[Athletic Training]

Head Impact Measurement Devices: A Clinical Review

Richelle M. Williams, MS, ATC,*†‡ Margaret Dowling, MPH,‡§ and Kathryn L. O'Connor, BA†‡

Context: Concussive injuries are at the forefront of sports medicine research. Recently, researchers have used a variety of head- and helmet-based impact-monitoring devices to quantify impacts sustained during contact sport participation. This review provides an up-to-date collection of head accelerometer use at the youth, high school, and collegiate levels.

Evidence Acquisition: PubMed was searched for articles published between 1980 and 2015 using the terms *accelerometer and concussion, impact sensor and concussion, head impact telemetry system, head impact telemetry,* and *linear acceleration and concussion*. An additional Google search was performed to capture devices without publications.

Study Design: Clinical review.

Level of Evidence: Level 4.

Results: Twenty-four products track and/or record head impact for clinical or research use. Ten of these head impact devices have publications supporting their utility.

Conclusion: Head impact measuring devices can describe athlete exposure in terms of magnitude and/or frequency, highlighting their utility within a multimodal approach for concussion assessment and diagnosis.

Keywords: concussion; accelerometers; subconcussive; head impacts; review

There is growing concern regarding concussions in football and contact sports, prompting legislation, clinical protocols, and research to improve prevention and treatment. To prevent injury, the mechanism of injury must be understood. Quantifying the biomechanical properties of a head injury may elucidate targets of prevention. Multiple head impact devices have been developed for in vivo use in athletics to relate mechanical force and acceleration to the clinical manifestation of concussion.[2]

Investigations have used head impact devices to monitor the number and magnitude of head impacts sustained in sports participation that do not result in concussion.[9,13,15,16,28,53,62] Unfortunately, no linear and/or rotational concussive threshold has been established.[31,35,69] The objectives of this clinical review are to provide an up-to-date assessment of head impact devices used for concussion monitoring and to provide guidance on their clinical utility at the college, high school, and youth levels.

METHODS

Research studies were identified via the PubMed database (1980-2015) through searches of keyword phrases: *accelerometer and concussion, impact sensor and concussion, head impact telemetry system, head impact telemetry*, and *linear acceleration and concussion*. From this search, 121 unique articles were identified. Peer-reviewed publications were then screened for inclusion based on the following

From the †School of Kinesiology, University of Michigan, Ann Arbor, Michigan, ‡NeuroTrauma Research Laboratory, University of Michigan, Ann Arbor, Michigan, and §School of Public Health, University of Michigan, Ann Arbor, Michigan

*Address correspondence to Richelle Williams, MS, ATC, School of Kinesiology, University of Michigan, 401 Washtenaw Avenue, Ann Arbor, MI 48109 (email: richellm@umich.edu).

The following authors declared potential conflicts of interest: Richelle M. Williams, MS, ATC, has grants/grants pending from NIH (1R15NS081691); Margaret Dowling, MPH, and Kathryn L. O'Connor, BA, have grants/grants pending from Grand Alliance Concussion Assessment, Research, and Education (CARE) Consortium, funded in part by the National Collegiate Athletic Association (NCAA) and the Department of Defense (DoD). The U.S. Army Medical Research Acquisition Activity, 820 Chandler Street, Ford Detrick, MD 21702-5014 is the awarding and administering acquisition office. This work was supported by the Office of the Assistant Secretary of Defense for Health Affairs through the Psychological Health and Traumatic Brain Injury Program under Award NO W81XWH-14-2-0151. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the Department of Defense (DHP funds.)

DOI: 10.1177/1941738116641912

Table 1. High school football and college head impact frequency and magnitude

	Total Season Impacts	Impacts per Player per Season	Linear Acceleration, g	Rotational Acceleration, rad/s^2	Most Frequent Impact Location
Football					
College	3312-90,054[20,21,34,62]	223-1354[16,20,47]	20-35[16,28,47,62]	1187-6990[22,34,59]	Top[47]
High school	413-652[8,60-63]	413-652[8,60-63]	21-27[13,14,43]	Up to 7701[9,63]	
Youth	748-11,978 [18,24,51,68]	106.9-252 [18,23,24,51,68]	16-22[18,23,48,55,68]	4-12,322[18,51]	Top, front, back[24,51]
Ice hockey					
College	28,178			1187-6990.5[22,34,59]	Top[47]
Male	15,281	347[7]	31.2[65]-43.7[7]	2,881.0[65]-4,764[7]	
Female	12,897	179.2[7]	28.54[65]-44.9[7]	1,766.8[65]-3,709[7]	
High school and youth	12,253[49]	223[49]	18.4[49]-35g[53]	1,464.5[49]	Side[49]

