Editorial

Special Issue on Concussions in Sports

(published online 25 August 2021)

Concussion in sports has gained increasing media and research focus in the past two decades. Concerns over the long-term effects of repeated head impacts and concussions fueled a drive for improvements in protective headgear and for strategies to reduce athlete head impact exposure.^{17,18,28} In 2019, the Annals of Biomedical Engineering (ABME) began publishing special issues on topics related to concussion in sports each fall. The 2019 issue featured research funded through a partnership between the National Collegiate Athletic Association (NCAA) and the U.S. Department of Defense (DoD).²⁵ The partnership, known as the NCAA-DoD Grand Alliance and Concussion Assessment, Research, and Education (CARE) Consortium, was established in 2014 with the goal of informing policy decisions on concussion and its long-term consequences. In the fall of 2020, ABME published a special issue focused on concussion biomechanics in football.²⁴ The papers in that issue covered the most recent advances in our understanding of concussion biomechanics through analysis of real-world impacts in football and new technologies to measure head impact kinematics. Applications of head impact biomechanics to concussion reduction strategies were also developed and reviewed. The current and third issue in this series expands on previous issues by including concussion research in all sports and recreational activities.

The NCAA-DoD issue included papers on concussion biomechanics and head impact exposure, as well as different aspects of concussion diagnosis and recovery. Several papers evaluated factors that may contribute to biomechanical concussion tolerance, since individual concussive impacts often seem unremarkable in a large dataset. Stemper et al. evaluated the effects of cumulative head impact exposure and risk-weighted exposure on concussion tolerance, and found that greater exposure may reduce individual concussion tolerance.³⁰ Other factors that influence an individual athlete's concussion tolerance were also explored by Campolettano et al. and Rowson et al.^{7,27} They confirmed that head impact exposure explains some of the variance in concussion tolerance, along with other physical characteristics like height, mass, age, race, and concussion history. These findings all support the need for a more individualized approach to

evaluating concussion tolerance, either assessing risk on a population or individual basis. Although concussion tolerance varies by athlete, reducing head impact exposure decreases the odds of concussion for all athletes. However, rules and regulations to reduce head impact exposure should be data-driven to ensure effectiveness. An NCAA rule eliminated 2-a-day practices during the college football preseason to reduce head impact exposure, but the number of contact days increased, resulting in an overall increase in head impact exposure after the ruling.²⁹ Other studies have quantified head impact exposure by practice drill type, which provides a basis for rulings that reduce avoidable head impacts.^{1,6} On-field head impact measurements have been important for reducing head injury risk to athletes by quantifying head impact exposure and concussion tolerance, but accurate measurements are difficult to obtain with current technology, especially in non-helmeted sports. Rich et al. developed and tested a custom instrumented mouthpiece to address the limitations of currently available sensors.²³

In addition to concussion biomechanics, the NCAA-DoD partnership addressed concussion screening tests that are commonly used. Chrisman et al. showed how factors like learning disorders and primary home language can influence baseline results for one sideline concussion screening test, the King-Devick test.⁸ Houston et al. showed poor agreement between human-rated and automated instrument-rated Balance Error Scoring System (BESS) scores.¹¹ Both studies suggest that caution should be used when comparing concussion screening test results between individuals and between different test administrators. Some screening tests such as BESS are also used to monitor athlete recovery following a concussion, but it is important to consider not only the patient's physical recovery, but also their perception of mental and physical recovery.³¹

The 2020 special issue on concussion in football focused on characterizing the biomechanics of concussion through on-field data collection, and applying that data to helmet evaluation and concussion prevention strategies. Laboratory reconstructions of on-field impacts and head impact sensors used to instrument athletes are the most commonly used methods to characterize concussions in sports, but both methods

have unique challenges. Head kinematics can be accurately measured with laboratory reconstructions, but determining impact conditions from video and using dummies to recreate impacts introduces error. Funk et al. showed that even using complex methods for video analysis to determine impact conditions, and closely matching conditions through video and iterative reconstruction testing, there were still substantial errors in helmet kinematics.⁹ These findings support the need for accurate wearable sensors to better understand concussion biomechanics. A variety of sensor types are available, but even if a sensor performs well in laboratory tests, it may not be accurate with on-field use.²² This is especially concerning since head impact sensor data is often taken at face value without using video to verify that all recorded impacts were true positives.²⁰ To provide an objective evaluation of both laboratory and on-field performance of head impact sensors, Kieffer et al. developed a two-phase approach to sensor testing.¹³ The first phase used a pendulum impactor to test laboratory performance, followed by the second phase of on-field testing from video verification of impacts if the sensor performed adequately in the laboratory. A custom-fit mouthguard sensor had high accuracy in both laboratory and on-field testing. Other studies also confirmed the accuracy and usability of some available mouthguard sensors.^{5,10,15}

