	Level (age)	Players	Impacts <sup>a</sup>	Concussions
Mihalik et al. [73]	Not reported	Ice hockey	Youth (13–16 years)	52	12,253	0
Ocwieja et al. [74]	2010	American football	Collegiate	46	7992	0
Rowson et al. [75]	2007–2009	American football	Collegiate	335	300,977	57
Rowson et al. [76]	2012	American football	Youth (7–12 years), middle school, high school	112	34,603	8
Urban et al. [77]	Not reported	American football	Youth (9–12 years)	50	11,978	4
Talavage et al. [79]	2009	American football	High school	21	15,264	4
Cobb et al. [78]	Not reported	American football	High school	40	16,502	5
Urban et al. [77, 80]	Not reported	American football	Youth (12–14 years)	17	4678	1
Stitzel et al. [81]	2012	American football	Youth (9–12 years)	36	9772	0
Wilcox et al. [83]	2009/2010–2011/2012	Ice hockey	Collegiate	41	19,880	0
Young et al. [84]	2011–2012	American football	Youth (7–8 years)	19	3059	0
Cummiskey [85]	2013	American football	High school	12	224	0
Munce et al. [86]	Not reported	American football	Youth (11–13 years)	22	6183	1

<sup>a</sup>Number of recorded impacts that surpass a predefined minimum linear acceleration threshold.

potential tool for the assessment of concussion during game play.

The X2 Impact mouthguard is a device instrumented with a triaxial accelerometer and gyroscope, which samples linear acceleration and angular velocity at 1 kHz and 800 Hz, respectively, during an impact. Angular velocity is interpolated to 1 kHz, filtered, and differentiated to generate angular acceleration. Using a similar design to the X2 Impact mouthguard, Camarillo et al. [97] evaluated the accuracy of an instrumented mouthguard for measuring kinematics of the head during impact. A custom ATD headform mounted on a Hybrid III ATD neck and wearing an American football helmet was impacted at various sites using a linear impactor. The normalised RMS errors for impact kinematic profiles were approximately 10% for peak linear acceleration, angular acceleration, and angular velocity. An impedance-based saliva sensor is incorporated for on-field use to determine actual impact events when the mouthguard is present in the mouth. King et al. [130] monitored head impacts of 38 New Zealand amateur rugby union players using the X2 Impact mouthguard during the 2013 season; however, no concussions were recorded. Siegmund et al. [108] assessed the validity of the X2 mouthguard using a linear impactor to impact a mandibular load-sensing headform (MLSH) [113], which was wearing an American football helmet and mounted on a Hybrid III ATD neck. Similar to the HIT System results from the same study, the X2 Impact mouthguard did not achieve level 1 validity for peak linear acceleration and peak angular acceleration.

Kuo et al. [107] investigated the effect of mandible constraints on the accuracy of an instrumented mouthguard for helmeted ATD and cadaver tests. RMS errors of 40% and 80% for angular velocity and acceleration, respectively, were found for the worst-case scenario of the unconstrained cadaver mandible; however, such errors could be mitigated to below 15% by isolating sensors from mandible loads. Hernandez et al. [131] used instrumented mouthguards to monitor head impacts of American football players during collegiate games and training, the data from which informed ATD reconstructions. In addition, Hernandez et al. [132] also monitored head impacts to boxers and mixed martial artists, which, in combination with video analysis, enabled such impacts to be reconstructed using a finite element human head model [133].

Wu et al. [134] developed an instrumented mouthguard with a triaxial high-range accelerometer and gyroscope. The device also incorporated infrared proximity sensing to determine if the mouthguard is worn on the teeth. Frequency domain features of linear acceleration and rotational velocity measured by a Hybrid III headform during impacts at speeds ranging from 2.1 to 8.5 m/s delivered by a linear impactor were used to train a support vector machine classifier. In a subsequent study, Wu et al. [106] assessed the validity of the instrumented mouthguard for soccer heading impacts by tracking fiducial grids with dual high-speed video. The instrumented mouthguard was worn by the volunteer during the heading of a soccer ball, which was projected at a speed of 7 m/s. Compared to the video-tracked kinematics in the sagittal plane, the instrumented mouthguard had RMS

errors of 16%, 18%, and 12% for peak anterior-posterior linear acceleration, peak inferior-superior linear acceleration, and peak angular velocity in the sagittal plane, respectively.

Contemporaneously, the Cleveland Clinic developed the Intelligent Mouthguard (IMG) [98, 99, 102], comprising a triaxial accelerometer and gyroscope, which is capable of sampling up to 4 kHz. A drop tower was used to validate the sensors used in the IMG for linear and angular accelerations ranging within 10–174 g and 0.85–10.00 krad/s<sup>2</sup>, respectively, with impact durations of 4.6–31.8 ms. The IMG underestimated the reference linear and angular accelerations by 3% and 17%, respectively. In addition, validation of the IMG was performed by impacting a modified Hybrid III ATD head, which was wearing either an American football helmet or boxing headgear, with a linear impactor at speeds of up to 8.5 m/s [102]. The accelerations recorded by the IMG correlated well with the headform data ( $R^2 = 0.99$ ) for both the American football helmet and boxing headgear tests. Bartsch et al. [102] instrumented two collegiate American football players and four amateur boxers during competition; however, no concussions were recorded.

## 5. Instrumented Skin Patches

The X2 X-Patch is a small microelectromechanical system, worn over the left or right mastoid process, which comprises a triaxial accelerometer and gyroscope [135]. The raw accelerometer data is transformed to the centre of gravity of the head using a rigid body transformation for linear acceleration and a five-point stencil for rotational acceleration. During an impact, the X-Patch samples linear acceleration and angular velocity at 1 kHz and 800 Hz, respectively. Several studies have used the X-Patch to record kinematic data during training sessions and competition games for male American football, female soccer and youth rugby (Table 2).

Nevins et al. [105] assessed the validity of the X-Patch using a Hybrid III ATD head-neck system mounted on a low friction sled. The headform was impacted to the chin and forehead in different orientations by pneumatically projected softballs, lacrosse balls, and soccer balls at speeds ranging from 10 to 31 m/s. Peak linear acceleration measured by the X-Patch displayed reasonable agreement with the Hybrid III ATD headform for the lacrosse and soccer balls. However, peak linear acceleration was underestimated by the X-Patch for softball impacts as was angular acceleration for all three sports balls. Nevins et al. [105] suggested that the poor agreement between the X-Patch and Hybrid III ATD headform for certain conditions was attributable to the relatively low sampling frequency of the former.

Kerr et al. [136] evaluated the effectiveness of the Heads Up Football (HUF) programme using the X-Patch to monitor head impacts of youth football players: HUF participants, 38 players, 7 teams, 2 leagues; controls, 32 players, 8 teams, 3 leagues. Players participating in the HUF programme accumulated fewer impacts per athletic exposure than controls. Similarly, Swartz et al. [88] evaluated the effectiveness of

TABLE 2: X2 X-Patch studies of athletes during training and games.

Study	Season(s)	Sport	Level (age)	Gender	Players	Impacts <sup>a</sup>	Concussions
Kerr et al. [87]	2014	American football	Youth (8–15 years)	M	70	7478	6
Swartz et al. [88]	2014-2015	American football <sup>b</sup>	Collegiate	M	50	Not reported	Not reported
McCuen et al. [89]	Not reported	Soccer	High school, collegiate	F	43	Not reported	0
Morrison et al. [90]	2015	American football	Collegiate	M	10	Not reported	0
Stucker [91]	Not reported	Soccer	Collegiate	F	25	13,479	0
Cummiskey [85]	2013	American football	High school	M	15	231	0
King et al. [92]	2015	Rugby	Youth (8-9 years)	M	14	721	3
Svaldi et al. [93]	Not reported	Soccer	High school	F	14	Not reported	0

<sup>a</sup>Number of recorded impacts that surpass a predefined minimum linear acceleration threshold. <sup>b</sup>Helmetless training drills.

the Helmetless Tackling Training (HuTT) programme, which incorporates tackling drills without helmets and shoulder pads into training sessions, over the 2014 and 2015 collegiate seasons. Intervention and control groups, each comprising 25 American football players, were instrumented with the XPatch with the former participating in the HuTT programme. Swartz et al. [88] found that the intervention group experienced 28% less head impacts per athletic exposure compared to the control group. In another study, which varied the level of equipment worn by American football players, Reynolds et al. [137] instrumented 20 collegiate players with the X-Patch during training and games comprising the 2013 season. The type of equipment worn during each training session was found to be associated with different head impact profiles as mean peak linear and angular accelerations for helmet-only training sessions were significantly less than mean peak accelerations for half-pad and full-pad training sessions and competitive games.

