THE STATE OF BIOMECHANICS OF ANGULAR HEAD MOTIONS 2015

Summary of IRCOBI- NOCSAE-PDB-SNELL Workshop

Held September 8, 2015 at
IFSTTAR — Institut Français des Sciences et Technologies des Transports
Bron (Lyon), France

IRCOBI NOCSAE PARTNERSHIP FOR DUMMY TECHNOLOGY AND BIOMECHANICS pdb SNELL MEMORIAL FOUNDATION

On September 8, 2015 IRCOBI organized, and NOCSAE, PDB and Snell sponsored, a congress of more than 75 participants from 20 countries to discuss the current state-of-the-science of the biomechanics and importance of brain injury from angular head motions (AHM). While there is no question that certain types of head or brain injury can be caused either by translational or rotational motions or their combinations, the focus of this workshop was angular head motions (AHM) only. The organizers invited internationally well-regarded scientists who have worked in the field of AHMs. Lectures summarizing various aspects of AHM were presented by 19 scientists over a five-hour period followed by two hours of open discussions. This represents the summary of the Workshop. The full, detailed presentations are available on the IRCOBI website (http://www.ircobi.org/downloads/ircobi-head-workshop-2015.pdf).

The role of the sponsors was to provide financial support and to assist in nominating lecturers. Once chosen, the scientists were free to present any material they wished and the sponsors imposed no control on the content of the speakers' presentations. Furthermore, each speaker spoke as an individual, expressing his or her personal opinions and not those of his university, company or agency.

The salient points that achieved consensus throughout the Workshop were the following:

Clinical Issues:

Regarding the importance of AHMs there was agreement that

- Important injuries associated with AHM include diffuse brain injuries, including concussion, subconcussion and prolonged traumatic coma not due to mass lesions, or to hypoxic or hypotensive injury (often called diffuse axonal injury or DAI)
- The definition of concussion has broadened in recent years, such that many Mechanically Induced Symptoms (MIS) now associated with concussion
    - Are not of cerebral origin
    - Are not of brain origin
    - May not be solely associated with AHM

- The progressive inclusion of many MIS in the diagnosis of concussions has resulted in a sliding "threshold," thus creating greater challenges for new or improved protective devices or helmets.

Kinematics and Metrics:

- Historical metrics that do not account for AHM cannot be used to predict many of today's brain injuries.
- Rotational kinematic predictors of the head have shown better correlations with brain strain magnitudes in on field studies and finite element (FE) models than translational kinematic predictors of the brain injury.
- Injury response appears to depend on angular velocity for pulse durations considerably less than the natural period, angular acceleration for durations considerably longer than the natural period, and combination of parameters (including angular acceleration, velocity or pulse duration) for intermediate length pulse durations in the vicinity of the natural period. The tolerance of the brain to AHM is also directionally-dependent.
- The Brain Injury Criterion (BrIC) is still in development and in evaluation, but it incorporates angular velocity and directionality, and it shows promise for correlation with a subset of AHM-related injuries. Consideration for pulse duration may not be necessary for certain subsets of AHM-related injuries.
- As FE models become more precise and similar to one another, models will be able to predict regional brain deformations in response to complex AHM time-histories that cannot be fully captured by kinematic predictors.

Mathematical Modeling (FE modeling):

- Contemporary FE models can replicate global brain strain measures that correlate with injury but differences in the strain-distributions within the brain may vary across models.
- Potentially injurious strains in the brain are mainly induced by AHM for the automotive and sports environments.
- That brain strain patterns and magnitudes vary with the time separation of acceleration and deceleration pulses and should be considered in experimental protocols and FE models.
- FE models with anisotropic representation of axonal fibers may improve the prediction of regional brain strain values. The later may correlate better with some types of brain injury than do other global metrics.

Sports and Helmets:

- Helmets have traditionally targeted designs that reduce the magnitude of translational acceleration.
- Acceleration time-histories vary widely in different sports depending on the impact source, location, direction, and head protection.
- It is possible to conceive of novel helmet designs that attempt to selectively diminish AHM.