Data collected from instrumented athletes have been applied to strategies to reduce concussion incidence. A review of regulations and interventions targeted at reducing concussion rates in football showed mixed results in terms of reductions in head impact exposure.²¹ These findings support the need for making data-driven decisions in concussion interventions. Maerlender et al. evaluated the safety and effectiveness of teaching athletes proper tackling technique through a rating system.¹⁶ The ratings showed that proper technique was both safe (less chance of head contact) and effective (fewer yards after contact), demonstrating that interventions to reduce concussions do not have to reduce player skill and performance. Rowson et al. developed a method for determining differences in individual concussion risk from real-world head impact data.²⁶ Concussion risk varies with different physical characteristics, so a more individualized risk assessment could be used to inform new concussion reduction strategies. In the future, concussion biomechanics may also play a role in predicting clinical recovery, but the complex nature of concussion symptoms and variability between athletes make it challenging to determine any associations.¹⁹

On-field head impact data has also been used to develop helmet evaluation protocols to drive improvements in helmet design. In the Concussion

Biomechanics in Football special issue, Bailey et al. published new evaluation methods for football helmets based on video analysis and laboratory reconstructions of National Football League (NFL) concussive impacts.^{3,4} When comparing laboratory performance with these evaluation methods to concussion rates in NFL players by helmet type, helmets that reduced impact severity in the lab also had lower concussion rates on the field.² These findings suggest that helmets designed to perform better in the lab can also reduce real-world concussion rates. Further analysis of concussive NFL impacts showed differences in impact conditions by player position, and unique features of helmet-to-ground impacts that could be used for more specific helmet evaluation and design.^{12,14}

This special issue on concussions in sports will build upon the previous issues by including studies on concussion biomechanics in a variety of sports and recreational activities. These studies are focused on real-world concussion biomechanics, helmet evaluation, laboratory reconstruction of impacts, head injury prediction metrics, and new head impact sensor technologies. By including all sports, the research presented here will have a broad impact on head injury mitigation strategies for different populations, and can provide a basis for future advancements in the field.

REFERENCES

- ¹Asken, B. M., Z. S. Brooke, T. C. Stevens, P. G. Silvestri, M. J. Graham, M. S. Jaffee, and J. R. Clugston. Drill-specific head impacts in collegiate football practice: implications for reducing “friendly fire” exposure. *Ann. Biomed. Eng.* 47:2094–2108, 2019.
- ²Bailey, A. M., T. L. McMurry, J. M. Cormier, J. R. Funk, J. R. Crandall, C. D. Mack, B. S. Myers, and K. B. Arbogast. Comparison of laboratory and on-field performance of American football helmets. *Ann. Biomed. Eng.* 48:2531–2541, 2020.
- ³Bailey, A. M., E. J. Sanchez, G. Park, L. F. Gabler, J. R. Funk, J. R. Crandall, M. Wonnacott, C. Withnall, B. S. Myers, and K. B. Arbogast. Development and evaluation of a test method for assessing the performance of American football helmets. *Ann. Biomed. Eng.* 48:2566–2579, 2020.
- ⁴Bailey, A. M., C. P. Sherwood, J. R. Funk, J. R. Crandall, N. Carter, D. Hessel, S. Beier, and W. Neale. Characterization of concussive events in professional American football using videogrammetry. *Ann. Biomed. Eng.* 48:2678–2690, 2020.
- ⁵Bartsch, A. J., D. Hedin, J. Alberts, E. C. Benz, J. Cruickshank, R. S. Gray, K. Cameron, M. N. Houston, T. Rooks, G. McGinty, E. Kozlowski, S. Rowson, J. C. Maroon, V. J. Miele, J. C. Ashton, G. P. Siegmund, A. Shah, M. McCrea, and B. Stemper. High energy side and rear American football head impacts cause obvious performance decrement on video. *Ann. Biomed. Eng.* 48:2667–2677, 2020.

