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Six Degree of Freedom Head Acceleration Measurements in Football Players

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ABSTRACT

The existing five degree of freedom HITS sensor used to measure head accelerations is incapable of measuring rotational head acceleration about the z-axis. A new six degree of freedom (6DOF) sensor has been developed capable of measuring linear and rotational accelerations for each axis. The 6DOF sensor consists of 12 accelerometers that integrate into football helmets and communicate wirelessly with a laptop on the sideline. An estimation algorithm processes the data from the 12 accelerometers to determine linear and rotational accelerations. The newly developed sensor is capable of accurately recording linear and rotational head accelerations experienced by football players. Twenty (20) players on the Virginia Tech football team will be instrumented with 6DOF sensors during the 2007 season.

INTRODUCTION

Each year, there are approximately 1.5 million traumatic brain injuries in the United States (Thurman et al., 1999); 75% of which are mild traumatic brain injuries (MTBI) (Sosin et al., 1996). About 300,000 of these concussions are sustained by athletes playing contact sports, with football having the largest occurrence (Thurman et al., 1998). The high incidence rate of concussions in football provides a unique opportunity to collect biomechanical data to characterize MTBI. Several injury metrics are used to predict head injury; however, all the criteria use limited data from human volunteers. Head injury criterion (HIC), peak acceleration, and severity index (SI) are injury metrics derived from linear head acceleration and are primarily based on cadaver tests with skull fractures. Rotational acceleration injury thresholds are based mostly on primate tests with severe concussion, diffuse axonal injury (DAI), or intracranial bleed.

One study has quantified head accelerations experienced by football players by recreating concussive impacts. The National Football League (NFL) reconstructed injurious game impacts using Hybrid III dummies based on game video (Pellman et al., 2003). The authors recreated 31 impacts, 25 of which were concussive. From the data collected in the reconstructed impacts, injury risk curves were developed for MTBI. Nominal injury values determined in this study were a peak linear acceleration of 80 g, SI of 300, HIC of 250, and peak rotational acceleration of 6000 rad/s^2. These values are too conservative because the NFL data is intentionally biased towards injurious impacts.

Another study has quantified head accelerations by instrumenting helmets worn by collegiate football players (Duma et al., 2005). In this study, a six accelerometer sensor was integrated into football helmets. These sensors recorded linear head acceleration for every head impact a player experienced, producing an unbiased dataset. Over 27,000 head impacts were recorded over 4 seasons, 4 of which were concussive. Although there is a limited injury dataset, this study gives insight to the lower limits of human tolerance to head acceleration. Using a unique statistical analysis on this data, injury risk curves were developed (Funk et al., 2007). The nominal injury values reported were a peak linear acceleration of 165 g and HIC of 400. These values are higher than the NFL injury values because the unbiased dataset included many high-g impacts that did not result in concussion. The main limitation of this study is that angular acceleration was not directly measured by the 6 accelerometer sensor.

The 6 accelerometer sensor used by Duma et al. (2005) is part of the Head Impact Telemetry System (HITS), developed by Simbex, LLC (Lebanon, NH). The HITS sensor consists of 6 nonorthogonally mounted single-axis accelerometers which are positioned normally to the head. The packaging of the accelerometers includes an integrated radio board that communicates wirelessly with a computer on the sideline. Each time an impact occurs, data is transmitted from the sensor to the computer, which processes and displays data in real-time. HITS utilizes a novel algorithm for determining impact magnitude and direction (Crisco et al., 2004). This algorithm is capable of calculating x, y, and z linear acceleration. HITS also estimates x and y rotational acceleration, but cannot completely model the head kinematics due to an unknown z rotational acceleration. This sensor is referred to as having five degrees of freedom (5DOF).

In order to collect data from football players capable of accurately characterizing MTBI, a sensor with the ability of measuring x, y, and z linear and angular acceleration needed to be developed. The goal of the current study is to utilize a newly developed six degree of freedom sensor to record head accelerations experienced by collegiate football players during all concussive and non-concussive impacts, resulting in a large, unbiased dataset.