- Some early studies with novel helmet designs show a modest reduction in angular acceleration in selected circumstances, but none has yet shown reductions in real-world brain injuries.
- Impact direction is an important variable in producing AHM and may offer opportunities for improved designs of head direction.
- Helmet testing requires vigorous study for the variability of all components of the test system.
- Head and neck kinematics prior to impact play a role in the resulting head response and injury.
- The test procedures that provide degrees-of-freedom at the neck with a neck representation can provide more realistic head kinematics for those impact situations where neck kinematics contribute to AHM.
- Numerous sensor systems are now available for capturing head motions in humans. These couple via helmet, scalp, ear canal, or mouth and are actively being investigated for impact detection, sensitivity, reproducibility and magnitude of error in different impact directions and impact magnitudes.

SYNTHESIS OF THE OVERALL WORKSHOP

The Current State of the Biomechanics of AHM:

- AHM remain an import cause of brain injuries and AHM need continued study and research.
- Prediction of head injury is converging on angular velocity for shorter duration events while longer duration events require additional information on the duration or the magnitude of angular acceleration
- Probability of injury is replacing the concept of a single threshold value for injury prediction.
- Different extant FE models are generally showing similar trends, but the precise magnitude and distribution of strains in the brain remain model dependent. Thus, harmonization among current FE models remains elusive.
- Output data from various types of experiments now are regularly being compared to regional strain values determined by FE modeling.
- The correlation of location-specific brain injuries to the output metrics of FE models remains under investigation, but shows promise as future injury predictors.
- Several test methods are being evaluated for AHM metrics but none is yet universally accepted.
- No agreeable performance test standards yet exist for AHM. However, despite no universally accepted test method, the introduction of test methods that introduce reasonable AHM have the potential of advancing the design of helmets and other protective devices.

Prospects for the Future

- While significant gains have been realized in the generalized predictive abilities of brain injury risk functions involving maximum values, and to some degree risk curve value distributions, of head kinematic parameters, these predictors need to be evaluated and validated across a broad spectrum of loading intensities, durations, and orientations.

- The influences of age-related, gender-related and associate-disease-related changes to injury risk need to be evaluated.

- The biomechanical mechanisms and tolerances (or injury risk functions) of various mechanically induced symptoms (smell, vision, auditory, vestibular, cervical, trigeminal, spinal, psychological symptoms) need to be correlated to advanced diagnosis, modeling, and neuroimaging, thereby achieving a separation of symptoms arising from the brain from those arising from non-brain structures. It is appreciated that not all mechanically induced symptoms will be caused exclusively by angular head motions.

- Despite advances in the biofidelity of finite element models of the head and brain and general global agreement between models, region-specific performance (e.g., corpus callosum, hippocampus, brain stem structures, etc.) among different models exhibits opportunities for improvement. Thus, an expanded set of model data from experiments with measurement of regional brain deformations, expansion of impact scenarios, and well-controlled boundary conditions needs to be developed. These data need to be validated against brain performance, physiology and anatomical disruption assessed with contemporary measures (fMRI, local blood flow, metabolites, DTI, fiber tracking, fractional anisotrophy mapping, connectivity, and others, for example).

- Gaps between extant animal experiments and missing biomechanical parameters need to be defined and filled and challenges for scaling results across species relative to the growing database of human data (sports, military, etc.) need to be addressed. A complete matrix of injury risk functions needs to be identified, assessed and filled across experimental subjects and humans.

- The definitions of certain brain injuries need to be refined relative to the severity of injury, the influence of prior brain injuries and the effect of multiple injuries of the same or different types.

- The effects and biomechanical mechanisms of cumulative and temporally spaced of head motions and head impact must be better understood.

- We need to develop consensus on laboratory test conditions and injury predictors that could be utilized to assess head protection equipment.