criteria. Inclusion—athlete population, in vivo studies, and reported magnitude (eg, linear acceleration); exclusion—review/commentary papers, case study, review article, accelerometer type and hardware not listed, and in vitro studies (n = 14). In total, 48 articles met the criteria. Whenever possible, impact count, top 1% and top 5% linear acceleration, rotational acceleration, and impact severity values were also collected. Three reviewers (RMW, MD, KLO) independently extracted relevant data from the studies. Of the 48 articles, 7 head impact systems were identified. Additional commercial head impact devices advertised for concussion were identified through a Google search using the terms *sports accelerometers* and *head impact accelerometers*, which identified an additional 17 head impact–monitoring devices. A total of 24 devices were identified (Table 1 in Appendix, available at http://sph.sagepub.com/content/by/supplemental-data).

Accelerometer Systems

The earliest in vivo research on head impact biomechanics was completed in the 1970s using triaxial accelerometers to measure head acceleration during football games.[50,56] More recently, a single triaxial accelerometer was used inside the helmets of 1 high school hockey player and 2 football players.[53] A single accelerometer fixed to the head or helmet provides limited information because headband systems are known to slip and helmet motion is largely independent of head motion.[42] The Head Impact Telemetry System (HITs) was the first modern era impact accelerometer system to estimate motion after impact.[19,42] The HITs implements 6 single axis accelerometers recording at 1000 Hz to capture data on linear acceleration. It also calculates rotational acceleration, impact duration and location, Gadd Severity Index (GSI), Head Injury Criterion (HIC15), and Head Impact Telemetry severity profile (HITsp). The HITs has been used extensively in head impact biomechanics (Table 2 in Appendix, available at http://sph.sagepub.com/content/by/supplemental-data). The specific outputs vary by system, but in general, all systems report linear and rotational acceleration, impact location, a time-stamp, GSI, HIC15, and HITsp (Table 2 in Appendix).

RESULTS

Ten of 24 (41.6%) market- or research-based head impact–monitoring devices have publications supporting their utility.[1,13-15,17,22,24,26,28,33,34,41,43,62,63,66,68] This suggests that some marketed head impact–monitoring devices have limited to no research supporting their use. The HITs is the most widely used head impact–monitoring device and has captured impacts from all levels of play for football and ice hockey (Table 1).

Concussion Threshold

Head impact measurement devices offer the potential for improving concussion diagnosis and accelerating concussion management if a biomechanical injury threshold can be identified.[35]

At the college level, the average linear acceleration for a concussive event ranges from 55.8g to 168.8g[17,36,62] with no consistency. The average rotational acceleration for collegiate concussive episodes was between 163.4 and 15397.1 rad/s^2.[28,36,62]

In a cohort of high school and collegiate athletes, 17 concussions occurred with 75% of the concussive impacts exceeding 96*g* and 7235 rad/s^2.[34] At the high school level, linear acceleration values range from 74*g* to 146*g*, with mean linear acceleration reported at 105*g*.[15,18,23] During a concussive episode, the average linear acceleration value was 93.6*g*, and rotational acceleration ranged from 5582.6 to 9515.6 rad/s^2.[10,13] This suggests that concussion threshold varies in both college and high school football players.[31] The fact that many impacts at similar magnitudes do not result in a concussive injury suggests that the individual injury threshold is dynamic.[31] Covariates to consider include sex, age, genotype, and history of concussion.

CLINICAL IMPLICATIONS

Head impact devices may be used in conjunction with other assessment tools to provide additional information regarding impacts.[33,37] Data from impact-monitoring devices may indirectly reduce concussion risk by influencing rule and coaching changes. Additionally, the ability to identify multiple subconcussive impacts may be important to calculate cumulative effects, as repeat subconcussive impacts may increase concussion risk.[5] Unfortunately, the lack of specificity with head impact devices precludes the practical application of accelerometer systems as a diagnostic tool.

Limitations

The fixation of the accelerometer to the head, helmet fit, and device hardware should be considered when evaluating an impact-monitoring device. Player helmet fit is a significant component of head impact–monitoring data variability. Athletes in nonhelmeted sports have accelerometers affixed to their skin or through a headband, which may cause error or variation in acceleration due to skin or device movement and sweat. Despite limited diagnostic utility, these devices identify which athletes sustain large-magnitude and frequent impacts.

CONCLUSION

Without an established injury threshold, clear accuracy and validity, impact-monitoring devices cannot replace a clinician's clinical judgment regarding a concussive event. Head impact–monitoring devices should not be used as a single assessment tool for concussion.

