



UNITED STATES ARMY AEROMEDICAL RESEARCH LABORATORY

Head Impact Brain Health Thresholds Expert Panel: Summary Report

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14. ABSTRACT Traumatic brain injury remains a significant threat to Warfighter brain health and military readiness. Although wearable sensors may improve detection of head acceleration events (HAEs) and reduce missed mild traumatic brain injury diagnoses, a 25-member expert panel convened by the U.S. Army Aeromedical Research Laboratory concluded that current science does not support a single linear or rotational acceleration threshold that can reliably predict concussion. The panel found that concussion risk is complex and individualized, affected by cumulative exposure, impact direction, location, frequency, and duration, as well as factors such as age, sex, prior concussion history, fatigue, hydration, sensor error, and limitations in clinical assessment. Wearable sensors are nevertheless useful for identifying high-risk environments and establishing baseline HAE exposure profiles.						
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14. Abstract (continued)

The panel recommends that the Department of War establish standardized terminology; develop Service-led capability requirements and independent sensor-validation standards; implement a four-phase HAE surveillance program to identify target environments, build data infrastructure, characterize baseline exposures, and eventually implement evidence-based thresholds; and fund a multidisciplinary brain-injury research strategy. A centralized, de-identified inter-branch data repository and research focused on repetitive impacts, individual susceptibility, field-deployable diagnostics, and clinical management are essential to develop more effective surveillance, diagnosis, and mitigation approaches that protect long-term Warfighter readiness.

Summary

Traumatic brain injury (TBI) is a major concern for the U.S. military as the brain health of Warfighters is essential to military readiness (operational capability, mission effectiveness, and lethality). The TBI Center of Excellence (TBICoE) reported 533,519 TBIs were diagnosed across the military branches between 2000 and 2025 (TBICoE, 2025). The Department of War (DoW) Warfighter Brain Health Initiative (WBHI) developed five WBHI Lines of Effort (LOE) to establish guidance for optimizing the brain health of Warfighters and mitigating the effects of TBI. LOE 2 focuses on identifying, monitoring, and mitigating head acceleration events (HAEs). Identifying a possible TBI from a head acceleration event can be a difficult task. This is true whether an HAE is caused by a blunt head impact exposure (HIE) or by an impact to the body that causes motion and acceleration of the head. Warfighters returning to duty with an undiagnosed concussion risk sequelae injuries or prolonged recovery times (Asken et al., 2016; McCrea et al., 2004; McLendon et al., 2016; O'Connor et al., 2017). The use of wearable sensors to monitor Warfighters for HAEs could improve the speed and accuracy of identifying concussions (i.e., mild TBI [mTBI]), easing concerns regarding missed diagnoses. However, a definite kinematic exposure threshold that can reliably predict the onset of concussions has not yet been established despite extensive research with wearable sensors over the past 22 years.

As part of an effort to develop concussion surveillance thresholds for use with wearable sensors in training environments, the United States Army Aeromedical Research Laboratory (USAARL) hosted and led a virtual two-day meeting, “Head Impact Brain Health Thresholds Expert Panel” (HIBHTEP), to review and document the state of the science for detecting events that affect brain health. The expert panel included 25 domestic and international subject matter experts (SMEs) from academia, professional athletics associations, engineering consultation companies, and Department of War (DoW) representatives (Table B1). Researchers in attendance spanned the fields of injury biomechanics, clinical neuroscience, and blunt, blast, and ballistic biomechanics. The meeting had two main objectives:

- 1) Determine if there is a consensus on a kinematic concussion threshold for a single HAE, and
- 2) Determine what critical near-term research gaps exist in concussion monitoring and detection that need to be addressed to further the science, including
 - A) identifying possible factors (e.g., sex, age, fatigue, hydration, etc.) that may influence head/brain health risk and/or individual tolerance levels and
 - B) identifying possible alternative parameters (e.g., frequency of impacts, measurements of impact density) for concussion monitoring and detection.

The documentation that captured input from the SMEs during the HIBHTEP included the SME Pre-Meeting Consultation Worksheet and Consensus Statements. The SME Pre-Meeting Consultation Worksheet gathered information on threshold metrics, values, covariates, and critical research gaps. The Consensus Statements were assertions designed to describe the current state of the science on various aspects of HAE research. Meeting leads (USAARL SMEs) analyzed the responses from these documents, presentations by the SMEs, and meeting transcripts to develop recommendations for implementing a military HAE surveillance program.

As indicated by the SME Pre-Meeting Consultation Worksheet responses, most SMEs did not believe a single threshold for either linear (63% of the 19 SMEs who responded) or rotational (74% of the 19 SMEs who responded) acceleration exists for identifying the onset of concussion. The SMEs were asked to include up to three critical research gaps on the SME Pre-Meeting Consultation Worksheet. Meeting leads categorized each identified gap by the topic area. Nine critical near-term research gap topics were identified. The SMEs indicated in the SME Pre-Meeting Consultation Worksheet responses that addressing these topics will enhance the effectiveness of sensor-based HAE monitoring, the development of concussion surveillance thresholds, and the mitigation of HAEs in military settings. Meeting leads ranked these nine research gap topics by frequency of occurrence in the SME Pre-Meeting Consultation Worksheet responses and identified the top four topics: (1) addressing technical requirements for sensor deployment, like battery life and sensor wear and tear (10 occurrences); (2) establishing well-defined mission use case (7 occurrences); (3) determining repetitive impact effects (5 occurrences); and (4) developing a sensitive and specific assessment for the defined injury (5 occurrences). Additionally, meeting leads asked the SMEs to list alternative parameters that influence head/brain health risk. The top four key alternative impact parameters identified were: (1) impact direction (15 occurrences), (2) impact frequency (13 occurrences), (3) impact location (8 occurrences), and (4) impact duration (7 occurrences). The SMEs indicated in the SME Pre-Meeting Consultation Worksheet responses that researching these alternative impact parameters will enhance the understanding of concussions, particularly those that occur during low kinematic magnitude exposures.

Despite extensive research conducted and published over the past two decades, the panel concluded that the current state of the science does not support a singular, universal kinematic threshold capable of predicting concussions with high sensitivity and specificity. This limitation stems partially from the highly individualized and complex nature of TBIs, which are influenced by cumulative exposure (impact density) and intrinsic human factors, specifically age, sex, prior concussion history, fatigue, and hydration status. Sensor errors and uncertainty in clinical measures also contribute to the difficulty in establishing a consensus threshold for kinematic metrics. However, the two-day SME panel did reveal that the current state of the science supports using wearable HAE sensors for the purpose of identifying high-risk military environments and characterizing baseline HAE kinematics. The conclusions formed by the SME panel were incorporated into the final eight Consensus Statements (Table 3). These Consensus Statements were developed using a rigorous multistage refinement process to ensure the final language accurately reflected the complexities of HAEs in military environments.

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The SME Pre-Meeting Consultation Worksheet responses, meeting transcripts (from SME presentations and discussions), and Consensus Statement responses were analyzed to develop the following recommendations for the DoW:

1. Publish a Standardized Nomenclature Document

Prior to drafting a Capabilities Development Document (CDD) or building any data infrastructure, the Army must publish a standardized nomenclature document to enforce uniform definitions across all branches and research partners. This document must clearly distinguish between exposure (e.g., impact exposure, HAEs), clinical deficits (e.g., sub-clinical deficit, physiological change), and specific severity of injury (e.g., loss of consciousness, percent performance decrement). A standardized document should categorize terms to ensure clarity between mechanical events and biological outcomes.

2. Draft a CDD

Procurement activities for each service must draft a CDD. Development of the CDD should include SMEs and transition partners to establish the operational requirements, resourcing, and minimum performance attributes required for a successful sensor technology integration. The CDD must require and define a multi-step independent sensor validation for all candidate sensor technologies. This independent sensor validation effort should include cadaveric laboratory testing followed by controlled human volunteer field testing. CDD development should be assigned to the Services with Army in the lead to build on current strong work in this area.

3. Implement a Four-Phase HAE Surveillance Program

The DoW should implement a four-phase HAE surveillance program (Table 1) and model it after the highly regarded program established by the World Rugby Federation (Fuller et al., 2017). The process involves

- (1) Target environment identification;
- (2) Data infrastructure development;
- (3) Baseline characterizations of separate targeted environments; and
- (4) Threshold implementation.

4. Prioritize a Multi-Disciplinary Brain Injury Research Strategy

The DoW must prioritize investment toward a multi-disciplinary brain injury research strategy to mitigate the mission impacts of HAEs and the long-term effects on Soldiers. This strategy should integrate kinematic exposure analysis and individual susceptibility through the development of field-deployable diagnostics, advanced clinical management, and a centralized inter-branch data repository. To secure continued funding, all academic and military research partners must share de-identified data into the centralized repository. The sharing of large datasets collected in military environments will allow for investigation into the effects of alternative impact parameters (e.g., repetitive HAE, impact density) and individual vulnerabilities (e.g., age, sex). This large-scale, real-world military dataset is critical to the research strategy's goal of analyzing alternative exposure parameters (e.g., repetitive HAEs, impact density) and vulnerability factors, and

establishing advanced diagnostic methods and the evidence-based treatments necessary to guarantee long-term Warfighter readiness.

Table 1. Recommended Phased Strategy Approach Adopted from the World Rugby Program

Implementation Phase	Operational Objective & Key Actions
Phase 1: Target Environment Identification	Identify specific training and operational environments with the highest risk of HAE exposure (e.g., airborne, combatives, high speed boats).
Phase 2: Data Infrastructure Development	Study and adapt the data collection, storage, and analysis methodologies employed by World Rugby to military applications. Build a secure, scalable data management architecture explicitly equipped to receive, process, and store a high volume of sensor data before the hardware is fielded.
Phase 3: Baseline Environment Characterizations	Deploy sensors into targeted Phase 1 environments strictly for data collection. No screening thresholds or operational interventions should be applied during this phase.
Phase 4: Threshold Implementation	Use the Phase 3 baseline data to establish initial, environment-specific tiered thresholds. Tier 1 (lower) will be a behavioral threshold that prompts immediate technique self-correction and tactical behavior modification. Tier 2 (higher) will be a medical screening threshold that serves as the official threshold for formal medical screening and clinical evaluations. Continuously refine these thresholds as military-specific head impact research matures.

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Introduction

Traumatic brain injury (TBI) is a major concern for the U.S. military as the brain health of Warfighters is essential to military readiness (operational capability, mission effectiveness, and lethality). The TBI Center of Excellence (TBICoE) reported a total of 533,519 TBIs diagnosed across the military branches between 2000 and 2025 (TBICoE, 2025). The Department of War (DoW) Warfighter Brain Health Initiative (WBHI) has developed five Lines of Effort (LOE) to optimize the brain health of Warfighters and mitigate the effects of TBI. The second LOE (LOE 2) focuses on identifying, monitoring, and mitigating exposures that occur during head acceleration events (HAEs) (Department of Defense WBHI, 2021). Concurrently, the Army Warfighter Brain Health Program (WBHP) advances this mission through a complementary LOE focused on deploying wearable sensors to monitor exposures and identify Military Occupational Specialties (MOS) at high risk of HAEs.

Identifying HAEs is a critical part of the LOEs for both DoW WBHI and Army WBHP. The rapid and accurate identification of HAEs is critical to prevent impaired Warfighters from returning to duty and risking sequela injuries, such as fatal second impact syndrome, or prolonged recovery times (Asken et al., 2016; McCrea et al., 2004; McLendon et al., 2016; O'Connor et al., 2017). Whether an HAE is caused by blunt head impact exposure (HIE) or an impact to the body that causes head motion and acceleration, identifying a possible TBI from the event can be a difficult task because TBIs often occur with delayed or visually undetectable symptom onset (Kroshus et al., 2015; O'Connor et al., 2017; Le Flao et al., 2022). Current standardization policies (HQDA EXORD 165-13 [Department of the Army, 2013] and DoDI 6490.11E [DoD, 2012]) rely heavily on subjective self-reporting of exposures by Warfighters and a predefined event list that may not capture all of the possible injury outcomes. Wearable sensors potentially offer a rapid, objective solution to identify potentially injurious HAEs and alleviate concerns over missed concussion diagnoses. However, current research has not yet determined a single, reliable, definitive kinematic exposure threshold to identify potentially concussed individuals with the wearable sensors.

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Background

The United States Army Aeromedical Research Laboratory (USAARL) has served as SMEs in the area of HAE research for years. USAARL has conducted several studies relevant to this area, for example, studies to develop combat helmet standards, design novel headforms for head injury research, and collect and assess head impact data with wearable sensors for the Environment Sensors in Training (ESiT) program (e.g., McEntire et al., 1996; Brozoski et al., 2006; Vasquez et al., 2011; Rooks et al., 2015; Sanchez et al., 2017; Rooks et al., 2018; Brozoski et al., 2021; Daniel et al., 2022; Rooks, Kelley, et al., 2023; Rooks, Novotny, et al., 2023). USAARL leverages a strong network of connections to HAE SMEs in academia, industry, and the military to engage emerging challenges in this space. One such effort was the Concussion Dosimeter Program through the Defense Health Program. To support this effort, USAARL was tasked with conducting a study to recommend kinematic concussion thresholds for wearable sensors used in military training environments. The study involved two approaches: (1) A systematic literature review with meta-analysis of wearable sensor data from HAEs, and (2) Contributions from SMEs. The literature review with meta-analysis and analysis of SME opinions aimed to explore whether nationally and internationally known experts could establish such thresholds based on their experience and the concussion literature. If not, the SMEs would document gaps and recommend a research strategy. This report summarizes the SME expert panel findings. The authors will present the systematic literature review with meta-analysis in a separate report (Gleason et al., 2026).

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Methods

The USAARL hosted and led a virtual Head Impact Brain Health Thresholds Expert Panel on January 27 and 28, 2026. The meeting brought together 25 domestic and international experts from academia, professional athletics associations, engineering consultation companies, and the DoW. There were two main objectives for the panel:

- 1) Determine if there is a consensus on a kinematic concussion threshold for a single HAE, and
- 2) Determine what critical near-term research gaps exist in concussion monitoring and detection that need to be addressed to further the science, including
 - A) Identifying possible factors (e.g. sex, age, fatigue, hydration, etc.) that may influence head/brain health risk and/or individual tolerance levels, and
 - B) Identifying possible alternative parameters (e.g., frequency of impacts, measurements of impact density) for concussion monitoring and detection.

SME Pre-Meeting Consultation Worksheet

The SME Pre-Meeting Consultation Worksheet was distributed by the meeting leads to all attendees via email before the meeting (Appendix D). The Worksheet contained questions about kinematic concussion threshold values and metrics, covariates, and research gaps.

The questions asked on the worksheet were:

1. What translational acceleration threshold do you recommend for Warfighter head/brain health (concussive) surveillance?
2. What is your confidence level in this threshold? (1-low through 5-high)
3. What rotational acceleration threshold do you recommend for Warfighter head/brain health (concussive) surveillance?
4. What is your confidence level in this threshold? (1-low through 5-high)
5. Which impact exposure metric do you believe is most associated with concussion risk? (Translational or Rotational)
6. What alternative parameters of an impact influence head/brain health risk? (e.g., impact direction, magnitude, location on the head, repetitive/frequency)
7. What factors do you believe also influence head/brain health risk and/or tolerance levels? (e.g., sex, age, fatigue, hydration)
8. List three knowledge/technology gaps that need to be addressed to establish a military blunt impact concussive surveillance program.
9. What assessment method(s) do you have the greatest confidence in to suggest the presence of a concussion?
10. Other thoughts and concerns.

Meeting Structure

The meeting was structured to provide a comprehensive baseline of current programs and research through formal presentations on Day 1. On Day 2, the meeting transitioned into collaborative analysis and consensus building sessions. The two-day meeting agenda can be found in Appendix C.

Day 1: Information Exchange:

- Strategic Context: DoW WBHI and Army WBHP leadership presented programmatic goals and current mission activities.
- Evidence Baseline: USAARL personnel briefed the results of the recent systematic literature review with meta-analysis and presented an overview of the wearable sensor research conducted by USAARL.
- SME Insights: Invited experts delivered presentations on wearable sensor challenges and identified the near-term research gaps essential for military HAE monitoring.

