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Analysis of an Unexpected Impact to the Crown of the Head

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Abstract: High levels of head acceleration associated with impacts to the head have been extensively studied in the area of sport and are a known mechanism for concussion and/or traumatic brain injury (TBI). Despite widespread research and investigation, there is no established threshold or clear criterion for injury prediction as a result of head impacts in the domain of sport or otherwise. Unexpected head impacts also occur in non-sports-related environments such as construction sites, public places, and shopping centers with no ability to assign risk or likelihood of TBI.

The following investigation is related to an incident that was captured on video surveillance and allegedly caused TBI. Laboratory testing with human volunteers was conducted and head accelerations associated with low-level, non-injurious impacts to the crown of the head were quantified. This data was compared to similar head acceleration data in the literature that resulted from impacts to the forehead. Whole body reactive motions of the volunteers were observed and compared with general motions exhibited in the surveillance video. The two primary outcomes of this preliminary study were the acquisition of linear head acceleration data related to non-injurious blows to the crown of the head and a better understanding of the natural, whole body response to unexpected head impacts.

Keywords: Brain Injury, Head Imapct, Whole Body Kinematics

1. Introduction

The occurrence of concussion in the sport of football and the corresponding immedicate and potential long-term effects of concussion on the players has received an increasing amount of attention in recent years. There exists a multitude of data that relate events to measured and recorded linear and angular head acceleration values (Broglio, 2010; Crisco, 2012; Rowson, 2009; Pellman, 2003; Duma, 2005; Urban, 2013; Daniel, 2014; Greenwald, 2008; Forbes, 2012; etc.). Despite the plethora of studies and published data that includes tens of thousands of recorded events, there is no universally accepted threshold level of head acceleration that is associated with the occurrence of TBI. However, in these studies, head impacts correlated with concussion or head injury (injurious events) have not been associated with linear head accelerations lower than about 70 g.

Non-injurious head impacts have also been studied and quantified in terms of levels of linear and angular head accelerations (Funk, 2011; Vijayakumar, 2006; Naunheim, 2003). These impacts are thought to be non-injurious because they could be encountered by the general population during everyday activities and/or experienced frequently by athletes such as soccer players. Levels of measured linear head accelerations associated with non-inurious impacts does not typically exceed approximately 21 g. Clearly there is a large “gray” area that exists between non-injurious and injurious impacts.

This particular investigation is related to an incident that was captured on video surveillance and allegedly caused TBI when an individual was struck on the top of the head by an undetermined amount of snow/ice mixture that fell from an unknown height. The challenge was to categorize this impact into one of the three (non-injurious, questionable, or injurious) regions of head acceleration, despite having no objective data from the incident other than depiction in the low resolution video surveillance. While we were unable to use the surveillance video in combination with scaling or other photogrometric tools in order to discern a speed or size of the alledged striking object, the video did reveal the gross whole body motions of the individual during the time of the alleged impact.

The purpose of this study was first to augment the body of existing literature with the quantification of linear head accelerations that result as a consequence of non-injurious ball impacts to the head. The novelty of this investigation is that the ball impacts were to the crown of the head as opposed to current soccer ball heading literature that is limited to impacts to the forehead region. It was our hypothesis that an impact to the crown of the head would not result in a significantly higher level of head center of gravity linear acceleration than a similar impact to the forehead. The second purpose of this study was to gain a better understanding of the natural whole body response to unexpected head impacts by the analysis of both the video surveillance footage and also the captured video footage of the volunteer testing.

2. Methods

This study was conducted in the laboratory facilities of Engineering Systems Inc. in Ann Arbor, Michigan. The eight study subjects (5 male and 3 female) ranged in age from 18 to 54 years and in height from 170 to 184 cm (5'6" to 6' ½"). Adjustable fabric elastic was used to secure 2 tri-axial accelerometers to subjects' heads, one on each side of the head and approximately in line with the head's center of gravity (Beier, 1979). Assuming that the head is symmetrical about its mid-sagittal plane and that the two accelerometers are rigidly linked, the linear acceleration of the head's center of gravity can be approximated as the mean of the linear accelerations of the two accelerometers. Acceleration data was sampled at 10,000 Hz; a 2 g rollover calibration test was completed at the start of testing. The tri-axial acceleration data was transformed such that the positive X-axis was directed forward, the Y-axis to the left, and the Z-axis upward. A 4^{th} order Butterworth filter with low-pass frequency of 100 Hz was applied to the data. Component acceleration as well as resultant traces and peak acceleration values calculated at the subject head centers of gravity were examined; the peak resultant acceleration was calculated for each impact.