Clinical Recommendations

SORT: Strength of Recommendation Taxonomy Grade

A: consistent, good-quality patient-oriented evidence

B: inconsistent or limited-quality patient-oriented evidence

C: consensus, disease-oriented evidence, usual practice, expert opinion, or case series

Clinical Recommendation	SORT Evidence Rating
1. Head impact–monitoring devices should not be used as a primary concussion diagnostic tool.	A
2. Head impact–monitoring devices are not a reliable indicator that a concussive episode has been sustained.	B
3. There is no single concussion assessment tool available to identify a concussion. Therefore, a multifaceted approach to concussion diagnosis is recommended.[11,30,46]	A
4. It is important for clinicians to be trained to use the head impact device and understand its limitations. By understanding each device's utility, clinicians can leverage the information provided by these devices during their concussion assessment and diagnosis.	C
5. The diagnosis of concussion requires a thorough clinical evaluation by a health care professional.	C

REFERENCES

1. Allison MA, Kang YS, Maltese MR, Bolte JHt, Arbogast KB. Measurement of Hybrid III head impact kinematics using an accelerometer and gyroscope system in ice hockey helmets. *Ann Biomed Eng*. 2015;43:1896-1906.
2. Barth JT, Freeman JR, Broshek DK, Varney RN. Acceleration-deceleration sport-related concussion: the gravity of it all. *J Athl Train*. 2001;36:253-256.
3. Bauer JA, Thomas TS, Cauraugh JH, Kaminski TW, Hass CJ. Impact forces and neck muscle activity in heading by collegiate female soccer players. *J Sports Sci*. 2001;19:171-179.
4. Bazarian JJ, Zhu T, Zhong J, et al. Persistent, long-term cerebral white matter changes after sports-related repetitive head impacts. *PloS One*. 2014;9:e94734.
5. Beckwith JG, Greenwald RM, Chu JJ, et al. Head impact exposure sustained by football players on days of diagnosed concussion. *Med Sci Sports Exerc*. 2013;45:737-746.
6. Beckwith JG, Greenwald RM, Chu JJ, et al. Timing of concussion diagnosis is related to head impact exposure prior to injury. *Med Sci Sports Exerc*. 2013;45:747-754.
7. Brainard LL, Beckwith JG, Chu JJ, et al. Gender differences in head impacts sustained by collegiate ice hockey players. *Med Sci Sports Exerc*. 2012;44:297-304.
8. Broglio SP, Eckner JT, Kutcher JS. Field-based measures of head impacts in high school football athletes. *Curr Opin Pediatr*. 2012;24:702-708.
9. Broglio SP, Eckner JT, Martini D, Sosnoff JJ, Kutcher JS, Randolph C. Cumulative head impact burden in high school football. *J Neurotrauma*. 2011;28:2069-2078.
10. Broglio SP, Eckner JT, Surma T, Kutcher JS. Post-concussion cognitive declines and symptomatology are not related to concussion biomechanics in high school football players. *J Neurotrauma*. 2011;28:2061-2068.
11. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurg*. 2007;60:1050-1057.
12. Broglio SP, Martini D, Kasper L, Eckner JT, Kutcher JS. Estimation of head impact exposure in high school football: implications for regulating contact practices. *Am J Sports Med*. 2013;41:2877-2884.