Day 2: Analysis and Consensus:

- Analysis: The meeting leads reviewed and discussed the SME Pre-Meeting Consultation Worksheet responses (Appendix D).
- Strategic Outcomes: The group identified specific research gaps and drafted Consensus Statements regarding HAE thresholds for subsequent SME voting.

Data Extraction

To fulfill the panel objectives, data were derived from dually scribed meeting notes, which covered SME presentations and discussions, and the SME Pre-Meeting Consultation Worksheet responses. These sources of information were analyzed to (1) determine if there was a consensus regarding kinematic thresholds and metrics; (2) identify research gaps; and (3) explore alternative parameters for detecting concussions that occur at low kinematic magnitudes. The meeting leads recorded SME Pre-Meeting Consultation Worksheet responses in a master spreadsheet using numerical values, discrete selections, and free form formats (Appendix E). Free form responses were coded by overall contained theme/topic in order for the responses to be tabulated and compared.

Consensus Statements

To establish expert consensus, the meeting leads employed an iterative drafting and voting process through five phases:

- Phase 1: Initial Drafting – Identify recurring themes from SME Pre-Meeting Consultation Worksheet responses, notes from SME presentations, and minutes from Discussion Session 1 to draft preliminary Consensus Statements.
- Phase 2: Live Refinement – Collect initial feedback from the SMEs of the Consensus Statements during the panel discussion and conduct the first rewrite of the statements.

- Phase 3: Secondary Refinement – Compile all information collected from the meeting and conduct a secondary rewrite of the Consensus Statements.
- Phase 4: Targeted Review – Solicit a second round of feedback from selected SMEs and complete the final rewrite of the Consensus Statements.
- Phase 5: Final Voting – Distribute the finalized Consensus Statements to all attendees for official voting and commentary.

The meeting leads analyzed the SME Pre-Meeting Consultation Worksheet responses, notes from SME presentations, and minutes from Discussion Session 1 using qualitative code methods. Recurring topics and themes in the data were used to draft the initial Consensus Statements. These drafted statements were then presented to attendees by the meeting leads to determine if a consensus of opinions could be reached on the statements. During Discussion Session 2, the meeting leads collected feedback on the first draft of the Consensus Statements and used the feedback to re-write the Consensus Statements. After the expert panel meeting, the meeting leads distributed the re-written statements via email to nine selected attendees for a targeted review. Feedback from this targeted review was used to amend the statements again. The meeting leads distributed the final version of the Consensus Statements to all attendees for an official vote. Attendees were asked to agree, disagree, or decline to respond. They were also provided the opportunity to add qualitative feedback.

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Head Impact Brain Health Thresholds Expert Panel Event Summary

The two-day HIBHTEP evaluated the current state of HAE exposure science and wearable sensor technologies. The group reviewed the current operational feasibility of implementing a widespread military HAE surveillance program. Day 1 featured comprehensive presentations from SMEs across academia, professional athletics associations, engineering, and the military. These presentations covered cross-domain (e.g., sports, age groups, level of play) kinematic data, intrinsic injury risk factors, and longitudinal concussion surveillance. The presentations focused on the real-world operational challenges of deploying wearable sensors in military environments, strategic research gaps that must be bridged, and technical milestones necessary for fielding readiness. On Day 2, the panel transitioned from the technical overview to strategic discussions driven by a review of the DoW WBHI mandates and SME Pre-Meeting Consultation Worksheet responses. Discussions centered around debating the operational framework required to transition wearable sensor technologies and the current state of HAE science to the fighting force. Day 2 concluded with the refinement of formal Consensus Statements, emphasizing the critical need for a standardized, cross-disciplinary nomenclature, and the immediate implementation of a multi-modal screening approach to optimize Warfighter brain health and force readiness.

Day 1: SME Presentations

DoW Warfighter Brain Health Initiative.

Presentation summary.

Ms. Kathy Lee from DoW WBHI presented information on the DoW WBHI and how head impact research fits within the program. To align the conversation with the array of audience backgrounds, Warfighter brain health was defined as “the physical, psychological, and cognitive status that affects a Warfighter's capacity to function adaptively in any environment and impacts readiness, operational capability, mission effectiveness, and the goal to achieve overmatch or superior lethality” (Department of Defense WBHI, 2021). Head impact exposure was identified as a threat in the Warfighter environment and research is required to better understand and mitigate the effects of head impact exposure. The WBHI follows five LOEs. The first four LOEs lead to the fifth LOE which is to advance Warfighter brain health science.

Discussion summary.

One question was posed after the DoW WBHI presentation about requesting access to the data that is being generated and how others can get involved and help the WBHP. Ms. Lee explained the best way to get involved is to find a collaborator to help navigate the government processes and put data sharing agreements in place.

Department of the Army WBHP.

Presentation summary.

Dr. Steven Porter provided an overview of the Department of the Army WBHP and described how the objectives of the Army WBHP align with those of the DoW WBHI. The

Army previously focused on what happens after a head impact occurs (i.e., treatment of the injury); however, this program focuses on prevention and protection. The major programmatic changes from Army Brain Health to the Army Warfighter Brain Health Program included: (1) assessing Warfighters at intervals throughout their career rather than before deployments only and (2) using a holistic approach comprising prevention, care, and recovery instead of an injury-centric model.

Discussion summary.

A single question was posed after the conclusion of the Department of Army Brain Health presentation about the biggest hurdle the Army WBHP faces. Dr. Porter explained that the biggest challenge is gathering all of the research from different sources (e.g., academia, other military services, etc.), synthesizing the information, and turning the collective research into actionable information for the Army.

USAARL literature review.

Presentation summary.

Dr. Allison Gleason from USAARL presented the results from a systematic literature review meta-analysis of publications containing concussion kinematics data captured with wearable head impact sensors. Information from 42 studies was presented. These studies included 2,802,284 total impacts recorded from 7,096 instrumented athletes, with 722 of those impacts resulting in a concussion. Dr. Gleason extracted activity, sensor used, subject age, subject sex, number of concussions, and concussion kinematics data from the literature. The literature review with meta-analysis framework was used to develop potential interim kinematic concussion thresholds for a DoW surveillance program. Previously published literature consistently reported only resultant peak linear and peak rotational acceleration, which allowed USAARL researchers to conduct a meta-analysis of only those metrics. Separate analyses for peak linear and peak rotational acceleration yielded pooled means of 70.93 G, where G is the acceleration due to the gravity of Earth, and 4559.01 radians per second squared (rad/s^2), respectively. While these pooled means may serve as interim thresholds, users should apply them only as surveillance or screening tools, not as diagnostic criteria for any injury.

Discussion summary.

One question was asked after the presentation about the validity of the data that was used in the analyses, given the known errors related to sensor use in prior studies, and lack of studies completed with military populations. Dr. Gleason explained that there is a lack of military-specific head impact data available, so this analysis provides a starting point for a surveillance program as wearable sensors are introduced to characterize military environments. Dr. Gleason explained that these means represent thresholds applicable to a general population because of the inclusion of both sexes and various age groups. The data are largely from athletic settings and will not reflect any characteristics unique to military populations. Dr. Gleason further explained that this type of analysis may be adjusted to remove data points that may not be applicable in a DoW setting (e.g., youth) or to add more applicable data as more military head impact data are acquired. The discussion was concluded at this point due to time constraints.

USAARL Environment Sensors in Training Program overview.

Presentation summary.

Dr. Johnson detailed the USAARL evaluation of commercial wearable sensors (e.g., headband, patch, and mouthguard) for use in monitoring accelerative head injuries incurred in military environments. Initial laboratory tests established performance baselines. Field testing revealed that although instrumented mouthguards offered good comfort and personal protective equipment compatibility, commercial sensors broadly struggle with military demands due to short battery lives, difficult false-positive rejection algorithms, and severe time drift that prevents accurate video verification of impacts. Despite these limitations, dose-response studies conducted during airborne training, combative courses, and military academy sports (e.g., rugby, boxing) observed that higher peak rotational velocities and impact frequencies were correlated with decreased non-postural balance performance. To make these technologies operationally viable, Dr. Johnson emphasized that field medics require simple, automated triage systems—green/yellow/amber alerts—to quickly assess large populations without being slowed down by manual data downloads. Ultimately, the successful deployment of a military surveillance program must overcome an unstable commercial sensor market while resolving persistent technical challenges related to head coupling, clock accuracy, and the inherent difficulty of capturing large sample sizes from real-world injury events.

Discussion summary.

There were no questions after the presentation concluded; however, the attendees were asked to think about terms and definitions. It was stated that there needs to be an understanding that there is a clear difference between sub-clinical and injury (i.e., concussion) exposures. Currently, the Army states that a concussion only occurs if there is an altered state of consciousness.

Biocore LLC.

Presentation summary.

Dr. Lee Gabler from Biocore presented on their past work gathering instrumented mouthguard data from the National Football League (NFL) and National Collegiate Athletic Association (NCAA) football players. The head kinematics data collected with mouthguards have been used to quantify the magnitude of impacts experienced by players, evaluate the effectiveness of intervention pathways (e.g., rule changes, equipment changes, introduction of better playing techniques), and test and rank helmet systems. The data have shown there is little difference in the severity of impacts between the levels of play (i.e., NFL, NCAA) and that there is a high degree of variability in impact kinematics between players. The Biocore data show a considerable amount of overlap between the kinematics of concussive and non-concussive impacts. While concussive impacts are generally higher in magnitude, no real threshold can be chosen between concussive and non-concussive for any metric. Rather, individual thresholds, governed by intrinsic factors, may better explain the variability seen in the concussion data.

Discussion summary.

Three questions were asked at the conclusion of the Biocore presentation. First, the presenter was asked why the NFL is not using a mouthguard sensor. Dr. Gabler explained that the Biocore team no longer use mouthguards as they have reached the end of their research effort to improve test methods for protective equipment. A follow-up question was asked about whether Biocore's decision to not use mouthguards for athlete monitoring was due to a belief in the lack of value in using the sensor. Dr. Gabler explained that this has more to do with players not being required to wear mouthguards. The lack of enforcement makes it difficult to recruit and retain many athletes for the research studies. The third question asked for the opinion of Dr. Gabler on the existence of a threshold used for monitoring, but not as an indicator of concussion. Dr. Gabler agreed that a monitoring threshold would be useful to capture high HIE, but he believes a profile or a baseline for the individual being monitored is necessary.

University of British Columbia.

Presentation summary.

Dr. Lyndia Wu from the University of British Columbia presented information on longitudinal studies completed across multiple sports while players wore wearable head impact sensors. Instrumented mouthguards were used to collect head impact exposure data in the studies to identify metrics that may predict concussion. Angular velocity and power metrics had the highest area under precision-recall curve (AUPRC) values for single impacts, while measures of impact density had the highest AUPRC for daily cumulative criteria. However, evidence was weak for using any of these metrics to calculate a kinematic concussion threshold. Dr. Wu identified issues with sensor coupling, missing data in longitudinal datasets, lack of standardization of a concussion definition, and underdeveloped methods for identifying and quantifying concussive injuries as gaps in this area of research.

Discussion summary.

Two questions were posed to Dr. Wu at the conclusion of her presentation. The first question asked if Dr. Wu had a hypothesis on why the angular velocity outperformed other metrics when correlating with concussion. Dr. Wu stated that she currently does not have a clear hypothesis and acknowledged that many of these metrics are correlated with each other. Dr. Wu said more data are needed to determine why angular velocity outperformed other metrics and to eliminate the potential for sample bias due to the small sample size. The second question asked if Dr. Wu considered any directional weighting when investigating cumulative impacts. Dr. Wu took single impact criteria and transformed them into cumulative impact criteria but has not experimented with any custom weighting.

World Rugby Research Unit.

Presentation summary.

Drs. Eanna Falvey and Ross Tucker from World Rugby presented information on the World Rugby Head Injury Assessment (HIA) Protocol. The World Rugby HIA Protocol involves the identification of high magnitude HAEs and a tiered assessment method for capturing

concussions. The HIA Protocol uses a threshold for translational and rotational acceleration with instrumented mouthguards as part of the criteria for removal from play for evaluation for concussion. The mouthguard is not used as a diagnostic tool but is instead used to identify players who have experienced a large magnitude HAE and need to be evaluated for a possible injury. Player mouthguards that register an impact at or above a peak linear acceleration (PLA) of 75 G and a peak rotational acceleration (PRA) of 4500 rad/s² trigger an automatic sideline evaluation for a concussion. That sideline evaluation may result in either a concussion diagnosis or a player being allowed to return to the game. A large dataset collected with the instrumented mouthguards was used to optimize the screening threshold to maximize concussion detection while minimizing non-concussive evaluations. The dataset used to optimize the mouthguard threshold contained 13,000 total impacts with 157 recorded concussions. The median PLA of non-concussive impacts was 12.7 G while the median PLA of concussive impacts was 64.5 G. Despite the difference in medians, there was significant overlap in the two datasets, and Drs. Falvey and Tucker believe more work needs to be done to understand concussions that occur at lower magnitudes and impacts at high magnitudes that do not result in concussion.

Discussion summary.

Due to time constraints, no discussion occurred at the conclusion of the World Rugby presentation.

Leeds Beckett University

Presentation summary.

Drs. Ben Jones and James Tooby from Leeds Beckett University presented their past and continuing work. Drs. Jones and Tooby have collected large HAE datasets using instrumented mouthguards worn by professional rugby players (Rugby Football League and World Rugby). For this presentation, they discussed instrumented mouthguard data associated with the HIA Protocol used by World Rugby. Video-matched mouthguard data for HAEs that resulted in athletes being flagged for the HIA Protocol, who either passed the HIA Protocol or were diagnosed with a concussion, were analyzed and compared to the control group. The datasets for the HAEs resulting in passing the HIA Protocol and those resulting in concussion largely overlapped, with only slight increases in the median values of peak kinematics of concussive impacts. Drs. Jones and Tooby are currently analyzing the HIA Protocol mouthguard data from the female cohort and have started using the mouthguards to monitor the cumulative exposure of individual athletes over different time spans.

Discussion summary.

The discussion following the presentation by Drs. Jones and Tooby started with explaining terms that the audience members were not familiar with, such as HAE and HIA. Based on the discussions, the group determined that in the context of this meeting, HIE and HAE are used synonymously. However, using HAE is more accurate because head injury can result from head accelerations without a direct impact to the head. Drs. Tooby and Jones were then asked to expand on their lessons learned when using mouthguard sensors at such a large scale. One lesson learned was to learn what other sports were doing, specifically the World Rugby

organization. Drs. Jones and Tooby explained that Rugby Football League likely would not have implemented some of the changes they made if not for World Rugby making those changes. Another lesson learned was that the validation study, presented by Drs. Jones and Tooby, was used to help garner support for the widespread implementation of mouthguard sensors into a monitoring program. It was further discussed that instituting any sensor will require extra effort for others (e.g., athletes, trainers), and if others do not fully believe in what is being done, the monitoring program will be met with challenges and skepticism. Another lesson learned was that the research needed to move toward clinical relevance. After the research developed a screening threshold for HAEs, there was increased cooperation with coaching and staff. The final lesson learned was that large-scale monitoring of data sources need to be integrated with good organizational frameworks and good data pipelines for the monitoring program to work. The final question was posed to Drs. Tooby and Jones regarding the number of false positives. This question brought about a large discussion on terms and definitions, as there was a different use for the term false positive by the presenters and other audience members. In the presentation, the word false positive referred to when a sensor indicated that there was an HAE above a threshold, but an HAE did not occur (i.e., a false reading by the sensor). Members in the audience were referring to a false positive as the sensor picking up an HAE above the set threshold, but that event was not causing a clinically diagnosable head injury. This conversation highlighted the importance of standardized terms and definitions that need to be shared across communities.

Stanford University

Presentation summary.