METHODS

For this study, a six degree of freedom (6DOF) sensor that can be integrated into existing Riddell (Elyria, OH) football helmets was developed. This sensor consists of 12 accelerometers and is capable of measuring x, y, and z axis linear and angular accelerations. 20 Virginia Tech football players were instrumented for the 2007 season and head impact data was collected for every game and practice.

Hardware

The 6DOF sensor is designed to be integrated into Riddell Revolution football helmets. The sensor is composed of two major pieces: vinyl casing and fabric padding. Velcro is used to attach the vinyl casing of the sensor to the helmet between its padding. The vinyl casing serves as the housing for all the electronics except the accelerometers. The fabric pad contains the accelerometers inside. Twelve (12) accelerometers are enclosed in the fabric padding, positioned in orthogonally oriented pairs at 6 different locations (Figure 1). The fabric pad also serves as a spring to keep the accelerometers in contact with the head. When the helmet is impacted, the padding inside the helmet compresses and the helmet shifts positions on the head. However, the fabric pad containing the accelerometers either compresses or expands to remain in contact with the player's head.

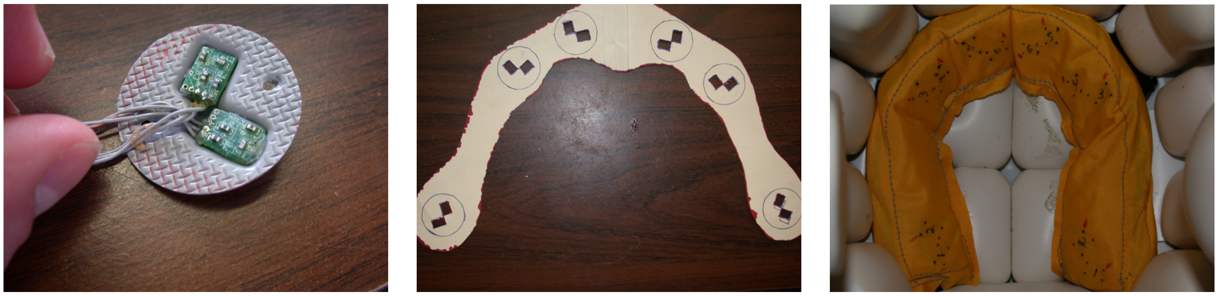

Figure 1: Each pair of accelerometers is oriented orthogonally to one another (left). The pairs of accelerometers are secured in 6 locations (center). The prototype (right) displays the locations of the accelerometers in the padding when installed in the helmet.

The 6DOF sensor utilizes single-axis, high-g iMEMS accelerometers (ADXL193, Analog Devices, Norwood, MA). Data acquisition is triggered when any accelerometer exceeds 10 g. Data is collected for 40 ms at 1000 Hz, of which 12 ms are pre-trigger and 28 ms are post-trigger. After each impact is recorded, the data is sent to a computer on the sideline via a 903-927 MHz wireless transceiver. If communication cannot be established with the sideline computer, the sensor has enough memory to store up to 120 impacts. Stored impacts are transmitted to the computer once communication is reestablished. Figure 2 displays the 6DOF sensor installed in the helmet.

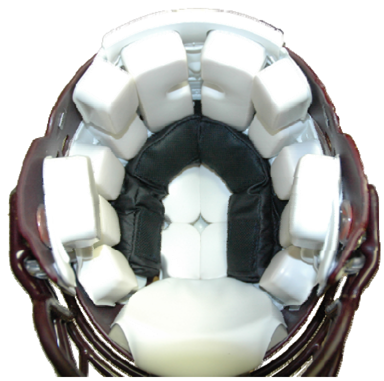

Figure 2: 6DOF sensor installed in a Riddell Revolution helmet.

