Assessing Women's Lacrosse Head Impacts Using Finite Element Modelling

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Abstract

Recently studies have assessed the ability of helmets to reduce peak linear and rotational acceleration for women's lacrosse head impacts. However, such measures have had low correlation with injury. Maximum principal strain interprets loading curves which provide better injury prediction than peak linear and rotational acceleration, especially in compliant situations which create low magnitude accelerations but long impact durations. The purpose of this study was to assess head and helmet impacts in women's lacrosse using finite element modelling. Linear and rotational acceleration loading curves from women's lacrosse impacts to a helmeted and an unhelmeted Hybrid III headform were input into the University College Dublin Brain Trauma Model. The finite element model was used to calculate maximum principal strain in the cerebrum. The results demonstrated for unhelmeted impacts, falls and ball impacts produce higher maximum principal strain values than stick and shoulder collisions. The strain values for falls and ball impacts were found to be within the range of concussion and traumatic brain injury. The results also showed that men's lacrosse helmets reduced maximum principal strain for follow-through slashing, falls and ball impacts. These findings are novel and demonstrate that for high risk events, maximum principal strain can be reduced by implementing the use of helmets if the rules of the sport do not effectively manage such situations.

Key Words: Concussion, Brain strain, Impact mechanics, Injury prevention, Helmet

Introduction

Despite women's lacrosse being described as a non-contact sport, head injuries remain an issue (Diamond and Gale, 2001; Hinton et al., 2005; Marar et al., 2012; Waicus and Smith, 2002; Xiang et al., 2014). The sport relies primarily on rules and sportsmanship to minimize head injuries, with little requirement for protective equipment to be worn. Currently, only eyewear and a mouth guard are worn. A study by Webster et al. (1999) found that there was a decrease in facial injuries, particularly to the periorbital and forehead regions, with the use of protective eyewear in scholastic women's lacrosse. They regarded protective eyewear as being a valuable method to decrease injuries which occur to and around the eyes. However, most of the head remains unprotected and concussion remains a major problem in the women's lacrosse (Marar et al., 2012; Xiang et al., 2014). As such, the use of protective headgear and helmets could serve to eliminate head and eye injuries (Otago et al., 2007).

The debate for protective headgear to be mandatory in women's lacrosse and the implications surrounding such a rule change has continued for over 20 years (Diamond and Gale, 2001; Dick et al., 2007; Goldenberg and Hossler, 1995; Harmer, 1993; Hinton et al., 2005; Lapidus et al., 1992; Lincoln et al., 2007; Marar et al., 2012; Otago et al., 2007; Xiang et al., 2014). Some experts contend that the use of helmets is unnecessary (Goldenberg and Hossler, 1995; Harmer, 1993), while others encourage the use of helmets (Diamond and Gale, 2001; Lincoln et al., 2007; Otago et al., 2007). Recently, studies have examined the potential for helmets to reduce linear and rotational acceleration of a headform for women's lacrosse head impacts (Clark and Hoshizaki, 2016; Rodowicz et al., 2015). Rodowicz et al. (2015) assessed both soft headgear and a men's lacrosse helmet under stick and ball impacts. It was found that soft headgear was ineffective at reducing the potential for head injury from high velocity ball impacts, such as those associated with shooting in women's lacrosse, whereas men's lacrosse helmets proved to be effective at reducing the risk of head injury for all ball impact speeds. For stick impacts, both soft headgear and men's lacrosse helmets were relatively ineffective at reducing the response of the head, with only small differences being seen for frontal impacts (Rodowicz et al., 2015). Clark and Hoshizaki (2016) assessed the ability of men's lacrosse helmets to decrease linear and angular acceleration for different striking techniques in women's field lacrosse. Their findings showed that men's lacrosse helmets were effective at reducing linear and rotational accelerations experienced by the headform for fall impacts as well as for ball and high velocity stick impact (Clark and Hoshizaki, 2016). These studies demonstrated that helmets could reduce the linear and rotational accelerations experienced by the head from impacts in women's lacrosse.