Ms. Jessica Towns from Stanford University presented her work investigating risk factors for concussion. Ms. Towns collated instrumented mouthguard data taken from multiple sports at Stanford and data reported from multiple sports in previous studies into a single dataset to investigate the predictive capabilities of multiple kinematic metrics. The dataset included a total of 203 participants across multiple sports with 3,805 non-concussive impacts and 47 concussive impacts. Ms. Towns evaluated PLA, PRA, peak rotational velocity (PRV), and 95th percentile maximum principal strain for their predictive capabilities. The concussive and non-concussive impact datasets showed overlap, but concussive impacts were significantly larger in magnitude across all metrics. PLA had the highest AUPRC. PRV was also shown to be a significant concussion risk factor. Results from this dataset showed a 50% risk of concussion at 99 G, 8,254 rad/s², and 39 radians/second (rad/s). The 99 G 50% risk of concussion may indicate that the current pass/fail criterion for Advanced Combat Helmet (ACH) certification of 150 G is too high for mitigating concussion. Ms. Towns identified the laborious process of impact video reviews, mouthguard damage, and participant non-compliance as challenges. Ms. Towns identified using artificial intelligence (AI) to increase the accuracy of sensors and assist in video monitoring, as well as developing mobile device neurological assessments, as research gaps.

Discussion summary.

The discussion following the presentation by Ms. Towns started with a question about how angular velocity was calculated, specifically whether peak angular velocity or the change in angular velocity from onset to peak was used. Dr. Tooby explained that he sees a lot of peak angular velocity in the pre-trigger sensor data, so they calculate the change in angular velocity to

normalize the value to the pre-trigger state. Ms. Towns explained that their research looked at the change in angular velocity, but this calculation did not yield results different from the calculations using peak angular velocity. The second question asked for an explanation about what might be different in the work presented by Ms. Towns that elevates the importance of linear acceleration when that metric has not been found to outperform others in other studies. Ms. Towns explained that she is still searching for that answer but has similar results to studies published by Virginia Tech University. She stated that the similarities between the studies could be because both studies used American football players as study subjects. Ms. Towns further explained that this question is relevant to the mechanism of injury, which is not yet fully understood. Once more research is completed to understand the mechanism of head injuries, the reason for these findings might be more apparent. The final question was whether the sensors used in this research measured angular velocity and computed angular acceleration, which Ms. Towns explained was correct. Dr. Siegmund explained that since angular acceleration was not directly measured, this could be an explanation for some of the findings presented, as it was shown that linear acceleration and angular velocity had similar results.

Medical College of Wisconsin

Presentation summary.

Dr. Brian Stemper from the Medical College of Wisconsin presented his past work with the Concussion Assessment, Research and Education (CARE) Consortium and a pre-clinical rodent model for HIE. Dr. Stemper acted as the Chair of the Head Impact Measurement (HIM) Core for the NCAA-DoD CARE Consortium. From 2015 through 2019, the CARE Consortium used the Head Impact Telemetry System (HITS) to collect a total of 718,713 head impacts, including 73 concussions. To identify athletes with high levels of impact exposure, a matching protocol was created, and 63 of the concussed athletes were paired with matched controls. The matching protocol and identification of players with high levels of impact exposure showed that nearly 50% of the concussed athletes had high levels of impact exposure without a single identified high magnitude impact linked to concussion. Eighteen percent of the concussed athletes had only a single large impact associated with their concussion. Dr. Stemper also discussed a separate study in high school players that assessed the changes in clinical assessment scores from baseline to mid-season and post-season timepoints. The assessment methods used in the study included the Sport Concussion Assessment Tool 5th Edition (SCAT5), Balance Error Score System (BESS), Standardized Assessment of Concussion (SAC), and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT). The number of concussion-like symptoms measured using the SCAT5 increased from baseline to mid-season and again from mid-season to post-season. Some athletes showed clinically significant decreases in BESS, SAC, and ImPACT scores. The most important factors found to be driving those changes were the highest magnitude head acceleration event over the entire period, followed by cumulative impact measures. Dr. Stemper identified three key takeaways from these studies: (1) the large number of football athletes with a concussion mechanism, including elevated HIE, (2) uninjured athletes reporting increased symptomology after a single football season, and (3) the largest impact of a season and cumulative impacts were the drivers of clinical changes. Dr. Stemper also presented an animal model where exposures scaled down from humans were used in a repetitive impact protocol with rats. Rats showed dose-dependent cognitive deficits, behavioral effects, and accumulation of blood biomarker neurofilament light (NfL), like humans.

Discussion summary.

Two questions were posed to Dr. Stemper at the conclusion of his presentation. The first question asked to further explain results, as a portion of the presentation suggested that cumulative impact exposure might be the best predictor of head injury, while other parts of the presentation showed that a single HAE was better correlated with health outcomes. Dr. Stemper explained that their dataset has about half of the athletes with a high number of low-level impacts, and the other half of the athletes have a single high-level impact; consequently, the researchers cannot endorse one monitoring method over another. But the researchers acknowledged that they are continuing to work in this area. The second question was regarding the random forest model (uses predictions of decision trees to produce a single result) and whether the rotational velocity metric was investigated. Dr. Stemper explained that angular metrics measured by the head impact telemetry system were analyzed. Linear and rotational metrics were highly correlated, as the linear metrics measured were used to calculate the rotational metrics.

The Ohio State University

Presentation summary.

Drs. Jaclyn Caccese and Enora Le Flao from The Ohio State University presented the results from three studies: (1) HAEs in Corrections Academy training (Law Enforcement Cadets), (2) hydration status as a risk factor for repetitive head impacts (RHI), and (3) neurodevelopmental effects of age of first exposure to American football. Corrections Academy cadets are an understudied population who participate in multiple activities with risks of HAE. In their study, mouthguards were used to measure the frequency and magnitude of HAEs in multiple cohorts. Boxing accounted for the highest proportion of HAEs of all training activities and resulted in the highest magnitude HAEs in both PLA and PRV. The SCAT evaluations during boxing training revealed that additional recovery time between sessions could prevent exacerbation of reported symptoms. The practice of matching cadets based on sex and perceived skill level appears to be effective in eliminating sex-based disparities in HAEs. There was no significant difference between the sexes in the number of HAEs or PRV per session, and a likely negligible difference in PLA. In the second study, the effect of hydration status on HIE was explored in combat sports. Muay Thai and mixed martial arts (MMA) athletes wore instrumented mouthguards during sparring sessions to measure HIE. There was no significant difference in the number of exposures between hydrated and dehydrated athletes. There was an increase in symptom reporting in dehydrated athletes, but the symptoms were largely linked to fatigue. The final study is an ongoing longitudinal study following first-year youth (eight to twelve years old) tackle American football players through a season while monitoring HIE and cognitive changes. Drs. Caccese and Le Flao identified data cleaning as an essential step for analysis, and they believe efforts should be focused on using AI to improve automated filtering methods to move away from time-intensive video verification. The lifespan of instrumented mouthguards and the effects on data quality from mouthguard damage were also identified as challenges.

Discussion summary.

After the presentation concluded, three questions were posed for the presenters. The first question asked the presenters to expand on the differences between head impacts in combat sports and head impacts in other contact sports. Drs. Caccese and Le Flao explained that the main differences are the location of head impacts and the frequency of impacts. Most impacts in combat sports are to the face or top of the head, which is different from other contact sports. The frequency of impacts in combat sports is much higher than other contact sports. The second question asked if video confirmation of the head impacts has been performed as a confirmation of mouthguard coupling. Drs. Caccese and Le Flao explained that although video review of head impacts has not been done yet, the researchers improved the coupling of the sensors by using 3D scans of the subjects' teeth and by comparing mouthguard coupling from the start to the end of the season. The final question was for an explanation of the commonalities and differences between the symptoms of concussion and dehydration. Drs. Caccese and Le Flao explained that many of the symptoms of dehydration and concussion are similar, but the major difference is dehydration symptoms subside in 24 hours and the symptoms of concussion last longer.

Children's Hospital of Philadelphia

Presentation summary.

Dr. Kristy Arbogast from the University of Pennsylvania and the Children's Hospital of Philadelphia presented her work on pediatric concussion. Dr. Arbogast has been involved in studies using both instrumented headbands and instrumented mouthguards to collect HIE data from athletes in multiple high school sports, including soccer, lacrosse, basketball, and field hockey. Across all sports, males consistently had higher HAE rates. Soccer, for both sexes, had the highest HAE rate, but soccer had a similar rate as other sports if purposeful heading events were not considered. The data revealed a large variability in HIE between individual players. A few players on a team will likely account for a large portion of the impacts throughout a season, while some percentage of the players on a team may not experience a single impact during a season. Summary metrics will likely overestimate or underestimate individual player HIE. An in-laboratory study involving controlled headers in male and female teenage soccer athletes did not reveal any significant immediate neurological changes. However, teenage female soccer players monitored over a season of play did show some correlation between HIE and neurological function in the most difficult tasks presented. Dr. Arbogast noted that comparing results across wearable sensor studies is challenging due to differences in sensor coupling and data processing techniques. The effects of filtering methods on kinematic data were shown with emphasis on the potential for data loss from over filtering. Dr. Arbogast noted that youth do appear to experience concussion differently, given the data that already exists, but that more granularity is needed in the data to determine how concussion risk may vary over the pediatric age range.

Discussion summary.

The discussion following the presentation by Dr. Arbogast started with a question about using a simplistic measurement like counts and what the value of simplistic measurements is for head impact health. Dr. Arbogast explained that the value depends on the goal. If the goal is to identify concussions, counts will not work, but if the goal is to compare training regimens,

counts will work. Dr. Arbogast further explained that the advantage of counts is in simpler data management and processing. Dr. Arbogast was asked for the triggering threshold used by the headband sensors used in her studies, and she replied that the sensor threshold was any HAE above 16 G in resultant linear acceleration. A third question asked about when the sensitivities of cognitive measures start to elicit a measurable effect. Dr. Arbogast explained that her clinical colleagues will have to increase the required cognitive demands, especially for high performing patients, to measure cognitive impairment. Dr. Arbogast further explained that military populations will probably be a similar case, where high-performing individuals can mask cognitive impairments, and harder tests will be needed to see measurable differences.

Wake Forest University School of Medicine

Presentation summary.

Dr. Jillian Urban from Wake Forest University School of Medicine presented several studies, including: (1) HAEs in soccer; (2) HAEs in grassroots dirt track racing (motor vehicle racing); and (3) Integrating HAE data with behavioral interventions for injury prevention in youth football. HIE was monitored in collegiate female soccer players with instrumented mouthguards. Intentional headers accounted for nearly 90% of HAEs and were associated with higher PLA and PRA than non-header HAEs. The kinematics of headers were seen to vary by play state (e.g., corner kick, free kick, throw in) and intent (e.g., pass, shoot, clear). HIE was also monitored in female youth (under 15 years old) soccer players to characterize HIE across common training activities. HIE in female youth soccer players was found to be dependent on activity with technical training activities accounting for higher impact rates and team interaction. Game play accounts for higher kinematics. Interventions may be designed to target different aspects of exposure (e.g., frequency, magnitude). Youth female soccer players were also evaluated to determine if heading technique affects HAE kinematics. Increased technique scores were associated with decreased PRA in games but with increased PRA in practices. Back extension and alignment of the shoulder and hip were identified as important technique criteria for reducing HAE kinematics. Dr. Urban has also used instrumented mouthguards to characterize the head kinematics that grassroots dirt track racers experience. Dirt track racers can experience serious injuries during crashes and experience smaller head perturbations during a typical lap that are poorly characterized. Characterization of perturbations revealed that a side-to-side motion of the head is the most frequent motion during a typical racing lap. In crash scenarios, the left, top, and rear of the vehicle were the most common contact locations. Contact to the left, front right, and top of the vehicle resulted in the highest median PLA, PRA, and PRV, respectively. Dr. Urban also discussed how data taken with instrumented mouthguards from youth football players has been used to develop the Communities Aligned to Reduce Concussion and Head Impact Exposure (COACH) program. Observations from years of data collection have been used to develop an intervention program geared toward involving coaches in adapting skill development and practice activities to focus on safety and mitigating HIE. Dr. Urban identified compliance as a challenge but noted that new form factors for sensors have allowed for better communication during use, which helps with compliance. Data collection modes that allow for data collection during longer events and accounting for environmental factors in data collection were also noted as challenges. Dr. Urban suggested building relationships and providing access to collected data as strategies to develop interest, build trust, and increase compliance.

Discussion summary.

Two questions were asked following the presentation by Dr. Urban. The first question asked for opinions on how to best achieve, or what lessons were learned in achieving, good compliance with users in environments that have been less studied (e.g., motocross). Dr. Urban explained that including the users in the design of the sensor was important for athlete compliance. Additionally, improving the sensor to be more comfortable and not impede necessary functions while wearing the sensors makes users more willing to participate. The team led by Dr. Urban moved from a retainer-style sensor to a dental-splint style sensor to improve comfort and reduce the effect of the device on the ability of the wearer to communicate. Furthermore, Dr. Urban explained that her team also provides crash reports to the athletes and delivers data on how the wearable sensors contribute to improved driver safety, which improves compliance. The final question asked about the specific filter cutoffs used for the American football data collected. Dr. Urban did not have the specific filter information available, but explained that, overall, kinematic metrics measured at the youth level were low.

Prevent Biometrics Inc.

Presentation summary.

Dr. Adam Bartsch from Prevent Biometrics presented data collected from Warfighters during Airborne Operations (ABO) training using instrumented mouthguards. Warfighters can often sustain TBIs upon landing during ABO. Instrumented mouthguards were used to measure head kinematics during static-line parachute jumps at the Basic Airborne School, the 82nd Airborne Division, and the 75th Ranger Regiment. Instrumented mouthguards were also used to measure head kinematics during freefall parachute jumps with the Special Operations Command (SOCOM). For this ongoing study, a combined threshold with PLA of 40 G and impact energy of 20 Joules (J) is being used as a flag on the instrumented mouthguards to indicate that a Warfighter needs to be screened for a concussion. Using this combined threshold, 7% of static-line jumps have been flagged by an instrumented mouthguard. Following evaluation, 60% of the Warfighters flagged by the instrumented mouthguards have shown clinical signs of a concussion. Dr. Bartsch noted that the ability to transfer data in real-time to assist medical personnel and Commanders in making decisions about pulling an individual for evaluation is crucial. The maintenance of the devices in military environments and the integration of the data into Warfighter records were also identified as concerns.

Discussion summary.

The discussion following the presentation by Dr. Bartsch started with a question about defining the term “hard hit.” Dr. Bartsch explained that “hard hits” were the term he used to define outliers in measured HAEs, or the top 1% of his data. The second question asked to clarify the threshold used: whether it was 40 G or 20 J, or whether both metrics had to be exceeded to indicate a subject should be screened. Dr. Bartsch explained that 40 G and 20 J are the same in this context, as the pulse width is the same among all subjects. Dr. Bartsch added that in ABO, about 90% of the impacts are to the rear of the head, and thus, his research has a directional sensitivity. The third and final question asked Dr. Bartsch to provide an opinion on why there were instances of clinical indicators (e.g., pupillometry, blood biomarkers) occurring

when no head impact was recorded by the sensor. Dr. Bartsch hypothesized that these unlinked clinical indicators are likely to be caused by the "opening shock" of the parachute or general variability in the tests and acknowledged that this phenomenon requires further investigation.

MEA Forensics Engineers & Scientists Inc.

Presentation summary.

Dr. Gunter Siegmund from MEA Forensic Engineers & Scientists and the University of British Columbia presented limitations of concussion injury risk functions developed with wearable sensors. The population injury risk function captures a distribution of individual injury thresholds. The injury risk function is affected by variance related to sensor accuracy, diagnostic accuracy, predictor (e.g., PLA, PRA), and statistical model. Sensor error leads to uncertainty related to the measurement of the injury predictor, which can make the confidence intervals of the injury risk function large and, depending on the sensor, asymmetrical. Confidence intervals may become large enough that the injury risk function provides no value in predicting injury. Injury risk functions based on different predictor variables may be correlated. While PLA and PRA are often considered as separate predictor variables that may have unique correlations with clinical concussion indicators, linear and angular data are often highly correlated. When the predictor variables are correlated in this way, it may be inappropriate to formulate injury risk functions for the variables individually. Oversampling of data is also a factor affecting injury risk function development. Dr. Siegmund suggested that an injury threshold is a property of an individual, not of an impact, and that many studies oversample non-injurious impacts, which biases the injury risk function. Missed concussion diagnoses and underreporting of injuries also bias the injury risk function. Dr. Siegmund indicated that the next steps in research should include selecting a valid metric for developing a threshold, completing more field validation studies with sensors, developing a clear definition for concussion, developing objective diagnostic tests, and investigating the effects of intrinsic factors.

