Test and Assessment Methods to Evaluate Combat Helmets for Rotation-Induced Injury

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Abstract. Military helmets are typically evaluated for blunt impact protection with a drop tower impact apparatus, where head motion is restricted to a single direction and acceleration is measured with a uniaxial accelerometer. Experimental methods that introduce rotational kinematics have been developed for the evaluation of recreational helmets across a number of sports and activities. This is in response to growing consensus among the medical community that excessive rotational kinematics can cause traumatic brain injury and further reflects the reality that typical head impacts involve both linear and rotational loading. This paper reports on a blunt impact test method of combat helmets that imparts combined linear and rotational loading to a headform. To better relate experimental head kinematic outputs to soldier experience, a recently published brain deformation assessment tool is explored that translates kinematic data into a predicted brain strain.

1. INTRODUCTION

An estimated 1.7 million Traumatic Brain Injuries (TBIs) occur in the United States each year as a result of automotive crashes, recreational activities, sports, falls, or other accidents [1]. TBI is also a significant threat to the United States military and has been described as the signature injury of recent conflicts in Iraq and Afghanistan. The threat of TBI in military populations is magnified due to the unpredictable and physically demanding nature of both training and combat environments. The Defense and Veterans Brain Injury Center (DVBIC) has tracked the incidence TBI from 2000 to 2019, reporting that over 400,000 TBIs were diagnosed in military service members [2]. Over 80% of the diagnosed TBIs in the military are classified as concussions, otherwise referred to as mild TBI[1].

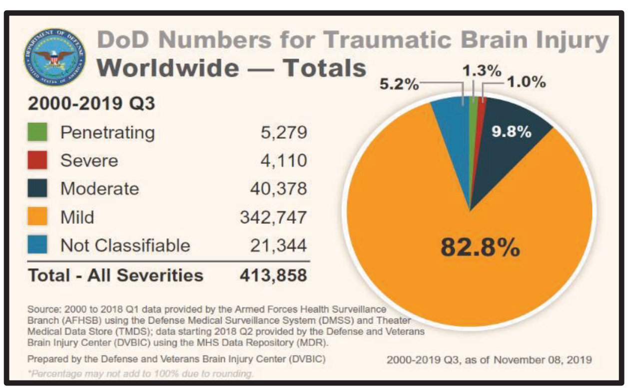

Figure 1. Medically diagnosed TBIs in United States military from 2000 to 2019 (DVBIC) [2].

The military related TBI considered in this research is solely blunt impact induced TBI. Other research groups have produced findings that probe the phenomenon of blast induced TBI [3]. In the soldier population, blunt impacts to the head can occur in a variety of situations, many of which are similar to those experienced by the general population, but may be more severe due to the inherent hazardous conditions of training and combat scenarios. Likewise these impacts rarely, if ever, consist of purely translational or rotational motion, but rather some combination of the two. The principle

[1] Mild TBI is classified by DVBIC as including the following symptoms: confusion or disorientation for less than 24 hours, memory loss lasting less than 24 hours, and loss of consciousness for up to 30 minutes. Brain imaging associated with mild TBI cases as classified by DVBIC do not contain any abnormalities.

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protection a soldier will have from all of these blunt impact scenarios is the combat helmet. Improvements to helmets can aid in reducing TBI if there exists better understanding of brain injury causations and methods that evaluate a helmet's ability to mitigate such causations.

Recent as well as historical biomechanics research suggests that mitigating excessive rotational kinematics during head impacts is a critical component in developing effective protection against impact induced TBI. The theory that rotational kinematics are the primary cause of brain deformation was first proposed in 1943 [4]. This theory has grown stronger in recent years, particularly with advancements in biomechanics tools such as human brain finite element models that have been used to demonstrate the severity of brain deformation resulting from rotational motion versus translation alone [5]. This response is due in large part to the inherent tissue level characteristics of the brain, where the bulk modulus is understood to be several orders of magnitude greater than its shear modulus [6]. Brain deformation has been proposed as a metric that can be related to the risk of sustaining a TBI based on available injury data [7]. Multiple kinematic based metrics have been proposed [8]. For example, studies have used angular velocity and acceleration to propose injury risk thresholds related to football helmet collisions to predict the likelihood of a TBI based on head kinematics [9]. The obvious advantage of such metrics is that head kinematics can be more easily measured than brain deformation, particularly on living human subjects. An improved understanding of the link between head kinematics and TBI risk is essential for creating effective performance standards to evaluate the protective capacity of helmets. Further there is a need to assess the performance of military helmets in more relevant impact conditions that impart rotational head kinematics, in conjunction with the current blunt impact test methods that solely evaluate a helmet's ability to protect against linear translation accelerations.

