Appendix 1: Participants

CHAMP leadership group:

- Kristy Arbogast, PhD – Children's Hospital of Philadelphia (CHOP) and University of Pennsylvania
- Jeff Crandall, PhD – Biocore, LLC
- James Funk, PhD – Biocore LLC
- Gary Solomon, PhD – National Football League Player Health and Safety

Workgroup leaders:

- Transparency and Disclosure
    - Kristy Arbogast, PhD – CHOP/University of Pennsylvania
    - Jaclyn Caccese, PhD – Ohio State University
- Study Design and Statistical Analysis in Studies of Head Acceleration Measurement
    - Steve Rowson, PhD – Virginia Tech
- Laboratory Validation of Wearable Head Kinematic Devices
    - Lyndia Wu, PhD – University of British Columbia
    - Lee Gabler, PhD - Biocore, LLC
- On-Field Validation and Use of Wearable Head Kinematic Devices
    - Jillian Urban, PhD – Wake Forest University
    - Calvin Kuo, PhD - University of British Columbia
    - Initial contributions by Nate Dau, PhD – formerly of Biocore, LLC
- Video Analysis of Head Acceleration Events

    - William Neale, MArch – J.S. Held

- Physical Reconstruction of Head Acceleration Events
    - James Funk, PhD – Biocore, LLC
- Computational Modeling of Head Acceleration Events
    - Joel Stitzel, PhD – Wake Forest University
    - Songbai Ji, PhD – Worcester Polytechnic Institute

Attendees – March 2022 CHAMP conference (in-person and virtual):

Last name	**First name**	**Affiliation**
Arbogast	Kristy	Children's Hospital of Philadelphia/University of Pennsylvania
Arrington	Dusty	Adamson Engineering, LLC
Bartsch	Adam	Prevent Biometrics
Begonia	Mark	Virginia Tech
Bergmann	Jeroen	University of Oxford
Broglio	Steven	University of Michigan
Buckley	Thomas	University of Delaware
Bussey	Melanie	University of Otago
Caccese	Jaclyn	Ohio State University
Chu	Jeff	Simbex
Crandall	Jeff	Biocore LLC
Esquivel	Amanda	University of Michigan - Dearborn

Falvey	Eanna	World Rugby
Funk	James	Biocore LLC
Gabler	Lee	Biocore LLC
Ghajari	Mazdak	Imperial College London
Goodger	Drew	Prevent Biometrics
Greenwald	Richard	Simbex
Harezlak	Jaroslaw	Indiana University
Harmon	Kimberly	University of Washington
Hawes	Damien	HITIQ
Heiderscheit	Bryan	University of Wisconsin
Huber	Colin	University of Pennsylvania
Ide	Thad	Riddell Sports
Ji	Songbai	Worcester Polytechnic Institute
Jones	Ben	Leeds Beckett University
Kaminski	Thomas	University of Delaware
Kelshaw	Patricia	University of New Hampshire
Kleiven	Svein	KTH Royal Institute of Technology
Kraft	Reuben	Penn State University
Kuo	Calvin	University of British Columbia
Laudenbach	Tom	HITIQ
Luck	Jason	Duke University

Lynall	Rob	University of Georgia
Makdissi	Michael	Australian Football League
Mao	Haojie	Western University
Mayer*	Thom	NFL Players Association
McIntosh	Andrew	McIntosh Consultancy & Research
Moran	Ryan	University of Alabama
Neale	William	JS Held
Panzer	Matthew	University of Virginia
Patton	Declan	Children's Hospital of Philadelphia
Reynier	Kristen	University of Virginia
Rooks	Tyler	U.S. Army Aeromedical Research Laboratory
Rowson	Steve	Virginia Tech
Schmidt	Julianne	University of Georgia
Shogren	Mike	Prevent Biometrics
Siegmund	Gunter	MEA Forensic Engineers & Scientists
Sills*	Allen	NFL
Smith	Terry	Galeatus LLC
Stitzel	Joel	Wake Forest University
Tierney	Gregory	Ulster University
Urban	Jillian	Wake Forest University
Willinger	Remy	University of Strasbourg

