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Research Paper

Characterization of persistent concussive syndrome using injury reconstruction and finite element modelling

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ABSTRACT

Concussions occur 1.7 million times a year in North America, and account for approximately 75% of all traumatic brain injuries (TBI). Concussions usually cause transient symptoms but 10 to 20% of patients can have symptoms that persist longer than a month. The purpose of this research was to use reconstructions and finite element modeling to determine the brain tissue stresses and strains that occur in impacts that led to persistent post concussive symptoms (PCS) in hospitalized patients. A total of 21 PCS patients had their head impacts reconstructed using computational, physical and finite element methods. The dependent variables measured were maximum principal strain, von Mises stress (VMS), strain rate, and product of strain and strain rate. For maximum principal strain alone there were large regions of brain tissue incurring 30 to 40% strain. This large field of strain was also evident when using strain rate, product of strain and strain rate. In addition, VMS also showed large magnitudes of stress throughout the cerebrum tissues. The distribution of strains throughout the brain tissues indicated peak responses were always present in the grey matter (0.481), with the white matter showing significantly lower strains (0.380) ($p<0.05$). The impact conditions of the PCS cases were severe in nature, with impacts against non-compliant surfaces (concrete, steel, ice) resulting in higher brain deformation. PCS biomechanical parameters were shown to fit between those that have been shown to cause transient post concussive symptoms and those that lead to actual pathologic damage like contusion, however, values of all metrics were characterized

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by large variance and high average responses. This data supports the theory that there exists a progressive continuum of impacts that lead to a progressive continuum of related severity of injury from transient symptoms to pathological damage.

1. Introduction

Concussive brain injuries resulting from impacts to the head are known to have serious short and long term effects (National Institutes of Health, 1999). In North America alone, an estimated 1.7 million concussions occur each year, accounting for approximately 75% of all traumatic brain injuries (TBI) (Bazarian et al., 2006). These injuries come with an estimated cost of over 60 billion $US, including health care costs as well as time away from work (Langlois et al., 2006). While most people who suffer concussions experience transient symptoms, some people suffer from persistent symptoms that last longer than three months. The World Health Organization defines these long term symptoms of concussion as 'persistent concussive syndrome' (PCS) when there are multiple clinical presentations (such as headache, fatigue, irritability etc) that last longer than six weeks (National Institutes of Health, 1999; McCrory et al., 2013). The significant impact PCS has on patients dictates the need to better understand the metrics that characterize the risk and severity of this brain injury. Brain injury reconstruction research has proposed peak linear and rotational acceleration and stress and strain parameters to characterize severity of injuries for those patients who experience transient concussive symptoms (King et al., 2003; Zhang et al., 2004; Kleiven, 2007), but no investigation has studied patients with PCS.

Currently, it is difficult, if not impossible to determine if a concussed individual will have a PCS injury. Even advanced neuroimaging with MRI is not able to predict which patient with a concussion will develop persistent symptoms. What is certain is that PCS, like other brain injuries, occurs through some form of injurious stress or strain applied to the brain tissue (Holbourn, 1943; Ommaya and Gennarelli, 1974; King et al., 2003; Kleiven, 2007; Post and Hoshizaki, 2012). This injurious loading can occur through contact (Willinger and Baumgartner, 2003; Zhang et al., 2004; Kleiven, 2007), or through non-contact loading (Gennarelli et al., 1971; Ommaya and Gennarelli, 1974). From a biomechanical perspective, brain injury, be it transient concussion or PCS, is likely linked to the characteristics of the event that caused the injury (Post and Hoshizaki, 2012). These characteristics have been defined in the past as combinations of mass, velocity, location of impact, and others that determine the stresses and strains in the brain tissue (Post et al., 2014; Karton et al., 2013). These brain injuries likely cause a complex series of cellular events that result in the symptomology associated with PCS (Giza and Hovda, 2001). A series of cellular events that for transient concussion is reversible, which is reflected by the short term symptomology. Morrison et al. (2000) correlated quantitative changes in gene expression in brain tissues of rats with mechanical stretch parameters. These changes are thought to be linked to concussive symptoms such as impaired coordination, attention, memory, and cognitive ability (Giza and Hovda, 2001). No definitive single gene expression has been linked to persistent symptoms after concussive injury. Shitaka et al. (2011) suggested the possibility of sustained activation of microglia for days to weeks after concussive injury to be partially responsible for persistent symptoms. Morrison et al. (2000) reported that the changes which occur following the mechanical impact of the brain could influence the severity of clinical outcome.

There has been some theories put forward suggesting that there is a continuum, or hierarchy, of brain injury (Hoshizaki et al., 2013; Post, 2013; Post et al., 2014). In the past researchers have shown that it is likely that no injury would be at the low ranges of head impact injury, followed by concussion, and finally TBI (Hoshizaki et al., 2013). However, recently there has been suggestions that within each of these brain injury categories (concussion and TBI) there is a further continuum that may be influenced by factors related not only to the increasing energy of impact, but to the characteristics of the event and how that affects the mechanisms of injury attached to particular anatomical structures (Hoshizaki et al., 2013; Post et al., 2014). While it is likely that severity of impact may affect the occurrence of PCS, the characteristics leading to this type of injury have not been examined or in any way quantified. Further refinement of the theory of continuums of injury within concussion is important as it will help establish transient concussion and PCS as two separate injuries that may be related to different impact event characteristics. Once these differences are identified it would then be possible to refine the understanding of these types of injuries to permit for improved interventions and innovations based on prevention. Therefore, the purpose of this research was to use reconstructive techniques and finite element modelling to characterize brain injuries resulting in persistent concussive syndrome.

2. Methods

Patients with PCS who were presented to one of three major urban hospitals in Canada were the subject population. Patients included in this research must have had accurate and complete eyewitness or personal accounts of the injury recorded by neurosurgeon that could be used in laboratory reconstructions. The description must have been complete enough to allow for estimation of the following criteria: head impact velocity, location, surface, and surface geometry. If there was no clear description of these parameters, the subject was excluded from the research dataset. In addition to these physical reconstruction parameters, CT and/or MRI