In a soccer heading study, Wu et al. [106] assessed the validity of the X-Patch by tracking fiducial grids with dual high-speed video. The X-Patch was attached to the mastoid process of a volunteer during the heading of a soccer ball, which was projected at a speed of 7 m/s. Compared to the video-tracked kinematics in the sagittal plane, the X-Patch had RMS errors of 14% for peak anterior-posterior linear acceleration and 29% for both peak inferior-superior linear acceleration and peak angular velocity in the sagittal plane.

More recently, King et al. [92] used the X-Patch to monitor the magnitude, frequency, and location of head impacts to junior rugby union players in New Zealand over four consecutive matches. Of the 14 instrumented players, three were medically diagnosed as having sustained a concussion. The standardisation of reporting of head impact biomechanical data was suggested to enable accurate comparison across published studies.

## 6. Instrumented Skullcaps and Headbands

The Checklight is a sensor device, which is integrated into the rear of a skullcap [138]. Impact data is not provided; however, green, yellow, and red lights are triggered for “mild,” “intermediate,” and “severe” impacts, respectively.

Cummiskey [85] used an impulse hammer to impact an American football helmet, which was worn by a Hybrid III ATD over the Checklight skullcap. The red light was triggered by four impacts, the most severe of which corresponded to peak linear and angular headform accelerations of 123 g and 7660 rad/s<sup>2</sup>, respectively. Bartsch et al. [102] used a Checklight skullcap in a validation assessment study; however, no results were reported. Harper et al. [139] monitored head impacts of youth and high school football players during training and games using the Checklight. Harper et al. [139] concluded that the Checklight has limited usefulness as it does not allow for real-time sideline data monitoring and threshold limits are unknown. In a soccer heading study, Wu et al. [106] assessed the validity of the Checklight skullcap sensor location by tracking fiducial grids with dual high-speed video. A 6DOF sensor device [134] was used in lieu of the Checklight sensor, which does not allow raw data extraction. Compared to the video-tracked kinematics in the sagittal plane, the skullcap had RMS errors of 16% for peak anterior-posterior linear acceleration and 13% for both peak inferior-superior linear acceleration and peak angular velocity in the sagittal plane.

Instead of traditional accelerometers, the Shockbox uses four binary force switches to measure differential voltage [140]. Foreman and Crossman [141] assessed the validation of the Shockbox by drop testing a rigid headform wearing an ice hockey helmet, which was instrumented with the device. Impact speeds ranged from 2.0 to 3.0 m/s at various helmet locations: front, front-oblique, side, rear-oblique, and rear. An aggregate difference of 9% between the Shockbox and headform data was reported. Cuminsky [85] used an impulse hammer to impact an American football helmet, which was worn by a Hybrid III ATD over the Shockbox headband. Peak linear acceleration from the Shockbox was compared to the headform data and RMS errors of 92–298% were found for seven impact locations. Wong et al. [142] instrumented the helmets of 22 youth American football players with the Shockbox device to monitor head impacts during the 2012 season. Other unpublished studies have used Shockbox to monitor head impacts in American football [143] and ice hockey [144, 145].

The SIM-G is a head impact sensor device, which comprises a triaxial gyroscope and two triaxial accelerometers,

TABLE 3: Validation studies of head instrumentation devices.

Study	Device	Sport	Method	Headform	Impact speed [m/s]	Error data	
						Linear	Angular
Crisco et al. [33]	HITS	American football	Pendulum	HIII head-neck	3.0–7.0	PLA: average error of 4% PAA: average error of 17%	
Manoogian et al. [35]	HITS	American football	Pendulum	HIII head-neck	2.0–5.0	HITS and HIII head measure similar linear acceleration responses	
Beckwith et al. [37]	HITS	Boxing	Pendulum	HIII head-neck	3.0–7.0	PLA: underestimate by 2%; $R^2 = 0.91$	PAA: overestimated by 8%; $R^2 = 0.91$
Hanlon and Bir [38]	HITS	Soccer	Ball canon Linear impactor	HIII head-neck	8.0–12.0	PLA: $R^2 = 0.34$	PAA: $R^2 = 0.57$
Rowson et al. [94]	6DOF System	American football	Linear impactor	HIII head-neck	Impact energy: 68–608 J	PLA: RMSE = 12.5 ± 8.3 g; $R^2 = 0.88$	PAA: RMSE = 907 ± 685 rad/s <sup>2</sup> ; $R^2 = 0.85$
Beckwith et al. [95]	HITS	American football	Linear impactor	HIII head-neck	4.4–11.2	PLA: $R^2 = 0.82–0.99$ ; overestimated by 1%	PAA: $R^2 = 0.42–0.98$ ; underestimated by 6%
Allison et al. [96]	HITS	Ice hockey	Linear impactor	HIII head-neck	1.5–5.0	PLA: average error of 18–31% (raw), 7–27% (adjusted); $R^2 = 0.81–0.97$	PAA: average error of 35–64% (raw), 13–38% (adjusted); $R^2 = 0.71–0.94$
Camarillo et al. [97]	MG	American football	Linear impactor	Custom head, HIII neck	3.0–8.5	PLA: RMSE = 3.9 ± 2.1 g; NRMSE = 9.9 ± 4.4%; $R^2 = 0.94–0.98$	PAA: RMSE = 202 ± 120 rad/s <sup>2</sup> ; NRMSE = 9.7 ± 7.0%; $R^2 = 0.61–0.98$ PAV: RMSE = 1.0 ± 0.8 rad/s; NRMSE = 10.4 ± 9.9%; $R^2 = 0.96–0.99$
Bartsch et al. [98], Aksu [99]	IMG	N/A	Drop	N/A	0.7–3.9	PLA: underestimated by 3%; $R^2 > 0.99$	PLA: underestimated by 17%; $R^2 = 0.98$
Jadischke et al. [100]	HITS	American football	Linear impactor	HIII head-neck	9.3 5.0–11.2	PLA: RMSE = 12–23% PLA: RMSE = 16–190% PLA: RMSE = 11–22%	PAA: RMSE = 30–111% PAA: RMSE = 51–96% PAA: RMSE = 10–26%
Allison et al. [101]	GFT	Ice hockey	Linear impactor	HIII head-neck	1.5–5.0	PLA: $R^2 = 0.77–0.99$	PAV: $R^2 = 0.78–0.99$
Bartsch et al. [102]	IMG	American football	Linear impactor	HII head (modified), HII neck	2.0–8.5	PLA: $R^2 = 0.99$	PAA: $R^2 = 0.98$ PAV: $R^2 = 0.99$
		Boxing	Linear impactor	HII head (modified), HII neck	1.8–7.5	PLA: $R^2 = 0.99$	PAA: $R^2 = 0.98$ PAV: $R^2 = 0.98$
Triax Technologies [103]	SIM-G	N/A	Pendulum	NOCSAE head, Hybrid III neck	Not reported	PLA: $R^2 = 0.84$	PAA: $R^2 = 0.78$ PAV: $R^2 = 0.98$
Campbell et al. [104]	GFT	American football	Linear impactor	HIII head-neck	3.0–5.5	PLA: MAPE = 26–72% (raw), 2–8% (adjusted); $R^2 = 0.82$ (raw), 0.97 (adjusted)	PAV: MAPE = 2–16% (raw), 1–13% (adjusted); $R^2 = 0.94$ (raw), 0.96 (adjusted)



TABLE 3: Continued.

