CORRELATIONS BETWEEN HEAD ROTATIONAL KINEMATICS AND BRAIN TISSUE STRAIN FOR LOW AND HIGH LEVEL FOOTBALL HELMET IMPACTS

R. Anna Oeur[1], Katrina Zanetti[1], Michael D. Gilchrist[1,2], and T. Blaine Hoshizaki[1]

Human Kinetics, University of Ottawa, Ottawa, Canada[1]
Mechanical and Materials Engineering, University College Dublin, Dublin, Ireland[2]

This study examined the correlation between head angular velocity and acceleration with brain strain for low and high level impacts. Impacts at 2.4m/s (low) and 11m/s (high) were delivered to a American football helmeted Hybrid III headform using a centric/non-centric protocol. A finite element model calculated strain from headform accelerations. The low-level impact data were obtained from a previous subset eliciting angular responses occurring at 20g, therefore linear acceleration relationships were not examined. High correlations (r=>0.8) existed for non-centric conditions between strain with angular acceleration and velocity, while centric conditions had moderate relationships (r=0.5-0.68). This research demonstrates that kinematic-strain relationships are dependent on the impact event, and that a single variable may not represent strain under all conditions.

KEY WORDS: brain tissue strain, correlation, dynamic response, head impact,

INTRODUCTION: In North America, the frequency of injury and number of participants in sport make sports related concussion one of the largest contributors to short and long-term disability (Daneschvar et al., 2011; Bazarian et al.,2005; Gavette et al., 2011). The primary cause of concussive trauma is from a rotationally induced strain deformation on the brain tissue (Holbourn, 1943; Ommaya & Gennarelli, 1974). A growing body of research has since supported the relationship between peak rotational acceleration and the risk of concussion, and as such, researchers have attributed angular velocity and acceleration as two important predictors of strain, and therefore concussion (Holbourn, 1943, Margulies & Thibault, 1992; Ommaya & Hirsch, 1970; Gennarelli et al., 1987).

A strong relationship between kinematic variables and tissue strains provides a platform with which helmet design and innovation can be improved to protect against tissue trauma responsible for injury. Measuring strain values for each impact is a time consuming computational process, and therefore if head impact dynamic variables can be substituted, it will expedite head protection innovation. If brain tissue strain is proportional to angular acceleration and velocity, mitigating the risk of injury from one variable will result in a decrease in the other. The purpose of this research was to examine the relationship between angular acceleration and velocity with brain tissue strain for low and high level impacts to represent the possible energy ranges that occur in sport.

METHODS: Head impact data were collected using a Hybrid III headform fitted with a standard NOCSAE certified American football helmet at 2.4 m/s representing the low level impact, and at 11 m/s for the high level impacts (Oeur et al., 2014; Zanetti et al., 2013; Pellman et al., 2003). A centric and non-centric impact protocol consisting of 9 distinct impact conditions selected to elicit linear and rotationally dominant responses was used to evaluate the kinematic-strain relationship (Walsh et al., 2011; Post et al., 2013). A 10kg pendulum was used to achieve low-level impacts, and a 13kg pneumatic linear impactor system driven by compressed air was used to achieve high-level impacts. Impact compliance for both systems were matched by using a nylon-vinyl nitrile striker cap designed to simulate helmet-to-helmet impacts in football (Pellman et al., 2006). Head dynamic responses of angular acceleration and velocity were captured using a 9-accelerometer array equipped headform (Padgaonkar et al., 1972). Acceleration-time histories of the event were inputted into the University College Dublin Brain Trauma Model (UCDBTM) to calculate maximum principal strain (MPS)

(Hogan & Gilchrist, 2003;2004). Pearson's correlation coefficients were calculated between angular acceleration and strain, as well as angular velocity and strain for centric and non-centric conditions. The low-level impact data were obtained from a previous subset of data eliciting angular responses occurring at 20g, therefore linear acceleration correlations with strain were not examined in this research (Oeur et al., 2014). The alpha level for significant differences was set to p<0.05.

RESULTS: Pearson correlation results for low and high level impacts between rotational kinematics and maximum principal strain are shown in Table 1. Correlations that were above an *r*-value of 0.8 are highlighted with bold text.