Discussion summary.

The discussion following the presentation by Dr. Siegmund started with a question about how to include subjects in the population who have never received a concussion in the injury risk model. Dr. Siegmund discussed that such subjects can be incorporated into the model by using their highest exposure occurrence and then censoring the data to state that this exposure is below their injury threshold. That response led to a follow-up question about how to incorporate subjects who have had multiple concussions into the model, as an audience member has subjects in their population of interest that are outliers with multiple concussions. Dr. Siegmund responded that ultimately it comes down to what we want to do with an injury risk function. Dr. Siegmund further explained that injury risk curves are a population-based function that may not be accurate when applied to an individual; however, understanding covariates might be a way to get closer to applying these functions to individuals. A final point Dr. Siegmund made was that injury risk functions are too easy to create without thinking about what the data is communicating and what data are actually needed to get to the answer that is desired.

Wayne State University

Presentation summary.

Dr. Dale Bass from Wayne State University presented prior work in wearable sensor validation and some considerations for possible military applications. Dr. Bass emphasized the importance of sensor coupling and sensor validation methods. Sensors like HITS and the X2 skin patch have documented errors associated with movement relative to the head during an impact. While the improved coupling reduced error, laboratory validations completed for instrumented mouthguards still revealed directionally dependent errors. Dr. Bass also stated that sensors should not be fielded for data collection without laboratory validation using cadaveric specimens, as anthropomorphic test devices (ATD) are not sufficient to characterize sensor errors. Dr. Bass emphasized that the sensitivity and specificity of a chosen threshold are highly dependent on the application. In the case of World Rugby, it may be acceptable for a player to be removed from a game to be examined and not be diagnosed with a concussion. This would be a false positive by the chosen threshold. In military environments, false positives may be less acceptable because personnel are being removed from training or operations unnecessarily. In military environments, the tolerance for false positives will likely be much lower than in sporting environments, but it will depend on the acceptable risk. With some concussions occurring at low kinematic values, setting a threshold that is both 100% sensitive and 100% specific is likely not possible at this point.

Discussion summary.

The discussion following the presentation by Dr. Bass was started by Dr. Siegmund, who added on to points made during the presentation about the response of wearable sensors when used on an ATD. He stated the method is not representative of a human wearing the device. He added that cadaver testing does provide evidence of the shortcomings of wearables sensors in comparison to laboratory grade sensors. Furthermore, Dr. Siegmund explained that although many errors can be identified through laboratory evaluation, there are still certain errors that can only be identified through human volunteer field testing (e.g., impact of sweat, environmental temperature, etc.). Dr. Bass reiterated in his presentation that it is crucial to use human cadavers for sensor validation but explained that he also believes the mouthguard sensors can work and have been shown to work. Dr. Bass further explained that the possible use cases for the mouthguard sensors needs to be discussed, as the mouthguard sensors are not applicable for all environments.

Uniformed Services University of the Health Sciences

Presentation summary.

Lieutenant Colonel (LTC) Bradley Dengler from the Uniformed Services University of the Health Sciences presented a study being performed with an ABO population. Paratroopers were fitted with instrumented mouthguards and pulled from training for screening if the mouthguards recorded an impact above 40 G. Blood and saliva biomarkers, pupillary light reflex, and concussion symptomology were evaluated. Blood levels of ubiquitin carboxy-terminal hydrolase L1 (UCH-L1) showed a correlation with higher magnitude impacts. Blood levels of

glial fibrillary acidic protein (GFAP) did not show a significant increase with higher magnitude impacts, but clinicians typically drew blood one to two hours after the impacts, and researchers know that GFAP levels peak later in the injury cascade. Pupillary light reflex readings did show a correlation with higher magnitude impacts. LTC Dengler noted that Warfighters most commonly complain of headaches in the 24 to 48 hours following a head impact. This is an ongoing study, but the LTC did report that for this application, he would rather pull more Warfighters for screening that test negative for a concussion (false positive) than miss a concussion diagnosis.

Discussion summary.

Two questions were posed after the presentation concluded. The first question asked about the differences in response metrics between vestibular/ocular motor screening (VOMS) and pupillometry. LTC Dengler explained that they test fundamentally different brain pathways. Neither tool is entirely mainstream yet, and pupillometry still requires further refinement, particularly for older populations. Similarly, while oculomotor tests perform well in controlled clinical settings, they have proven unreliable in the field due to environmental variables like outdoor lighting. Given these limitations, the speaker indicated that blood biomarkers currently show the most promise for accurately tracking brain damage. The second question asked about diagnostic accuracy and future testing of blood biomarkers. LTC Dengler explained that preliminary data indicate a direct correlation between elevated blood biomarker levels and increased brain damage, though in-depth analysis is still ongoing. It was noted that while NfL is not being tracked in the current cohort, another study that used baseline and post-injury blood draws from cadets will have analyzed NfL data available within the next six months. Despite the promise of blood biomarkers, some concern was raised by SMEs regarding the wide variation of data when pairing the biomarkers with mouthguard kinematic measurements (e.g., PLA), suggesting that combining the two has limited standalone diagnostic capability.

Day 2: Threshold Consensus and Surveillance Transition Discussion

The second day of discussion focused on achieving SME consensus on kinematic concussion thresholds and developing an operational framework for implementing a widespread surveillance program in the military. Driven by congressional mandates and the WBHI, the primary objective of a surveillance program is to implement wearable sensor-based injury screening for at-risk populations (e.g., artillery blast overpressure, combative), avoiding the technological pitfalls of the legacy helmet sensors fielded two decades ago. The group expressed general concerns regarding how broadly the program should be applied, given the current technical limitations of sensor hardware, data analysis techniques, and data management systems. The SMEs highlighted the operational risks of deploying sensors that currently exhibit weak specificity and sensitivity across diverse, rugged training environments. Questions were raised regarding clinical protocols for handling repeated, low-level impacts that demonstrate weak correlation to immediate cognitive change. To address these technical and operational concerns, the panel evaluated the mitigation framework modeled after current blast exposure protocols. The SMEs advocated for an "80% solution," which uses a baseline threshold (conceptually similar to the 4 pounds per square inch [psi] threshold used for blast exposure). Rather than mandating immediate removal from training events, this initial threshold would

serve as a triage tool to identify potentially concussed Warfighters for continued medical monitoring and evaluation.

The discussion transitioned to the established DoW framework: identify, monitor, and mitigate at-risk personnel. This framework provided the context for evaluating international best practices, especially the models currently used by World Rugby. World Rugby uses wearable technology as a triage mechanism rather than a definitive diagnostic tool. Data recorded by the instrumented mouthguards serves as a threshold to flag an 'amber group' for TBI symptom screening, not as a clinical diagnosis. By treating thresholds as screening triggers, the organization avoids the high statistical burden of proof required for directly diagnosing concussion. Furthermore, World Rugby collected data for a three-year baseline period without intervening on the field, and a retrospective analysis of the data was completed before any decision making occurred. The consensus focused on a shift toward monitoring functional capacity to optimize overall force readiness. The DoW application of this strategy includes several key considerations: (1) holistic brain health: factors like fatigue and dehydration impact brain function and must be accounted for in screening protocols; and (2) screening frequency (streamlined screening beyond annual assessments to maintain an accurate readiness posture). A critical DoW decision point that remains is determining which specific sensor-derived data points will be integrated into DoW official medical records.

A review of the SME Pre-Meeting Consultation Worksheet responses revealed a lack of consensus regarding definitive kinematic concussion thresholds. This precipitated a technical debate on the prioritization and operational viability of specific kinematic metrics for field use. Rotational acceleration is often viewed as a better predictor for outcomes like LOC, but it is notoriously difficult to accurately measure in field environments independently of linear acceleration. The group also discussed alternative metrics like the Head Injury Criterion (HIC) used in the automotive field. While the HIC was historically useful for automotive regulatory testing, the SMEs noted that it lacks the necessary granularity for precise human threshold modeling.

The discussion progressed to the practical application of sensor feedback mechanisms in training environments. The SMEs evaluated the use of real-time indicator systems to drive immediate behavior changes to mitigate the risk of injury. A primary example discussed was the use of instrumented mouthguards equipped with indicator lights (e.g., triggering at 40 G). This immediate feedback could motivate the Warfighter to self-correct techniques on the spot, such as reinforcing proper chin-tuck procedures during airborne jumps. Expanding on the concept of an "80% solution," the panel cautioned that adopting an interim solution strategy requires a formal framework to explicitly document any accepted clinical or statistical compromises being made. To bridge the gap between data collection and operational utility, the SMEs proposed a pragmatic approach: deploying sensors initially to high-exposure environments to establish baseline data, governed by a two-tier threshold system:

- Tier 1 (lower threshold) – Behavior: Prompts immediate technique self-correction and tactical behavior modification.
- Tier 2 (higher threshold) – Medical: Serves as the official threshold for formal medical screening and clinical evaluations.

The final session on Day 2 focused on the critical review and refinement of the group's Consensus Statements. A frequent recognition during this effort was the lack of standardization of professional lexicon or precise terminology to ensure clarity across medical, technical, and operational commands, such as distinguishing between "diagnosis" and "screening." Defining these terms would establish a clear boundary between an operational triage event (screening) and a formal medical determination (diagnosis). Differentiating between "threshold" and "tolerance" would standardize the terms used for measurable kinematic limits ("threshold") and subjective biological variation ("tolerance"). Appendix A contains a list of terms discussed by the panel and the definitions used in this report. The group reached a consensus that while a singular "gold standard" diagnostic tool does not currently exist, a multi-modal approach to early screening (e.g., blood biomarkers, physiological symptoms) is the most viable path forward for force health protection.

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Results

The SME Pre-Meeting Consultation Worksheet was distributed to 25 attendees, and 20 responded (77%). Two attendees responded together as a single organization, resulting in a total of 19 responses. Anonymized response data from all respondents are in Appendix D.

Consensus Single Exposure Kinematic Threshold Identification

Translational (linear) and rotational acceleration were identified, through the previously published USAARL meta-analysis, as the two metrics associated with injury most frequently reported in the literature (Gleason et al., 2026). The SME Pre-Meeting Consultation Worksheet was used to gauge SME consensus on specific kinematic concussion threshold values and which of the aforementioned metrics should be prioritized. When forced to pick between translational and rotational acceleration, the majority of attendees who responded to the SME Pre-Meeting Consultation Worksheet (68%, 13/19) prioritized rotational acceleration as a better predictor of concussion (Figure 1). When asked specifically about translational acceleration, 58% (11/19) of the respondents did not specify a single exposure threshold value (Figure 2). Of the 7 respondents (7/19, 37%) who did recommend a translational acceleration threshold value, the values ranged from 10 to 100 G with the average being 66 G. One respondent gave separate values for males and females (75 G for males and 65 G for females), another respondent gave a separate value for ABO and athletic activities (40 G for ABO and 75 G for athletic activities), and one respondent specified a range of values, 60 to 70 G. When asked specifically about rotational acceleration, 74% (14/19) of attendees concluded that a single rotational acceleration exposure threshold value cannot be identified. Three respondents provided rotational acceleration threshold values of 4000, 4500, and 5000 rad/s^2 , while 14 (74%) did not recommend a threshold (Figure 3). Two respondents did not provide an answer for the rotational acceleration threshold question. Overall, the results demonstrated a strong consensus that establishing a single kinematic exposure threshold is currently unfeasible for both metrics.

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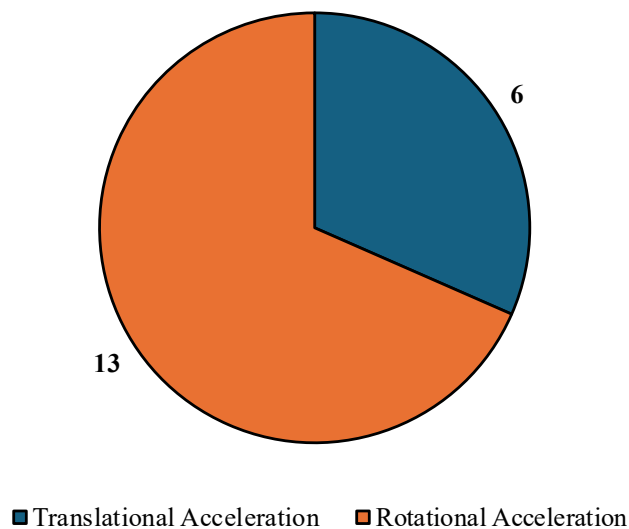


Figure 1. The SME Pre-Meeting Consultation Worksheet responses on metric prioritization are displayed to show the proportions of attendees who favor rotational acceleration over translational (linear) acceleration as a better predictor of concussion.

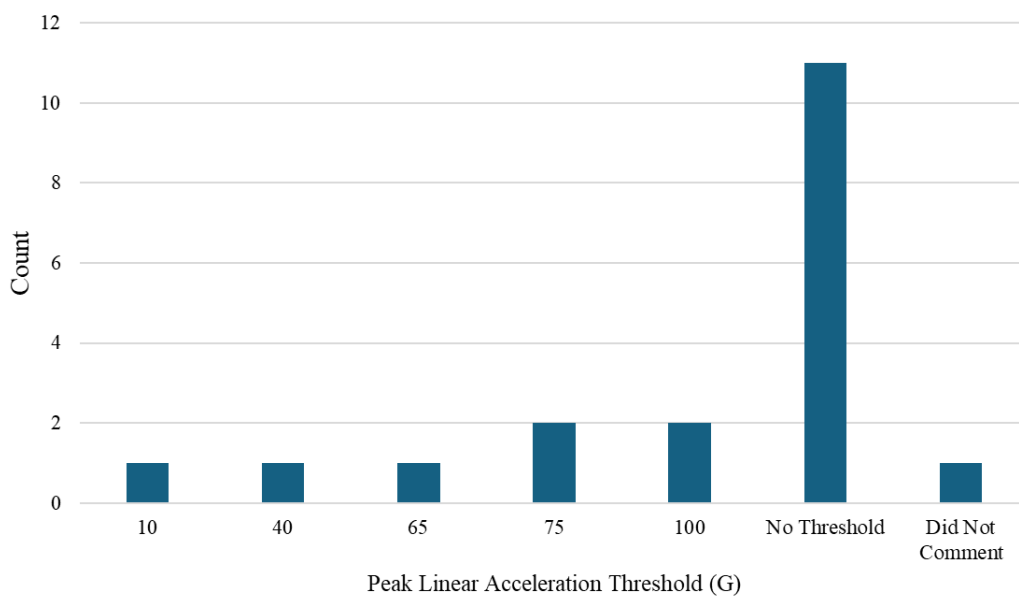


Figure 2. Nineteen attendees returned responses to the SME Pre-Meeting Consultation Worksheet. Among the respondents, 37% (7/19) gave a value or range of values for what they thought the peak linear acceleration threshold should be. Fifty-eight percent (11/19) answered that there should be no threshold based on peak linear acceleration. One attendee did not answer the question.