Study	Device	Sport	Method	Headform	Impact speed [m/s]	Error data	
						Linear	Angular
Cummiskey [85]	HITS	American football	Impulse hammer	HIII head-neck	Not reported	PLA: RMSE = 33–198%	PAA: RMSE = 27–209%
	X2	American football	Impulse hammer	HIII head-neck	Not reported	PLA: RMSE = 11–59%	PAA: RMSE = 11–350%
	X-Patch	American football	Impulse hammer	HIII head-neck	Not reported	PLA: RMSE = 92–298%	
	Shockbox	American football	Impulse hammer	HIII head-neck	Not reported	PLA: RMSE = 13–75%	
Nevins et al. [105]	SIM-G	American football	Impulse hammer	HIII head-neck	Not reported		
	X2	Soccer	Ball canon	HIII head-neck	13–27		
	X-Patch	Softball	Ball canon	HIII head-neck	10–20	PLA: underestimated by <25%	
Wu et al. [106]	MG	Soccer	Ball canon	Human volunteer	7	PLA: 16 ± 6% (A-P); 18 ± 10% (I-S)	PAV: 12 ± 7% (sagittal)
	X2	Soccer	Ball canon	Human volunteer	7	PLA: 14 ± 2% (A-P); 29 ± 30% (I-S)	PAV: 29 ± 9% (sagittal)
	X-Patch	Soccer	Ball canon	Human volunteer	7	PLA: 16 ± 9% (A-P); 13 ± 5% (I-S)	PAV: 13 ± 11% (sagittal)
Kuo et al. [107]	MG	American football	Drop	ATD (no mandible)	1.4–4.4	PLA: NRMSE > 20% for 8/162 drops;	
						$R^2 = 0.85-0.99$	
						PLA: $R^2 = 0.62-0.99$	
						PLA: $R^2 = 0.94-0.99$	
Siegmund et al. [108]	HITS	American football	Linear impactor	MLSH, HIII neck	3.6–11.2	PLA: NRMSE > 20% for 26/108 drops	
						$R^2 = 0.85-0.99$	
						PLA: mean coefficients of variation of 15 ± 9%; mean relative error of 20 ± 50%; MAPE = 32 ± 43%; $R^2 = 0.63$	
						PAA: mean coefficients of variation of 8 ± 4%; mean relative error of -8 ± 14%; MAPE = 12 ± 10%; $R^2 = 0.90$	
Siegmond et al. [108]	X2 MG	American football	Linear impactor	MLSH, HIII neck	3.6–11.2	PAA: mean coefficients of variation of 21 ± 21%; mean relative error of 9 ± 49%; MAPE = 35 ± 36%; $R^2 = 0.59$	
						PLA: mean coefficients of variation of 23 ± 9%; mean relative error of 26 ± 61%; MAPE = 41 ± 51%; $R^2 = 0.56$	
						PAA: $R^2 = 0.62-0.99$	
						PAV: $R^2 = 0.84-0.99$	
PAA: $R^2 = 0.56-0.99$							
PAA: $R^2 = 0.65-0.99$							
PAA: $R^2 = 0.92-0.99$							
PAV: $R^2 = 0.98-0.99$							
PAA: NRMSE = 80%							
PAV: NRMSE = 40%							

HITS: Head Impact Telemetry System. I2DOF: twelve degree-of-freedom measurement device. MG: mouthguard. IMG: Intelligent Mouthguard. GFT: GForceTracker. MMA: mixed-martial arts. HIII: Hybrid III. ATD: anthropomorphic test device. MLSH: modified load sensing headform. PLA: peak linear acceleration. PAA: peak angular acceleration. PAV: peak angular velocity. MAPE: mean absolute percentage error. A-P: anterior-posterior. I-S: inferior-superior.

high-g, and low-g, mounted on a headband [103]. The developers of the SIM-G, Triax Technologies, assessed the validation of the device using a pendulum to impact the NOCSAE headform in 11 locations. Peak angular velocity measured by the SIM-G correlated strongly with the headform data ( $R^2 = 0.98$ ); however, correlations were not as strong for peak linear acceleration ( $R^2 = 0.84$ ) and peak angular acceleration ( $R^2 = 0.78$ ). Cummiskey [85] used an impulse hammer to impact an American football helmet, which was worn by a Hybrid III ATD over the SIM-G headband. Peak linear acceleration from the SIM-G was compared to the headform data and RMS errors of 18–75% were found for seven impact locations.

## 7. Other Instrumented Equipment

Circa 2000, instrumented earplugs were developed for motorsport drivers after it was shown that instrumented helmets moved relative to the head during collisions [146, 147]. Such ear-mounted devices were also tested by military cadets during boxing matches [148]. In addition to the HIT System studies in boxing [36, 37, 149, 150], instrumented gloves have also been used to estimate punch force in the laboratory [151, 152] and during boxing matches [138, 152, 153]. Boxing shirts have also been developed, which are instrumented and detect hits during amateur boxing matches [154–159].

In recent years, global positioning system (GPS) units are commonly worn by elite rugby league [160, 161], rugby union [162–165], and Australian football [166, 167] players; however, the validity of such microsensors to detect collisions has been questioned [168]. Another device provides video footage from a first-person perspective using rugby headgear instrumented with a video camera [169, 170]; however, due to rules regarding rugby headgear design [171], the primary application of such a device is as a training tool to assess performance [170].

## 8. Conclusion

Recent advances in technology have enabled the development of instrumented equipment: helmets, headgear, headbands, skullcaps, skin patches, and mouthguards. The current study was conducted to review the development, validity and potential of such instrumented equipment, which estimates the head impact kinematics of human subjects *in vivo*.

The HIT System is widely used; however, it is expensive and limited in that it can only be incorporated into particular helmets and headgear. Other head impact sensors are less expensive, such as the Checklight and Shockbox, and are commercially available despite the lack of validation. In contrast, the GForceTracker is continually undergoing validation assessments and is only currently available for use in research. For some devices, laboratory validation studies have found large discrepancies between device measurements and headform data (Table 3), especially for certain impact directions. Such discrepancies may be a result of nonrigid skull coupling for helmets, headgear, headbands, skullcaps,

and skin patches. Relatively small errors have been reported for instrumented mouthguards; however, constraint limitations have been identified with clenched teeth providing the most accurate results.

Over the past decade, instrumented equipment has recorded millions of impacts in the laboratory, on the field, in the ring, and on the ice. Instrumented equipment is not without limitations; however, *in vivo* head impact data is crucial to investigate head injury mechanisms and further the understanding of concussion.

## Competing Interests

The author declares that they have no competing interests.

## References

- [1] R. C. Schneider, E. Reifel, H. O. Crisler, and B. G. Oosterbaan, "Serious and fatal football injuries involving the head and spinal cord," *The Journal of the American Medical Association*, vol. 177, no. 6, pp. 362–367, 1961.
- [2] J. S. Aagaard and J. L. Du Bois, "Telemetry impact data from the football field," *Electronics*, vol. 35, pp. 46–47, 1962.
- [3] S. E. Reid, J. A. Tarkington, and M. Petrovick, "Radiotelemetry study of head injuries in football," in *Football Injuries: Papers Presented at a Workshop*, Injuries NRCSOA, Ed., pp. 83–93, National Academy of Sciences, Washington, DC, USA, 1970.
- [4] D. W. Moon, C. W. Beedle, and C. R. Kovacic, "Peak head acceleration of athletes during competition—football," *Medicine & Science in Sports*, vol. 3, no. 1, pp. 44–50, 1971.
- [5] A. H. Hirsch, "Current problems in head protection," in *Proceedings of the Head Injury Conference*, 1966.
- [6] E. S. Gurdjian, H. R. Lissner, and L. M. Patrick, "Protection of the head and neck in sports," *The Journal of the American Medical Association*, vol. 182, no. 5, pp. 509–512, 1962.
- [7] S. E. Reid, J. A. Tarkington, H. M. Epstein, and T. J. O'Dea, "Brain tolerance to impact in football," *Surgery Gynecology & Obstetrics*, vol. 133, no. 6, pp. 929–936, 1971.
- [8] S. E. Reid, H. M. Epstein, T. J. O'Dea, M. W. Louis, and S. E. Reid Jr., "Head protection in football," *The American Journal of Sports Medicine*, vol. 2, no. 2, pp. 86–92, 1974.
- [9] S. E. Reid, H. M. Epstein, M. W. Louis, and S. E. Reid, "Physiologic response to impact," *Journal of Trauma—Injury, Infection and Critical Care*, vol. 15, no. 2, pp. 150–152, 1975.
- [10] S. E. Reid, H. M. Epstein, T. J. O'Dea, M. W. Louis, and S. E. Reid Jr., "A study of impacts in living man using radiotelemetry," in *Proceedings of the International Conference on the Biomechanics of Serious Trauma*, Birmingham, UK, 1975.
- [11] American Society for Testing and Materials, "Standard specification for football helmets," ASTM F717, American Society for Testing and Materials, West Conshohocken, Pa, USA, 2010.
- [12] P. R. McCrory, W. H. Meeuwisse, M. Aubry et al., "Consensus statement on concussion in sport: the 4th international conference on concussion in sport held in Zurich, November 2012," *British Journal of Sports Medicine*, vol. 47, no. 5, pp. 250–258, 2013.
- [13] V. R. Hodgson and L. M. Thomas, "Effect of long-duration impact on head," in *Proceedings of the 16th Stapp Car Crash Conference*, Detroit, Mich, USA, 1972.
- [14] H. J. Mertz, *The kinematics and kinetics of whiplash [Ph.D. thesis]*, Wayne State University, Detroit, Mich, USA, 1967.