2. MATERIAL AND METHODS

The current Army blunt impact performance standard for the ACH is based on a modified version of the Federal Motor Vehicles Safety Standard 218 (FMVS 218) for testing motorcycle helmets [10]. The test consists of a headform and helmet assembly that is dropped from a height to achieve a specific striking velocity, guided by a monorail, so that impact occurs onto a rigid stationary anvil with a hemispherical shape. The headform specified is a magnesium DOT headform instrumented with a single accelerometer. The current performance standard requires that helmets must limit linear headform acceleration to less than 150 g (g-force, 9.81 m/s^2) for impact at 3.05 m/s (10 ft/s) at each impact site. The seven impact sites include the crown, front, rear, sides, and nape regions. There are currently no performance standards in place to evaluate the effectiveness of military helmets to mitigate rotational kinematics. The purpose of this research study is to determine suitability and feasibility of using an alternative format based on a pneumatic ram impact to evaluate military helmet technologies.

The pneumatic ram impact test is commonly employed in the evaluation and certification of American football helmets. The largest professional football organization, the National Football League (NFL), has adopted the pneumatic ram test method to certify or ban certain helmet designs (NFL Helmet Test Protocol 2019) [11]. Additionally NOCSAE, the National Operating Committee on Standards for Athletic Equipment, which certifies all amateur football helmets in the United States, instituted a similar test as part of its helmet as a certification process (NOCSAE DOC (ND) 081) [12]. The pneumatic ram format was chosen to test helmets in this study.

Within the pneumatic ram format, also known as the linear impactor format, the ram is propelled by compressed air, launching it at a repeatable velocity in a linear motion toward the headform. A head-neck assembly, initially at rest, is attached to a sliding carriage and is free to translate along the direction of the impact vector once struck. The head and neck may be rotated and posed to achieve desired head orientation with respect to the ram. The manufacturer of the machine used in this study was Biokinetics LLC. The impacting ram mass is 14.3 kg and the mass of the head-neck and sliding table assembly is 17.7 kg. The impactor on the end of the ram consists of a metallic cap with a radius of curvature of 127 mm backed by a compliant elastomer, as used in NOCSAE testing.

The neck presents a critical boundary condition in defining the degree of rotation that the head will experience during an impact. Within this study the Hybrid III head and neck were chosen to measure impact kinematics, where rotational motion is achieved at the head-neck joint, as well as in the flexible neck itself in this setup. The tension in the Hybrid III neck is controlled by cables that run along its primary axis, which in this study were torqued to 1.4 N.m (12 in.lb$_f$) and checked intermittently between testing to maintain consistent response. The Hybrid III neck is the most widely used surrogate in evaluating helmets for blunt impact protection due in part to its availability and compatibility with the Hybrid III and NOCSAE headforms [13,14]. However, the biofidelity of the Hybrid III neck in impact conditions has been a topic of debate, as it has been validated for inertial loadings specific to automotive

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crashworthiness testing. A recent head impact study suggests that the Hybrid III neck may be too stiff in lateral impact scenarios, when compared to neck surrogates specifically validated for lateral inertial loading [15]. Investigations into the human neck response during short duration impact events, including the effect of muscle activation and pre-tensioning, are ongoing in the field of biomechanics and can be potentially used to improve upon available neck surrogate designs in the future [16].

The Hybrid III head is instrumented with a nine-accelerometer array package, or NAP, which consists of nine linear accelerometers in a 3-2-2-2 arrangement. The first set of three accelerometers in this package are located at the center of gravity of the Hybrid III head, while the additional three sets of two accelerometers are set a fixed distance away. This accelerometer package allows for the calculation of linear and rotational kinematics of the head as detailed in Padgaonkar 1975 [17]. A NAP check tool is used at the beginning of each test series to verify that the accelerometers of the NAP are giving consistent results. This spreadsheet based tool is made available by Biocore LLC [18].

The example helmet tested in this methods paper is an Advanced Combat Helmet (ACH), a widely fielded combat helmet that consists of a ballistic protective shell, 7-pad suspension system, and a 4-point chin to nape retention strap system. The suspension system (Zorbium Action Pad – ZAP, Team Wendy) employs seven pads made from a polyurethane based foam enclosed in a moisture resistant membrane. The ACH meets the existing U.S. Army blunt impact performance standard as described in the purchase description, where blunt impact testing by traditional monorail format is performed at 3.05 m/s (10 ft/s) at 7 specific impact locations around the helmet [19]. Those impact locations were mirrored in the pneumatic ram testing described herein, where Figure 2 illustrates a single frame during an impact to the rear location on the Hybrid III head-neck fitted with an ACH, along with accompanying kinematic traces.