Willmott	Catherine	Australian Football League
Withnall	Chris	Biokinetics and Associates Ltd.
Wu	Lyndia	University of British Columbia

*observers only

Appendix 2: Voting results for each summary statement

Summary statements	Number voting	Voting results
1. Laboratory Validation of Wearable Head Kinematic Devices		
1.1. A wearable device that measures head kinematics must be independently validated for its intended application through controlled laboratory testing, and the laboratory should simulate the real-world loading environment in which the device will be used.*	33	100% support
1.2. Laboratory testing of wearable devices should use a validated biofidelic anthropomorphic test device (ATD) headform combined with a repeatable and reproducible test setup that enables testing across multiple levels of magnitude, duration and direction that simulate on-field linear and angular head kinematics relevant to the setting of study.*	35	97% support
1.3. Reference sensor setup and validation metric selection depend on the intended application of the wearable device, which can vary on four main levels: impact counting, impact magnitude, impact direction, and the	33	97% support

time-history measurement of six-degree-of-freedom (6DOF) head kinematics.		
1.4. If a wearable device is designed to measure and report metrics derived from head kinematics, ground truth measurements must be collected with an ATD-embedded laboratory-grade reference sensor system. If a wearable device is designed to count impacts only, a reduced reference setup enabling verification of impact events may be applied.	35	86% support
1.5. Processed data from the wearable device must be compared with ground truth measurements using validation metrics and statistical methods that enable complete, unbiased, and application-relevant assessment of accuracy and uncertainty.	35	83% support
2. On-Field Validation and Use of Wearable Head Kinematic Devices		
2.1. A head acceleration event (HAE) is defined as an event/incident that gives rise to an acceleration response of the head caused by an external short-duration collision force applied directly to the head or indirectly via the body in sport, recreational, military, or other activities of interest. Wearable devices are often both kinematically	32	91% support

and field validated for direct HAEs and not indirect HAEs due to the limitation of reproducing indirect HAEs in the lab and identifying indirect HAEs on the field, respectively.		
2.2. Kinematic data must be filtered to remove potential false positive recordings and verify valid HAEs. Data windowing, video verification, and pre- and post-processing techniques aid in data validation. Individual verification of HAEs is challenging, and time consuming but improper data validation may lead to errors in estimation of exposure.*	31	100% support
2.3. Video review serves as an independent verification of HAEs for a given application (e.g. device development, sport setting) and provides contextual information for HAEs. However, video should not be considered ground truth as the confidence in video review depends on video quality and a robust labelling process. Guided and blinded video review of head acceleration events are useful components to device performance in an on-field environment.*	32	100% support
2.4. Advanced processing techniques (e.g. algorithms or hardware solutions) have the potential to offer fast and reliable verification of valid HAEs. However, they are often	32	100% support

developed for specific wearable devices in specific applications (e.g., collegiate football) and it is best practice to independently validate processing methods for use in the intended application.*		
2.5. Before deploying head acceleration measurement devices in an on-field environment, users should establish data collection and analysis protocols according to the activity, resources, and research questions. Additionally, users should ensure 1) the devices are functional, 2) the batteries are charged, 3) the devices are attached securely to the individual, and 4) the wearable device is time-synchronized with other concurrent data sources (e.g. video, GPS systems).*	33	100% support
3. Physical Reconstruction of Head Acceleration Events		
3.1. Physical reconstructions are a valuable methodology for understanding the dynamics of head acceleration events captured on video.	32	97% support
3.2. Due to selection bias and a small sample size, physical reconstruction study designs are typically limited to case series and case-control studies.	31	100% support

