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Every Newton Hertz: A Macro to Micro Approach to Investigating Brain Injury

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Abstract— **The high incidence of concussion in contact sports provides a unique opportunity to collect data to characterize mild traumatic brain injury. This paper outlines a macro to micro approach in which the organ level response of the head is analyzed through head acceleration data from human volunteers and the tissue level response is analyzed through finite element analysis of these data. The helmets of Virginia Tech football players are instrumented with multi-accelerometer measurement devices to record linear and rotational head accelerations for every impact during a game or practice. These impacts are then modeled using the Simulated Injury Monitor (SIMon) finite element head model. Cumulative strain damage measure was investigated for the impacts resulting in the high linear and rotational accelerations. The effect of head impacts on functional performance in football players is also investigated to identify any cognitive effects from repetitive sub-concussive impacts. A better understanding of the effects of head impacts and the mechanisms of brain injury will likely result in insight to future head injury prevention methods and cellular research on brain injury.**

I. Introduction

An estimated 1.6 to 3.8 million sports-related concussions occur annually in the United States [1]. The high incidence of concussions in contact sports, particularly American football, has gained the attention of scientists as a potential research avenue to investigate the biomechanical mechanisms and pathomechanics of concussions in humans. The archetypal thought of such research is: by observing a population that is at high risk for concussion, data characterizing concussion can be obtained in a natural and ethically sound manner. Several injury metrics are used to predict head injury. These injury metrics are primarily derived from cadaver tests with skull fractures and animal tests with primates and dogs [2, 3]. Optimally, these metrics would be based on data from human volunteers. Using recently developed technology, Head Impact Telemetry System (HITS) (Simbex, Lebanon, NH), several researchers have instrumented the helmets of collegiate and high school football players with a six accelerometer measurement device that measures linear head acceleration for every head impact a player experiences [4-7]. Greenwald et al. (2008) compiled data collected from 13 institutions, which resulted in a dataset comprised of over 289,000 head impacts that included 17 concussions [8]. Using a subset of these data collected from Virginia Tech, Funk et al. (2007) created injury risk curves to assess the risk of mild traumatic brain injury for a given head acceleration [9]. A dataset comprising of more concussions is needed to create more accurate injury risk estimates for wide-spread acceptance in academia and industry. While these studies offer promising insight to the effect of linear acceleration on the brain, they are limited by their inability to capture the rotational kinematics of the head, which are thought by many to be the main mechanism of brain injury [10]. Improvement of this technology was warranted to capture the complete linear and rotational responses of the head.

The purpose of this paper is to highlight the current interdisciplinary work being done at Virginia Tech to biomechanically characterize the effect of head impacts in football on the brain. A macro to micro approach is utilized in which the kinematics of the head are investigated at the organ level and the resulting stresses and strains on the brain at the tissue level. In addition to the organ-level and tissue-level responses from head impact, the cognitive effects of these impacts are also investigated. A better understanding of the effects of head impacts and the mechanisms of brain injury will likely result in insight for future head injury prevention methods and cellular research on brain injury.

II. Methodology

Linear head acceleration data collection continues at Virginia Tech using the commercially available HIT system (Simbex, Lebanon, NH). Currently, the helmets of 64 Virginia Tech football players are instrumented with this measurement device. The device consists of 6 accelerometers that are spring mounted so that they remain in contact with the head at all times, ensuring that head acceleration and not helmet acceleration is measured [11]. The device is designed to fit into the free space of Riddell (Elyria, OH) football helmets. Players are instrumented for every game and practice. Any time a helmet impact results in an accelerometer measuring 10 g or greater, data

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acquisition is triggered and the data are wirelessly downloaded to a computer on the sideline. Each player that participated in the study gave written informed consent with Institutional Review Board approval from both Virginia Tech and the Edward Via College of Osteopathic Medicine. Injuries are diagnosed by the Virginia Tech football team physician. This summarized methodology is described in great detail by Duma et al. (2005) [4]. With each concussion, neuropsychological tests are given to the player to measure functional deficiencies resulting from the concussive impact.