- [15] H. F. J. Mertz Jr. and L. M. Patrick, "Investigation of the kinematics and kinetics of whiplash," in *Proceedings of the 11th Stapp Car Crash Conference*, Anaheim, Calif, USA, October 1967.
- [16] C. L. Ewing, D. J. Thomas, G. W. Beeler Jr., L. M. Patrick, and D. B. Gillis, "Dynamic response of the head and neck of the living human to  $-G_x$  impact acceleration," in *Proceedings of the 12th Stapp Car Crash Conference*, Detroit, Mich, USA, 1968.
- [17] C. L. Ewing, D. J. Thomas, L. M. Patrick, G. W. Beeler Jr., and M. J. Smith, "Living human dynamic response to  $-G_x$  impact acceleration. II—accelerations measured in the head and neck," in *Proceedings of the 13th Stapp Car Crash Conference*, Boston, Mass, USA, December 1969.
- [18] C. L. Ewing and D. J. Thomas, "Human head and neck response to  $-G_x$  impact acceleration," in *Proceedings of the Linear Acceleration of Impact Type: An Aerospace Medical Panel Specialist Meeting*, Oporto, Portugal, June 1971.
- [19] H. F. J. Mertz Jr. and L. M. Patrick, "Strength and response of the human neck," in *Proceedings of the 15th Stapp Car Crash Conference*, Coronado, Calif, USA, November 1971.
- [20] C. L. Ewing and D. J. Thomas, *Human Head and Neck Response to Impact Acceleration*, Naval Aerospace Medical Institute, Naval Aerospace and Regional Medical Center, New Orleans, La, USA, 1972.
- [21] C. L. Ewing and D. J. Thomas, "Torque versus angular displacement response of human head to  $-G_x$  impact acceleration," in *Proceedings of the 17th Stapp Car Crash Conference*, Oklahoma City, Okla, USA, 1973.
- [22] C. L. Ewing, D. J. Thomas, L. Lustick, E. Becker, G. C. Willems, and W. H. Muzzy III, "The effect of the initial position of the head and neck to  $-G_x$  impact acceleration," in *Proceedings of the 19th Stapp Car Crash Conference*, San Diego, Calif, USA, 1975.
- [23] C. L. Ewing, D. J. Thomas, L. Lustick, W. H. Muzzy III, G. C. Willems, and P. L. Majewski, "The effect of duration, rate of onset and peak sled acceleration on the dynamic response of the human head and neck," in *Proceedings of the 20th Stapp Car Crash Conference*, Dearborn, Mich, USA, 1976.
- [24] C. L. Ewing, D. J. Thomas, and L. Lustick, "Multiaxis dynamic response of the human head and neck to impact acceleration," in *Proceedings of the AGARD Conference, Models and Analogues for the Evaluation of Human Biodynamic Response, Performance and Protection*, Paris, France, November 1978.
- [25] A. V. Zaborowski, "Human tolerance to lateral impact with lap belt only," in *Proceedings of the 8th Stapp Car Crash Conference*, Detroit, Mich, USA, 1964.
- [26] C. L. Ewing, D. J. Thomas, L. Lustick, W. H. Muzzy III, G. C. Willems, and P. L. Majewski, "Dynamic response of the human head and neck to  $+G_y$  impact acceleration," in *Proceedings of the 21st Stapp Car Crash Conference*, Dearborn, Mich, USA, 1977.
- [27] C. L. Ewing, D. J. Thomas, L. Lustick, W. H. Muzzy III, G. C. Willems, and P. L. Majewski, "Effect of initial position on the human head and neck response to  $+Y$  impact acceleration," in *Proceedings of the 22nd Stapp Car Crash Conference*, Ann Arbor, Mich, USA, 1978.
- [28] W. E. Morrison, *Calibration and utilization of an instrumented football helmet for the monitoring of impact accelerations [Ph.D. thesis]*, Department of Physical Education, Penn State University, State College, Pa, USA, 1983.
- [29] R. S. Naunheim, J. Standeven, C. Richter, and L. M. Lewis, "Comparison of impact data in hockey, football, and soccer," *Journal of Trauma—Injury, Infection and Critical Care*, vol. 48, no. 5, pp. 938–941, 2000.
- [30] R. M. Greenwald, J. J. Chu, J. J. Crisco, and J. A. Finkelstein, "Head Impact Telemetry System (HITS) for measurement of head acceleration in the field," in *Proceedings of the American Society of Biomechanics Annual Meeting*, Toledo, Ohio, USA, September 2003.
- [31] J. J. Crisco, R. M. Greenwald, and J. J. Chu, "A novel algorithm for estimating head impact magnitude and location," in *Proceedings of the 4th World Congress of Biomechanics*, Calgary, Canada, 2002.
- [32] J. J. Crisco, J. J. Chu, and R. M. Greenwald, "An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers," *Journal of Biomechanical Engineering*, vol. 126, no. 6, pp. 849–854, 2004.
- [33] J. J. Crisco, J. J. Chu, and R. M. Greenwald, "An approach to calculating linear head accelerations is not affected by rotational head accelerations," in *Proceedings of the 20th Congress of the International Society of Biomechanics*, Cleveland, Ohio, USA, 2005.
- [34] S. J. Manoogian, D. McNeely, M. W. Goforth, P. G. Brolinson, and S. M. Duma, "Head acceleration is less than 10 percent of helmet acceleration during a football impact," in *Proceedings of the 20th Congress of the International Society of Biomechanics*, Cleveland, Ohio, USA, 2005.
- [35] S. J. Manoogian, D. McNeely, S. M. Duma, P. G. Brolinson, and R. M. Greenwald, "Head acceleration is less than 10 percent of helmet acceleration in football impacts," *Biomedical Sciences Instrumentation*, vol. 42, pp. 383–388, 2006.
- [36] J. G. Beckwith, J. J. Chu, and R. M. Greenwald, "Development and validation of the head impact telemetry system™ for use in amateur boxing," *Journal of Biomechanics*, vol. 39, supplement 1, p. S153, 2006.
- [37] J. G. Beckwith, J. J. Chu, and R. M. Greenwald, "Validation of a noninvasive system for measuring head acceleration for use during boxing competition," *Journal of Applied Biomechanics*, vol. 23, no. 3, pp. 238–244, 2007.
- [38] E. Hanlon and C. A. Bir, "Validation of a wireless head acceleration measurement system for use in soccer play," *Journal of Applied Biomechanics*, vol. 26, no. 4, pp. 424–431, 2010.
- [39] S. M. Duma, S. J. Manoogian, P. G. Brolinson et al., "Measuring real-time head accelerations in collegiate football players," in *Proceedings of the Fundamentals and Advanced Concepts for Automobile and Sports Injury Biomechanics Conference*, Roanoke, Va, USA, 2004.
- [40] S. M. Duma, S. J. Manoogian, W. R. Bussone et al., "Analysis of real-time head accelerations in collegiate football players," *Clinical Journal of Sport Medicine*, vol. 15, no. 1, pp. 3–8, 2005.
- [41] P. G. Brolinson, S. Manoogian, D. McNeely, M. W. Goforth, R. M. Greenwald, and S. M. Duma, "Analysis of linear head accelerations from collegiate football impacts," *Current Sports Medicine Reports*, vol. 5, no. 1, pp. 23–28, 2006.
- [42] J. Gwin, J. Chu, and R. Greenwald, "Head impact telemetry system™ for measurement of head acceleration in ice hockey," *Journal of Biomechanics*, vol. 39, p. S153, 2006.
- [43] R. M. Greenwald, J. J. Chu, J. G. Beckwith, J. T. Gwin, A. T. Buck, and J. J. Crisco, "On-field measurement of head impact acceleration in helmeted sports," in *Proceedings of the American Society for Biomechanics Annual Meeting*, Blacksburg, Va, USA, 2006.
- [44] J. R. Funk, S. M. Duma, S. J. Manoogian, and S. Rowson, "Development of concussion risk curves based on head impact data from collegiate football players," in *Proceedings of the*