- ⁶Campolettano, E. T., S. Rowson, and S. M. Duma. Drill-specific head impact exposure in youth football practice. *J. Neurosurg. Pediatr.* 18:536–541, 2016.
- ⁷Campolettano, E. T., S. Rowson, S. M. Duma, B. Stemper, A. Shah, J. Harezlak, L. D. Riggen, J. Mihalik, A. Brooks, and K. Cameron. Factors affecting head impact exposure in college football practices: a multi-institutional study. *Ann. Biomed. Eng.* 47:2086–2093, 2019.
- ⁸Chrisman, S., K. Harmon, J. Schmidt, T. Kaminski, T. Buckley, A. Kontos, J. Clugston, M. McCrea, T. McAllister, and S. Broglio. Impact of factors that affect reading skill level on King-Devick baseline performance time. *Ann. Biomed. Eng.* 47:2122–2127, 2019.
- ⁹Funk, J. R., R. Jadischke, A. Bailey, J. Crandall, J. McCarthy, K. Arbogast, and B. Myers. Laboratory reconstructions of concussive helmet-to-helmet impacts in the National Football League. *Ann. Biomed. Eng.* 48:2652–2666, 2020.
- ¹⁰Gabler, L. F., S. H. Huddleston, N. Z. Dau, D. J. Lessley, K. B. Arbogast, X. Thompson, J. E. Resch, and J. R. Crandall. On-field performance of an instrumented mouthguard for detecting head impacts in American Football. *Ann. Biomed. Eng.* 48:2599–2612, 2020.
- ¹¹Houston, M. N., M. C. Hoch, S. R. Malvasi, K. Y. Peck, S. J. Svoboda, and K. L. Cameron. Level of agreement between human-rated and instrumented balance error scoring system scores. *Ann. Biomed. Eng.* 47:2128–2135, 2019.
- ¹²Kent, R., J. Forman, A. Bailey, J. Cormier, G. Park, J. Crandall, K. B. Arbogast, and B. Myers. Surface contact features, impact obliquity, and preimpact rotational motion in concussive helmet-to-ground impacts: assessment via a new impact test device. *Ann. Biomed. Eng.* 48:2639–2651, 2020.
- ¹³Kieffer, E. E., M. T. Begonia, A. M. Tyson, and S. Rowson. A two-phased approach to quantifying head impact sensor accuracy: in-laboratory and on-field assessments. *Ann. Biomed. Eng.* 48:2613–2625, 2020.
- ¹⁴Lessley, D. J., R. W. Kent, J. M. Cormier, C. P. Sherwood, J. R. Funk, J. R. Crandall, B. S. Myers, and K. B. Arbogast. Position-specific circumstances of concussions in the NFL: toward the development of position-specific helmets. *Ann. Biomed. Eng.* 48:2542–2554, 2020.
- ¹⁵Liu, Y., A. G. Domel, S. A. Yousefsani, J. Kondic, G. Grant, M. Zeineh, and D. B. Camarillo. Validation and comparison of instrumented mouthguards for measuring head kinematics and assessing brain deformation in football impacts. *Ann. Biomed. Eng.* 48:2580–2598, 2020.
- ¹⁶Maerlender, A., C. J. Masterson, R. Norris, and A. Hinthorne. Validating tackle mechanics in American football: improving safety and performance. *Ann. Biomed. Eng.* 48:2691–2700, 2020.
- ¹⁷McCrea, M. A., A. Shah, S. Duma, S. Rowson, J. Harezlak, T. W. McAllister, S. P. Broglio, C. C. Giza, J. Goldman, K. L. Cameron, M. N. Houston, G. McGinty, J. C. Jackson, K. Guskiewicz, J. P. Mihalik, M. A. Brooks, P. Pasquina, and B. D. Stemper. Opportunities for prevention of concussion and repetitive head impact exposure in college football players. *JAMA Neurol.* 78:346, 2021.
- ¹⁸McKee, A. C., N. J. Cairns, D. W. Dickson, R. D. Folkerth, C. D. Keene, I. Litvan, D. P. Perl, T. D. Stein, J.-P. Vonsattel, and W. Stewart. The first NINDS/NIBIB consensus meeting to define neuropathological criteria for the diagnosis of chronic traumatic encephalopathy. *Acta Neuropathol.* 131:75–86, 2016.