3.3. Common test surrogates (Hybrid III dummy, NOCSAE headform) are limited in their ability to match the size, stiffness, posture, and active muscle tension of a particular athlete in a reconstruction.	32	88% support
3.4. The test apparatus in a physical reconstruction should be designed to recreate the 3-D interaction of the head and collision partner by matching their effective masses, combined stiffness (including head protection), closing speed, path eccentricity, and impact locations.	31	90% support
3.5. When conducting physical reconstructions, iterative testing should be performed to match video-derived parameters, both pre- and post-impact, and assess the repeatability and sensitivity of the test results to variance in test conditions.*	30	100% support
3.6. Researchers should identify and quantify the biomechanical parameters of interest and evaluate the accuracy, repeatability, and sensitivity of the reconstruction process relative to the effect size of the biomechanical parameters.*	29	100% support
4. Video Analysis of Head Acceleration Events		

4.1. Video analysis and videogrammetry are critical tools to understand the position, orientation, and motion of objects observable in video, such as the head or body of a sports athlete, or the helmet and equipment positioning and orientation. Analysis of these positions and orientations can be used to calculate change in linear and rotational velocities of the head as a result of an impact event. These techniques and procedures expand beyond sports and are applicable to the measuring of motion and position of most anything observable in video.	24	92% support
4.2. When applied properly, and validated, current video tracking methods have been shown to accurately estimate pre and post impact velocities. These estimates can be used to calculate characteristics of impact severity, such as change in velocity, using industry standard methodologies.	24	83% support
4.3. There are several variables (e.g. frame rate, resolution) that can affect the quality of the results of video analysis. The effect these variables have on the quality of the analysis should be quantified when possible, establishing a range of certainty for the specific set of parameters used in a given analysis.*	26	100% support

4.4. Videogrammetry provides valuable input when reconstructing head acceleration events in the laboratory or when performing multi-body or finite element modeling.*	29	100% support
4.5. Videogrammetry should consider and correct, when possible, sources of error including lens distortion, interlacing, down sampling, compression, and variance in timestep.*	25	100% support
5. Computational Modeling of Head Acceleration Events		
5.1. Brain biomechanical models have strong potential to improve injury prediction and interpret impact exposure over impact kinematics alone. They provide the ability to interrogate physics-based tissue level response, estimate risk of injury, and offer insight into injury specifics such as location and extent of structural damage.*	32	100% support
5.2. The modeling community advocates for the sensor community to standardize reporting of head kinematic data. Standardized reporting should include sensor hardware and software details as well as specifics on coordinate system, post-processing, sampling frequency, and subjects' morphological and demographic information.*	33	100% support

5.3. It is recommended model quality be assessed comprehensively by comparing with experimental data related to the metric used for model predictions (e.g. deformation, strain, stress), correlating against real-world data, and then where possible, comparing to responses from existing models. It is also recommended that models be reevaluated for validation quality when new experimental data or analytic strategies become available.*	32	97% support
5.4. We recommend modelers explore modern data science techniques to efficiently process large amounts of sensor impact data.	32	94% support
5.5. The modeling community advocates for a curated open-access database repository to facilitate sharing of real-world data such as subject-specific head kinematics, injury diagnoses, and other associated information including head/brain morphology. In addition, simulation results from existing models using idealized kinematic profiles should be shared as a benchmark for cross-model examination.*	32	94% support
6. Study Design and Statistical Analyses		

6.1. Head impact sensor studies are typically observational in design, which limits their conclusiveness because they are easily contaminated by unseen confounding factors and biases. Investigators should be wary of selection and sampling biases when composing their samples. Efforts should be made to measure and account for suspected confounders.	36	83% support
6.2. Head impact sensor studies benefit from multidisciplinary teams with essential expertise. In addition, establishing partnerships with the research participant community can help produce more representative and reliable conclusions.	36	89% support
6.3. Proper operational planning for sensor maintenance and technical failures will help minimize missing data. In addition, video recording of data collection sessions is recommended as a resource for explaining and verifying impact events as needed.	36	86% support
6.4. Data quality must be assessed for outliers and spurious data and addressed through data cleaning practices. Suspected missing data should be noted, and all kinematic waveforms should be inspected, either computationally or	34	91% support

manually. Sensor validity should dictate the necessity and scope of these practices.*		
6.5. Investigators should employ analysis techniques that minimize sampling bias effects. Further, we recommend statistical transparency in both procedure and output.*	33	94% support
6.6. Investigators should perform a common-sense check on the data and their analysis results. Care should be taken to investigate results that appear to be inconsistent, unrealistic or counterintuitive. Explanations and disclosures of disparities with reality will help inform better data collection, cleaning, and analysis techniques.*	29	93% support