Furthermore, a custom 6 degree of freedom (6DOF) head acceleration measurement device has been developed by Simbex (Lebanon, NH) and validated at Virginia Tech that is capable of measuring linear and rotational acceleration about each axis of the head. The measurement device is unique in that it consists of 12 accelerometers with sensing axes that are oriented tangentially to the skull. This results in the centripetal acceleration term being negligible when calculating rotational acceleration, resulting in an analytical solution. The 6DOF device is designed to be integrated into existing Riddell Revolution football helmets. The 6DOF device's padding serves as a spring to keep the accelerometers in contact with the head at all times to ensure that head acceleration is measured. The helmets of 9 Virginia Tech football players are currently instrumented with the 6DOF device. The measurement device and data collections methods are described in greater detail by Rowson et al. (2009) [12].

While the linear and rotational accelerations give insight to the organ-level response of such impacts, computational modeling can be used to determine the tissue-level response. The Simulated Injury Monitor (SIMon) is a finite element head model that consists of the rigid skull, the dura-CSF layer, the brain, the falx cerebri, and the bridging veins [13]. Since the time histories of linear and rotational acceleration for each impact are known when data are collected with the 6DOF device, skull acceleration can be used as input to SIMon. Any impacts with accelerations greater than the nominal injury values (80 g or 6000 rad/s^2) reported in previous studies were modeled using SIMon [14, 15]. Cumulative strain damage measure (CSDM) reports the volume of the brain that has exceeded a specified strain threshold. CSDM with a strain threshold of 0.15 in SIMon has been shown to correlate strongly with concussion, and therefore was used to determine the probability of concussion for each of the selected impacts [13].

In addition to the effects of concussive impacts, the effects of sub-concussive impacts are being studied using a natural dataset and biomechanical measures. The football coaching staff reviews film and evaluates each player's performance on the field. Evaluations involve grading a participant based on specific criteria in the form of points. In general, points were awarded for good plays/decisions and deducted for poor plays/decisions. A relatively low number of points would translate into an overall poor in-game performance, while a relatively high number of points would translate into an overall good in-game performance. Overall grades were determined for each player for each game. We hypothesize that differences in a player's functional performance in the field can be affected by impacts that are not diagnosed with injury. These performance data are being correlated with biomechanical parameters derived from head acceleration data collected with HITS using non-parametric statistical analyses. The methods used for these correlations are described in detail by Rowson et al. (2009) [16]. Using these methods, correlations for 3 players over a range of 11 to 19 games were computed. Only defensive players were considered for this analysis due to a more detailed performance evaluation from the coaching staff compared to the offensive players. These players were each of different defensive positions and had the most overlap between head impact data and performance data.

III. Results

Linear head acceleration data from Virginia Tech has been collected every football season from 2003 to 2008. The resulting dataset consists of 71,300 head impacts. Of these impacts, 6 were concussive. Figure 1 displays the cumulative distribution of head impacts by peak resultant linear acceleration. Impacts ranged from 10 g to 227 g and the median resultant linear acceleration recorded is 19 g. Concussive impacts are denoted by the vertical lines on the plot, which were 73 g, 81 g, 129 g, 139 g, 172 g, and 200 g.

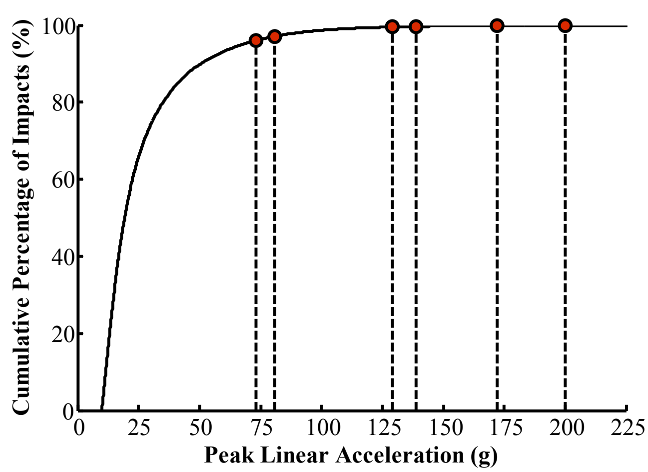

Figure 1: Cumulative distribution of impacts.