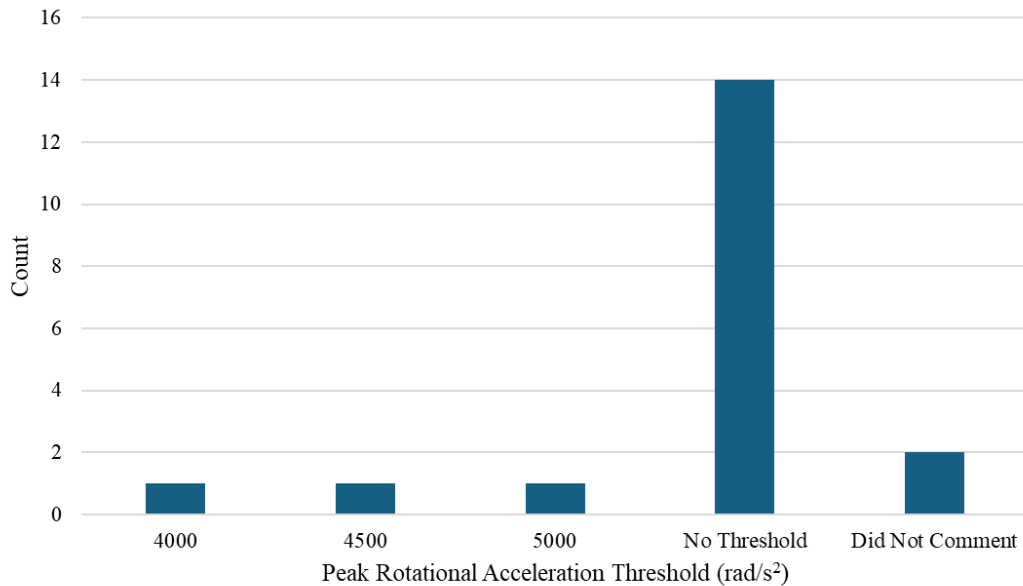


Figure 3. Nineteen attendees returned responses to the SME Pre-Meeting Consultation Worksheet. Among the respondents, 16% (3/19) gave a value for what they thought the peak rotational acceleration threshold should be. Seventy-four percent (14/19) believed that there should be no threshold based on peak rotational acceleration. Two attendees did not answer the question.

Identification of Research and Capability Gaps

The meeting leads reviewed the freeform SME Pre-Meeting Consultation Worksheet responses and identified several recurring themes or topics regarding current capability limitations and research gaps. Each SME was instructed to list up to three research gaps, but there were instances where more than three gaps were provided on the worksheet. The leads tabulated the responses by topic and calculated the frequency of each occurrence to prioritize future scientific and operational efforts (Table 2). The most prevalent concern, with 10 occurrences, was "Considerations for sensor deployment in military environments," which encompasses practical challenges like real-time data collection, battery life, and sensor wear and tear. The second most-cited gap was "Determining a well-defined use case for the sensors or program in a military environment," mentioned 7 times. Following this, two topics were each identified 5 times: understanding the "Effects of measures of repetitive impacts or impact density on concussion risk" and the need for "Developing a sensitive and specific assessment for the defined injury." Several other critical gaps were each raised 4 times, including the "Need for sensor validation," "the effects of intrinsic factors on concussion risk," "data quality and analysis considerations," and the "lack of epidemiological data on Warfighters." The foundational challenge of "Developing a well-defined injury for this application" (e.g., is a concussion defined by a LOC or only a certain percent of performance decrement) was the least mentioned of the recurring themes, with 3 occurrences.

Table 2. Recurring Topics and Themes from Research Gaps Identified by Attendees

Topic or Theme	Number of Occurrences
Considerations for sensor deployment in military environments (e.g., real-time data collection, battery life, sensor wear and tear)	10
Determining a well-defined use case for the sensors or program in a military environment	7
Effects of measures of repetitive impacts or impact density on concussion risk	5
Developing a sensitive and specific assessment for the defined injury	5
Validating a sensor for the application	4
Effects of intrinsic factors on concussion risk	4
Considerations for sensor data quality and data analysis	4
Lack of epidemiological data on Warfighters	4
Developing a well-defined injury for this application (e.g., LOC, percent performance decrement)	3

Alternative Predictive Parameters and Intrinsic Factors

The SME Pre-Meeting Consultation Worksheet also solicited SME input on alternative impact mechanics and intrinsic human factors that may offer superior predictive value for concussions compared to standard kinematic metrics, as summarized in Figures 4 and 5. The SMEs were instructed to provide free-form responses and were not limited by the number of entries, and thus the number of responses exceeds the number of attendees who responded. Impact direction was identified most frequently as the primary alternative parameter for predicting concussion outcomes. Repetitive impact measures (e.g., frequency of impacts, measurements of impact density) were highly prioritized as alternative impact parameters, which aligns with one of the recurring themes identified in the research gaps analysis (Table 2). The SMEs also quantified the intrinsic variables most likely to influence the concussion risk profile of individuals. The most identified intrinsic factors that may act as concussion predictors were sex (14 mentions), age (13 mentions), and prior history of concussion (11 mentions). Fatigue/hydration was the next most mentioned intrinsic factor (7) of interest by the SMEs. The results highlight a strategic need to look beyond single-event kinematic metrics and account for the cumulative and physiological realities of Warfighters.

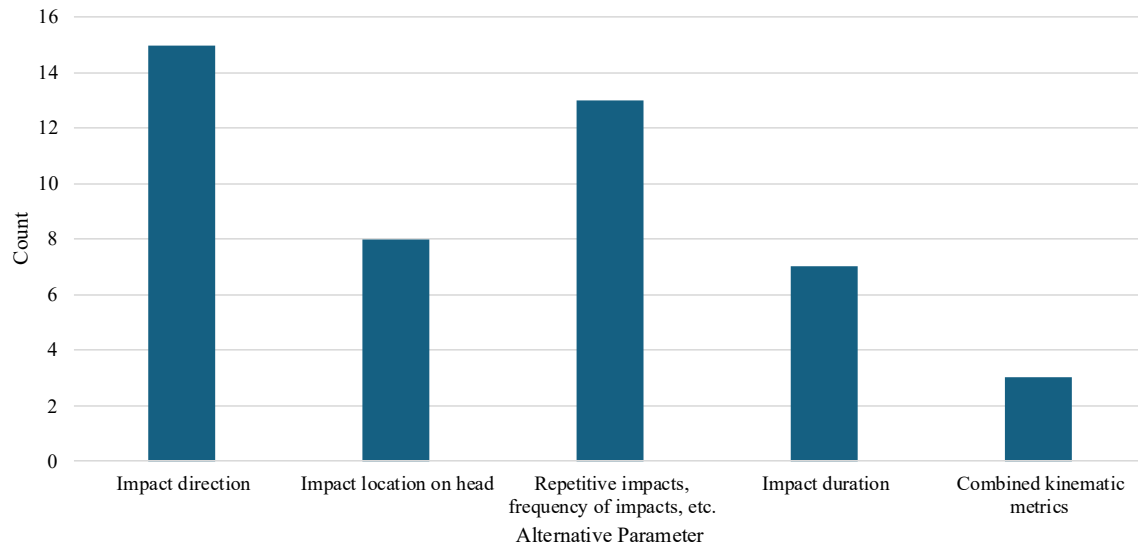


Figure 4. The two most frequently identified parameters for alternative concussion predictors were impact direction with 15 responses (15/49, 31%) and repetitive impacts (frequency of impacts, etc.) with 13 responses (13/49, 27%). Impact location on the head was the next highest with 8 mentions (8/49, 16%).

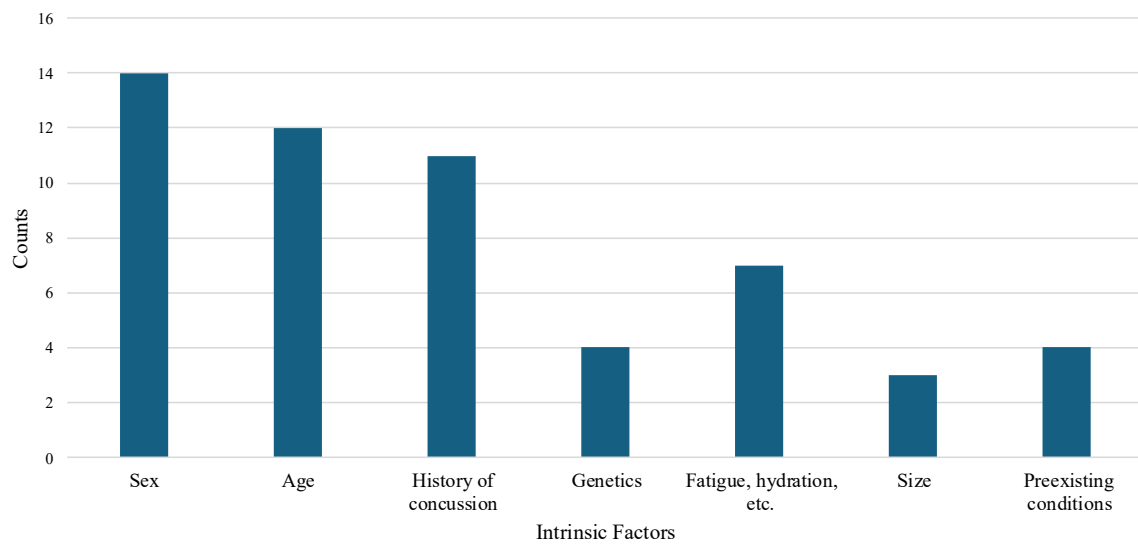


Figure 5. The two most frequently identified intrinsic predictors for concussion were sex (14/61, 23%) and age (12/61, 20%). History of prior concussion was the next highest with 11 mentions (11/61, 18%).

Consensus Statements

The development of the Consensus Statements followed a rigorous multistage refinement process to ensure the final language accurately reflected the complexities of the HAEs in military environments. The meeting leads drafted seven initial Consensus Statements based on SME presentations and SME Pre-Meeting Consultation Worksheet responses. The leads briefed, discussed, and re-worded the statements based on real-time feedback and presented them to the scientific community on Day 2. After the meeting, the leads expanded the list to eight Consensus Statements to address specific gaps. The leads provided the eight Consensus Statements to select attendees for a final edit and review. Responses were received and the Consensus Statements were finalized (Table 3). The leads sent the finalized eight Statements to 25 attendees for a vote (agree, disagree, or decline to respond for each statement). Thirteen attendees (48%) returned the voting form. Results are shown in Figure 6.

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Table 3. Final Version of the Eight Consensus Statements and SME Responses

Consensus Statements	Agree	Disagree	Decline to Respond
Statement 1: The current state of the science does not provide sufficient evidence to support a singular (threshold) value for any HAE metric that can reliably predict the onset of a TBI.	12	1	0
Statement 2: Research on HAEs has largely reported the exposure as magnitudes of linear acceleration, rotational acceleration, and rotational velocity. While these metrics have shown some correlation with head/brain health outcomes, they have not shown success as diagnostic tools. Higher-fidelity sensing technology and more sensitive clinical markers may increase the diagnostic utility of these metrics.	10	1	2
Statement 3: The current state of the science indicates that repetitive head acceleration exposure (RHAЕ) may be an important factor to track as a potential indicator related to Warfighter Brain Health effects.	13	0	0
Statement 4: The current state of the science supports that the currently available wearable HAE sensor technologies may be suitable for identifying military environments with a high risk of HAE and for characterizing HAE kinematics.	11	2	0
Statement 5: Data from wearable sensor technologies may prove useful in monitoring the severity of HAEs in military environments, but the sensors have a degree of error and data quality issues that must be considered. Independent validation of wearable sensors, through both laboratory and field studies that span the range of impact locations, directions, and magnitudes associated with military environments, must be completed to characterize the data quality and degree of error expected in the field.	12	0	1
Statement 6: The current state of the science indicates that coupling wearable sensors to the wearer's head is essential for obtaining accurate HAE measurements. Sensor technologies used to monitor HAEs in military environments should be coupled directly to the head and not to protective headgear, such as helmets.	7	5	1
Statement 7: The current state of the science and currently available wearable HAE sensor technology may support implementation of a sensor-dependent interim HAE threshold as an initial screening tool for identifying Warfighters exposed to high magnitude HAEs for field pre-clinical assessment for TBI. An interim threshold can be adjusted based on data collection from HAE characterization in military environments.	9	2	2
Statement 8: The current state of the science indicates there are several diagnostic tools and assessment methods (i.e., SCAT/SCOAT, blood biomarker assays, pupillary reflex assessment, and vestibular/ocular-motor, etc.) that show promise in screening for pre-clinical indicators of TBI following HAEs. However, these diagnostic tools need to be further advanced for use in military field and training environments.	9	3	1

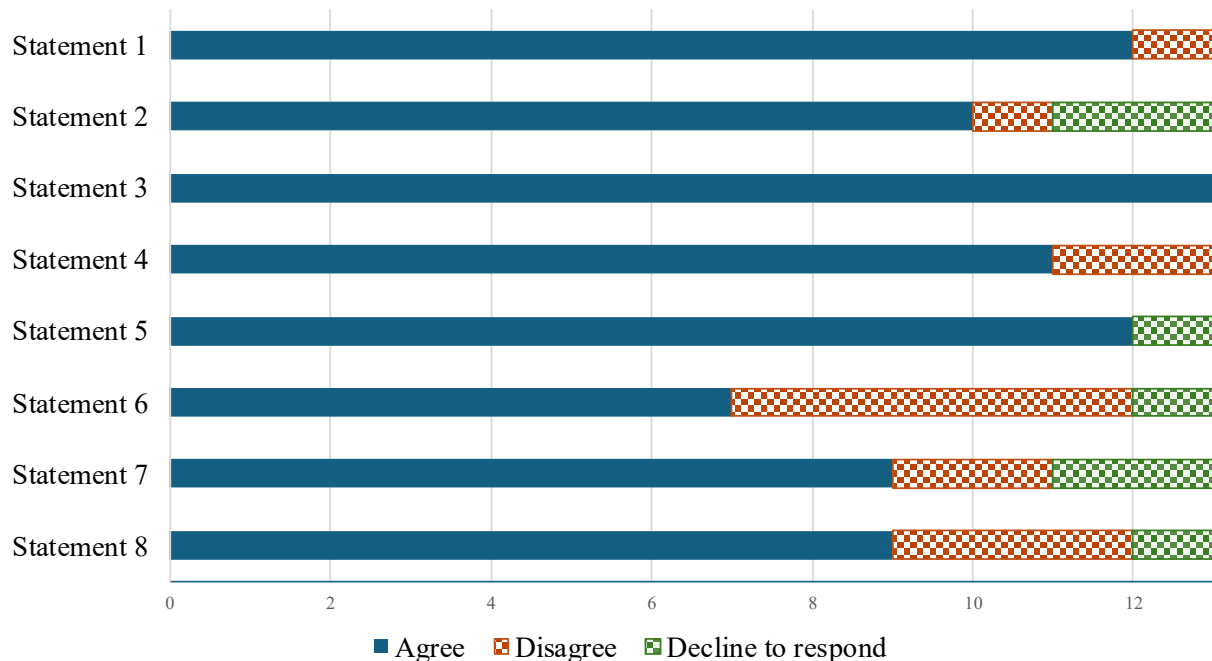


Figure 6. The attendees were asked to vote on the finalized Consensus Statements. The bar for each statement shows the number of respondents that agreed, disagreed, or declined to respond to the statement. The total number of responses for each statement was 13.

Statement 1: The current state of the science does not provide sufficient evidence to support a singular (threshold) value for any HAE metric that can reliably predict the onset of a TBI.

Statement 1 asserts that the current state of science does not support the selection of a single kinematic value to accurately predict the onset of a concussion. This statement received overwhelming consensus, with 92% of respondents in agreement. However, the nuanced justification provided by SMEs highlights critical considerations for how the military should frame risk moving forward. Two of the respondents who agreed with the statement provided justification. One of the justifications discussed the possibility of a high threshold (e.g., 250 G) where a concussion would be reliably predicted; thus, the sensitivity of the threshold needs to be included. It was noted that while an impractically high threshold might reliably predict a concussion, any operationally useful threshold must explicitly account for diagnostic sensitivity. The other respondent who agreed and provided justification stated, “Frankly, it (state of the science) may never support a threshold.” It is argued that science may not support a hard threshold. Instead, the DoW should adopt a probabilistic ‘risk assessment’ model (similar to radar confidence levels). The respondent further stated, “Framing the data this way will help stakeholders better understand the tradeoffs in equipment design, operational planning, and injury assessments.” A single respondent disagreed with the statement and argued that the community can agree on a “lower bound” threshold where “TBI has minimal risk.” This lower bound could serve as the threshold to begin counting cumulative HAEs.

Statement 2: Research on HAEs has largely reported the exposure as magnitudes of linear acceleration, rotational acceleration, and rotational velocity. While these metrics have shown some correlation with head/brain health outcomes, they have not shown success as diagnostic tools. Higher-fidelity sensing technology and more sensitive clinical markers may increase the diagnostic utility of these metrics.