- ¹⁹Mihalik, J. P., A. Chandran, J. R. Powell, P. R. Roby, K. M. Guskiewicz, B. D. Stemper, A. S. Shah, S. Rowson, S. Duma, and J. Harezlak. Do head injury biomechanics predict concussion clinical recovery in college American football players? *Ann. Biomed. Eng.* 48:2555–2565, 2020.
- ²⁰Patton, D. A., C. M. Huber, D. Jain, R. K. Myers, C. C. McDonald, S. S. Margulies, C. L. Master, and K. B. Arbogast. Head impact sensor studies in sports: a systematic review of exposure confirmation methods. *Ann. Biomed. Eng.* 48:2497–2507, 2020.
- ²¹Phillips, N., and J. J. Crisco. The effectiveness of regulations and behavioral interventions on head impacts and concussions in youth, high-school, and collegiate football: a systematized review. *Ann. Biomed. Eng.* 48:1–23, 2020.
- ²²Press, J. N., and S. Rowson. Quantifying head impact exposure in collegiate women's soccer. *Clin. J. Sport Med.* 27:104–110, 2017.
- ²³Rich, A. M., T. M. Filben, L. E. Miller, B. T. Tomblin, A. R. Van Gorkom, M. A. Hurst, R. T. Barnard, D. S. Kohn, J. E. Urban, and J. D. Stitzel. Development, validation and pilot field deployment of a custom mouthpiece for head impact measurement. *Ann. Biomed. Eng.* 47:2109–2121, 2019.
- ²⁴Rowson, B., and S. M. Duma. Special issue on concussion biomechanics in football. *Ann. Biomed. Eng.* 48:2495–2496, 2020.
- ²⁵Rowson, B., J. D. Stitzel, and S. M. Duma. Special issue on the NCAA-DoD CARE Consortium Research. *Ann. Biomed. Eng.* 47:2045–2047, 2019.
- ²⁶Rowson, S., E. T. Campolettano, S. M. Duma, B. Stemper, A. Shah, J. Harezlak, L. Riggen, J. P. Mihalik, A. Brooks, and K. L. Cameron. Concussion risk between individual football players: survival analysis of recurrent events and non-events. *Ann. Biomed. Eng.* 48:2626–2638, 2020.
- ²⁷Rowson, S., E. T. Campolettano, S. M. Duma, B. Stemper, A. Shah, J. Harezlak, L. Riggen, J. P. Mihalik, K. M. Guskiewicz, and C. Giza. Accounting for variance in concussion tolerance between individuals: comparing head accelerations between concussed and physically matched control subjects. *Ann. Biomed. Eng.* 47:2048–2056, 2019.
- ²⁸Rowson, S., and S. M. Duma. Development of the STAR evaluation system for football helmets: integrating player head impact exposure and risk of concussion. *Ann. Biomed. Eng.* 39:2130–2140, 2011.
- ²⁹Stemper, B. D., A. S. Shah, J. Harezlak, S. Rowson, S. Duma, J. P. Mihalik, L. D. Riggen, A. Brooks, K. L. Cameron, and C. C. Giza. Repetitive head impact exposure in college football following an NCAA rule change to eliminate two-a-day preseason practices: a study from the NCAA-DoD CARE Consortium. *Ann. Biomed. Eng.* 47:2073–2085, 2019.
- ³⁰Stemper, B. D., A. S. Shah, J. Harezlak, S. Rowson, J. P. Mihalik, S. M. Duma, L. D. Riggen, A. Brooks, K. L. Cameron, and D. Campbell. Comparison of head impact exposure between concussed football athletes and matched controls: evidence for a possible second mechanism of sport-related concussion. *Ann. Biomed. Eng.* 47:2057–2072, 2019.
- ³¹Weber, M., R. Lynall, N. Hoffman, E. Miller, T. Kaminski, T. Buckley, H. Benjamin, C. Miles, C. Whitlow, and L. Lintner. Health-related quality of life following concussion in collegiate student-athletes with and without concussion history. *Ann. Biomed. Eng.* 47:2136–2146, 2019.

BETHANY ROWSON AND STEFAN M. DUMA

Institute for Critical Technology and
Applied Science (ICTAS)
Virginia Tech
Electronic mail:
browson@vt.edu

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.