Table 1
Correlations for low and high level impacts

Dependent Variable	Centric		Non-Centric	
	MPS			
	2m/s	11m/s	2m/s	11m/s
Angular Acceleration	0.683 (p=0.002)	0.573 (p=0.020)	**0.838 (P=0.005)**	**0.910 (p=0.001)**
Angular Velocity	0.522 (p=0.026)	0.562 (p=0.015)	**0.822 (p=0.006)**	0.500 (p=0.171)

Interestingly, all relationships were significant with the exception for angular velocity and strain for non-centric conditions at 11 m/s. All other non-centric impacts, at both the low and high levels, were significantly correlated above an *r*=0.8. The centric conditions resulted in relatively lower and more moderate relationships, around *r*=0.58.

Figure 1: The front boss positive azimuth location shown on a typical American football helmet. A striker cap is shown to demonstrate the possible complex interactions between the helmet shell and liner for this type of non-centric location.

DISCUSSION: Research using animal and physical experimental models have identified head rotation as an important factor in the mechanism of concussion (Gennarelli et al., 1987; Holbourn, 1943; Ommaya & Hirsch, 1971). Based on the notion that strain deformation is the primary mode of injury to the tissue, this study shows that angular acceleration and velocity have strong correlations for non-centric impacts. This is consistent with the results of the research that established the impact protocol used in this study. The authors selected the non-centric conditions based on their contribution to identifying concussive risk (Walsh et al., 2011).

In Holbourn's theory of concussion, he proposed that strain would be proportional to angular velocity for short duration impacts, and angular acceleration for longer duration impacts and that a change from one law to the other would occur for between 2-200 ms (Holbourn, 1943). In this study, a 2.4m/s impact resulted in a 15ms duration and an 11m/s impact resulted in a

12.5ms duration. Based Holbourn's theory, stronger relationships would be expected with angular velocity at high-level impacts (relatively shorter duration) and with angular acceleration for low-level impacts (relatively longer duration). These trends suggested by Holbourn were not observed in this data set, and a closer examination shows that no significant relationships were found at 11m/s for angular velocity under non-centric conditions. This could be due the narrow range of impact durations found in this study (12.5 and 15ms), which may not be large enough examine the law change as proposed by Holbourn. The relationship between angular velocity and strain at 11m/s showed that there was a larger spread in the data due to impact location differences. Most impact locations had a tendency to be linearly related, however data points for the front boss positive azimuth location shown in Figure 1 tend to cluster below the others. Therefore, overall relationships for non-centric conditions were not significant. These differences could be attributed to the complex interactions between the helmet liner and shell, and the impact site that resulted in relatively lower levels of strain for the same magnitudes of angular velocity.

The dynamic response and MPS relationships for the centric impacts were not as strong, which suggests that the loading conditions play a major role in the strength of the kinematic-strain relationship, and that there may be potentially better-suited variables to capture this risk. Interestingly, the strength of the correlations remained consistent between impact levels, indicating that these relationships may be inferred for other impact velocities. Furthermore, this research supports the notion that appropriate variables to characterize concussion risk, either head dynamic response or tissue response, is strongly influenced by the injury event.

The relationship between head dynamic impact response and brain tissue response is an important aspect of injury prevention for head impact biomechanics, as this serves as the foundation for which improvements in system design and innovation can be made to decrease injury risk (Goldsmith, 2001; Viano et al., 1989). In the context of head protection, improvements in helmet design have yet to successfully decrease the risk of concussions (Bazarian et al., 2005; Daneschvar et al., 2011). One reason for the ongoing incidence of injury could be due to a poor understanding of the cause and effect relationships for concussion, where there is a discrepancy between how helmets are designed and tested, and how people are getting injured.

CONCLUSION: This research examined the relationship between head angular velocity and acceleration with brain tissue strain for low and high level impacts on football helmets. Nearly all non-centric conditions at low and high levels resulted in significantly correlated rotational kinematic-strain relationships, meanwhile all centric impacts were found to be moderately correlated. This research demonstrates that the link between angular kinematics and brain tissue strain, and subsequent injury risk, is specific to the conditions that define the impact event. The moderate relationships found for centric impacts suggest that other dependent variables may be required to capture injury risk under these conditions.

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