- 34th International Injury Biomechanics Research Workshop, Dearborn, Mich, USA, 2006.
- [45] J. R. Funk, S. M. Duma, S. J. Manoogian, and S. Rowson, "Biomechanical risk estimates for mild traumatic brain injury," in *Proceedings of the 51st Annual Association for the Advancement of Automotive Medicine*, Melbourne, Australia, October 2007.
- [46] K. M. Guskiewicz, J. P. Mihalik, V. Shankar et al., "Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion," *Neurosurgery*, vol. 61, no. 6, pp. 1244–1253, 2007.
- [47] J. P. Mihalik, D. R. Bell, S. W. Marshall, and K. M. Guskiewicz, "Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences," *Neurosurgery*, vol. 61, no. 6, pp. 1229–1235, 2007.
- [48] B. Schnebel, J. T. Gwin, S. Anderson, and R. Gatlin, "In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association division I versus high school impacts," *Neurosurgery*, vol. 60, no. 3, pp. 490–495, 2007.
- [49] R. M. Greenwald, J. T. Gwin, J. J. Chu, and J. J. Crisco, "Head impact severity measures for evaluating mild traumatic brain injury risk exposure," *Neurosurgery*, vol. 62, no. 4, pp. 789–798, 2008.
- [50] J. P. Mihalik, K. M. Guskiewicz, J. A. Jeffries, R. M. Greenwald, and S. W. Marshall, "Characteristics of head impacts sustained by youth ice hockey players," *Journal of Sports Engineering and Technology*, vol. 222, no. 1, pp. 45–52, 2008.
- [51] J. G. Beckwith, J. J. Chu, J. J. Crisco et al., "Severity of head impacts resulting in mild traumatic brain injury," in *Proceedings of the American Society of Biomechanics Annual Meeting*, State College, Pa, USA, August 2009.
- [52] L. L. Brainard, J. G. Beckwith, C.-S. Chu et al., "Gender differences in head impact acceleration in collegiate ice Hockey," in *Proceedings of the American Society of Biomechanics Annual Meeting*, State College, Pa, USA, 2009.
- [53] S. P. Broglio, J. J. Sosnoff, S. Shin, X. He, C. Alcaraz, and J. Zimmerman, "Head impacts during high school football: a biomechanical assessment," *Journal of Athletic Training*, vol. 44, no. 4, pp. 342–349, 2009.
- [54] J. Cubos, J. R. Baker, B. E. Faught et al., "Relationships among risk factors for concussion in minor ice hockey," *Journal of ASTM International*, vol. 6, no. 6, Article ID JAI101878, 2009.
- [55] S. M. Duma and S. Rowson, "Every newton hertz: a macro to micro approach to investigating brain injury," in *Proceedings of the 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC '09)*, pp. 1123–1126, Minneapolis, Minn, USA, September 2009.
- [56] J. T. Gwin, J. J. Chu, T. A. McAllister, and R. M. Greenwald, "In situ measures of head impact acceleration in NCAA division I men's ice hockey: implications for ASTM F1045 and other ice hockey helmet standards," *Journal of ASTM International*, vol. 6, no. 6, pp. 42–51, 2009.
- [57] S. Rowson, P. G. Brolinson, M. W. Goforth, D. Dietter, and S. M. Duma, "Linear and angular head acceleration measurements in collegiate football," *Journal of Biomechanical Engineering*, vol. 131, no. 6, Article ID 061016, 2009.
- [58] S. P. Broglio, B. Schnebel, J. J. Sosnoff et al., "Biomechanical properties of concussions in high school football," *Medicine & Science in Sports & Exercise*, vol. 42, no. 11, pp. 2064–2071, 2010.
- [59] J. J. Crisco, R. Fiore, J. G. Beckwith et al., "Frequency and location of head impact exposures in individual collegiate football players," *Journal of Athletic Training*, vol. 45, no. 6, pp. 549–559, 2010.
- [60] J. P. Mihalik, J. T. Blackburn, R. M. Greenwald, R. C. Cantu, S. W. Marshall, and K. M. Guskiewicz, "Collision type and player anticipation affect head impact severity among youth ice hockey players," *Pediatrics*, vol. 125, no. 6, pp. e1394–e1401, 2010.
- [61] N. Reed, T. Taha, M. L. Keightley et al., "Measurement of head impacts in youth ice hockey players," *International Journal of Sports Medicine*, vol. 31, no. 11, pp. 826–833, 2010.
- [62] H. Kimpara, Y. Nakahira, M. Iwamoto, S. Rowson, and S. M. Duma, "Head injury prediction methods based on 6 degree of freedom head acceleration measurements during impact," *International Journal of Automotive Engineering*, vol. 2, no. 2, pp. 13–19, 2011.
- [63] J. G. Beckwith, R. M. Greenwald, J. J. Chu et al., "Severity and frequency of head impacts sustained by football players on days of diagnosed concussion diagnosis," *Brain Injury*, vol. 26, no. 4–5, pp. 728–729, 2012.
- [64] J. G. Beckwith, R. M. Greenwald, J. J. Chu et al., "Timing of concussion diagnosis is related to head impact exposure prior to injury," *Medicine & Science in Sports & Exercise*, vol. 45, no. 4, pp. 747–754, 2013.
- [65] J. G. Beckwith, R. M. Greenwald, J. J. Chu et al., "Head impact exposure sustained by football players on days of diagnosed concussion," *Medicine & Science in Sports & Exercise*, vol. 45, no. 4, pp. 737–746, 2013.
- [66] L. L. Brainard, J. G. Beckwith, J. J. Chu et al., "Gender differences in head impacts sustained by collegiate ice hockey players," *Medicine and Science in Sports and Exercise*, vol. 44, no. 2, pp. 297–304, 2012.
- [67] E. L. Breedlove, M. Robinson, T. M. Talavage et al., "Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football," *Journal of Biomechanics*, vol. 45, no. 7, pp. 1265–1272, 2012.
- [68] R. W. Daniel II, S. Rowson, and S. M. Duma, "Head impact exposure in youth football," *Annals of Biomedical Engineering*, vol. 40, no. 4, pp. 976–981, 2012.
- [69] R. W. Daniel II, *Head acceleration measurements in Helmet-Helmet impacts and the youth population [M.S. thesis]*, School of Biomedical Engineering and Sciences, Virginia Polytechnic Institute and State University, Blacksburg, Va, USA, 2012.
- [70] A.-C. Duhaime, J. G. Beckwith, A. C. Maerlender et al., "Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets," *Journal of Neurosurgery*, vol. 117, no. 6, pp. 1092–1099, 2012.
- [71] J. R. Funk, S. Rowson, R. W. Daniel II, and S. M. Duma, "Validation of concussion risk curves for collegiate football players derived from HITS data," *Annals of Biomedical Engineering*, vol. 40, no. 1, pp. 79–89, 2012.
- [72] S. M. Gysland, J. P. Mihalik, J. K. Register-Mihalik, S. C. Trulock, E. W. Shields, and K. M. Guskiewicz, "The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players," *Annals of Biomedical Engineering*, vol. 40, no. 1, pp. 14–22, 2012.
- [73] J. P. Mihalik, K. M. Guskiewicz, S. W. Marshall, J. T. Blackburn, R. C. Cantu, and R. M. Greenwald, "Head impact biomechanics in youth hockey: comparisons across playing position, event types, and impact locations," *Annals of Biomedical Engineering*, vol. 40, no. 1, pp. 141–149, 2012.
- [74] K. E. Owieja, J. P. Mihalik, S. W. Marshall, J. D. Schmidt, S. C. Trulock, and K. M. Guskiewicz, "The effect of play type