Invited Participants

Co-Chairs of the Workshop:

Thomas A. Gennarelli, M.D., Emeritus Professor of Neurosurgery, Medical College of Wisconsin, Milwaukee, WI, USA, and Clinical Professor of Neurosurgery, George Washington University, Washington, DC, USA. Dr. Gennarelli is an author of more than 470 scientific publications in medical, neurosurgical and engineering journals in the fields of head injury causation and treatment, biomechanics of brain injury, sports injury, automotive, motorcycle and pedestrian medicine and crash-injury relationships. In addition, for 25 years he was head of the International Injury Scaling Committee that developed the Abbreviated Injury Scale versions of 1980, 1985, 1990, 1998, and 2005. He co-founded and directed for several years one of the CIREN (Crash Injury Research Engineering Networks) centers in the United States and has been on the Board of Directors of the International Neurotrauma Society (co-founder, former President), the US National Neurotrauma Society, IRCOBI, the American Association for the Surgery of Trauma, the Eastern Association for the Surgery of Trauma (co-founder), the American College of Surgeons Committee on Trauma, the Association for the Advancement of Automotive Medicine (former President), the Snell Memorial Foundation, and the Stapp Car Crash Conference.

Jeff Crandall, PhD. Nancy and Neal Wade Professor of Engineering and Applied Sciences; Director, Center for Applied Biomechanics, University of Virginia, Charlottesville, VA, USA. Prof. Crandall holds appointments in Mechanical and Aerospace Engineering, Biomedical Engineering, and Emergency Medicine. He is a fellow of SAE and the Association of Automotive Medicine (AAAM) and a past-president of the AAAM and the International Research Council on Biomechanics of Injury (IRCOBI). He currently serves as chair of the NFL Head, Neck, and Spine engineering subcommittee. He has authored more than 600 technical papers and has received numerous awards including the United States Government Award for Engineering Excellence.

Invited Lecturers:

James Newman founder and former President of Biokinetics and Associates Ltd., Ottawa Canada

Dr. Newman is considered one of the world's experts on the design and performance of helmets and their relationship to head and neck injury mechanisms and In addition to chairing several Canadian Standards Association helmet committees for many years, he has represented Canada on various US and international bodies involved in the development of protective equipment standards. He has served as a Director of the Snell Memorial Foundation and was a member of the Stapp Car Crash Conference Advisory Board for a decade. For twenty years, he was the main consultant to Transport Canada on the biomechanics of car crash safety. Later he was a biomechanics consultant to the National Football League as it dealt with the issues surrounding player concussion. His research has led to the development of better protective headgear in nearly every field including hockey, football, bicycling, military, bomb disposal, aircrew, firefighting, coast guard operations, industrial, as well as in motorcycling. He led the team that developed the GAMBIT and HIP head injury metrics. In recognition of his contributions to head protection research, he was named in 2002 a Fellow of the Society of Automotive Engineers. Previously he had been inducted into the International Health and Safety Hall of Fame and in 1995 was elected as a Fellow of the Association for the Advancement of Automotive Medicine. In 2005 he was the recipient of the IRCOBI Aldman Award for "Outstanding contributions to the subject of biomechanics." In 2014 he was invited to present the opening Stapp Memorial Address at the Stapp Car Crash Conference.In addition to his 150 technical publications and several helmet patents, he is the author of the Schiffer Publishing book, *Modern Sports Helmets; Their History, Science and Art*. He currently is working on a new form of head and neck protection for automobile racing drivers.

Daniel Thomas, M.D., MPH, Snell Memorial Foundation, President, North Highlands, CA USA

Dr. Thomas, President of Snell Memorial Foundation, is a physician board certified in preventive medicine (Aerospace Medicine) and a consultant in bioengineering. He was a Naval Fight surgeon (1964-1968) with the U.S. Marines, founded the bioengineering department of the US Army Aeromedical Research Laboratory, served as a liaison officer for aeromedical research between the Army and Navy during the Vietnam war, and was on several panels of the Advisory group for Aerospace Medical Research and Development (AGARD) of NATO. He helped found the Naval Biodynamics Laboratory, New Orleans, LA serving as Deputy Scientific Director and Chief of the Human Research Division (1969-1984). From 1984-2000 he was Medical Director of Celanese's Specialty Operations, Hoechst Celanese, and V.P. Global Medical Director of Hoechst Marion Roussel and Aventis Pharmaceutical Corporation. Dr. Thomas received his undergraduate Physics education at the Massachusetts Institute of Technology, his medical education at Jefferson Medical School, Philadelphia, PA; U.S. Naval School of Aviation Medicine, and Master of Public Health at the Harvard School of Public Health. Dr. Thomas' field of expertise is in occupational medicine, head, neck and spinal trauma and he is the author and collaborator of more than 50 published papers in the scientific area and contributing editor of two books on impact injury of the head and spine.