While HITS has been used to collect linear acceleration data for head impacts for six years, the 6DOF device has only recently been developed and has been used to collect data for the 2007 and 2008 football seasons. The resulting 6DOF dataset consists of a total of 4,709 impacts. Figure 2 displays the cumulative impact distribution for peak resultant linear acceleration. Impacts ranged from 9 g to 149 g and the median peak linear acceleration recorded is 17 g.

No 6DOF device instrumented player sustained a concussion during the 2007 or 2008 season.

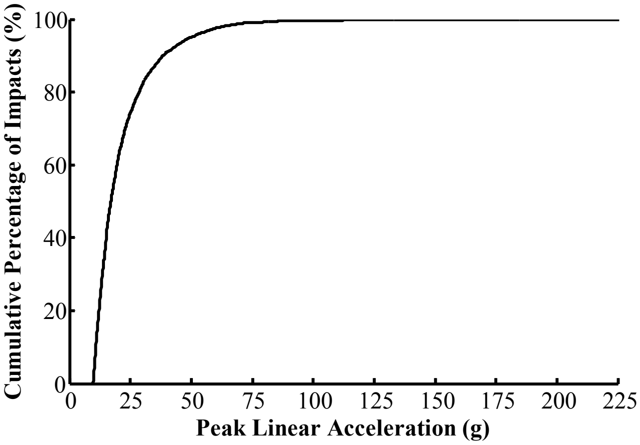

Figure 2: Cumulative impact distribution for 6DOF linear acceleration.

Figure 3 displays the cumulative impact distribution for peak resultant rotational acceleration. Rotational accelerations ranged from 107 rad/s^2 to 10,222 rad/s^2 and the median rotational head acceleration recorded is 931 rad/s^2.

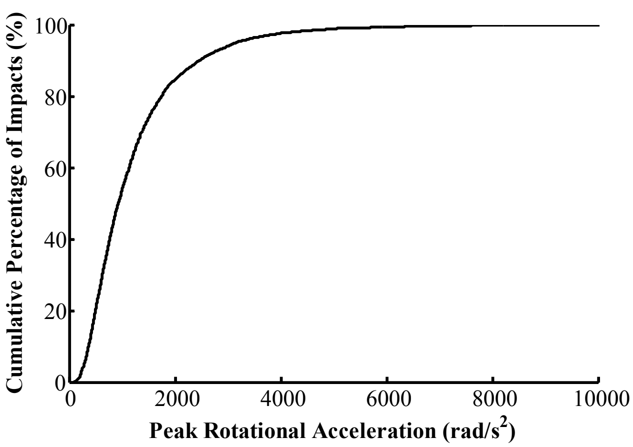

Figure 3: Cumulative impact distribution for 6DOF rotational acceleration.

Table 1 displays the impact percentiles taken from cumulative impact distributions for the HITS device peak linear acceleration, 6DOF device peak linear acceleration, and 6DOF device peak rotational acceleration.

TABLE I

IMPACT ACCELERATION PERCENTILES

	HITS (g)	**6DOF (g)**	**6DOF (rad/s^2)**
25%	14	13	566
50%	19	17	931
75%	31	26	1537
90%	51	39	2478

While no concussive impacts were recorded in the 6DOF datasets, these impacts could be analyzed at the tissue level through finite element analysis using SIMon. A total of 24 head impacts were modeled and the probability of concussion analyzed through a CDSM (strain = 0.15) analysis. Table 2 presents the results of the 10 impacts that resulted in the highest probability of concussion.

TABLE II

KINEMATICS OF THE MODELED IMPACTS.