Peak linear and rotational acceleration have been shown to have a low correlation to injury (Kleiven, 2007; Zhang et al., 2004), and it has been suggested that the resulting acceleration loading curve created from an impact, rather than the peak resultant accelerations, is more representative of actual brain injury (Post et al., 2012). As such, the findings of Rodowicz et al. (2015) and Clark and Hoshizaki (2016) which solely examine peak linear and rotational acceleration may not be representative of actual brain response. Finite element modelling allows for the interpretation of linear and rotational acceleration curves and how they influence the response of brain tissue to an impact. Researchers have suggested that the use of finite element models to measure brain tissue strains could be more informative (Forero et al., 2011; King et al., 2003; Post et al., 2012; Post and Hoshizaki, 2012). One commonly used variable to interpret acceleration loading curves in the finite element analysis of brain injuries is maximum principal strain (MPS) and it has been identified as a possible indicator of concussion (Kleiven, 2002; Willinger and Baumgartner, 2003; Zhang et al., 2004; Zhou et al., 1995). The relevance of MPS to predict concussion has been seen particularly in conditions where there is a high level of compliance, resulting in long duration impacts (Rousseau, 2014). Rousseau (2014) found that while peak linear and rotational accelerations associated with concussion were lower for ice hockey shoulder and elbow impacts when compared to head impacts in American football, rugby and Australian rules football (Kleiven, 2007; Patton et al., 2012; Zhang et al., 2004), the levels of MPS were similar. As a result, the purpose of the present study was to assess head and helmet impacts in women's lacrosse impacts using finite element modelling.

Methods

Procedure

Live subjects and physical reconstructions were used to obtain impacts to a helmeted and unhelmeted 50th percentile Hybrid III headform (4.54 kg) and neckform (1.54 kg), as described by Clark and Hoshizaki (2016). Eleven athletic females representing a post-collegiate population [mean weight = 63.1 kg (SD 12.0); mean height = 1.65m (SD 0.08); mean age = 29.2 years (SD 3.9)] took part in the study. The participants struck the headform using the shaft of a lacrosse stick with 5 striking techniques, including one-handed slash, two-handed slash, moderate two handed slash, severe two-handed slash and follow-through slash (Clark and Hoshizaki, 2016). Ball-to-head impacts were performed by Clark and Hoshizaki (2016) using an air cannon which fired a lacrosse ball at 28.3 m/s (SD 2.2). This velocity was selected as a shot in women's lacrosse have been reported to have ball velocities up to 60mph (26.8 m/s) (Lincoln et al., 2007). Shoulder impacts were reconstructed using a pneumatic linear impactor with an impacting arm of 13.1 kg with 67.79mm of R338 vinyl nitile (VN) foam (Rousseau and Hoshizaki, 2015). The inbound velocity was 5.0 m/s and chosen to reflect high speed running of female soccer players (Krustrup et al., 2005; Mohr et al., 2008). Falls were reconstructed using a monorail drop rig with a modular elastomer programmer (MEP) anvil to simulate the playing surface. An inbound velocity of 4.5 m/s was selected by Clark and Hoshizaki (2016), after using Mathematical Dynamic Models (MADYMO) simulations to determine that a 1.57m tall female being pushed forward at 1.0 m/s resulted in a head impact velocity of 4.5 m/s. The headform was impacted at the front and side since these were the most common impact locations in women's lacrosse (Caswell et al. 2012). Further details of the impact techniques used in this study can be found in Clark and Hoshizaki (2016).

Nine single-axis Endevco7264C-2KTZ-2-300 accelerometers (Endevco, San Juan Capistrano, CA) were instrumented in the Hybrid III headform in a 3-2-2-2 accelerometer array (Padgaonkar et al., 1975). The skull of the headform was made of aluminum and considered to be rigid. A TDAS Pro Lab system (DTS, Seal Beach CA) collected signals from the nine accelerometers at 20 kHz and the signals were filtered using a CFC class 1000 filter in accordance with the SAE J211 convention (SAE, 2007). Linear and rotational accelerations of the headform were collected for three trials of each condition by Clark and Hoshizaki (2016). For the stick impacts each participant performed 3 impacts per striking technique. The resulting linear and rotational acceleration-time histories obtained by Clark and Hoshizaki (2016) were input into a finite element model of the head and brain at the centre of gravity.