Narayan Yoganandan, PhD, Professor, Department of Neurosurgery, Medical College of Wisconsin, Milwaukee, WI, USA

Narayan Yoganandan is a professor of Neurosurgery and Orthopaedic Surgery and Chair of Biomedical Engineering in the Department of Neurosurgery at the Medical College of Wisconsin. In addition to an h-index of 59, his PubMed citation includes more than 275 full-length journal papers. He is a Fellow of AIMBE, AAAM, ASME and SAE and has won numerous honors.

Warren N. Hardy, PhD, Virginia Technical University Center for Injury Biomechanics, Blacksburg, VA, USA

Dr. Hardy is Associate Professor of Mechanical Engineering at Virginia Tech and Wake Forest universities. He serves as the director of the Virginia Tech-Wake Forest University Center for Injury Biomechanics on the VT campus and holds a bachelor's degree in Engineering Science (Bioengineering option) from the University of Michigan; and a master's degree in Mechanical Engineering (Biomechanics) and a PhD in Biomedical Engineering from Wayne State University. His research interests are impact and injury response and tolerance, macro- and micro-mechanisms of trauma, and automotive crash testing; his teaching interests are biomedical instrumentation design and experimental methods in impact biomechanics trauma.

Cameron R. Bass, PhD. Department of Biomedical Engineering, Duke University, Durham, NC, USA

Cameron R. 'Dale' Bass is an Associate Research Professor with Duke's Department of Biomedical Engineering and Director of the Injury and Othopaedic Biomechanics Laboratory. A major research focus of Dr. Bass is the study of blast-related brain injury and injury mechanisms. Past research has concentrated air containing organs, such as the lungs and bowel. Results from the limited evidence of over 80 years of experimentation suggested that the brain tolerance for blast was much greater than the pulmonary tolerance for blast. However, recent anecdotal evidence suggests that many soldiers returning from combat have symptoms that are consistent with underlying brain injuries. The etiology for these injuries is unclear and may include a spectrum of sources from blunt impact injuries to post traumatic stress disorder to primary blast injuries**.**

Matthew B. Panzer, PhD, University of Virginia, Charlottesville, VA, USA.

Dr. Panzer is head of the computational research group at the UVA-CAB, is a lead on TBI research at the CAB, and is a tenure-track faculty member in the UVA Department of Mechanical and Aerospace Engineering. He joined the CAB after graduating from Duke University with his PhD in Biomedical Engineering. Dr. Panzer has nearly 12 years' experience with computational biomechanics research studying high-rate non-linear mechanics in the fields of impact biomechanics, vehicle crashworthiness, military blast, and sports injury. Within these fields, Dr. Panzer is proficient in traumatic brain injury biomechanics, material characterization, vehicle model development and crashworthiness simulation, human body models (THUMS and GHBMC), ATD model development (including NHTSA THOR FE model), animal model development, and large-scale DOE.

Remy Willinger, PhD., Strasbourg University, Strasbourg, France.

Since 1992 he has managed a research team working on Impact Biomechanics. His background is in mechanical engineering applied to biomechanics. The activity ranges from biological tissues identification and modelling to human body characterization followed by mathematical modelling. Once validated the models are used for accident simulation in order to derive tolerance limits relative to specific injury mechanisms. Human models are also coupled to protective systems in order to optimise them in respect to biomechanical criteria. Most of his work addressed the head-neck system. He co-authored over 100 papers and was involved in 110 contracts. At EU level main involvement of this research group was in CHILD, APROSYS, ADSEAR and CASPER, ADSEAT, Safe-EV projects. The group also takes part in several EU network activities (3 COST projects, APSN, ISN, EARPA, MOTORIST). He is a member of CEN TC 158-WG11 as well as ISO SC36-WG6 working groups and regularly attends ASTM meetings.