Linear Acceleration (g)	**Rotational Acceleration (rad/s^2)**	**CSDM**	**Probability of Concussion**
21	6352	7.9%	**7%**
19	6446	8.5%	**7%**
35	6870	12.4%	**8%**
36	8427	16.4%	**10%**
36	7034	17.4%	**11%**
26	6783	19.6%	**12%**
84	9919	23.4%	**14%**
39	8709	35.3%	**25%**
32	8863	35.0%	**25%**
35	5824	39.1%	**29%**

Player performance data was compiled for a linebacker, defensive back, and defensive lineman over the course of 11, 18 and 19 games, respectively. Through non-parametric statistical analysis, no statistically significant correlations with any head impact measures were found.

IV. DISCUSSION

Over 76,000 head impacts were recorded using helmet instrumentation through 6 years of data collection. Over these impacts, 6 were concussive ranging from 73 g to 200 g in magnitude. Compiling a large concussive biomechanical database will take some time seeing that Virginia Tech is averaging one recorded concussion per year. Although this is a long process, valuable information is being compiled on human tolerance to acceleration. Over 50% of these impacts are of very low severity (< 20 g), with only the top 10% of impacts being greater than 50 g. However, it seems that human tolerance to head acceleration may be greater than previously thought.

The HITS device and 6DOF device display similar distributions of peak linear acceleration. However, it is noticeable that the HITS device recorded more high severity impacts, as seen with the impact acceleration percentiles. This is a result of the players that were instrumented with each measurement device. The HITS device was instrumented in the helmets of both lineman and skill players, while the 6DOF device was only installed in the helmets of lineman due to the device's large size. We believe this difference is a positional effect in the data, as skill players are typically exposed to greater severity impacts. Using this inference, we can hypothesize that the rotational accelerations in skill players may be slightly higher than what is reported in this paper.

With regards to injury risk, previously published logistic regressions of the dummy reconstructions produced injury thresholds of 79-82 g and 5757-5900 rad/s^2 representing 50% risk of concussion [10, 15]. Less conservative injury thresholds that were based on head impact data from human volunteers defined 165 g and 9000 rad/s^2 as representing 10% risk of concussion [9]; however, these values are a result of a limited injury dataset and estimated rotational accelerations. Other studies reported rotational injury thresholds of 4500 rad/s^2 to 16,000 rad/s^2. Although we have not collected enough data to create our own injury risk thresholds, our injuries fall within the extremes of the previously reported thresholds. The advantage to the dataset we are creating is that it is large and unbiased since every head impact a player experiences during a season is recorded. This should result in an improvement in the predictive capabilities for concussion.

An interesting component of this study is the finite element analysis of head accelerations at potentially injurious severities from human volunteers. When looking at these data, increase in rotational acceleration seems to correlate with probability of concussion more than increase in linear acceleration. This is most likely an artifact of the model used. CSDM is a strain based injury metric which is very sensitive to rotational acceleration due to the injury data it is validated against. From looking at the CSDM-predicted probabilities of concussion, the maximum likelihood of any impact for concussion was 29%. Seeing that only 3 impacts had a greater than 20% predicted risk of injury, SIMon agrees with the 6DOF data not including a concussion. Modeling such impacts using more advanced models may give further insight to the tissue-level response of the brain to impact.

While no statistically significant correlation was found between repetitive head impacts and player performance, we believe this topic warrants further research. Correlations were only investigated using the raw performance stats from the coaching staff for each player. Perhaps a more detailed performance grading procedure will give further insight. This may include position specific grading criteria or separate analysis of the learning domains. This is a topic we will investigate further.

V. Conclusions

In this paper our current methods for investigating mild traumatic brain injury are presented along with our current results. Head impacts at potentially injurious severities in human volunteers are being recorded and analyzed. The dataset is large and unbiased and may improve upon the current predictive capabilities of injury risk. The 6 degree of freedom data has the unique ability to be modeled using finite element analysis. Doing so results in computation of the stresses and strains in the brain as a result of impact, which may be better predictors of brain injury than the kinematics of the skull. Such research is considered a promising avenue in the investigation of brain injury.

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