- and collision closing distance on head impact biomechanics,” *Annals of Biomedical Engineering*, vol. 40, no. 1, pp. 90–96, 2012.
- [75] S. Rowson, S. M. Duma, J. G. Beckwith et al., “Rotational head kinematics in football impacts: an injury risk function for concussion,” *Annals of Biomedical Engineering*, vol. 40, no. 1, pp. 1–13, 2012.
- [76] S. Rowson, R. W. Daniel, T. J. Young et al., “Head acceleration measurements during head impact in pediatric populations,” in *Proceedings of the 40th International Workshop on Human Subjects for Biomechanical Research*, Savannah, Ga, USA, 2012.
- [77] J. E. Urban, R. W. Daniel, B. R. Cobb et al., “Cumulative exposure risk of concussion for youth and high school football head impacts,” in *Proceedings of the Injury Biomechanics Symposium*, Columbus, Ohio, USA, May 2013.
- [78] B. R. Cobb, J. E. Urban, E. M. Davenport et al., “Head impact exposure in youth football: elementary school ages 9–12 years and the effect of practice structure,” *Annals of Biomedical Engineering*, vol. 41, no. 12, pp. 2463–2473, 2013.
- [79] T. M. Talavage, E. A. Nauman, E. L. Breedlove et al., “Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion,” *Journal of Neurotrauma*, vol. 31, no. 4, pp. 327–338, 2014.
- [80] J. E. Urban, E. M. Davenport, A. J. Golman et al., “Head impact exposure in youth football: high school ages 14 to 18 years and cumulative impact analysis,” *Annals of Biomedical Engineering*, vol. 41, no. 12, pp. 2474–2487, 2013.
- [81] J. D. Stitzel, J. E. Urban, E. M. Davenport, J. Maldjian, C. Whitlow, and A. Powers, “Development of a risk weighted cumulative exposure metric for the analysis of head impact data,” in *Proceedings of the 10th World Congress on Brain Injury*, San Francisco, Calif, USA, 2014.
- [82] R. W. Daniel II, S. Rowson, and S. M. Duma, “Head impact exposure in youth football: middle school ages 12–14 years,” *Journal of Biomechanical Engineering*, vol. 136, no. 9, Article ID 094501, 2014.
- [83] B. J. Wilcox, J. G. Beckwith, R. M. Greenwald et al., “Head impact exposure in male and female collegiate ice hockey players,” *Journal of Biomechanics*, vol. 47, no. 1, pp. 109–114, 2014.
- [84] T. J. Young, R. W. Daniel II, S. Rowson, and S. M. Duma, “Head impact exposure in youth football: elementary school ages 7–8 years and the effect of returning players,” *Clinical Journal of Sport Medicine*, vol. 24, no. 5, pp. 416–421, 2014.
- [85] B. R. Cummiskey, *Characterization and evaluation of head impact sensors and varsity football helmets [M.S. thesis]*, Purdue University, West Lafayette, Ind, USA, 2015.
- [86] T. A. Munce, J. C. Dorman, P. A. Thompson, V. D. Valentine, and M. F. Bergeron, “Head impact exposure and neurologic function of youth football players,” *Medicine and Science in Sports and Exercise*, vol. 47, no. 8, pp. 1567–1576, 2015.
- [87] Z. Y. Kerr, A. C. Littleton, L. M. Cox et al., “Estimating contact exposure in football using the head impact exposure estimate,” *Journal of Neurotrauma*, vol. 32, no. 14, pp. 1083–1089, 2015.
- [88] E. E. Swartz, S. P. Broglio, S. B. Cook et al., “Early results of a helmetless-tackling intervention to decrease head impacts in football players,” *Journal of Athletic Training*, vol. 50, no. 12, pp. 1219–1222, 2015.
- [89] E. McCuen, D. Svaldi, K. Breedlove et al., “Collegiate women’s soccer players suffer greater cumulative head impacts than their high school counterparts,” *Journal of Biomechanics*, vol. 48, no. 13, pp. 3729–3732, 2015.
- [90] M. Morrison, J. N. Daigle, and J. Ralston, “A biosensing approach for detecting and managing head injuries in american football,” *Journal of Biosensors & Bioelectronics*, vol. 6, article 189, 2015.
- [91] J. C. Stucker, *Head impact biomechanics in collegiate female soccer players [M.S. thesis]*, Department of Exercise and Sport Science, University of North Carolina, Chapel Hill, NC, USA, 2015.
- [92] D. A. King, P. A. Hume, C. Gissane, and T. N. Clark, “Similar head impact acceleration measured using instrumented ear patches in a junior rugby union team during matches in comparison with other sports,” *Journal of Neurosurgery: Pediatrics*, 2016.
- [93] D. O. Svaldi, E. C. McCuen, C. Joshi et al., “Cerebrovascular reactivity changes in asymptomatic female athletes attributable to high school soccer participation,” *Brain Imaging and Behavior*, pp. 1–15, 2016.
- [94] S. Rowson, J. G. Beckwith, J. J. Chu, D. S. Leonard, R. M. Greenwald, and S. M. Duma, “A six degree of freedom head acceleration measurement device for use in football,” *Journal of Applied Biomechanics*, vol. 27, no. 1, pp. 8–14, 2011.
- [95] J. G. Beckwith, R. M. Greenwald, and J. J. Chu, “Measuring head kinematics in football: correlation between the head impact telemetry system and hybrid III headform,” *Annals of Biomedical Engineering*, vol. 40, no. 1, pp. 237–248, 2012.
- [96] M. A. Allison, Y.-S. Kang, J. H. Bolte IV, M. R. Maltese, and K. B. Arbogast, “Validation of a helmet-based system to measure head impact biomechanics in ice hockey,” *Medicine & Science in Sports & Exercise*, vol. 46, no. 1, pp. 115–123, 2014.
- [97] D. B. Camarillo, P. B. Shull, J. Mattson, R. Shultz, and D. Garza, “An instrumented mouthguard for measuring linear and angular head impact kinematics in american football,” *Annals of Biomedical Engineering*, vol. 41, no. 9, pp. 1939–1949, 2013.
- [98] A. J. Bartsch and S. Samorezov, “Cleveland clinic intelligent mouthguard: a new technology to accurately measure head impact in athletes and soldiers,” in *Sensing Technologies for Global Health, Military Medicine, and Environmental Monitoring III. Military Medicine I: Traumatic Brain Injury and PTSD*, Š. O. Southern, Ed., vol. 8723 of *Proceedings of SPIE*, May 2013.
- [99] A. Aksu, *Benchtop validation of ‘intelligent’ mouthguard [M.S. thesis]*, Fenn College of Engineering, Cleveland State University, Cleveland, Ohio, USA, 2013.
- [100] R. Jadischke, D. C. Viano, N. Dau, A. I. King, and J. McCarthy, “On the accuracy of the head impact telemetry (HIT) system used in football helmets,” *Journal of Biomechanics*, vol. 46, no. 13, pp. 2310–2315, 2013.
- [101] M. A. Allison, Y.-S. Kang, M. R. Maltese, J. H. Bolte IV, and K. B. Arbogast, “Measurement of hybrid III head impact kinematics using an accelerometer and gyroscope system in ice hockey helmets,” *Annals of Biomedical Engineering*, vol. 43, no. 8, pp. 1896–1906, 2015.
- [102] A. J. Bartsch, S. Samorezov, E. C. Benzel, V. J. Miele, and D. Brett, “Validation of an ‘intelligent mouthguard’ single event head impact dosimeter,” *Stapp Car Crash Journal*, vol. 58, pp. 14S–17S, 2014.
- [103] Triax Technologies, *Laboratory Validation of the SIM-G Head Impact Sensor*, Triax Technologies, Norwalk, Conn, USA, 2014.
- [104] K. R. Campbell, M. J. Warnica, I. C. Levine et al., “Laboratory evaluation of the gForce tracker™, a head impact kinematic measuring device for use in football helmets,” *Annals of Biomedical Engineering*, vol. 44, no. 4, pp. 1246–1256, 2016.