Subjects were exposed to series of controlled head impacts that consisted of 6 balls falling from a specified height of approximately 4.1 m (13'6") above the floor onto the crown of the subject's head. The ball speed at impact as calculated via a basic fall equation was dependent on subject height and ranged from 6.67 to 6.87 m/s (22.0 to 22.6 ft/s). During each series, two regulation size volleyballs, followed by a regulation size 5 soccer ball, another volleyball, and finally another soccer ball were dropped onto the top of the subjects' heads. The average weight of the volleyballs and soccer balls was 271 and 429 grams, respectively; all balls were inflated to a pressure of 9 psi for the duration of the testing. Subjects were asked to stand in an open-gait stance with their right foot forward. Subjects underwent at least a single series of impacts to the crown of their head and up to no more than three series of impacts.

While subjects of the study knew generally that they would be experiencing ball impacts to the head, efforts were made in order to conceal the exact timing of the controlled impacts. During the testing, the time interval between impacts was inconsistent and unpredictable to the subject. Additionally, subjects were asked to close their eyes and listen to music via earphones in an attempt to make them as unaware as possible of the timing of the impending impacts. The purposely-limited audible and visual sensory information prohibited external cues to signify an impending drop.

In addition to observations made by researchers during the testing, video footage was recorded from two vantage points for the duration of the testing. The first video camera (1) was positioned at the front of the testing area, allowing for a straight-on view of the subjects. A second video camera (2) was positioned perpendicular to the first video camera and perpendicular to what would be the subjects' direction of travel. Figure 1 illustrates an example of a recorded impact to the head recorded by camera (2).

Figure 1. Exemplar volleyball impact.

Prior to the testing, subjects were appropriately notified of the nature of the testing, namely that objects would be dropped onto their heads. However, one of the main purposes of this study was to observe and identify the response to a completely unexpected impact to the head. Subjects would expect the head impacts to occur in the well-controlled laboratory environment. Therefore, the researchers made a single attempt to achieve a completely unanticipated, “surprise” head impact while subjects walked to the testing area. Head acceleration levels were recorded and a single “hidden” camera was positioned approximately directly in front of the subjects’ paths to document the attempt.

3. Results

Six of the seven subjects reported experiencing no symptoms immediately after completion of the study. One of the subjects reported minor transient discomfort on the crown of the head due to the direct contact between the ball and his head, which resolved within minutes without any medical treatment. A follow-up survey of subjects approximately 10 days after completion of the study was performed with subjects reporting no additional symptoms.

3.1 Controlled Impacts

A total of 104 controlled impacts to the crown of the head were recorded during testing; 68 impacts from volleyballs and 36 impacts from soccer balls. The head center of gravity average peak resultant linear acceleration as a result of the volleyball and soccer ball impacts was 3.9 $\pm$ 0.7 g and 5.6 $\pm$ 1.3 g, with peak ranges of 1.9-7.6 g and 3.7-7.8 g, respectively. Figures 2-4 below summarize the peak resultant head acceleration findings for all subjects by ball type. Due to the heavier average weight of the soccer balls compared to the volleyballs, it was anticipated that the peak linear resultant acceleration of the head center of gravity would be greater for the soccer ball impacts. The measured acceleration during the testing was consistent with that expectation; a simple t-test revealed that the head accelerations associated with the soccer ball impacts were significantly ($p < 0.0$) greater than the head accelerations associated with volleyball impacts.

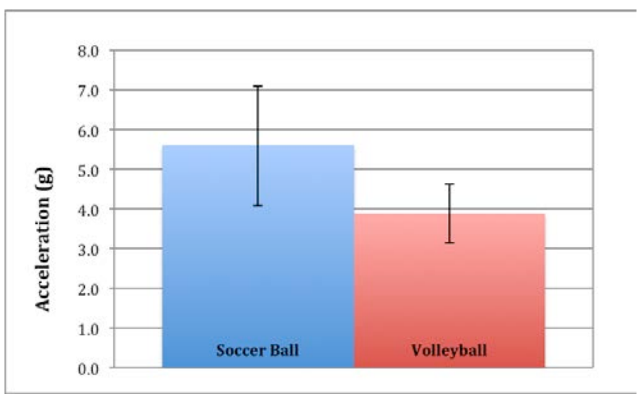

Figure 2. Ave. Peak Resultant Head Accel.; Error Bars Represent $\pm$ SD.