*Revised from initial draft after group discussion

Appendix 3: Disclosures – March 2022 CHAMP conference participants and work group members

Support for attendance or participation in the conference content or activities	K. Arbogast	Football Research Inc., payments made to institution
	A. Bartsch	Prevent Biometrics
	M. Bussey	World Rugby, University of Otago
	J. Caccese	NFL, travel funds for attendance
	J. Crandall	NFL and Football Research Inc., payments made to Biocore
	J. Funk	NFL and Football Research Inc., payments made to Biocore
	L. Gabler	NFL and Football Research Inc., payments made to Biocore
	K. Harmon	Gift fund to institution support concussion research
	D. Hawes	HITIQ
	T. Ide	Riddell
	S. Ji	NIH, NSF
	R. Kraft	NSF
	T. Laudenbach	HITIQ
	T. Smith	Galeatus LLC

Grants or contracts from entities (government support excluded)	K. Arbogast	Football Research Inc., Chuck Noll Brain Research Foundation (payments to institution)
	A. Bartsch	World Rugby
	J. Bergmann	Lab10x; Podium Analytics Youth Sport Centre at University of Oxford
	S. Broglio	NCAA (payments to institution)
	T. Buckley	State Space Labs, Henry M. Jackson Foundation for the Advancement of Military Medicine, NCAA/DoD CARE Grand Alliance (payments to institution); University of Nevada COBRE (payment to individual).
	M. Bussey	World Rugby
	J. Caccese	American College of Sports Medicine (payment to institution).
	J. Chu	Riddell
	J. Crandall	Football Research, Inc. (contract to Biocore), NFL (contract to Biocore)
	R. Greenwald	Riddell
	J. Harezlak	NCAA
	K. Harmon	Football Research Inc. (payment to institution)
	D. Hawes	HITIQ

	B. Heiderscheit	Football Research Inc., NFL, GE Healthcare, Rheon (payments to institution)
	P. Kelshaw	USA Lacrosse, NOCSAE
	T. Laudenbach	HITIQ
	R. Lynall	NOSCAE, Andee's Army, Georgia Clinical and Translational Science Alliance, NFL and Football Research Inc. (payments to institution)
	J. Mihalik	NCAA, NFL, Football Res. Inc. (payments to institution)
	R. Moran	Southeast Athletic Trainers Association, Football Research Inc. (payments to institution).
	M. Panzer	Diversified Technical Systems, Inc.
	D. Patton	Football Research Inc. (payment to institution)
	S. Rowson	NCAA, NOCSAE (payments to institution).
	J. Schmidt	NCAA (payments to institution)
	M. Shogren	World Rugby
	J. Stitzel	Childress Institute for Pediatric Trauma, NASCAR, Toyota Racing Development (payments made to institution)
	G. Tierney	World Rugby and Rugby Football League

	J. Urban	Childress Institute for Pediatric Trauma, Toyota Racing Development (payments made to institution)
	C. Withnall	Football Research Inc.
	R. Willinger	Humanetics
Royalties or licenses	A. Bartsch	Cleveland Clinic, Prevent Biometrics
	J. Chu	For Riddell Insite and Sideline Response System
	R. Greenwald	For Riddell Insite and Sideline Response System
	M. Shogren	Cleveland Clinic
	R. Willinger	Humanetics
Consulting fees	K. Arbogast	NFL Players Association, grant reviews
	D. Arrington	Various defense firms, reconstruction of vehicle and pedestrian collisions
	S. Broglio	Medicolegal, grant reviews
	T. Buckley	Grant Reviews
	J. Crandall	NASCAR Head Neck and Spine Committee
	J. Funk	Football Research Inc.
	B. Heiderscheit	Altec, Inc, Biocore LLC
	R. Lynall	Biocore LLC via UNC Chapel Hill