- [105] D. Nevins, L. Smith, and J. Kensrud, "Laboratory evaluation of wireless head impact sensor," in *Proceedings of the 7th Asia-Pacific Congress on Sports Technology (APCST '15)*, pp. 175–179, Barcelona, Spain, September 2015.
- [106] L. C. Wu, V. Nangia, K. Bui et al., "In vivo evaluation of wearable head impact sensors," *Annals of Biomedical Engineering*, vol. 44, no. 4, pp. 1234–1245, 2016.
- [107] C. Kuo, L. C. Wu, B. T. Hammoor et al., "Effect of the mandible on mouthguard measurements of head kinematics," *Journal of Biomechanics*, vol. 49, no. 9, pp. 1845–1853, 2016.
- [108] G. P. Siegmund, K. M. Guskiewicz, S. W. Marshall, A. L. DeMarco, and S. J. Bonin, "Laboratory validation of two wearable sensor systems for measuring head impact severity in football players," *Annals of Biomedical Engineering*, vol. 44, no. 4, pp. 1257–1274, 2016.
- [109] J. J. Chu, J. G. Beckwith, J. J. Crisco, and R. M. Greenwald, "A novel algorithm to measure linear and rotational head acceleration using single-axis accelerometers," *Journal of Biomechanics*, vol. 39, supplement 1, p. S534, 2006.
- [110] B. R. Cobb, "Measuring head impact exposure and mild traumatic brain injury in humans," in *Proceedings of the Brain Injuries & Biomechanics Symposium*, Arlington, Va, USA, 2013.
- [111] B. J. Wilcox, J. G. Beckwith, R. M. Greenwald, and J. J. Crisco, "Limitations of 'validation study of helmet-based impact measurement system in hockey,'" *Medicine & Science in Sports & Exercise*, vol. 46, no. 3, pp. 640–641, 2014.
- [112] K. B. Arbogast, M. A. Allison, M. R. Maltese, and J. H. Bolte IV, "Response," *Medicine & Science in Sports & Exercise*, vol. 46, no. 3, 642 pages, 2014.
- [113] G. P. Siegmund, K. M. Guskiewicz, S. W. Marshall, A. L. DeMarco, and S. J. Bonin, "A headform for testing helmet and mouthguard sensors that measure head impact severity in football players," *Annals of Biomedical Engineering*, vol. 42, no. 9, pp. 1834–1845, 2014.
- [114] S. M. Duma and S. Rowson, "Past, present, and future of head injury research," *Exercise and Sport Sciences Reviews*, vol. 39, no. 1, pp. 2–3, 2011.
- [115] K. M. Guskiewicz and J. P. Mihalik, "Biomechanics of sport concussion: quest for the elusive injury threshold," *Exercise and Sport Sciences Reviews*, vol. 39, no. 1, pp. 4–11, 2011.
- [116] B. J. Wilcox, J. G. Beckwith, R. M. Greenwald et al., "Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players," *Journal of Biomechanics*, vol. 48, no. 10, pp. 2201–2204, 2015.
- [117] GForceTracker, *How It Works*, GForceTracker, Richmond Hill, Canada, 2016.
- [118] B. De Lench and L. B. Straus, "Standard-setting by non-governmental agencies in the field of sports safety equipment: promoting the interests of consumers or manufacturers?" *Journal of Business & Technology Law*, vol. 10, no. 1, pp. 47–60, 2015.
- [119] National Operating Committee on Standards for Athletic Equipment, *NOCSAE Statement on Third Party Helmet Add-On Products and Certification*, Overland Park, KS, USA, NOCSAE, 2013.
- [120] National Operating Committee on Standards for Athletic Equipment, *Certification to NOCSAE Standards and Add-On Helmet Products*, NOCSAE, Overland Park, Kan, USA, 2013.
- [121] L. M. Lewis, R. Naunheim, J. Standeven, C. Lauryssen, C. Richter, and B. Jeffords, "Do football helmets reduce acceleration of impact in blunt head injuries?" *Academic Emergency Medicine*, vol. 8, no. 6, pp. 604–609, 2001.
- [122] C. Withnall, N. Shewchenko, M. Wonnacott, and J. Dvorak, "Effectiveness of headgear in football," *British Journal of Sports Medicine*, vol. 39, no. 1, pp. i40–i48, 2005.
- [123] R. T. Tierney, M. Higgins, S. V. Caswell et al., "Sex differences in head acceleration during heading while wearing soccer headgear," *Journal of Athletic Training*, vol. 43, no. 6, pp. 578–584, 2008.
- [124] M. Keown, J. A. Shewchenko, and J. Dvorak, "Numerical investigation of impact severity reduction in football heading," in *Proceedings of the 4th European MADYMO User Conference*, Brussels, Belgium, October 2003.
- [125] N. Shewchenko, C. Withnall, M. Keown, R. Gittens, and J. Dvorak, "Heading in football. Part 1: development of biomechanical methods to investigate head response," *British Journal of Sports Medicine*, vol. 39, supplement 1, pp. i10–i25, 2005.
- [126] B. P. Self, J. Beck, D. Schill, C. Eames, T. Knox, and J. Plaga, "Head accelerations during soccer heading," in *The Engineering of Sport 6, Volume 2: Developments for Disciplines, Section 3: Measurement Techniques*, E. F. Moritz and S. Haake, Eds., vol. 6, pp. 81–86, Springer, New York, NY, USA, 2006.
- [127] M. Higgins, P. D. Halstead, L. Snyder-Mackler, and D. Barlow, "Measurement of impact acceleration: mouthpiece accelerometer versus helmet accelerometer," *Journal of Athletic Training*, vol. 42, no. 1, pp. 5–10, 2007.
- [128] A. J. Paris, K. R. Antonini, and J. M. Brock, "Accelerations of the head during soccer ball heading," in *Proceedings of the ASME Summer Bioengineering Conference (SBC '10)*, pp. 815–816, Naples, Fla, USA, June 2010.
- [129] T. M. Kara, J. A. DelSignore, J. M. Brock, J. Lund, and A. J. Paris, "Evaluation of an instrumented mouthguard to measure the accelerations of the head due to soccer ball heading," in *Proceedings of the 12th Pan-American Congress of Applied Mechanics*, Port of Spain, Trinidad, January 2012.
- [130] D. A. King, P. A. Hume, M. Brughelli, and C. Gissane, "Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches," *The American Journal of Sports Medicine*, vol. 43, no. 3, pp. 614–624, 2015.
- [131] F. Hernandez, P. B. Shull, and D. B. Camarillo, "Evaluation of a laboratory model of human head impact biomechanics," *Journal of Biomechanics*, vol. 48, no. 12, pp. 3469–3477, 2015.
- [132] F. Hernandez, L. C. Wu, M. C. Yip et al., "Six degree-of-freedom measurements of human mild traumatic brain injury," *Annals of Biomedical Engineering*, vol. 43, no. 8, pp. 1918–1934, 2015.
- [133] S. Kleiven, *Finite element modelling of the human head [Ph.D. thesis]*, Department of Aeronautics, School of Technology and Health, Royal Institute of Technology, Huddinge, Sweden, 2002.
- [134] L. C. Wu, L. Zarnescu, V. Nangia, B. Cam, and D. B. Camarillo, "A head impact detection system using SVM classification and proximity sensing in an instrumented mouthguard," *IEEE Transactions on Biomedical Engineering*, vol. 61, no. 11, pp. 2659–2668, 2014.
- [135] X2 Biosystems, *The X-Patch: The World's Most Widely Deployed Wearable Head Impact Monitor*, X2 Biosystems, Redwood City, Calif, USA, 2016.
- [136] Z. Y. Kerr, S. Yeargin, T. C. V. McLeod et al., "Comprehensive coach education reduces head impact exposure in american youth football," *Orthopaedic Journal of Sports Medicine*, vol. 3, no. 10, 2015.
- [137] B. B. Reynolds, J. Patrie, E. J. Henry et al., "Practice type effects on head impact in collegiate football," *Journal of Neurosurgery*, vol. 124, no. 2, pp. 501–510, 2016.