13. Broglio SP, Schnebel B, Sosnoff JJ, et al. Biomechanical properties of concussions in high school football. *Med Sci Sports Exerc*. 2010;42:2064-2071.
14. Broglio SP, Sosnoff JJ, Shin S, He X, Alcaraz C, Zimmerman J. Head impacts during high school football: a biomechanical assessment. *J Athl Train*. 2009;44:342-349.
15. Broglio SP, Surma T, Ashton-Miller JA. High school and collegiate football athlete concussions: a biomechanical review. *Ann Biomed Eng*. 2012;40:37-46.
16. Brolinson PG, Manoogian S, McNeely D, Goforth M, Greenwald R, Duma S. Analysis of linear head accelerations from collegiate football impacts. *Curr Sports Med Rep*. 2006;5:23-28.
17. Camarillo DB, Shull PB, Mattson J, Shultz R, Garza D. An instrumented mouthguard for measuring linear and angular head impact kinematics in American football. *Ann Biomed Eng*. 2013;41:1939-1949.
18. Cobb BR, Urban JE, Davenport EM, et al. Head impact exposure in youth football: elementary school ages 9-12 years and the effect of practice structure. *Ann Biomed Eng*. 2013;41:2463-2473.
19. Crisco JJ, Chu JJ, Greenwald RM. An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers. *J Biomech Eng*. 2004;126:849-854.
20. Crisco JJ, Greenwald RM. Let's get the head further out of the game: a proposal for reducing brain injuries in helmeted contact sports. *Curr Sports Med Rep*. 2011;10:7-9.
21. Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *J Biomech*. 2011;44:2673-2678.
22. Crisco JJ, Wilcox BJ, Machan JT, et al. Magnitude of head impact exposures in individual collegiate football players. *J Appl Biomech*. 2012;28:174-183.
23. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football. *Ann Biomed Eng*. 2012;40:976-981.
24. Daniel RW, Rowson S, Duma SM. Head acceleration measurements in middle school football. *Biomed Sci Instrum*. 2014;50:291-296.
25. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football: middle school ages 12-14 years. *J Biomech Eng*. 2014;136:094501.
26. Dorminy M, Hoogeveen A, Tierney RT, Higgins M, McDevitt JK, Kretzschmar J. Effect of soccer heading ball speed on S100B, sideline concussion assessments and head impact kinematics. *Brain Inj*. 2015;29:1158-1164.
27. Duhaime AC, Beckwith JG, Maerlender AC, et al. Spectrum of acute clinical characteristics of diagnosed concussions in college athletes wearing instrumented helmets: clinical article. *J Neurosurg*. 2012;117:1092-1099.
28. Duma SM, Manoogian SJ, Bussone WR, et al. Analysis of real-time head accelerations in collegiate football players. *Clin J Sport Med*. 2005;15:3-8.
29. Duma SM, Rowson S. Every Newton Hertz: a macro to micro approach to investigating brain injury. *Conf Proc IEEE Eng Med Biol Soc*. 2009;2009:1123-1126.
30. Eckner JT, Kutcher JS. Concussion symptom scales and sideline assessment tools: a critical literature update. *Curr Sports Med Rep*. 2010;9:8-15.
31. Eckner JT, Sabin M, Kutcher JS, Broglio SP. No evidence for a cumulative impact effect on concussion injury threshold. *J Neurotrauma*. 2011;28:2079-2090.
32. Funk JR, Rowson S, Daniel RW, Duma SM. Validation of concussion risk curves for collegiate football players derived from HITS data. *Ann Biomed Eng*. 2012;40:79-89.
33. Gioia GA. Multimodal evaluation and management of children with concussion: using our heads and available evidence. *Brain Inj*. 2015;29:195-206.
34. Greenwald RM, Gwin JT, Chu JJ, Crisco JJ. Head impact severity measures for evaluating mild traumatic brain injury risk exposure. *Neurosurgery*. 2008;62:789-798.
35. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: quest for the elusive injury threshold. *Exerc Sport Sci Rev*. 2011;39:4-11.
36. Guskiewicz KM, Mihalik JP, Shankar V, et al. Measurement of head impacts in collegiate football players: relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery*. 2007;61:1244-1252.
37. Guskiewicz KM, Register-Mihalik JK. Postconcussive impairment differences across a multifaceted concussion assessment protocol. *PM R*. 2011;3(10 suppl 2):S445-S451.
38. Gysland S, Mihalik J, Register-Mihalik J, Trulock S, Shields E, Guskiewicz K. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng*. 2012;40:14-22.
39. Hanlon EM, Bir CA. Real-time head acceleration measurement in girls' youth soccer. *Med Sci Sports Exerc*. 2012;44:1102-1108.
40. Hasegawa K, Takeda T, Nakajima K, et al. Does clenching reduce indirect head acceleration during rugby contact? *Dent Traumatol*. 2014;30:259-264.
41. King D, Hume PA, Brughelli M, Gissane C. Instrumented mouthguard acceleration analyses for head impacts in amateur rugby union players over a season of matches. *Am J Sports Med*. 2015;43:614-624.