	A. McIntosh	Self-employed consultant. Consulting fees from insurance companies, law firms, Racing Australia, Transport for New South Wales, AFL, Worksafe Victoria, IOC, and Cricket Australia.
	G. Solomon	NFL
Payment or honoraria (lectures, presentations, speaker bureaus, manuscript writing, educational events)	K. Arbogast	American Academy of Pediatrics
	T. Buckley	Journal of Sport and Health Sciences – Editorial Board, Precision Athletic Training, Eastern Athletic Trainers Association, Pennsylvania Athletic Trainers Society, Shandong Sport University
	J. Caccese	Child Neurology Society, Eastern Athletic Trainers Association.
	J. Funk	Football Research Inc.
	K. Harmon	NFL Head, Neck and Spine Committee
	R. Moran	Southeast Athletic Trainers Association, National Athletic Trainers Association, Mississippi Athletic Trainers Association (MATA)
	S. Rowson	NOCSAE Scientific Advisory Committee
	J. Urban	International Association for Dance Medicine & Science
	T. Smith	Hockey Equipment Certification Council

Payment for expert testimony	D. Arrington	Various defense firms, reconstruction of vehicle and pedestrian collisions
	J. Funk	Expert witness work, sometimes related to head injury.
	A. McIntosh	Expert testimony on the causation of head injuries in criminal and civil legal matters. Fees paid to company. Very few, if any of these matters, involve concussion in sport.
	G. Siegmund	MEA Forensic Engineers & Scientists (am a salaried employee and owner of the firm). Fees paid to company. None of my forensic cases involve wearable sensors.
Support for attending meetings or travel (government support excluded)	K. Arbogast	NFL Players Association, Football Research Inc., NOCSAE Scientific Advisory Committee
	A. Bartsch	Prevent Biometrics, Department of Defense
	M. Bussey	University of Otago
	J. Caccese	American College of Sports Medicine, Child Neurology Society, Eastern Athletic Trainers Association.
	J. Crandall	Football Research Inc., NFL, Biocore
	J. Funk	NFL
	L. Gabler	Football Research Inc., NFL, Biocore

	K. Harmon	NFL Head, Neck, and Spine Committee
	B. Heiderscheit	NFL Soft Tissue Injury Task Force
	R. Lynall	NATA, University of Georgia
	A. McIntosh	IOC
	M. Shogren	Prevent Biometrics
	G. Siegmund	MEA Forensic Engineers & Scientists
	C. Willmott	Australian Football League, Monash University
Patents, issued and pending	A. Bartsch	2011278996, 2011278997, 2011278999, 2012219306, 2019379578, 2019404197, 21183467.6, 19817851.9, 19845637.8, 2,805,252, 2,805,250, 2805266, 2,837,239, EP2593010, 3338631, 2593015, 2592998, EP2675356, EP2593010, 2593015, 2592998, 16/781,119, 16/737,325, 16/682,767, 16/720,589, 15/432,107, 63/170,217, 63/181,574, EP2675356, EP2593010, 2593015, 602011054987.1, EP2675356, EP2593010, 2593015, 502019000006365, EP2593010, 2593015, 2592998, EP2593010, 2593015, 2592998, EP2675356, 9,149,227, 10,582,883, 9,289,176, 9,044,198, 9,585,619 (Prevent Biometrics, Cleveland Clinic).

	J. Bergmann	WO 2019/020969/ US20200155033/ EP3658009; WO 2021/111132
	S. Broglio	U.S. Application No. 17/164,490 - pending
	J. Chu	All IP related to InSite and Sideline Response System assigned to Riddell
	J. Crandall	U.S. Patent 20190110746 - U.S. Patent 2019010584 - Co-inventor, Biocore ownership
	R. Greenwald	All IP related to InSite and Sideline Response System assigned to Riddell
	D. Hawes	Australian Innovation Patent (Patent No. 2021107530 and Patent No. 2021107528)
	T. Ide	Riddell (Riddell owns Head Acceleration Measurement patents).
	T. Laudenbach	Australian Innovation Patent (Patent No. 2021107530 and Patent No. 2021107528)
	J. Luck	US 2016/0345903
	M. Shogren	US Patent 9,149,227, US Patent 9,585,619, US Patent 10,582,883, AU Patent 2011278996, AU Patent 2011278997, AU Patent 2011278999, AU Patent 2012219306, CA Patent 2,805,252, CA Patent 2,805,250, CA Patent 2,837,239, CA Patent 2,805,266,