- [138] K. Lightman, "Silicon gets sporty," *Institute of Electrical and Electronics Engineers Spectrum*, vol. 53, no. 3, pp. 48–53, 2016.
- [139] B. Harper, A. Siyufy, J. Castleberry et al., "Clinical experiences using a hit impact indicator in youth football," *Sport Journal*, 2015.
- [140] il Biometrics, *Shockbox Helmet Sensors*, il Biometrics, Kirkland, Wash, USA, 2016.
- [141] S. Foreman and D. Crossman, "Comparative analysis for the measurement of head accelerations in ice hockey helmets using non-accelerometer based systems," in *Proceedings of the ASTM Symposium on the Mechanism of Concussion in Sports*, pp. 3–12, Atlanta, Ga, USA, November 2012.
- [142] R. H. Wong, A. K. Wong, and J. E. Bailes, "Frequency, magnitude, and distribution of head impacts in Pop Warner football: the cumulative burden," *Clinical Neurology and Neurosurgery*, vol. 118, pp. 1–4, 2014.
- [143] D. Crossman, J. E. Bailes, R. Oueis, L. Doyle, and T. Bailey, *Monitoring of Higher Magnitude Head Impact Exposure in Youth and High School Football Players*, il Biometrics, Kirkland, Wash, USA, 2013.
- [144] S. Dakan, R. J. Elbin, W. P. Meehan, M. W. Collins, and A. P. Kontos, *Impact Forces to the Head and Their Effects on Youth Ice Hockey Players*, il Biometrics, Kirkland, Wash, USA, 2012.
- [145] S. Foreman, D. Crossman, B. Roy, and T. Taylor, *Evaluation of Direct Head Impacts Sustained During Varsity Women's Noncontact Ice Hockey Using Head Impact Alert Sensors*, il Biometrics, Kirkland, Wash, USA, 2013.
- [146] T. Knox, J. Pelletiere, C. Perry, J. Plaga, and J. Bonfeld, "New sensors to track head acceleration during possible injurious events," *International Journal of Passenger Cars—Electronic and Electrical Systems*, vol. 1, no. 1, pp. 652–663, 2008.
- [147] T. Knox, "Validation of earplug accelerometers as a means of measuring head motion," in *Proceedings of the Motorsports Engineering Conference & Exhibition*, Dearborn, Mich, USA, 2004.
- [148] B. P. Self, C. Karins, and T. Knox, "Head accelerations during impact events," in *Proceedings of the 5th International Conference on the Engineering of Sport*, Davis, Calif, USA, 2004.
- [149] S. E. Stojsh, M. A. Boitano, and C. A. Bir, "Head impact accelerations in boxing using telemetry system," in *Proceedings of the 17th Annual Meeting of the American Medical Society for Sports Medicine*, Las Vegas, Nev, USA, 2008.
- [150] S. E. Stojsh, M. A. Boitano, M. Wilhelm, and C. A. Bir, "A prospective study of punch biomechanics and cognitive function for amateur boxers," *British Journal of Sports Medicine*, vol. 44, no. 10, pp. 725–730, 2010.
- [151] N. Dau, H. C. Chien, D. C. Sherman, and C. A. Bir, "Effectiveness of boxing headgear for limiting injury," in *Proceedings of the Annual Conference of the American Society of Biomechanics*, Blacksburg, Va, USA, 2006.
- [152] J. D. Pierce, K. A. Reinbold, B. C. Lyngard, R. J. Goldman, and C. M. Pastore, "Direct measurement of punch force during six professional boxing matches," *Journal of Quantitative Analysis in Sports*, vol. 2, no. 2, article 3, 2006.
- [153] N. J. Langholz, *Pulling punches: a non-parameteric approach to punch force estimation and the development of novel boxing metrics [Ph.D. thesis]*, University of California, Los Angeles, Calif, USA, 2013.
- [154] A. G. Hahn, "Box'Tag: a modified form of boxing competition aimed at improving community fitness and health," *Sport Health*, vol. 25, no. 3, pp. 6–8, 2007.
- [155] R. Daly, D. Furstinger, T. Sashegyi, N. Schmidt, and M. Shah, *W.I.S.H.—wireless impact sensing headband [Honour's thesis]*, Santa Clara University, Santa Clara, Calif, USA, 2014.
- [156] K. Partridge, J. P. Hayes, D. James, C. Hill, G. Gin, and A. Hahn, "A wireless-sensor scoring and training system for combative sports," in *Proceedings of the Smart Structures, Devices, and Systems II*, pp. 402–408, Sydney, Australia, December 2005.
- [157] H. Bruch, A. G. Hahn, R. J. N. Helmer, C. Mackintosh, I. Blanchonette, and M. J. McKenna, "Evaluation of an automated scoring system in a modified form of competitive boxing," in *Proceedings of the 5th Asia-Pacific Congress on Sports Technology*, Vienna, Austria, 2011.
- [158] R. J. N. Helmer, A. G. Hahn, L. M. Staynes, R. J. Denning, A. Krajewski, and I. Blanchonette, "Design and development of interactive textiles for impact detection and use with an automated boxing scoring system," in *Proceedings of the 8th Conference of the International Sports Engineering Association*, Vienna, Austria, July 2010.
- [159] A. Krajewski, R. J. N. Helmer, and S. R. Lucas, "Signal processing for valid score determination in amateur boxing," in *Proceedings of the 5th Asia-Pacific Congress on Sports Technology (APCST '11)*, Melbourne, Australia, August 2011.
- [160] T. J. Gabbett, D. Jenkins, and B. Abernethy, "Physical collisions and injury during professional rugby league skills training," *Journal of Science and Medicine in Sport*, vol. 13, no. 6, pp. 578–583, 2010.
- [161] C. P. McLellan, D. I. Lovell, and G. C. Gass, "Biochemical and endocrine responses to impact and collision during elite rugby league match play," *Journal of Strength & Conditioning Research*, vol. 25, no. 6, pp. 1553–1562, 2011.
- [162] B. Cunniffe, W. Proctor, J. S. Baker, and B. Davies, "An evaluation of the physiological demands of elite rugby union using global positioning system tracking software," *Journal of Strength & Conditioning Research*, vol. 23, no. 4, pp. 1195–1203, 2009.
- [163] L. J. Suárez-Arrones, L. J. Portillo, J. M. González-Ravé, V. E. Muñoz, and F. Sanchez, "Match running performance in Spanish elite male rugby union using global positioning system," *Isokinetics and Exercise Science*, vol. 20, no. 2, pp. 77–83, 2012.
- [164] R. E. Venter, E. Opperman, and S. Opperman, "The use of Global Positioning System (GPS) tracking devices to assess movement demands and impacts in Under-19 Rugby Union match play," *African Journal for Physical, Health Education, Recreation and Dance*, vol. 17, no. 1, 8 pages, 2011.
- [165] D. Kelly, G. F. Coughlan, B. S. Green, and B. Caulfield, "Automatic detection of collisions in elite level rugby union using a wearable sensing device," *Sports Engineering*, vol. 15, no. 2, pp. 81–92, 2012.
- [166] P. B. Gastin, O. McLean, M. Spittle, and R. V. P. Breed, "Quantification of tackling demands in professional Australian football using integrated wearable athlete tracking technology," *Journal of Science and Medicine in Sport*, vol. 16, no. 6, pp. 589–593, 2013.
- [167] P. B. Gastin, O. C. McLean, R. V. P. Breed, and M. Spittle, "Tackle and impact detection in elite Australian football using wearable microsensor technology," *Journal of Sports Sciences*, vol. 32, no. 10, pp. 947–953, 2014.
- [168] T. J. Gabbett, "Quantifying the physical demands of collision sports: does microsensor technology measure what it claims to measure?" *Journal of Strength and Conditioning Research*, vol. 27, no. 8, pp. 2319–2322, 2013.
- [169] H. Croft and D. C. Ribeiro, "The development and application of a live transmitting head camera for video feedback in rugby

decision making,” in *Proceedings of the 6th Asia-Pacific Congress on Sports Technology*, Melbourne, Australia, 2013.

- [170] H. Croft, E. K. Suwarganda, and S. F. S. Omar, “Development and application of a live transmitting player-mounted head camera,” *Sports Technology*, vol. 6, no. 2, pp. 97–110, 2013.
- [171] World Rugby, *Regulation 12. Schedule 1. Specifications Relating to Players’ Dress. Law 4-Players’ Clothing*, World Rugby, Dublin, Ireland, 2015.