Algorithm

The algorithm uses rigid body dynamics to solve for linear and resultant acceleration of the head center of gravity (CG). Equation 1 sums the linear and rotational accelerations to calculate what each accelerometer should be reading. $\|a_i\|$ is the acceleration magnitude at each individual accelerometer, $\overrightarrow{r_{ai}}$ is the orientation of the sensing axis of each accelerometer, $\overrightarrow{H}$ is the head CG linear acceleration, $\overrightarrow{\alpha}$ is angular acceleration about the head CG, $\overrightarrow{r_i}$ is the accelerometer location relative to the head CG, and $\overrightarrow{\omega_i}$ is the angular velocity about the head CG.

$$\|a_i\| = \overrightarrow{r_{ai}} \bullet \overrightarrow{H} + \overrightarrow{r_{ai}} \bullet \left(\overrightarrow{\alpha} \times \overrightarrow{r_i}\right) + \overrightarrow{r_{ai}} \bullet \left(\overrightarrow{\omega_i} \times \left(\overrightarrow{\omega_i} \times \overrightarrow{r_i}\right)\right) \quad (1)$$

Since the accelerometers are oriented tangentially to the head CG, the centripetal acceleration term of Equation 1 cancels out, simplifying to Equation 2. Removing $\overrightarrow{\omega_i}$ simplifies the equation from a nonlinear differential equation to an equation that can be solved algebraically.

$$\|a_i\| = \overrightarrow{r_{ai}} \bullet \overrightarrow{H} + \overrightarrow{r_{ai}} \bullet \left(\overrightarrow{\alpha} \times \overrightarrow{r_i}\right) \tag{2}$$

Since 12 accelerometers are in the sensor, the solution can be optimized. The algorithm uses an iterative optimization approach to solve for linear and angular acceleration (Chu et al., 2006).

Data Collection

For the 2007 Virginia Tech football season, 20 helmets were instrumented with the 6DOF sensor. For each game and practice, the HITS computer was setup on the sideline, and the 6DOF sensors communicated with the computer, sending data throughout that day's session. Each measured impact is time-stamped so that it can be matched with video footage. Duma et al. (2005) describe the data collection methodology in greater detail.

RESULTS

The data presented in this paper is preliminary data collected during practices and games for 16 players between August 1, 2007 and October 19, 2007. A total of 740 impacts were recorded above 20 g, with the large majority of impacts below 40 g in severity, as shown in Figure 3.

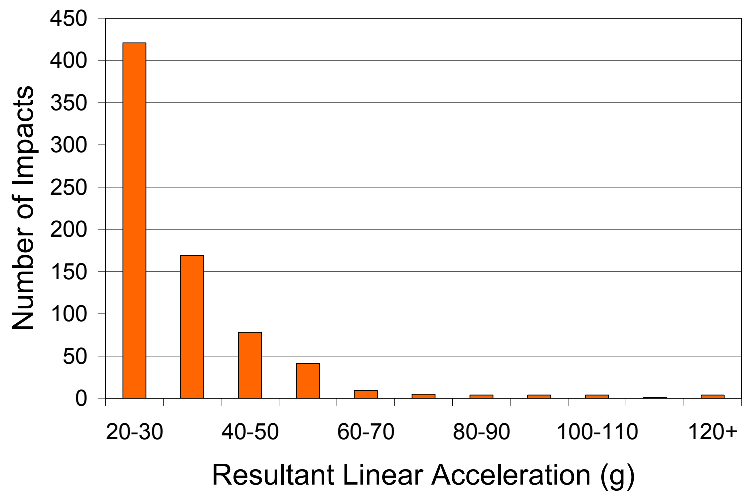

Figure 3: Histogram of resultant linear accelerations experienced by 6DOF instrumented players.

Figure 4 compares the 6DOF data collected this season with 5DOF data collected between 2003 and 2006. A similar distribution of impacts can be seen between the 5DOF and 6DOF data.