Statement 2 addressed the current limitations of kinematic metrics as reliable predictors of concussion. The statement garnered a solid majority with 77% of respondents in agreement. Despite the high agreement rate, the qualitative feedback revealed a spectrum of opinions regarding whether the current limitation stems from the hardware (sensors), the data analysis methodology, or the fundamental role of kinematics in medical diagnosis. It was suggested that the current sensing technology may not be the limiting factor. Instead, there may be an unknown combination of current available metrics that could reliably predict outcomes. There was support for continued research into translational and rotational accelerations. One respondent noted that well-instrumented large animal models do not exhibit the measurement variance and diagnostic challenges currently observed with human-worn sensors. One respondent disagreed with the statement and argued against using sensor data for medical decision-making, stating, “This feels like the pursuit of using the data for diagnosis. I believe diagnosis should always be made by a clinical expert, not with kinematic data.” One respondent formally declined to vote, citing a lack of expertise in the area. Another declined to respond stating, “I don’t know that the sensing technology is the problem as it was in past years. More sensitive/specific biomarkers may be the key. I also wouldn’t say the sensors have failed, they just haven’t fully been tested yet.”

Statement 3: The current state of the science indicates that RHAE may be an important factor to track as a potential indicator related to Warfighter Brain Health effects.

Statement 3 highlights the unanimous prioritization of understanding and monitoring the long-term effects of repetitive head impacts. This statement achieved 100% agreement among all respondents, underscoring its critical importance to force health protection and mission readiness. While agreement was unanimous, specific technical and linguistic feedback was provided to refine the operational application of this statement. One respondent suggested a distinction between “repetitive” and “repeated,” advocating for the use of “repeated” as the more accurate term for this operational context. Another respondent noted that their agreement was conditional on the tracking mechanism maintaining a high degree of data fidelity (accuracy and reliability) to ensure the cumulative data is actionable.

Statement 4: The current state of the science supports that the currently available wearable HAE sensor technologies may be suitable for identifying military environments with a high risk of HAEs and for characterizing HAE kinematics.

Statement 4 addressed the capability of current sensor technologies to characterize the HAEs across specific populations. The statement received strong support, with 85% of respondents in agreement. Two respondents disagreed and raised critical concerns regarding environmental suitability and hardware accuracy. While the majority agreed, a total of three respondents provided feedback highlighting the logistical and technical limitations of deploying these sensors at the population level. One respondent emphasized that sensor suitability is highly dependent on the specific operational environment. Key logistical factors include the practicality

of using mouthguards in certain settings and whether sensor battery life is sufficient for the duration of monitored activity. One respondent objected to the implication that all currently available technologies are suitable. The respondent clarified that realistically, only a select subset of currently available hardware may meet operational standards. A third respondent argued that currently, epidemiological injury studies remain the superior method for evaluating high-exposure populations in contrast to using wearable sensors as a method for evaluating high-exposure populations. The respondent noted that the current sensor sensitivity and specificity are quite low to reliably discriminate between populations at various risk levels of head injuries.

Statement 5: Data from wearable sensor technologies may prove useful in monitoring the severity of HAEs in military environments, but the sensors have a degree of error and data quality issues that must be considered. Independent validation of wearable sensors, through both laboratory and field studies that span the range of impact locations, directions, and magnitudes associated with military environments, must be completed to characterize the data quality and degree of error expected in the field.

Statement 5 addresses the inherent error rates of wearable sensors and the critical necessity of validating these tools within military environments to accurately characterize data quality issues. The statement achieved near-unanimous support, with 92% of respondents in agreement. While the agreement rate was high, three SMEs provided detailed technical feedback. One respondent recommended leveraging the World Rugby 2.0 validation requirements as a baseline framework to support DoW monitoring in specialized environments, such as ABO. Another respondent suggested reducing this consensus statement, stating, “Validations in field looking at data quality and error are not feasible due to a lack of criterion measure. The sensors themselves should be highly accurate and validated; the error is mostly introduced by noise due to independent movement from the skull.” The third respondent advocated for a proper multi-step validation of head impact sensors: initial laboratory testing on human cadavers, followed by controlled sub-injurious human testing, and finally, field studies linking data to specific health outcomes. This critical caveat highlighted that current field screening suffers from low sensitivity and specificity; overlapping impact data between concussed and non-concussed populations currently generate an unmanageable number of false positives. One respondent declined to vote, citing lack of expertise in sensor validation methodologies.

Statement 6: The current state of the science indicates that coupling wearable sensors to the wearer’s head is essential for obtaining accurate HAE measurements. Sensor technologies used to monitor HAEs in military environments should be coupled directly to the head and not to protective head gear, such as helmets.

Statement 6 asserts the importance of directly coupling a wearable sensor to the head to collect accurate kinematics data. This statement proved to be the most contentious, passing with the narrowest margin of all the Consensus Statements at only 54% agreement. A significant portion of the panel disagreed, sparking a debate between the clinical need for high fidelity data (direct head coupling required) versus the operational reality of troop tolerability and broader surveillance goals (less rigid coupling acceptable). A total of seven respondents provided feedback on their votes, clearly delineating the operational use cases for both direct coupled and less rigidly coupled sensors. One respondent stated that the less rigidly coupled (headgear-based) sensors might be useful as simple impact counters only in highly controlled environments, where

non-activity impacts can be manually filtered. Another respondent acknowledged that while direct coupling is currently required for high accuracy, future technological solutions may obviate the need for direct coupling. Five respondents disagreed. One respondent stated that the choice of sensor is often dictated by cohort tolerability and feasibility rather than strict clinical accuracy. Less rigidly coupled sensors still hold significant utility for broader programmatic goals. For example, one respondent disagreed with Statement 6, stating, “It depends on the use case for the data and what sensor a particular cohort is willing to tolerate wearing. If detailed 6 degree-of-freedom (DOF) head kinematics is needed, then coupling becomes a primary factor. If a sensor is needed to count head impacts or bin severity into high/low categories, then coupling is less strict, and modalities of measuring head impacts, like helmet-mounted sensors, may be a reasonable solution.”

Statement 7: The current state of the science and currently available wearable HAE sensor technology may support implementation of a sensor-dependent interim HAE threshold as an initial screening tool for identifying Warfighters exposed to high magnitude HAEs for field pre-clinical assessment for TBI. An interim threshold can be adjusted based on data collection from HAE characterization in military environments.

Statement 7 addresses the potential for using current sensor designs to establish an interim kinematic threshold. Derived from concussion kinematics data, this threshold would serve as an operational screening tool to identify Warfighters who should be evaluated for an injury. The statement achieved a solid majority, with 69% of respondents in agreement. Some respondents highlighted critical concerns regarding the risk of false positives if these thresholds are applied at the individual level. Two respondents disagreed with Consensus Statement 7. One of the respondents believed the statement was too strong, stating, “One can use this as a population assessment alone, not a screening tool for individuals. If it is used as a screening tool, it will produce numerous false positives at the present stage.” The second respondent suggested that the statement was confusing but overall agreed with the idea that an interim threshold that is refined over time would be appropriate. Two more respondents declined to respond. One elaborated that the validity of any interim threshold is entirely dependent on the specific operational environment in which the data is collected.

Statement 8: The current state of the science indicates there are several diagnostic tools and assessment methods (i.e., SCAT/SCOAT, blood biomarker assays, pupillary reflex assessment, and vestibular/ocular-motor, etc.) that show promise in screening for pre-clinical indicators of TBI following HAEs. However, these diagnostic tools need to be further advanced for use in military field and training environments.

Statement 8 addresses the current state of concussion assessment methods and highlights the critical operational requirements to develop advanced, field-expedient assessment tools tailored for military environments. The statement passed with a majority consensus of 69% in agreement. The qualitative feedback emphasized a need for a precise medical lexicon, a shift in data integration strategies, and a broader scope beyond diagnosed TBI. One respondent noted that “serial assessments of cumulative exposure to RHAEs, even those that don't meet the clinical threshold for a TBI diagnosis, may also be of interest.” Three respondents disagreed with this statement, and all three included additional feedback with their answer. One respondent agreed with the overall sentiment of the statement but stressed the importance of a precise

medical lexicon, recommending that the term “pre-clinical” be replaced with “sub-clinical” to accurately reflect the data. Another respondent suggested removing the final sentence of the statement and argued that the primary capability gap is not necessarily the need to effectively pair diagnostic tests with accurate sensor data. The final comment received from a respondent who disagreed suggested that the statement overstates current capabilities, stating “These are not useful tools at this point on an individual basis. You can vaguely tell population differences, but individual differences are not assessable owing to poor sensitivity and specificity.” One respondent declined to respond and did not provide any further comment.

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Discussion

The primary objective of this expert panel was twofold: 1) to determine if a consensus kinematic threshold exists for identifying concussive events via wearable sensors; and 2) to identify the critical knowledge and technology gaps in concussion monitoring and detection, which hinder the implementation of an HAE surveillance program across the military. Supported by SME briefings, SME Pre-Meeting Consultation Worksheet responses, and the overwhelming consensus on Statements 1 and 2, the meeting leads made the following conclusions:

- A singular, universal kinematic threshold for diagnosing concussion does not currently exist.
- Establishing a purely kinematic-based threshold for brain injury onset via wearable sensors is not currently supported by the available data recognized by the expert panel.

The panel identified several clinical and statistical factors that invalidate the use of a binary (injured versus not injured) kinematic threshold value. A universal value falsely assumes that an impact exceeding a specific limit will uniformly cause injury across a population. This approach disregards complex individual and environmental variables. A concussion is not a singular, tightly defined injury. It encompasses a wide spectrum of physiological conditions, ranging from definite LOC to subjective symptomatic complaints. Even when isolating a specific condition like LOC, the SME data demonstrated a high degree of overlap in the kinematic magnitudes of concussive and non-concussive HAEs. The SMEs discussed that brain injury onset is highly dependent on individual physiological tolerance rather than impact mechanics alone. Individual tolerance is heavily influenced by the frequency of repeated HAEs, as well as intrinsic factors such as age, sex, hydration, fatigue, and prior concussion history that are currently poorly understood by the scientific community.

Implementing any interim kinematic threshold inherently introduces two primary categories of statistical error: false positives and false negatives. In a military surveillance program, both error types introduce significant complications and carry severe programmatic penalties that the command must balance. While false negatives represent a severe risk to individual force health, SMEs emphasized that false positives are the primary threat to any programmatic surveillance viability. The operational disruption of training exercises and the limited availability of field medical personnel make high false positive rates an unacceptable outcome for implementation in any military environment.

To optimize an interim threshold and minimize both error rates, the baseline kinematics experienced by the specific population of interest (e.g., ABO, high speed boats) must first be comprehensively characterized. Establishing this baseline data prior to enforcing actionable thresholds as clinical triggers will be key in working to optimize a surveillance program by reducing the risk of both types of false results. This type of strategy was employed successfully by World Rugby in developing its screening program using instrumented mouthguard data. Similarly, the Army Blast Overpressure (BOP) effort has employed an interim threshold based on a human injury criterion (i.e., eardrum rupture) and is collecting sensor data for BOP to characterize environments and weapons systems and optimize the current threshold.

Presentations from SMEs associated with World Rugby and Rugby Football League demonstrated the operational viability of utilizing wearable sensors strictly as initial screening tools. The World Rugby strategy uses the wearable sensors as a “check-engine” light to indicate when an athlete needs further screening. Aligning with the strong majority agreement on Consensus Statement 7, the panel recommends the DoW adopt this strategy for the WBHI stating that wearable sensors might have an immediate utility to be used in this “check-engine” fashion to direct Soldiers when further evaluation may be needed. One key to the success of the World Rugby strategy was the strict separation of data collection and operational intervention. Athletes wore mouthguard sensors for three years to collect baseline data before any actionable screening threshold was enforced. Additionally, because SME consensus indicated thresholds must be environmental and sensor specific, the SME panel recommends that the military adopt the multiphase approach to a field HAE surveillance program, and the initial phase should involve characterization of unique operational environments prior to implementation. The data collection, storage, and analysis methods employed by World Rugby should be studied and adapted to build a data management structure equipped to process the sensor data to ensure the military is prepared to collect and analyze the sensor data. Initial data collection for HAE characterization should be completed prior to selecting any screening threshold.

Beyond the conclusion that a single impact threshold for concussion is not viable, the panel strongly prioritized research into alternative parameters that influence head/brain health risk, especially repetitive HAEs. Supported by unanimous agreement on Consensus Statement 3, data from athletics cohorts (e.g., CARE Consortium) demonstrated that significant clinical and cognitive changes often occur due to repetitive HAEs, even in the absence of a single acute concussive event. Consequently, the panel indicated that a successful military surveillance program must record both peak kinematic outliers and the longitudinal, cumulative impact dose over the career of a Warfighter.

While the physiological objectives of a surveillance program are clear, the expert panel identified several critical technological barriers that currently hinder a large-scale surveillance effort, as shown in Table 4.

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Table 4. Technological Barriers for a Surveillance Program

Barrier Category	Operational Impact & SME Observations
Measurement Error & Validation	Sensor-introduced errors compound the uncertainty of correlating kinematic data to individualized injury profiles. This is exacerbated by a lack of rigorous sensor validation within specific military environments and exposure levels.
Hardware Limitations	Current commercial technologies suffer from internal clock time drift (which prevents accurate video-to-data synchronization), poor false-positive rejection algorithms, and insufficient battery life to support multi-day field training exercises.
Sensor Coupling (Consensus Statement 6)	This remains the most contested operational topic. While direct head coupling (e.g., mouthguards) provides the highest data fidelity, strict adherence to this requirement limits operational feasibility. For basic use cases like impact counting or severity binning, less rigidly coupled devices (e.g., helmet-mounted sensors) may represent a necessary compromise to ensure high Warfighter compliance and logistical sustainability.

In addition to technological barriers, significant uncertainty remains regarding the current pre-clinical assessment methodologies. As noted during the review of Consensus Statement 8, diagnostic tools like SCAT/SCOAT, VOMS, pupillary light reflex, and blood biomarkers (e.g., UCH-L1, NfL) currently exhibit weak correlations with measurable kinematic metrics. Different populations have shown different symptom profiles associated with injuries broadly categorized as ‘concussions,’ making standardized field evaluation difficult. Furthermore, environmental factors (e.g., outdoor lighting affecting pupillometry) and delayed peak times for certain blood biomarkers complicate effective in-field assessments. Ideally, the state of the science must progress to a point where automated, real-time sensor alerts (e.g., a green/yellow/amber system) are directly fused with advanced pre-clinical assessments to provide field medics and commanders with actionable, objective data for force health protection.

A recurring operational challenge identified throughout the meeting was the lack of standardized nomenclature. Various disciplines frequently use identical terminology to describe fundamentally different clinical or technical concepts, leading to significant friction in cross-domain communication and data interpretation. For instance, the phrase "false positive" caused notable confusion during the presentations; engineers and sensor developers used it to describe a technical error (the sensor recording an impact that never actually occurred), whereas medical personnel and clinicians used it to describe a clinical/physiological outcome (a valid, high-magnitude impact that simply did not result in a diagnosed concussion). Similarly, the definition of "injury" varied drastically depending on the speaker. The SME panel emphasized that prior to a widespread implementation of any military surveillance program, the DoW must formalize, establish, and enforce a unified taxonomy to ensure seamless data integration and accurate communication across all engineering, medical, and operational partners or stakeholders.

The SME consensus indicates that the complex, individualized nature of concussion injuries likely precludes the identification of a universal population threshold for diagnosis. Individual thresholds to HAEs are unique and based on many factors that are currently poorly

understood. While increased data collection from specific populations may eventually yield more sensitive and specific thresholds, they will likely remain probabilistic rather than absolute. There will be a level of risk of false positives or false negatives associated with any binary threshold value that the user will have to understand and accept. The level of risk associated with a false positive or false negative is highly dependent on the operational environment. In athletic environments, a false positive would involve removing an athlete from play (even temporarily), which could affect their preparation and potentially the outcome of the contest, undesirable outcomes that all decrease the trust and confidence in the sensor. In a military application, a false positive sensor reading removes the Warfighter from the training, which could have significant consequences on the Warfighter's military career or result in being removed from participating in a unit operation. On a larger scale, false positives will unnecessarily burden the military health services' resources with 'cases' that require attention to clear and release back to duty. In contrast, every false negative event results in a delayed (or missed) concussion diagnosis and treatment. Ultimately, in military applications, the level of acceptable risk associated with an HAE screening program should be dependent on the specific military operational and training environment.