Svein Kleiven, PhD, Division of Neuronic Engineering, KTH Royal Institute of Technology, Stockholm, Sweden.

Professor Svein Kleiven has more than 15 years of experience in continuum mechanics, dynamic, non-linear FEA, and head injury biomechanics. He has a PhD in Biomechanics, B.Sc. in Automotive Eng., M.Sc. in Mechanical Eng. and in 2013 was appointed as Professor by KTH. He is Director of Doctoral Programs in Technology and Health and Applied Medical Engineering at KTH and Director of a Joint Doctoral Program between Karolinska Institute and KTH in Medical Technology. He has been the principal supervisor for 2 PhDs and over 30 MSc theses. He is editorial board member for ISRN Biomedical Engineering, Associate editor of Frontiers in Biomechanics, Scientific Review Committee member for IRCOBI, and a regular reviewer for the main journals in the research area such as J. Biomechanics and Medical Engineering and Physics and has acted as an external examiner in the evaluation of 12 PhD theses since. He has more than 60 scientific articles in peer reviewed journals and proceedings and he has more than 20 invited or key-note lectures.

Erik G. Takhounts, PhD. Department of Transportation, Washington, DC. USA.

Dr. Erik Takhounts is currently employed by the National Highway Traffic Safety Administration in the Human Injury Research Division – a research unit responsible for conducting and sponsoring state of the art biomechanical research necessary to understand human response and tolerance to mechanical loading typical to those occurring in automotive crashes. His research interests are mostly in the areas of computational impact biomechanics, mechanically induced brain injury mechanisms, reconstruction of car crashes using probabilistic methods, statistical ambiguities, etc. He obtained his Ph.D. degree in Mechanical and Aerospace Engineering in 1998 from The University of Virginia where he studied non-linear mechanical response of brain tissue in shear. Since then he authored multiple papers on brain tissue response and brain injury mechanisms.

T. Blaine Hoshizaki, PhD. Neurotrauma Impact Science Laboratory, University of Ottawa, Ottawa, Canada

Dr. Hoshizaki is the Director of the Neurotrauma Impact Science Laboratory at the University of Ottawa. His research has focused on decreasing the risk of head injuries in sport. His group primarily investigates the relationship between the accident event and resulting brain tissue trauma. His role is to lead head injury reconstructive research employing physical event reconstructions and computational modeling. This allows the undertaking of head injury reconstructions using hospital medical reports, video footage, and medical imaging of real-life head impact events. Finite element modeling generates the measurements of subsequent mechanical stresses and strains and location occurring in the brain tissue that are associated with specific injury outcomes. This information guides the improvement of preventive measures such as helmets, certification standards and heightens awareness of high risk situations for incurring both mild and traumatic brain injury. Refereed scientific publications 104; Scientific presentations 212.

David Halstead, Southern Impact Research Center, TN, USA

Dave Halstead is the Technical Director of Southern Impact Research Center (SIRC) responsible for the technical and scientific actions of the A2LA accredited test lab, as well as overseeing the technical aspects of all testing, consulting and other services provided by SIRC staff. Dave is an expert in the field of head injury and helmets. His background is non-traditional in many ways and does not include a traditional college degree. In addition to his duties at SIRC, Dave is the Laboratory Director of the University of Tennessee Sports Biomechanics Impact Research Lab and Principal Scientist with the University's Engineering Institute for Injury and Trauma Prevention in the College of Engineering. The lab's work has included cadaver and living subject studies in areas of motorcycle injury, finger and ankle injury, spine injury, and head/brain and face injury. Research has been diversified from airbag deployment impacts, injuries from beach volleyball facial impacts, and a number of other areas all-resulting in increased understanding of human injury tolerance and thresholds