		CA Patent 2,907,745, EP Patent 2,593,010, EP Patent 2,675,356, EP Patent 3,338,631, EP Patent 2,593,015, EP Patent 2,592,998. Other patents pending
	G. Siegmund	US Patent No. 10,548,510
	J. Stitzel	2 patents pending on mouthpiece-based head acceleration measurement technology
	J. Urban	Patent pending for mouthpiece-based head acceleration measurement technology
	L. Wu	U.S. Patent 10,172,555. US PCT Patent Application PCT/US2019/066088 – Inventor, Patent applications assigned to Stanford University.
Participating in DSM Board or Advisory Board	K. Arbogast	NOCSAE Scientific Advisory Committee
	J. Crandall	NASCAR Head, Neck and Spine Committee
	S. Rowson	NOCSAE Scientific Advisory Committee
Leadership or fiduciary role in relevant entity, other board, society, committee or advocacy grp. Paid or unpaid	K. Arbogast	NFL Engineering Committee and NFL Sensor Committee
	J. Bergmann	Lab10X
	M. Bussey	Sport and Exercise Science New Zealand
	J. Crandall	NFL Engineering Committee
	K. Harmon	NFL Head, Neck and Spine Committee, Pac-12 Brain Trauma Task Force

	D. Hawes	HITIQ
	B. Heiderscheit	NFL Soft Tissue Injury Task Force
	T. Laudenbach	HITIQ
	J. Luck	The Ohio State University Injury Biomechanics Symposium
	A. McIntosh	Standards Australia committees ISO working group on occupational protective helmets.
	J. Mihalik	Senaptec, Inc - Co-Founder; Chief Science Officer
	M. Shogren	Prevent Biometrics
	J. Stitzel	Elemance, LLC
	C. Willmott	Australian Football League, Monash-Epworth Rehabilitation Research Centre Advisory Board
Stock and stock options	A. Bartsch	Prevent Biometrics
	J. Bergmann	RegMetrics
	J. Crandall	Biocore LLC – Owner
	D. Hawes	HITIQ
	T. Ide	BRG Sports (Equity holder in Riddell parent BRG Sports)

	T. Laudenbach	HITIQ
	J. Mihalik	Senaptec, Inc - Co-Founder, Equity stakeholder
	M. Shogren	Prevent Biometrics
	J. Stitzel	Elemance, LLC – ownership interest
Receipt of equip., materials, drugs, medical writing, gifts or other services	B. Jones	I have received equipment from Biocore-FRI, HitIQ, Prevent and ORB to undertake a validity study. All costs associated with the study were funded by Leeds Beckett University.
	G. Siegmund	MIPS (equipment and advice for the construction of a free fall drop tower used for helmet testing.)
Employment/salary from relevant entity	A. Bartsch	Prevent Biometrics
	J. Chu	Simbex
	J. Crandall	Biocore LLC – Owner
	E. Falvey	World Rugby
	J. Funk	Biocore LLC
	L. Gabler	Biocore LLC
	D. Goodger	Prevent Biometrics
	R. Greenwald	Simbex
	D. Hawes	HITIQ
	K. Harmon	Pac-12 Research Development Director

	T. Ide	Riddell
	T. Laudenbach	HITIQ
	M. Shogren	Prevent Biometrics
	G. Siegmund	MEA Forensic Engineering and Scientists
	C. Willmott	Australian Football League
	C. Withnall	Biokinetics and Associates, Ltd.
Other	A. Bartsch	Immediate family members own stock in Prevent Biometrics
	S. Broglio	Proceeds from Biomechanics of Injury (3rd edition, Human Kinetics) – book
	R. Kraft	BrainSim Technologies Inc.