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Conclusions

Traumatic brain injury and concussion remain critical concerns for the health and readiness of Warfighters. To address this, USAARL convened a Head Impact Brain Health Thresholds Expert Panel to evaluate current head impact science and determine the viability of establishing consensus kinematic/concussion thresholds using wearable sensors. Despite extensive research, the panel concluded that the current state of the science does not support a singular, universal kinematic threshold capable of predicting or diagnosing concussions with high sensitivity and specificity. This limitation stems partially from the highly individualized and complex nature of traumatic brain injuries, which are heavily influenced by cumulative exposure (impact density) and intrinsic human factors such as age, sex, prior injury history, fatigue, and hydration. Sensor errors and uncertainty in clinical measures also contribute to the lack of a consensus threshold. However, the two-day meeting with SMEs revealed that the current state of the science does support using wearable HAE sensors for identifying high-risk military environments and characterizing baseline HAE kinematics. The overall consensus of the SMEs is that a mouthguard-based sensor system is currently the best option for implementation but may not be applicable for all environments.

To advance the development of a surveillance program for HAE, it is suggested that the military adopt a phased approach modeled after the World Rugby strategy. Due to the current deficit of baseline HAE sensor data within military populations, initial efforts must focus on identifying and characterizing specific, high-exposure populations and environments prior to implementing actionable clinical screening systems. The SMEs agreed that devices that couple directly to the head are more favorable for characterizing HAEs in military training and operational environments, as this approach is the most optimal coupling technique for obtaining detailed kinematic information. While SMEs supported mouthguard-based sensors for high-fidelity data, operational realities such as communication impedance and physical durability must be assessed. Furthermore, it is necessary to explore alternative form factors and coupling techniques (e.g., in-ear sensors). Any sensor selected for deployment in military environments must meet operational and validation criteria such as:

- Undergo a two-step validation: in the laboratory with rigorous testing up to and including injurious exposure levels and environmental testing within the exact operational environments and expected range of exposures.
- Be environmentally robust and capable of collecting data continuously for long periods without experiencing time-drift or requiring video verification of sensor events.
- Low maintenance and easy to use without impeding the Warfighter to ensure maximum compliance with a sensor program.

While more concentrated efforts are underway to identify a concussion threshold for wearable sensors, the SMEs recommend that the military allocate resources to investigate the foundational mechanics of head injuries, factors that affect individual tolerances, and emerging diagnostic methods. Hydration, fatigue, and sleep deprivation significantly alter individual injury tolerance. Given the prevalence of those factors in military training and operational environments, research into those factors should be included in the top priorities. Modalities such as the pupillary light reflex and specific blood biomarkers (e.g., UCH-L1) demonstrate operational promise as diagnostic tools for concussion and require accelerated research and development for ruggedized, point-of-injury deployment. The military can create a surveillance

program that will simultaneously preserve the brain health of the Warfighter and ensure military readiness by combining continued research efforts on kinematic concussion thresholds with the implementation of a phased sensor deployment strategy.

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Recommendations

Based on the analysis of the SME Pre-Meeting Consultation Worksheet responses, meeting transcripts, and Consensus Statement response results, the following recommendations were developed for the DoW WBHI:

1. Publish a Standardized Nomenclature Document

Prior to drafting a Capabilities Development Document (CDD) or building any data infrastructure, the Army must publish a standardized nomenclature document to enforce uniform definitions across all branches and research partners. This document must clearly distinguish between exposure (e.g., impact exposure, HAE), clinical deficits (e.g., sub-clinical deficit, physiological change), and specific severity of injury (e.g., LOC, percent performance decrement). A standardized document should categorize terms to ensure clarity between mechanical events and biological outcomes.

2. Draft a CDD

Procurement activities for each Service must draft a Capabilities Development Document (CDD). Development of the CDD should include SMEs and transition partners to establish the operational requirements, resourcing, and minimum performance attributes required for a successful sensor technology integration. The CDD must require and define a multi-step independent sensor validation for all candidate sensor technologies. This independent sensor validation effort should include cadaveric laboratory testing followed by controlled human volunteer field testing. CDD development should be assigned to the Services with Army in the lead to build on current strong work in this area.

3. Implement a Four-Phase HAE Surveillance Program

The DoW should implement a four-phase HAE surveillance program (Table 1) and model it after the highly regarded program established by the World Rugby Federation (Fuller et al., 2017). The process involves

- (1) Target environment identification;
- (2) Data infrastructure development;
- (3) Baseline characterizations of separate targeted environments; and
- (4) Threshold implementation.

4. Prioritize a Multi-Disciplinary Brain Injury Research Strategy

The DoW must prioritize investment toward a multi-disciplinary brain injury research strategy to mitigate the mission impacts of HAEs and the long-term effects on Soldiers. This strategy should integrate kinematic exposure analysis and individual susceptibility through the development of field-deployable diagnostics, advanced clinical management, and a centralized inter-branch data repository. To secure continued funding, all academic and military research partners must share de-identified data into the centralized repository. The sharing of large data sets collected in military environments will allow for

investigation into the effects of alternative impact parameters (e.g., repetitive HAE, impact density) and individual vulnerabilities (e.g., age, sex). This large-scale, real-world military dataset is critical to the research strategy's goal of analyzing alternative exposure parameters (e.g., repetitive HAE, impact density) and vulnerability factors and establishing advanced diagnostic methods and the evidence-based treatments necessary to guarantee long-term Warfighter readiness.

Table 5. Recommended Phased Strategy Approach Adopted from the World Rugby Program

Implementation Phase	Operational Objective & Key Actions
Phase 1: Target Environment Identification	Identify specific training and operational environments with the highest risk of HAE exposure (e.g., airborne, combatives, high speed boats).
Phase 2: Data Infrastructure Development	Study and adapt the data collection, storage, and analysis methodologies employed by World Rugby to military applications. Build a secure, scalable data management architecture explicitly equipped to receive, process, and store a high volume of sensor data before the hardware is fielded.
Phase 3: Baseline Environment Characterizations	Deploy sensors into targeted Phase 1 environments strictly for data collection. No screening thresholds or operational interventions should be applied during this phase.
Phase 4: Threshold Implementation	Use the Phase 3 baseline data to establish initial, environment-specific tiered thresholds. Tier 1 (lower) will be a behavioral threshold that prompts immediate technique self-correction and tactical behavior modification. Tier 2 (higher) will be a medical screening threshold that serves as the official threshold for formal medical screening and clinical evaluations. Continuously refine these thresholds as military-specific head impact research matures.

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Appendix A. Acronyms and Nomenclature

Table A1. Acronyms

Acronym	Definitions
ACH	Advanced Combat Helmet
ABO	Airborne Operations
AI	Artificial Intelligence
ANAM	Automated Neuropsychological Assessment Metrics
ATD	Anthropomorphic Test Device
AUPRC	Area Under Precision-Recall Curve
BESS	Balance Error Score System
CARE	Concussion Assessment, Research and Education
CDD	Capabilities Development Document
COACH	Communities Aligned to Reduce Concussion and Head Impact Exposure
CT	Computed Tomography
DHP	Defense Health Program
DoD	Department of Defense
DoDI	Department of Defense Instruction
DoW	Department of War
EXORD	Executive Order
G	Acceleration Due to the Gravity of Earth
GFAP	Glial Fibrillary Acidic Protein
HAE	Head Acceleration Event
HIA	Head Injury Assessment
HIBHTEP	Head Impact Brain Health Thresholds Expert Panel
HIC	Head Injury Criterion
HIE	Head Impact Exposure
HITS	Head Impact Telemetry System
ImPACT	Immediate Post-Concussion Assessment and Cognitive Test
J	Joule
LOC	Loss of Consciousness
LOE	Line of Effort
LTC	Lieutenant Colonel
MACE	Military Acute Concussion Evaluation
MMA	Mixed Martial Arts
MOS	Military Occupational Specialties
NCAA	National Collegiate Athletic Association
NFL	National Football League
NfL	Neurofilament light
PLA	Peak Linear Acceleration

Acronym	Definitions
PPE	Personal Protective Equipment
PRV	Peak Rotational Velocity
PRA	Peak Rotational Acceleration
psi	Pound Per Square Inch
rad/s	Radians/Second
rad/s ²	Radians/Second Squared
RHAE	Repetitive Head Acceleration Event
RHI	Repetitive Head Impact
ROC	Receiver Operating Characteristic
SAC	Standardized Assessment of Concussion
SCAT5	Sport Concussion Assessment Tool 5 th Edition
SCOAT	Sport Concussion Office Assessment Tool
SME	Subject Matter Expert
SOCOM	Special Operations Command
SWCC	Special Warfare Combatant-Craft Crewmen
TBI	Traumatic Brain Injury
TBICoE	TBI Center of Excellence
UCH-L1	Ubiquitin Carboxy-Terminal Hydrolase L1
VOMS	Vestibular/Ocular Motor Screening
WBHI	Warfighter Brain Health Initiative
WBHP	Warfighter Brain Health Program
USAARL	U.S. Army Aeromedical Research Laboratory

One of the challenges identified throughout the meeting was a lack of standardized nomenclature. Prior to a widespread implementation of any military surveillance program, the DoW must formalize, establish, and enforce a unified taxonomy to ensure seamless data integration and accurate communication across all engineering, medical, and operational partners or stakeholders. Table A2 provides a list of the terms that arose throughout the meeting that generated confusion and suggested definitions to include in a standardized nomenclature document (Recommendation 3).

Table A2. Commonly Used Terms and Definitions

Term	Definitions
Concussion	The clinical DoW diagnosis requires two conditions to be met: 1) An injury event must have occurred 2) The individual must have experienced normal structural neuroimaging by head computed tomography (CT) or magnetic resonance imaging (MRI) and one of the following: a. Alteration of consciousness lasting less than 24 hours b. LOC, if any, lasting less than 30 minutes c. Memory loss after the event for events immediately surrounding the injury that lasts less than 24 hours
Technical False Positive	The sensor triggers and records when no actual HAE occurs
Screening False Positive	A sensor indicates that an actual HAE occurred that requires a medical evaluation, but the medical evaluation does not find an injury
Screening	Operational triage event
Diagnosis	A formal medical determination
Sub-Clinical Effect	An effect that does not reach the level of clinical injury diagnosis
Pre-Clinical Assessments	An assessment performed to screen an individual before clinical evaluation is recommended
Human Tolerance	A human physiological property that determines when an injury, or subject biological variation, will occur
Sensor Threshold	A measurable kinematic limit paired with a chosen metric that may be used with a sensor to detect events of interest

Appendix B. Meeting Attendees

Table B1. List of All Attendees and Their Roles

Name	Role	Organization	Location
Dr. Kristy Arbogast	SME/Presenter	Children’s Hospital of Philadelphia	Philadelphia, PA
Dr. Adam Bartsch	SME/Presenter	Prevent Biometrics, Inc	Edina, MN
Dr. Dale Bass	SME/Presenter	Wayne State University	Detroit, MI
Mr. Fred Brozowski	Lead	USAARL	Fort Rucker, AL
Dr. Jaclyn Caccese	SME/Presenter	The Ohio State University	Columbus, OH
Dr. David Camarillo	SME	Stanford University	Stanford, CA
Dr. Carol Chancey	Lead	USAARL	Fort Rucker, AL
Dr. John Crowley	Lead	USAARL	Fort Rucker, AL
Dr. Thomas DeGraba	SME	Walter Reed National Military Medical Center	Bethesda, MD
LTC Brad Dengler	SME/Presenter	Uniformed Services University of the Health Sciences	Bethesda, MD
Dr. Eanna Falvey	SME/Presenter	World Rugby Research Unit	Dublin, Ireland
Dr. Lee Gabler	SME/Presenter	Biocore LLC	Charlottesville, VA
Dr. Allison Gleason	Lead/Presenter	USAARL	Fort Rucker, AL
Dr. Blake Johnson	Lead/Presenter	USAARL	Fort Rucker, AL
Dr. Ben Jones	SME/Presenter	Leeds Beckett University	Leeds, UK
Dr. Ian Kloo	SME	Biocore LLC	Charlottesville, VA
Dr. Enora Le Flao	SME/Presenter	The Ohio State University	Columbus, OH
Ms. Kathy Lee	SME/Presenter	Department of War Warfighter Brain Health	Falls Church, VA
LTC Matthew LoPresti	SME	Walter Reed Army Institute of Research	Silver Spring, MD
Mr. Zaryan Masood	Invited Guest	University of British Columbia	Vancouver, Canada
Mr. Joe McEntire	Lead	USAARL	Fort Rucker, AL
Dr. Declan Patton	SME	Children’s Hospital of Philadelphia	Philadelphia, PA
Dr. Thuvan Piehler	Sponsor Rep.	USA Medical Research & Development Command	Fort Detrick, MD
Dr. James Phillips	Invited Guest	USA Medical Research & Development Command	Fort Detrick, MD
Dr. Steven Porter	Presenter	USA Warfighter Brain Health	Falls Church, VA
Dr. Kristen Reynier	SME	Biocore LLC	Charlottesville, VA
Dr. Tyler Rooks	SME	Medical College of Wisconsin	Milwaukee, WI
Dr. Gunter Siegmund	SME/Presenter	MEA Forensic Engineers & Scientists Inc.	Laguna Hills, CA
Dr. Stephanie Sloley	SME	Traumatic Brain Injury Center of Excellence	Silver Spring, MD
Dr. Brian Stemper	SME/Presenter	Medical College of Wisconsin	Milwaukee, WI
Dr. James Tooby	SME/Presenter	Leeds Becket University	Leeds, UK
Ms. Jessica Towns	SME	Stanford University	Stanford, CA
Dr. Ross Tucker	SME/Presenter	World Rugby Research Unit	Cape Town, South Africa
Dr. Jill Urban	SME/Presenter	Wake Forest School of Medicine	Winston-Salem, NC
Dr. Lyndia Wu	SME/Presenter	University of British Columbia	Vancouver, Canada

Appendix C. Meeting Agenda

Table C1. Agenda for Day 1 of Head Impact Brain Health Thresholds Expert Panel Meeting

Time (EST)	Description
0800-0805	Welcome
0805-0830	Introductions and Day 1 Overview with Consultation Worksheet
0830-0845	DoW Warfighter Brain Health Initiative
0845-0900	Army Warfighter Brain Health Program
0900-0915	USAARL Literature Review with Meta-Analysis
0915-0930	USAARL Wearable Sensor Work
0930-0945	Break
0945-1010	Biocore
1010-1035	University of British Columbia
1035-1100	World Rugby
1100-1125	Leeds Beckett University
1145-1230	Lunch
1230-1255	Stanford University
1255-1320	Medical College of Wisconsin
1320-1345	The Ohio State University
1345-1410	Children's Hospital of Philadelphia
1410-1420	Break
1420-1445	Wake Forest University
1445-1510	Prevent Biometrics
1510-1535	MEA Forensics
1535-1600	Wayne State University

Table C2. Agenda for Day 2 of Head Impact Brain Health Thresholds Expert Panel Meeting

Time (EST)	Description
0800-0805	Day 2 Overview
0805-0830	Army Airborne Population
0830-0845	Presentation of Day 1 Worksheet Results
0845-1015	Discussion
1015-1030	Break
1030-1200	Discussion
1200-1300	Lunch
1300-1420	Discussion
1420-1540	Discussion
1540-1550	Break
1550-1630	Wrap up
1630	Meeting Dismissed

Appendix D. SME Pre-Meeting Consultation Worksheet

Name: _____

Affiliation: _____

Surveillance Thresholds

What **translational acceleration** threshold do you recommend for Warfighter head/brain health (concussive) surveillance? _____

What is your confidence level in this threshold?