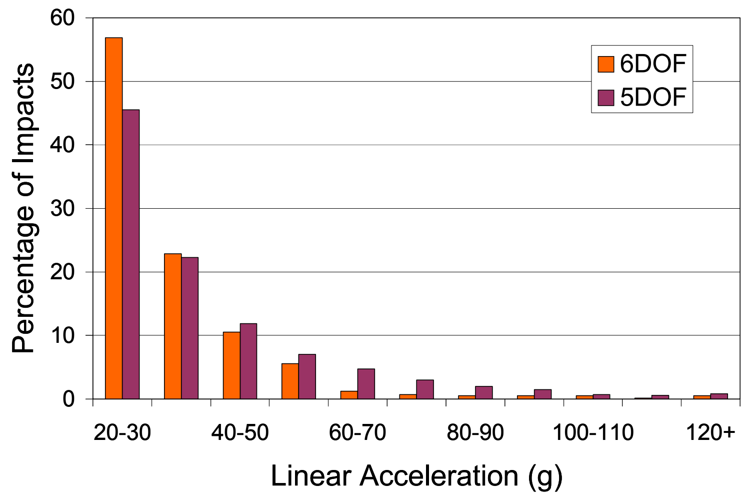

Figure 4: Comparison of the distribution of resultant linear accelerations collected by 6DOF and 5DOF sensors.

Figure 5 displays a histogram of the resultant rotational accelerations recorded with the 6DOF sensor. The majority of these impacts had resultant rotational accelerations less than 3000 rad/s^2. However, a number of impacts were recorded with angular accelerations greater than 6000 rad/s^2. To date, no injury has been recorded with a 6DOF sensor.

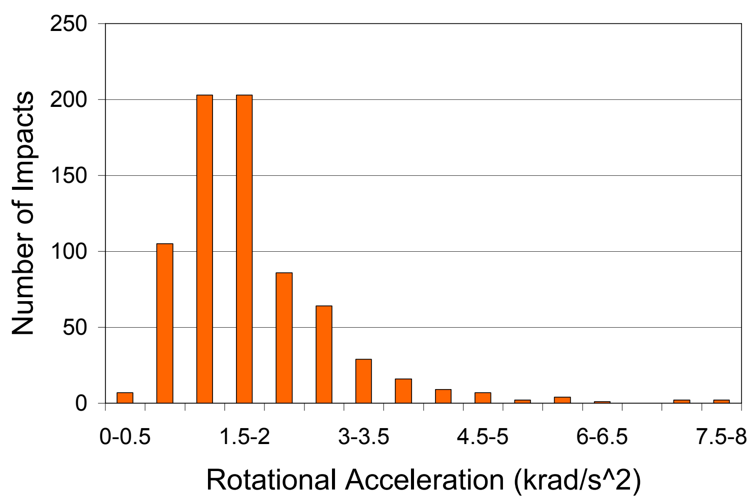

Figure 5: Histogram of resultant rotational accelerations experienced by 6DOF instrumented players.

CONCLUSIONS

A 6DOF sensor has been developed that can be used to measure linear and angular accelerations experienced by football players. For the 2007 Virginia Tech football season, 20 players were instrumented with the 6DOF sensor. Data collection over the next several years will produce a large, unbiased dataset including non-injury and concussive impacts. The data collected in this study will have applications beyond football, such as determining MTBI tolerance levels in humans.

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DISCUSSION

PAPER: **Six Degree of Freedom Head Acceleration Measurements in Football Players**

PRESENTER: ***Steve Rowson, Virginia Tech – Wake Forest Center for Injury Biomechanics***

QUESTION: *Guy Nusholtz, DaimlerChrysler*
Have you thought of trying to develop a mapping that goes from what you see in your accelerometers—your 12-accelerometer array—and what you see in the dummy or is it primarily a random difference between the two? The two curves that you showed looked like they were fairly repeatable. And in addition, have you considered that there might be a difference between the human and the Hybrid III in terms of a mapping?

ANSWER: We haven't looked at anything between the human and the Hybrid III, but the hit sensors—the six-degrees-of-freedom is designed to predict Hybrid III acceleration and we're making an assumption that the head masks in the helmets are that of the Hybrid III.

Q: Okay. And I notice in the last slide, you had a disclaimer. So you haven't thought of doing a mapping. I guess that's the answer to the first part of the question.

