Surrogate Head Forms for the Evaluation of Head Injury Risk

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ABSTRACT

This paper summarizes the use of surrogate head forms in biomechanical research pertaining to head injury and, more specifically, mild traumatic brain injury. Because cadavers are limited and controlled studies of brain injury using live human subjects would be unethical, surrogate head forms are used to study the response of the human head to impact. Different head forms have been developed and optimized for different purposes. The Hybrid III 50th percentile male crash test dummy was developed for use in vehicle crash testing and instrumented in such a way as to provide HIC values in frontal crash tests. The NOCSAE head form is used by the National Operating Committee on Standards for Athletic Equipment to be used in the certification of commercially produced athletic helmets. The Facial and Ocular Countermeasure Safety (FOCUS) head form was developed jointly by the Virgina Tech – Wake Forest Center for Injury Biomechanics, Robert A. Denton, Inc., and the United States Army Aeromedical Research Laboratory as a tool to aid in the development and evaluation of safety devices designed to prevent face and eye injuries. The vast majority of biomechanical research of head injury conducted using surrogate anthropomorphic test devices (ATDs) utilized one of these three head forms.

Key Words: Mild traumatic brain injury, head, head form, brain injury

PRESENTATION SUMMARY

It is estimated that up to 3.8 million sports related concussions occur in the United States each year [1]. An additional 10,000 to 28,000 cases of mTBI are reported each year in the United States military [2]. During wartime, the incidence of mTBI increases significantly in the military [3]. In the current Iraq and Afghanistan wars it is estimated that as many as 22.8% of military personnel sustained a concussion while deployed [2]. Concussion is now thought to contribute to long term neurocognitive deficits, rather than just simple transient symptoms, increasing the need for research into the biomechanics of concussion and head injury. Because controlled studies of concussion using live human volunteers would be unethical, and cadavers available for research are limited, researchers use surrogate head form anthropomorphic test devices (ATDs) to evaluate the biomechanics of concussion. Three of the head forms most commonly used to evaluate brain and face injury mechanisms are the Hybrid III 50th percentile male headform, the NOCSAE medium head form, and the FOCUS head form.

Hybrid III

The Hybrid III head form is the most extensively used head form in biomechanical research (**Figure 1**). The Hybrid III has been used in the fields of auto safety, military safety and sports biomechanics but was first developed and validated for use in vehicle crash tests. The dummy was developed by Hubbard and McLeod in 1974 [4].The Hybrid III ATD was built to the dimensions of the 50th percentile male. Despite the biofidelity of the head form in total mass and crown circumference, the Hybrid III head form lacks anatomical accuracy. The stylized facial features of the head form replace accurate bone structure. Missing from the head form are anatomically accurate zygoma, maxilla and mandible. The absence of these features can lead to difficulty in testing any device or equipment designed to engage the human face. Currently, a complete ‘family’ of Hybrid III ATDs is manufactured, including a 5th percentile female and child sized dummies modeling various ages and stages of development. These differently sized ATDs allow for surrogate testing of biomechanical responses more representative of the population as a whole, but exhibit the same anatomical inaccuracy as the original 50th percentile male head form. The Hybrid III 50th percentile male dummy and head form are still used more frequently than any of the other Hybrid III ATDs.

Figure 1. Hybrid III 50th percentile male head form

The head form of the Hybrid III dummy was originally instrumented with an accelerometer array that provided researchers with the necessary data to calculate the head injury criteria (HIC) value experienced by the ATD in a particular crash mode. The HIC value was used to determine if a car passed or failed the standards for sale in the United States. As ATD instrumentation became more advanced, the Hybrid III became useful in evaluating a wide variety of biomechanical responses to different stimuli. The Hybrid III ATD has been used in published research investigating the effects of restraint performance and airbag interactions [5,6]. Additional research has been conducted comparing the relative responses of the Hybrid III dummy and post mortem human surrogates (PMHS), validating the biomechanical response of the Hybrid III to another type of human surrogate [7].

As sports concussion moved into public and research focus in the early 2000’s, the Hybrid III ATD, including the head form, was used by Pellman and Viano to reconstruct impacts thought to cause concussion during NFL game play [8-14]. Although the authors used the entire head, body and extremities of the Hybrid III in their reconstructions of game impacts, 100% of the concussions observed came from direct head impacts, as opposed to body impacts that resulted in head movement. In 2012, Viano conducted a study using only the Hybrid III head form to investigate the response of the head form to impact on different field types at different temperatures [15]. The ability of the Hybrid III head form to be used independently or with an attached surrogate neck allows a broad array of biomechanical research to be performed to using the Hybrid III.

The Hybrid III head form was used by the Virginia Tech – Wake Forest Center for Injury Biomechanics and other institutions to validate the Riddell HIT System (Head Impact Telemetry

System) and the custom 6 degree of freedom helmet impact sensor system designed at Virginia Tech [16,17]. The validation of these two systems using the Hybrid III head form is the foundation for a large data set of concussive and non-concussive head impacts collected from 2003 to 2012 from 11 collegiate football teams and several high school and youth football teams [16,18-40]. This data set in turn contributed to the development of the Virginia Tech – Wake Forest Center for Injury Biomechanics Summation of Tests for the Analysis of Risk (STAR) system for evaluating commercially available football helmets [31].