1	2	3	4	5
Very Low	Low	Medium	High	Very High

What **rotational acceleration** threshold do you recommend for Warfighter head/brain health (concussive) surveillance? _____

What is your confidence level in this threshold?

1	2	3	4	5
Very Low	Low	Medium	High	Very High

Which impact exposure metric do you believe is most associated with concussion risk?

(Please Circle) **Translational** or **Rotational**

Factors

What alternative parameters of an impact influence head/brain health risk? (such as: impact direction, magnitude, location on the head, repetitive/frequency, etc.)

What factors do you believe also influence head/brain health risk and/or tolerance levels?
(factors such as: sex, age, fatigue, hydration, etc.)

Knowledge gaps

List three knowledge/technology gaps that need to be addressed to establish a military blunt impact concussive surveillance program.

1.

2.

3.

Diagnostics

What assessment method(s) do you have the greatest confidence in to suggest the presence of a concussion?

Other thoughts & concerns

Appendix E. SME Pre-Meeting Consultation Worksheet Responses

Table E1. Anonymous SME Pre-Meeting Consultation Worksheet Responses

Attendee	Translational Threshold (G)	Confidence Low – High (1 – 5)	Rotational Threshold (rad/s ²)	Confidence Low – High (1 – 5)	Translational/ Rotational	Alternative Parameters	Additional Factors	Gaps	Diagnostics	Observations
1	Our data show wide range of TAs associated with Sports Concussion. HIE plays a role.	5	Our data show wide range of TAs associated with Sports Concussion . HIE plays a role.	5	Rotational	Impact direct was shown by Gennarelli to influence injury risk and severity. HIE is a factor in producing concussion symptoms and likely reducing concussion tolerance.		How does HIE reduce tolerance for concussion from a quantitative standpoint? How does history of concussion and HIE reduce tolerance for concussion? How can we monitor HIE in real time? Are there any reliable sensors for daily use?	Our biomechanical analyses have shown promise in cognitive assessments such as SAC and ImPACT, and concussion symptom reporting such as SCAT. Our preclinical work also consistently identified emotional changes (e.g., aggression) following concussion and HIE. Emotional assessments have not been examined as much in humans but this might be an important issue for military personnel.	*No response recorded*
2	Not sure there is a single threshold	5	Not sure there is a single threshold	5	Rotational	Impact direction, frequency/density of impacts	Sex, age, prior concussion history, genetics, pre-existing comorbidities such as anxiety and depression	Consistent, multi-faceted assessment of injury (thinking beyond cognitive health, including visio-vestibular, autonomic nervous system assessment),	See SCAT and SCOAT. Include visio-vestibular assessment, pupillometry assessment	*No response recorded*

Attendee	Translational Threshold (G)	Confidence Low – High (1 – 5)	Rotational Threshold (rad/s ²)	Confidence Low – High (1 – 5)	Translational/ Rotational	Alternative Parameters	Additional Factors	Gaps	Diagnostics	Observations
								biofluid biomarkers of injury and monitoring repetitive head impact, frictionless measurement of head impact exposure		
3	100	3	Harder to say	5	Translational	Impact direction (e.g., coronal, sagittal, axial), impact magnitude	Sex, as females are disproportionately affected by concussion and axonal injury	Impact monitoring using iMG or some technology, with appropriate triggering thresholds, Epidemiologic-al information on high-risk scenarios/training methods	Reported signs and symptoms, or visual signs of concussion (i.e., not kinematics- or strain-based), given kinematics/strain can vary based on filtering methods, individual tolerance, etc.	Though I circled translational metrics being most associated with concussion risk, I believe both translation and rotation require equal attention.
4	Easy to measure, indirectly related to brain injury	2	Hard to measure, more closely related to brain injury	2	Rotational	Brain strain (or some brain-based metric), which captures many of the other factors	This is not my area, I suspect all of the factors you list are potentially relevant	Reliable/consistent diagnostic methods and metrics, field validity of wearable sensors in all impact directions and conditions	Diagnostics is one of the main challenges for generating useful injury risk functions. Current subjective diagnostic methods do not seem to be reliable (based on published studies). Concussion covers a wide range of injury severity. Consider grading concussion injury. Some kind of objective	I am concerned that we do not have clinical or wearable-sensor data of sufficient quality to generate reliable injury risk functions. Poor clinical data and sensor data with large errors bias the injury risk functions and alter the confidence bounds of the risk functions in ways that make them unreliable. Another concern is that injury risk

Attendee	Translational Threshold (G)	Confidence Low – High (1 – 5)	Rotational Threshold (rad/s ²)	Confidence Low – High (1 – 5)	Translational/ Rotational	Alternative Parameters	Additional Factors	Gaps	Diagnostics	Observations
									diagnostic test would be more reliable and could be more readily validated and the error rate could be more readily quantified. Is there work being done on biomarkers for concussive brain injury?	functions are population-based functions and applying a risk function to an individual is difficult. The distribution inherent in a risk function will generate large false positives and false negatives.
5	Unsure	1	Unsure	1	Rotational	Rotational velocity, impact direction, impulse duration, impact frequency, impact power/energy	Sex, age, concussion history, impact history, fatigue, substance use, sleep	Military blunt impact data, Definition / quantification of concussive injury, Reliable sensor technology	For now we still need to rely on patient symptoms for diagnosis, there is not yet sufficient evidence for an objective and quantitative method. That being said, we probably should start looking into subtyping of injury, and separating / grouping injuries by subtype.	1. I am not sure we are really ready to answer the threshold questions on the first page. I don't think there is sufficient high quality research evidence yet. 2. Data quality is critical for any application of head impact sensor data and needs to be quantified and improved. 3. More data sharing and collaboration is needed given very limited injury data, especially outcome assessment data that go beyond clinical diagnosis and standard assessments.

Attendee	Translational Threshold (G)	Confidence Low – High (1 – 5)	Rotational Threshold (rad/s ²)	Confidence Low – High (1 – 5)	Translational/ Rotational	Alternative Parameters	Additional Factors	Gaps	Diagnostics	Observations
6	?	1	?	1	Rotational	all of the above; Location on the head will translate to impact direction, pulse duration	All of the above + history of concussion + cognitive reserve + pre-existing conditions (migraines, attention disorders, etc.)	Capacity to measure 24/7 (compared to current sensors that record for a few hours), peak accelerations aren't enough	I think the person's report of how they're feeling is still the most relevant, although very biased and imperfect.	I don't think searching for one global threshold is the way to go. Personalized thresholds are more likely. Also accounting for previous exposure rather than the one big impact.
7	10	3		1	Rotational	Repetitive/frequency, impact direction, location on the head, impact duration	Age, sex, cumulative history	False positives, coupling to skull, sensor wear and tear	Symptoms, clinical exam	*No response recorded*
8	75 (men), 65 (women)	3	4500	5	Rotational	Intrinsic- sex, concussion history, number of cumulative pre-impacts, fatigue; extrinsic - direction, duration (area under ROC) of impact, location of impact, frequency	Sex, age, concussion history, fatigue	Evaluate better objective markers, understand role of sub-clinical impacts	Still a clinical diagnosis - recommend protocol of series of evaluations; Biomarkers - promising serum biomarkers	*No response recorded*
9	As low as possible based on ability to manage clinical screening workload	5	As low as possible based on ability to manage clinical screening workload	5	Rotational	In addition to those listed: impact/pulse duration	In addition to those listed: clinical history of previous concussions; age/sex/head size	Establishing criterion assessment (e.g., physiological measures of brain injury), the frequency/magnitude of head impacts experienced by military personnel; relationship between clinical,	Clinical diagnosis by a medical doctor; Multimodal assessment (clinical assessment, biomarkers and biomechanical data)	1. We believe that BOTH linear and angular components are important to consider for concussion risk 2. We do not believe that current clinical data are enough to support threshold values for identifying concussion, and the sensor should be used as a tool

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								physiological and biomechanical measures		to identify individuals who can be screened clinically. 3. A pragmatic approach to screening as many individuals that have either higher magnitude head impacts or higher accumulation of lower magnitude HAEs may be the best approach given the lack of clinical evidence/ diagnostic capability. 4. This would entail setting a threshold which can be dealt with. In sports (e.g., rugby) the rates of concussion increase with the rates of clinical screening, therefore until all individuals are screened, regardless of magnitude, it remains a known-unknown how many people are concussed.
10	no recommendation, would need to be a	3	No recommendation, would need	3	Rotational	Impact mechanism, direction of impact,	Sex, age, density/ frequency of exposure	Continuous/ hybrid data collection for longer duration	SCAT6, showing promise - pupillometry	Engaging the end users (the person wearing the mouthpiece,

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	screening threshold		to be a screening threshold			density/frequency of exposure prior to the event	prior to the event, individual tolerance	data capture, machine learning techniques to facilitate true positive identification, film review req'd, acceptability of the device in a field setting		those making decisions, etc) is incredibly important in the implementation of instrumented technology, surveillance approaches, and any change measures. Understand what the motivation is - why is this data important to them, why is concussion identification, prevention, etc., a priority for them. What other data can compliment the head acceleration data.
11	No single threshold	5	No single threshold	5	Rotational	Magnitude, duration, an direction of linear and angular head acceleration of a head impact are primary factors. Secondary factors that may influence concussion tolerance include timing and severity of prior impacts"	We categorize these factors as intrinsic (player-related) factors. In addition to the above, concussion history, refractory (recovery) periods, anatomy and physiology.	Impact data quality, missing impact data (gaps), consistency in application of clinical judgement in concussion diagnosis	*No response recorded*	There is no head acceleration threshold for concussion for the population. A practical approach may be to start with both a linear and angular threshold that balances detection (sensitivity/ recall) and false positives (precision). However, having high quality head impact data on Warfighters would be needed

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										to make decisions on the initial thresholds.
12	No single translation acceleration exists for population level thresholds.	5	No single rotational acceleration exists for population level thresholds.	5	Rotational	Combination of both linear and angular kinematics, including magnitude, direction, and duration of loading.	Sex and history of concussion may affect brain injury tolerance.	Effect of individual intrinsic factors on injury thresholds, frictionless wearable sensor technology (e.g., powerful battery life, non-invasive, simple syncing and downloading), detailed contextual information fused with 6DOF head kinematic data collection	Comparison of cognitive metrics to individual baselines. While biomarkers are continuing to advance, more mild traumatic brain injury research with these advancing biomarkers is needed before they are ready for widespread release.	*No response recorded*
13	None, depends on the purpose for the surveillance	1	None, depends on the purpose for the surveillance	1	Translational	Including these things, but context matters. What are we trying to do with the surveillance program?	All of these, including size, previous health history, psychological state. But, context matters here too. Cognitive state and mission are very important here.	An injury risk assessment for whatever TBI is of interest in the program, some well-validated way to measure individual injury risk, some sensitive/specific method with tight confidence interval to determine injury risk.	Depends on context. Most confidence is in unconsciousness, but that is not particularly insightful.	Every assessment has tradeoffs. While we potentially move into monitoring, we have a major risk in using inadequate risk assessments with inadequate tools with open ended goals. Hopefully, these crucial issues will be addressed in some meaningful way. This will require research to address the

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										issues that are desirable here.
14	40 (ABO), 75 (Athletics)	5	Don't use PAA, Use energy - 20J (ABO), 40J (Athletics)	5	Translational	Location - ABO is 90% back of head. Athletics is 0% top of head and roughly 75% to side of head. Single impacts >40 g/20 J are the issue across all activities SWCC is the only area where cumulative impact is an issue	Getting hit once, really hard, and 'sucking it up' without any tx/dx/help.	Getting the data to the medical/health record	I think blood/pupils are showing clear signal MACE/ANAM etc. are showing random outputs	*No response recorded*
15	*No response recorded*	*No response recorded*	*No response recorded*	*No response recorded*	Translational	*No response recorded*	would refer to areas borrowed from TBI that we know have an influence on brain health risk. There are known as modifiers and outlined in a recent NIH study. Can send the table.	First have to decide if intent is a surveillance program which would mean that we'd be trying to establish occupational exposure limits vice clinical thresholds, easier thing to do is to start with clinical thresholds since we are measuring a brain health effect; then move back to before symptoms are reported to get an exposure limit, need clear indications of head impact exposures	based on DoW definition of concussion: have injury event and a "sign" of an alteration of consciousness which is usually followed temporally by symptoms. I can answer also with some objective assessment methods that I think will suggest the greatest chance of finding a brain health effect which would be in cognition, eye tracking, balance/ vestibular... all which seem to be affected by linear acceleration forces to the brain	I think we can always refine the sensors but we do have to be at a place where we say "pencils down" and start using them in a more scalable way. We can argue for the next decade about how reliable and valid the sensors are (and while we do that, multiple exposures are occurring). Take the 80% solution now

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								mapped to brain health effects which is a knowledge gap		
16	Not able to recommend at this time	1	Not able to recommend at this time	1	Translational	Repetitive head impacts, and specifically the influence of the frequency of these impacts should be considered. It is likely that, even if the magnitude of the head impacts are low, sustaining a high frequency with shorter intervals between impacts can play a role in overall symptom burden and function alternations.	History of impact exposure and TBI history will likely play a role in susceptibility to functional alteration following head impacts. For military service members, history of hazardous brain health exposures should also be considered when assessing the outcomes related to head impact exposure.	The influence of brain health history (e.g., TBI history, exposures) on response to head impact exposure, Reliable recording of head impacts that can be mapped to functional outcomes and brain health changes, The intersection between functional/perf ormance changes associated with cumulative head impact exposure and clinically diagnosable injury.	Examination of specific brain health domains such as neurocognitive function, biological correlates, and neurosensory function are promising assessment targets for objective indicators of functional changes related to concussions. Variability across function are promising assessment targets for objective indicators of functional changes related to concussions. Variability across function are promising assessment targets for objective indicators of functional changes related to concussions. Variability across	*No response recorded*

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17	Subject Specific	1	Subject Specific	1	Rotational	Kinematics: magnitude, direction, location, repetitive impacts Summary: HIC, DAMAGE, HARM Tissue-level: axonal strain, maximum principal strain, strain rate, Von Mises stress	Sex, age, maturation, genetic predisposition, concussion history, protective equipment, fatigue, hydration, alcohol and drug (performance enhancing/recreational/medication) use	Knowledge: How and why repetitive impacts affect tolerance, knowledge: how and why tolerance varies across individuals, technology: continuous recording rather than linear acceleration-based trigger	Clinical history and physical exam, SCAT5, functional near-infrared spectroscopy during complex tasks (e.g., King-Devick Test, Complex Tandem Gait, etc.), pupillometry, eye-tracking, biomarkers (i.e., blood, urine, saliva)	*No response recorded*
18	60-70 g	3	4000 rad/s ²	3	Rotational	Impact direction and relevant location versus head CG (i.e., offset impacts influencing degree of rotation), repetitive/ accumulation of exposure which may "erode" on individual tolerances	*No response recorded*	Define the military application(s) for use. Different applications may require different thresholds, Determine the importance of cumulative/ repetitive load in the military context. Does it happen?, Identify a sensor, or sensors, that are applicable for military context that may not align with athletics	Clinical diagnosis is current best dual task paradigms (i.e., reciting alphabet backwards while walking on a straight line) Eye-tracking and/or PLR measures, imaging and blood/saliva based biomarkers.	The two biggest issues with implementation for the military are managing the cybersecurity aspects of sensors (how to connect to a DOW/military network to enable transfer of data to relevant parties) and determining which sensor will work for which environment (operational? training? type of training?) and ensuring the different sensors report similar exposures given an impact.

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19	100	3	5000	5	Translational	Impact direction, impact history, contact pressure/location ?	Sex, age, genetics	False positive rate in your environment (i.e. distribution of injury/non-injury accels), stakeholder tolerances to false positives and false negatives, sensors that require less user participation (e.g. in-helmet sensors with AI)	Blood biomarkers have best potential, but unproven, regular symptom surveillance	I do not agree with the described prescription of how to do biostatistics “correctly,” need to pool all of our data, it’s difficult for us to advise on any thresholds without understanding specific Army need, even if wearable surveillance isn’t clinically practical, data can be used for helmet tests, angular velocity is better than angular accel because of time duration in athletes

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