42. Manoogian S, McNeely D, Duma S, Brolinson G, Greenwald R. Head acceleration is less than 10 percent of helmet acceleration in football impacts. *Biomed Sci Instrum*. 2006;42:383-388.
43. Martini D, Eckner J, Kutcher J, Broglio SP. Subconcussive head impact biomechanics: comparing differing offensive schemes. *Med Sci Sports Exerc*. 2013;45:755-761.
44. McAllister TW, Flashman LA, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology*. 2012;78:1777-1784.
45. McAllister TW, Ford JC, Flashman LA, et al. Effect of head impacts on diffusivity measures in a cohort of collegiate contact sport athletes. *Neurology*. 2014;82:63-69.
46. McCrea M, Iverson GL, Echemendia RJ, Makdissi M, Raftery M. Day of injury assessment of sport-related concussion. *Br J Sports Med*. 2013;47:272-284.
47. Mihalik JP, Bell DR, Marshall SW, Guskiewicz KM. Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. *Neurosurgery*. 2007;61:1229-1235.
48. Mihalik JP, Greenwald RM, Blackburn JT, Cantu RC, Marshall SW, Guskiewicz KM. Effect of infraction type on head impact severity in youth ice hockey. *Med Sci Sports Exerc*. 2010;42:1431-1438.
49. Mihalik JP, Guskiewicz KM, Marshall SW, Blackburn JT, Cantu RC, Greenwald RM. Head impact biomechanics in youth hockey: comparisons across playing position, event types, and impact locations. *Ann Biomed Eng*. 2012;40:141-149.
50. Moon DW, Beedle CW, Kovacic CR. Peak head acceleration of athletes during competition—football. *Med Sci Sports*. 1971;3:44-50.
51. Munce TA, Dorman JC, Thompson PA, Valentine VD, Bergeron MF. Head impact exposure and neurologic function of youth football players. *Med Sci Sports Exerc*. 2015;47:1567-1576.
52. Naunheim R, McGurren M, Standeven J, Fucetola R, Lauryssen C, Deibert E. Does the use of artificial turf contribute to head injuries? *J Trauma*. 2002;53:691-694.
53. Naunheim RS, Standeven J, Richter C, Lewis LM. Comparison of impact data in hockey, football, and soccer. *J Trauma*. 2000;48:938-941.
54. Ocwieja KE, Mihalik JP, Marshall SW, Schmidt JD, Trulock SC, Guskiewicz KM. The effect of play type and collision closing distance on head impact biomechanics. *Ann Biomed Eng*. 2012;40:90-96.
55. Reed N, Taha T, Keightley M, et al. Measurement of head impacts in youth ice hockey players. *Int J Sports Med*. 2010;31:826-833.
56. Reid SE, Epstein HM, O'Dea TJ, Louis MW, Reid SE Jr. Head protection in football. *J Sports Med*. 1974;2:86-92.
57. Rowson S, Duma SM, Beckwith JG, et al. Rotational head kinematics in football impacts: an injury risk function for concussion. *Ann Biomed Eng*. 2012;40:1-13.
58. Rowson S, Duma SM, Greenwald RM, et al. Can helmet design reduce the risk of concussion in football? *J Neurosurg*. 2014;120:919-922.
59. Rowson S, Goforth MW, Dietter D, Brolinson PG, Duma SM. Correlating cumulative sub-concussive head impacts in football with player performance—Biomed 2009. *Biomed Sci Instrum*. 2009;45:113-118.
60. Schmidt JD, Guskiewicz KM, Blackburn JT, Mihalik JP, Siegmund GP, Marshall SW. The influence of cervical muscle characteristics on head impact biomechanics in football. *Am J Sports Med*. 2014;42:2056-2066.
61. Schmidt JD, Guskiewicz KM, Mihalik JP, Blackburn JT, Siegmund GP, Marshall SW. Does visual performance influence head impact severity among high school football athletes? *Clin J Sport Med*. 2015;25:494-501.
62. Schnebel B, Gwin JT, Anderson S, Gatlin R. In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association Division I versus high school impacts. *Neurosurgery*. 2007;60:490-495.
63. Urban JE, Davenport EM, Golman AJ, et al. Head impact exposure in youth football: high school ages 14 to 18 years and cumulative impact analysis. *Ann Biomed Eng*. 2013;41:2474-2487.
64. Wilcox BJ, Beckwith JG, Greenwald RM, et al. Head impact exposure in male and female collegiate ice hockey players. *J Biomech*. 2014;47:109-114.
65. Wilcox BJ, Machan JT, Beckwith JG, Greenwald RM, Burmeister E, Crisco JJ. Head-impact mechanisms in men's and women's collegiate ice hockey. *J Athl Train*. 2014;49:514-520.
66. Wong RH, Wong AK, Bailes JE. Frequency, magnitude, and distribution of head impacts in Pop Warner football: the cumulative burden. *Clin Neurol Neurosurg*. 2014;118:1-4.
67. Wu LC, Zarnescu L, Nangia V, Cam B, Camarillo DB. A head impact detection system using SVM classification and proximity sensing in an instrumented mouthguard. *IEEE Trans Biomed Eng*. 2014;61:2659-2668.
68. Young TJ, Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football: elementary school ages 7-8 years and the effect of returning players. *Clin J Sport Med*. 2014;24:416-421.
69. Zhang L, Yang KH, King AI. A proposed injury threshold for mild traumatic brain injury. *J Biomech Eng*. 2004;126:226-236.