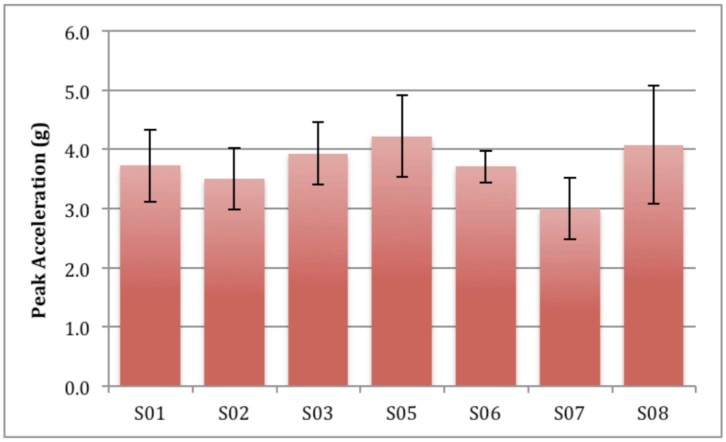

Figure 3. Ave. Peak Resultant Head Accel. for Volleyball Impacts; Error Bars Represent ± SD.

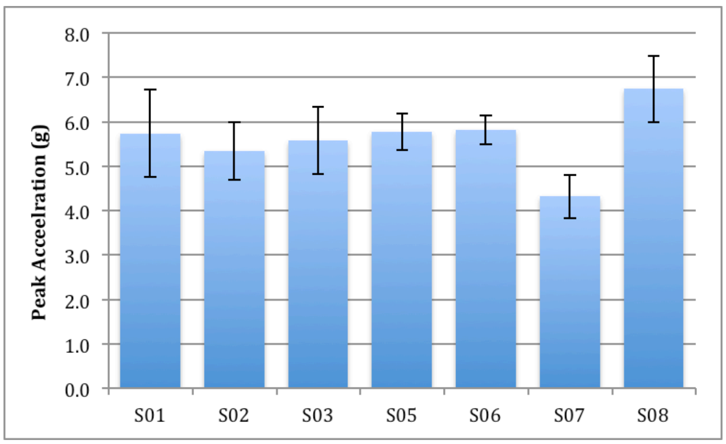

Figure 4. Ave. Peak Resultant Head Accel. for Soccer Ball Impacts; Error Bars Represent ± SD.

During laboratory testing and also during subsequent analysis of video, the reactive whole body motion(s) of unaware subjects during a controlled impact to the head were observed. Notable body motions of the subjects in response to the impact included interruption and recovery of split stance, forward flexion of the head and neck, and forward flexion of the torso, though these motions were not evident in all impacts and all subjects.

3.2 Surprise Impacts

It was determined via post-testing questioning and analysis that only two of the participating subjects were fully unaware of the impending "surprise" impact. Observations of those two subjects' reactions to the surprise impact included appreciable interruption of normal gait by side-stepping or stopping and forward flexion of the head, neck, and torso, the same motions that were noted during the controlled ball drops. However, these motions were more pronounced for the "surprise" impacts than for the "controlled" impacts. An image from one of the successful surprise impacts taken from the hidden camera footage is shown in Figure 5. The measured peak linear resultant head accelerations for subjects 2 and 4 during the surprise impacts were 2.0 g and 4.7 g, respectively.

Figure 5. Subject 2 “Surprise” Impact.