Elizabeth McCalley, Southern Impact Research Center, TN, USA

Elizabeth received her Bachelor of Science degree in Biomedical Engineering from the Mechanical, Aerospace and Engineering Science Department within the College of Engineering at The University of Tennessee in 2006. Elizabeth is interested in biomechanics and running shoe design and conducted an independent study in this field in 2006. Elizabeth's duties include researching and designing new products used in wrestling, gymnastics, and cheerleading, conducting the testing of current product in accordance with ASTM standards, and designing a test laboratory for the manufacturing facility in Fort Worth, Texas.

Lyndia C. Wu, PhD, Department of Bioengineering, Stanford University, Palo Alto, CA, USA

Lyndia Wu is a Ph.D. candidate in the Bioengineering Department at Stanford University. Her Ph.D. work focuses on the development and validation of head impact sensors for traumatic brain injury research. In addition, she studies the biomechanical mechanism of traumatic brain injury by identifying the link between head impact kinematics and injury outcomes.

Edward Becker, MS, Snell Memorial Foundation, North Highlands, CA, USA

Mr. Becker holds Bachelor's and Master's degrees in Mechanical Engineering from the Massachusetts Institute of Technology and is the Executive Director for the Snell Memorial Foundation. Prior to joining Snell in 1989, he worked for the Naval Biodynamics Laboratory in New Orleans studying human response to crash impact acceleration. He is responsible to the Board of Directors for the operation of all the Snell's helmet certification programs and oversees its laboratory testing facility.

Luca Cenedese, PhD. Director, Newton Laboratory, Milan, Italy

Luca Cenedese is a civil engineer trained at the University of Padova in Italy who, since 2000, has been the director of Newton Labs (Newton – Dynamic Testing Center) in Milan. This facility tests various types of automotive and non-automotive equipment and is certified by Snell, FIA and other organizations.

Terry Smith, PhD., Dynamic Research, Inc., Torrance, CA, USA

Over a career spanning more than 25 years, Dr. Smith has engaged in numerous investigations of accident involved helmets and numerous performance and design evaluations of helmets for both recreation (e.g. bicycle, equestrian) as well as public safety (police riot helmets, firefighter helmets, etc.) and military applications. He has participated in several specific helmet design projects, including the use of finite element analysis to improve naval pilot headgear, headgear for riot police, headgear for airport firefighters, bicycle helmets, equestrian helmets and motorcycle helmets. His other activities include regular participation on several international head protection standard committees including the American Society for Testing and Materials (ASTM) F-08 Headgear Committee, Canadian Standards Association (CSA) and the International Standards Organization (ISO).

Peter Halldin, PhD., Division of Neuronic Engineering, KTH Royal Institute of Technology; MIPS AB, Stockholm, Sweden.

Peter Halldin, PhD in biomechanics has more than 15 years of experience in dynamic FEA of the head and cervical spine, biomechanics, and helmet design. Dr. Halldin, who is a helmet researcher, was also President, and is currently a development manager for a company that aims to commercialize a new helmet concept (MIPS) since 2001.

Organizer:

IRCOBI, the International Research Council on the Biomechanics of Impact is a group of 20-25 scientists from around the world who, since 1973, organize annual conferences that present current biomechanical, accident investigation and clinical papers. Founded in 1973, IRCOBI is a non-for-profit organization whose meetings typically occur in Europe although an IRCOBI Asia meeting is soon to commence. www.ircobi.org

Sponsors:

NOCSAE, the National Operating Committee on Standards for Athletic Equipment, is a US based organization charged since 1969 to reduce injuries in sport by setting standards for safety equipment. http://nocsae.org

PDB, the Partnership for Dummy Technology and Biomechanics, was founded in 2002 as a cooperative venture between German car manufacturers to link standards between them. www.pdb-org.com

The Snell Memorial Foundation is a US based, non-for-profit foundation, founded in 1957, composed of five members dedicated to education, testing and development of performance standards for many types of helmets. http://smf.org