In addition to the major football studies, the Hybrid III head form has also been used with the attached Hybrid III dummy to test the efficacy of different styles of neck collars to prevent stingers in football [41]. The Hybrid III head form has been used without the Hybrid III dummy in studies designed to measure the efficacy of catcher's masks to reduce head accelerations in baseball [42,43].

NOCSAE

The head form used by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) is named for the organization itself. The NOCSAE head form was developed by Dr. Voigt Hodgson at Wayne State University to accurately simulate human head response to impact [44]. The NOCSAE head form is considered more anatomically correct than the Hybrid III and includes appropriate facial features and bone structure. However, because the NOCSAE head form was designed to be mounted to a rigid arm rather than a surrogate neck, it cannot be used to study the effects of a neck strength and anisotropic bending of the neck on head acceleration.

Figure 2. Medium NOCSAE head form

The NOCSAE head form is available in three different adult sizes; $6^5/_8$ (small), $7^1/_4$ (medium) and $7^5/_8$ (large). The medium NOCSAE head form (**Figure 2**) is constructed to approximately the same dimension as a 50th percentile male and fits a large size football helmet [45,46]. The NOCSAE head form is instrumented with an array of accelerometers to measure acceleration in the anterior-posterior direction, the superior-inferior direction and the left-right direction [45]. Accelerations measured during a helmet test are used to calculate the Gadd Severity Index (GSI) of a particular impact. NOCSAE tests helmets under a variety of different impact conditions and passes, or certifies, only helmets that maintain GSI values of less than a given value, determined by NOCSAE. Football helmets must reduce the head form acceleration to a GSI of less than 1200 for all impact types tested in order to gain NOCSAE certification [46].

In 2011, Rowson and Duma of the Virginia Tech – Wake Forest Center for Injury Biomechanics used the medium NOCSAE medium head form in conjunction with the football impact exposure data collected using the HIT system to develop the STAR evaluation system for football helmets [31,47]. Linear acceleration data collected from the HIT system was used to quantify impact exposure and concussion risk of football players. The NOCSAE head form and NOCSAE style drop tower were used to perform drop tests at varying heights and impact locations on commercially available helmet models to quantify their relative performances [47].

Revised concussion risk functions were developed by Rowson and Duma in 2012 that take into account rotational accelerations of the head [24]. In 2013, Rowson and Duma published combined probability of concussion contours, based on both rotational and linear head accelerations [48]. These risk functions can be used with a modified STAR equation to better characterize the relative performances of different football helmet models.

FOCUS

The Facial and Ocular Countermeasures Safety (FOCUS) head form (**Figure 3**) was developed through a collaboration between the U.S. Army Aeromedical Research Laboratory, Virginia Tech-Wake Forest Center for Injury Biomechanics, and Denton, Inc. to allow for testing of facial and ocular protective equipment without the use of cadavers [49]. The FOCUS head form models the 50th percentile male soldier in all head dimensions, and is compatible with the Hybrid III surrogate neck. The neck and body attachment capabilities and biofidelic facial structure are two major strengths of the Hybrid III and NOCSAE head forms respectively combined into one surrogate head form. However, the FOCUS head form is not currently manufactured in any additional sizes and is therefore not useful in studies that may emphasize particular sub groups of the general population.

Figure 3. FOCUS head form

The surrogate skull of the FOCUS head form is unique in that it consists of 8 separate pieces representing the left and right frontal bones, the left and right zygoma, the left and right maxilla, the nasal bone and the mandible [49]. Each segment is instrumented separately with a three-axis load cell capable of measuring up to 1000 pounds. Data from the load cells of each skull segment can be used in conjunction with carefully developed risk functions for fracture to predict injury to a human in a given loading scenario [50-54].

The eyes of the FOCUS head form are also unique among ATDs [49,55]. Each synthetic eyeball rests in a cup of synthetic extraocular tissue, held by a simulated orbit. Each eye assembly is mounted to the face of a load cell. Force measurements obtained during testing by the eye socket load cells can be used to predict injury according to risk functions developed by Kennedy et al. Extensive work to validate the response of the FOCUS synthetic eye to the response of human cadaver eyes was conducted by the Virginia

Tech – Wake Forest Center for Injury Biomechanics and other colleagues to create the most biofidelic eyes possible [55-67]. In addition to its distinct facial instrumentation, the FOCUS head form is also instrumented similarly to the Hybrid III with an accelerometer array located at the center of gravity of the head form. Data from these accelerometers can be used to determine the biomechanical response of the head form to impact.

Although the FOCUS head form contains all of the appropriate instrumentation to be used in concussion and head injury research, it has primarily been used to study facial and ocular injury because if its specialized additional features and instrumentation. At the Virginia Tech – Wake Forest Center for Injury Biomechanics, extensive eye injury research has been done using the FOCUS head form. Alphonse et al. have used the head form to study eye injury resulting from fireworks and Duma et al. used the head form to study risk of injury from different types of impact, including water streams and high speed projectiles [58,60,68-71]. The FOCUS head form has been used in portions of studies conducted by Weaver et al. on modeling the human eye orbit [72-74]. Much of the continuing research on eye orbit anthropometry may be incorporated into future iterations of the FOCUS head form.

It is important to note that because of the particular technological features and geometrical properties of each of the different head forms, they cannot be considered interchangeable. Careful consideration of the biomechanical features of the system to be tested is necessary in choosing the ideal head form for any study of head and mild traumatic brain injury mechanisms.

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