Finite Element Model

The University College Dublin Brain Trauma Model (UCDBTM) (Horgan and Gilchrist, 2003, 2004) was used to calculate MPS in the cerebrum. The geometry of the UCDBTM was extracted from computed tomography (CT) and magnetic resonance imaging scans (MRI) of a male human cadaver (Horgan and Gilchrist, 2003). The model of the head and brain comprised of the scalp, skull, pia, falx, tentorium, CSF, grey and white matter, cerebellum and brain stem, represented by 26,000 reduced integration 8-node hexahedral elements (Horgan and Gilchrist, 2003, 2004). The values representing the material characteristics of the UCDBTM were taken from the literature (Tables 1, 2) (Kleiven and von Holst, 2002; Ruan, 1994; Willinger et al., 1995; Zhang et al., 2001; Zhou et al., 1995). A linear viscoelastic material model combined with large deformation theory was used to model the material behaviour of the brain tissue, the linear viscoelastic characteristics of which were described for shear with a deviatoric stress rate dependent on the shear relaxation modulus (Horgan and Gilchrist, 2003). The shear characteristics of the viscoelastic behaviour of the brain were expressed as follows:

$$G(t) = G_{\infty} + (G_0 - G_{\infty})e^{\beta t}$$

where G_{∞}, is the long term shear modulus, G_0, is the short term shear modulus and β is the decay factor (Horgan and Gilchrist, 2003). The skull brain interface was modelled using a sliding boundary condition between the pia and CSF, with the contact interaction assigned no separation (Horgan and Gilchrist, 2004). The CSF was modelled using solid elements with the bulk modulus of water and a low shear modulus (Horgan and Gilchrist, 2003, 2004). A friction coefficient of 0.2 was used for the sliding surfaces (Miller et al., 1998). Subsequent modifications have been performed by Doorly (2007) to increase mesh density and introduce bridging veins.

Model validation was performed against intercranial pressure response and brain motion response of previous cadaver research (Hardy et al., 2001; Nahum et al., 1977; Trosseille et al., 1992). Further comparisons were performed by Doorly and Gilchrist (2006) and Post et al. (2015b) through reconstructions of real world traumatic brain injury (TBI) incidents with results that were in agreement with anatomical tissue thresholds. To ensure the mesh density was sufficient a convergence analysis was performed by Horgan and Gilchrist (2003) and was found to obtain a convergent solution. The hourglass energies were checked and remained below the recommended 10% of total energy (Horgan, 2005).

Table 1: Material properties of UCDBTM.

Material	Young's modulus (MPa)	Density (kg/m^3)	Poisson's Ratio
Scalp	16.7	1000	0.42
Cortical Bone	15000	2000	0.22
Trabecular Bone	1000	1300	0.24
Dura	31.5	1130	0.45
Pia	11.5	1130	0.45
Falx	31.5	1140	0.45
Tentorium	31.5	1140	0.45
CSF	Water	1000	0.5
Grey Matter	Viscoelastic	1060	0.49
White Matter	Viscoelastic	1060	0.49

Table 2: Material characteristics of the brain tissue for the UCDBTM.

Material	G_0	G_∞	Bulk Modulus (GPa)	Decay Constant (s^{-1})
Cerebellum	10	2	2.19	80
Brain Stem	22.5	4.5	2.19	80
White Matter	12.5	2.5	2.19	80
Grey Matter	10	2	2.19	80

Statistics

Maximum principal strain was used to assess head impacts experienced in women's lacrosse. Kruskal-Wallis tests were used to compare striking techniques conducted on unhelmeted impacts at each impact location. Mann-Whitney tests were performed to compare helmeted and unhelmeted conditions of each striking technique at both impact locations. The confidence interval was set at 95%. All data analyses were performed using the statistical software package SPSS 19.0 for Windows (SPSS Inc, Chicago, IL, USA).

Results

The mean six degrees of freedom linear and rotational acceleration traces for slashing, shoulder collisions, ball impacts and falls are presented in Fig. 1. Fig. 2 illustrates the strain distribution at maximum for one case of slashing, shoulder collision, ball impact and fall.