A: Right.

Q: Okay. In the last slide, you sort of had a disclaimer that this may have applications only on the football field. Are you also looking at the time histories? Because I think the time histories are going to be much longer than what we might see in an automotive and the complexity of that particular type of motion might be such that you might be able to describe it simply with a single level descriptor, such as you're using peak acceleration. I recognize that you're going to try and run it through SIMon and use that as your method of predicting whether they get a concussion or not. Is that basically the approach you're using? Because I think you're going to have very complicated time histories.

A: It's possible. I haven't looked into it too much, but we will be using SIMon to do that.

Q: Okay. So, then you—Have you attempted to validate SIMon over those complicated type of motions?

A: No, we haven't gotten that far yet.

Q: Okay. Thank you.

A: Thank you.

Q: *Gunter Siegmund, MEA Forensic*
I have a bit of a follow-up there on what Guy was saying. It strikes me that the interface between a Hybrid III and its helmet would be very different between the interface between a sweaty footballer's head and this helmet. How much slipping, particularly rotationally, do you see or can you see when these things are used on the field?

A: We have nearly quantified what the football players, I guess, lack of friction in the helmet with their head is. But with the Hybrid III in the testing, we put pretty much the equivalent of a stocking over the head because there's a very high friction coefficient with the helmet and the Hybrid III head. So the helmet is able to move somewhat on the Hybrid III head and some of these players wear the same thing on their head. It's pretty much a skullcap that we put on the Hybrid III dummy that's nylon. So for some players, it's going to have a very similar friction coefficient between them.

Q: Thank you.

Q: *Pat Kaiker, retired, Chrysler*
Did you mention, and maybe I missed it, whether, in your database for how the total number for individuals, did people in a game get more than one recording of head impact? And, have you filtered

your data? If so, did you filter your data out to account for, maybe, changes in the helmet? Or, did you change the foam between impact?

A: The foam doesn't need to be changed. Are you asking if it's only good for one impact?

Q: Yes. Usually, the kind of experiments we used to do back in the day when I was a baby, we always used fresh material in the labs between each test to not worry about changes in material properties and be sure that we had clear measurements. And I just wondered: In your database, besides data, if you're pretty confident that you're not seeing changes in your foam that you have to worry about, did you have—take for each player maybe three hits in a game? Did you check your instrumentation between hits?

A: A lot of times, you see over 10 hits per player per game that are fairly significant. Football player helmets are kind of designed so that they have the same response throughout numerous impacts. It's not like a one-time impact. So, a lot of these players wear the same helmet throughout the whole season. And for our testing on our Hybrid III, we used the same helmet. And throughout these tests for the same impacts, whether it's in the beginning or the end, you see similar head accelerations for the Hybrid III so it shouldn't really affect the response of the sensor.

Q: Okay. I was more interested in the foam your sensors were imbedded in between the helmet and the human or the dummy.

A: Ah, the foam. The foam in the sensor doesn't get changed either. It's assumed to have repeated elastic properties where it won't have memory, should I say.

Q: Okay. So you don't see any degradation in that?

A: No.

Q: Have you looked?

A: We haven't looked at that.

Q: Okay.

A: It's a good idea.

Q: *Jeff Crandall, University of Virginia*
Interesting. I had a question on the accelerations. Are those translated to the CG of the head?

A: Yes.

Q: So for each player, you do a custom location of where the accelerometers are located for that player?

A: Well, for the six-degrees-of-freedom sensor or the five-degree? Because the five-degree-of-freedom sensor—

Q: For the new one: the six degrees of freedom.

A: For six degrees of freedom, they're assumed to be in the same location of a person's head for each sensor. So, it's not customly fit for each player.

Q: Because you had pretty high, sort of, centripetal or rotational effects. So I think if you had one player that was pushing, say, statically out or in on those sensors, you'd have different distances.

A: Yes.

Q: So they could influence your accelerations at the CG.

A: That's good. We haven't looked at, say, the effect of different players' head sizes at this point.