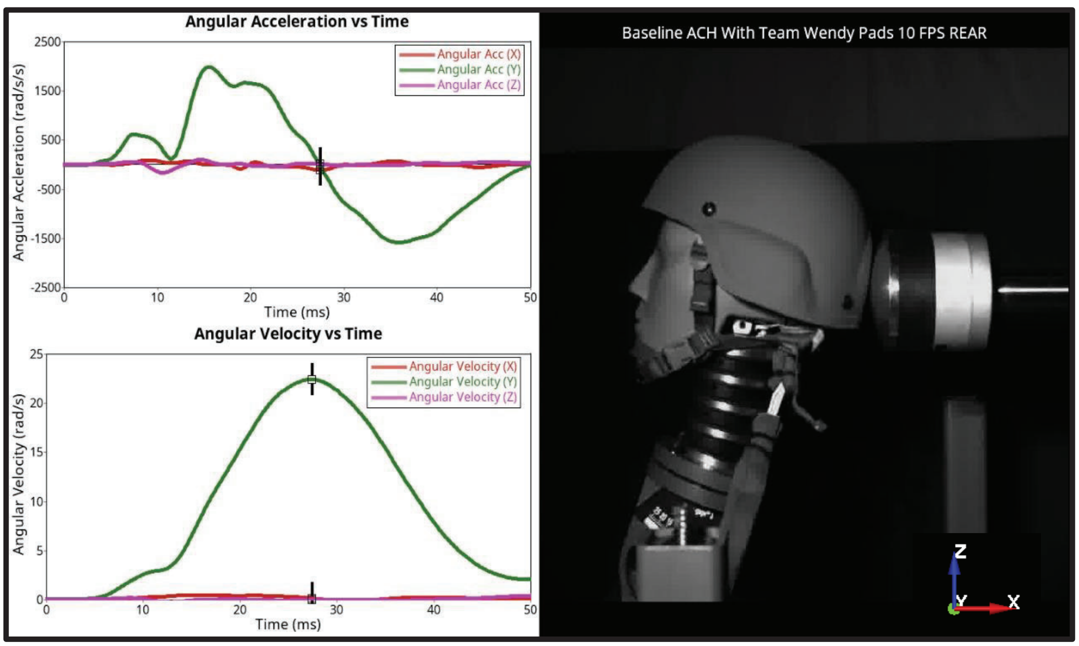

Figure 2. Rotational acceleration and velocity data traces with a synched video frame at the time of peak angular velocity of the Hybrid III head.

3. DISCUSSION

The assessment of combined linear and angular kinematic data and its relation to brain injury is a topic of ongoing research in the biomedical community. While the tissue level damage mechanisms and related injury thresholds are being studied and developed, brain deformation has been identified as one of the metrics often correlated to TBI, and is commonly estimated through computational modeling by calculating maximum principal strain (MPS) using finite element analysis [20,21,22]. On its own this metric can serve as a convenient quantitative assessment for relative comparisons between head protection systems. Towards injury prediction, a relationship between MPS and injury risk at various severity levels has been proposed by National Highway Transportation Safety Administration (NHTSA) based on scaled animal injury data, automotive crash and football impact data using ATDs, and strain

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calculations using the SIMon and GHBMC brain models [7]. These relationships serve as a starting point while more extensive testing and human response data can be applied across a number of loading scenarios and durations to develop injury risk curves with wide acceptance.

To alleviate the computational expense and time of modeling every impact scenario, various analytical tools have been developed to offer a quick assessment and prediction of brain strain. The Diffuse Axonal Multi-Axis General Evaluation (DAMAGE) is a multibody kinematic assessment tool that translates linear and rotational kinematic data traces into a predicted maximum brain strain and has demonstrated high correlation to finite element model results across a wide range of impact durations [23]. In contrast to other models that rely solely on the peak linear and/or angular kinematics, the DAMAGE model considers the full duration of the kinematic event.