4. Discussion

Resultant acceleration measurements of the head center of gravity during soccer ball impacts to the forehead area (such as during heading in soccer) have been reported in the literature (Funk, 2011; Naunheim, 2003). Funk (2011) reported head center of gravity accelerations for soccer ball impacts to the forehead at speeds of 5 m/s and 8.5 m/s. The average peak values of the resultant linear acceleration for these two impacts speeds were 6.8 $\pm$ 1.0 g and 15 $\pm$ 2.9 g, respectively. While the subjects did not attempt to actively head the soccer balls in this study, Naunheim (2003) subjects were instructed to head the ball back toward the direction of travel as opposed to allowing the ball to strike the forehead. The Naunheim (2003) data included and average peak head center of gravity resultant acceleration of 16 $\pm$ 2 g for a ball impact speed of 9 m/s.

These previously published studies included ball speeds similar to the impact speed utilized in the current study, but resultant acceleration levels were slightly higher. Some of the disparity in acceleration results can likely be attributed to differences in experimental design. For example, in the study performed by Naunheim (2003), subjects were instructed to actively head the soccer ball as opposed to simply allowing the ball to impact the head. The Funk study methods more closely matched those of the current study, the primary difference being the impact location. However, the peak resultant head acceleration was still greater even for the lower speed impacts. Consistent with our expectations, the results of this preliminary study do not suggest that levels of head acceleration are significantly higher for impacts to the crown of the head as compared to similar speed impacts to the forehead.

Not all impacts were associated with substantial disruptions in quiet standing. Potential variability in the subject’s preparedness (i.e. inadvertent muscle tensing among and across subjects) for the impact, in the exact head-ball contact location, and in the over-all posture of the subjects may have contributed to whether significant reactive motions were noted. However, when a disruption was evident, the nature of the reactive motions were consistent. Reactive motions were more easily observed from camera (2) located to the side of the subjects, but were also evident from the video captured from camera (1) positioned ahead of the subjects.

The video surviellance footage that captured the incident in question was more similar to the orientation of camera (1) during the described testing. The surveillance video did not clearly depict any gross body motions of the subject consistent with interuption of stance or gait or florward flexion of the head neck or torso. The relatively resolution and the vantage point of the surveillance video may have influenced the ability to notice any slight motions of this type.

A limitation of this study includes having a relatively ill-defined subject incident due to a lack of information. Regardless of the design of the laboratory experiment, there would be difficulty in applying results directly to this incident in question. In other words, limited data regarding the contact location, material, and impact speed at the time of the subject incident, precludes us from being able to knowingly replicate the subject impact in a laboratory setting. The data gathered during the controlled ball drops simply quantifies non-injurious impacts to the crown of the head and the associated accelerations and puts into context what might be expected as reactive whole body motions as a result of those impacts.

An obvious difference between the subject incident and the controlled testing setup was that the individual in the surveillance video was walking while the testing subjects were standing. The benefit of asking the subjects to remain still during the testing was to ensure a direct contact from the dropped ball to the head. An impact to the head whil walking is a more dynamic event and could introduce somewhat different reactive body motions depending on the phase of gait.

Addtionally, truly surprising the test subjects by a ball drop was only possible once, if at all. Beyond the first attempt, subjects would be more likely to expect and be more watchful for an impending ball drop. Therefore, the possible sample size for truly unexpected head impacts will be small.

Considerations for future work include in some way quantifying the level of subject preparedness for each controlled impact and establishing a threshold for including a given impact into the category of unexpected. This could potentially be done via subject questioning immediately following the testing or via muscle activation monitoring during the testing. Furthermore, additional observations and data for both “controlled” and “surprise” type impacts from the recruitment and testing of additional subjects could confirm and enhance this preliminary work.

5. Conclusion

This preliminary study has set forth a methodology for quantifying and characterizing linear head accelerations related to single unexpected and non-injurious ball impacts to the crown of the head. The measured head accelerations augment and complement the data that exists in the current body of literature and will be useful for comparison to future work related to the sensitivity of head accelerations to impact location and subject preparedness.

The reactive whole body motions to unexpected imapcts to the crown of the head as exhibited by some subjects were qualitatively identified. Yet, some individual impacts and some subjects displayed limited if any reactive whole body motions. The individual depicted in the the incident in question video surviellance did not exhibit any appreciable interruption of normal stride length or cadence, nor does the individual appear to bend forward or lower her head. While unable to use the acquired data to definitely associate the subject incident with a likelihood of injury, we were able to observe and put into context non-injurious impacts to the crown of the head to give examples of what might be expected as a result of an unexpected non-injurious impact to the crown of the head.

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