Currently the U.S. Army does not currently endorse any one particular brain injury risk metric or risk function for evaluation of helmet performance under combined translational and rotational impact testing. For demonstration purposes the DAMAGE score for the example impact in Figure 2 was calculated using a script available from Biocore LLC and related to the probability of AIS2 and AIS4 brain injury based upon the injury risk functions in equations 1 and 2 from NHTSA [7].

$$P(mTBI) = 1 - e^{-\left(\frac{MPS}{0.505}\right)^{2.84}} \quad (1)$$

$$P(sTBI) = 1 - e^{-\left(\frac{MPS}{0.823}\right)^{2.84}} \quad (2)$$

Relating back to the DVBIC study, AIS2 injuries correspond to mild TBI (mTBI) whereas AIS4 injuries correspond to severe TBI (sTBI). For the impact to the rear of the helmet at 3.05 m/s (10 ft/s), the DAMAGE score was 0.207, which equates to a predicted maximum principal strain (MPS) of 20.7%. This MPS would estimate a probability of mTBI to be 8% and sTBI 2%. Note that the current Army blunt impact test method does not induce any rotational head kinematics and is unable to generate rotation based DAMAGE scores.

4. CONCLUSION

TBI remains a significant threat to military service members. The combat helmet is the primary piece of head protective equipment to protect a soldier from the severity of blunt impact loading. Current U.S. military blunt impact test and performance standards are based on methods that solely evaluate the helmet's ability to mitigate linear acceleration. The biomedical community has begun to converge on a consensus that rotational kinematics are a significant contributor to blunt impact induced TBI. This research outlines a helmet evaluation method that utilizes an experimental apparatus to impart combined linear and rotational motion in a soldier-relevant head impact scenario. Headform kinematics were measured for impact to the rear location of a helmeted ATD and, using the kinematic assessment tool DAMAGE, were used to predict a maximum principal strain in the brain. The ability to quickly determine predicted brain response from a complex head loading scenario is useful, particularly when paired with injury risk functions to determine severity and probability of TBI. As improvements in the understanding of TBI injury classification and human brain finite element models continue greater confidence can be attributed to determination of injury risk.

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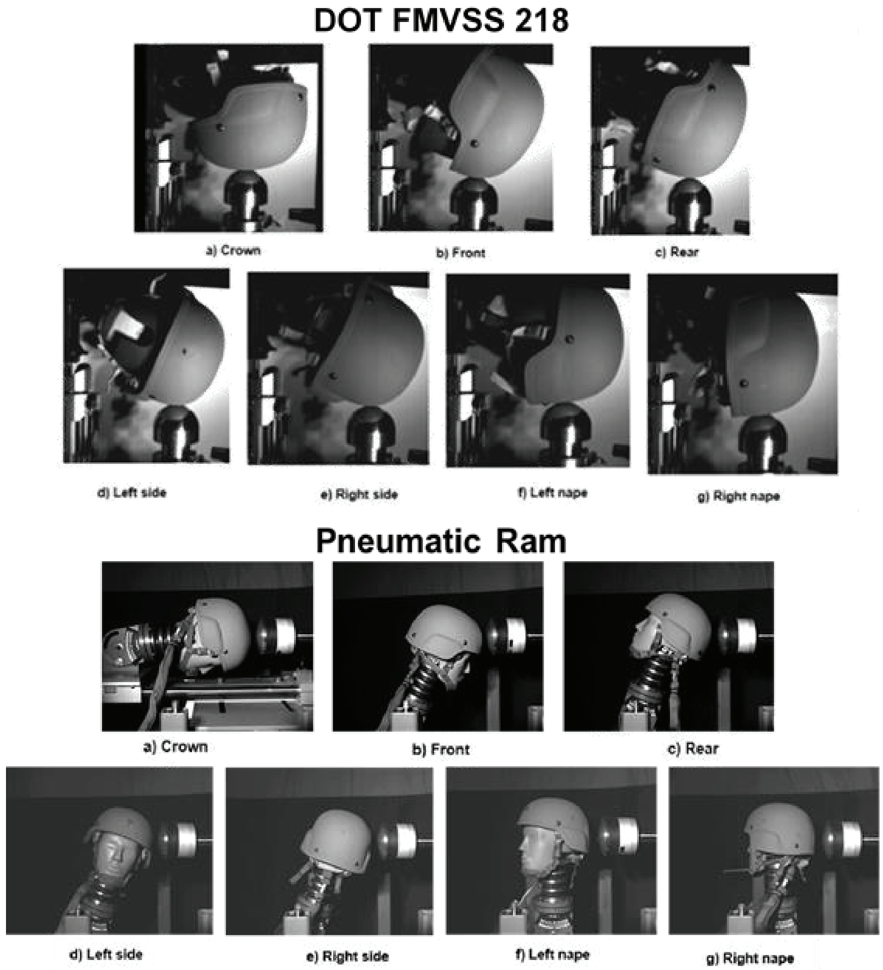

Figure 3. Top) Helmet impact location per current guided monorail U.S. Army Blunt Impact testing format. Bottom) Helmet impact locations for pneumatic ram test configuration, with reference to the existing current impact locations. Reporting on these tests is planned for future release.

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