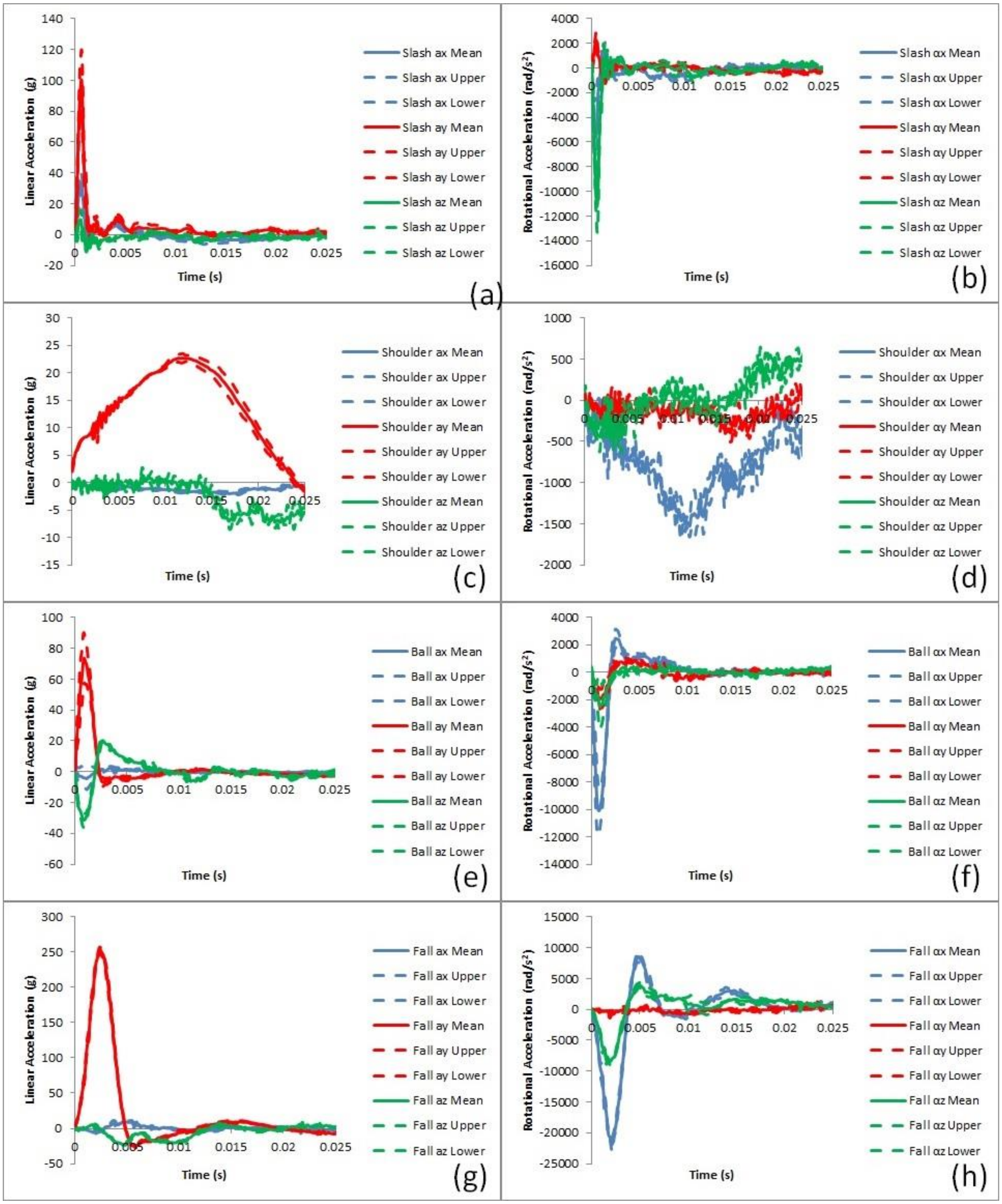

Fig. 1. Mean six degrees of freedom linear and rotational traces from a Hybrid III headform for slashing, shoulder collisions, ball impacts and falls (Clark and Hoshizaki, 2016): (a) Linear acceleration traces for slashing, (b) Rotational acceleration traces for slashing, (c) Linear acceleration traces for shoulder collisions, (d) Rotational acceleration traces for shoulder collisions, (e) Linear acceleration traces for ball impacts, (f) Rotational acceleration traces for ball impacts, (g) Linear acceleration traces for falls, (h) Rotational acceleration traces for falls.

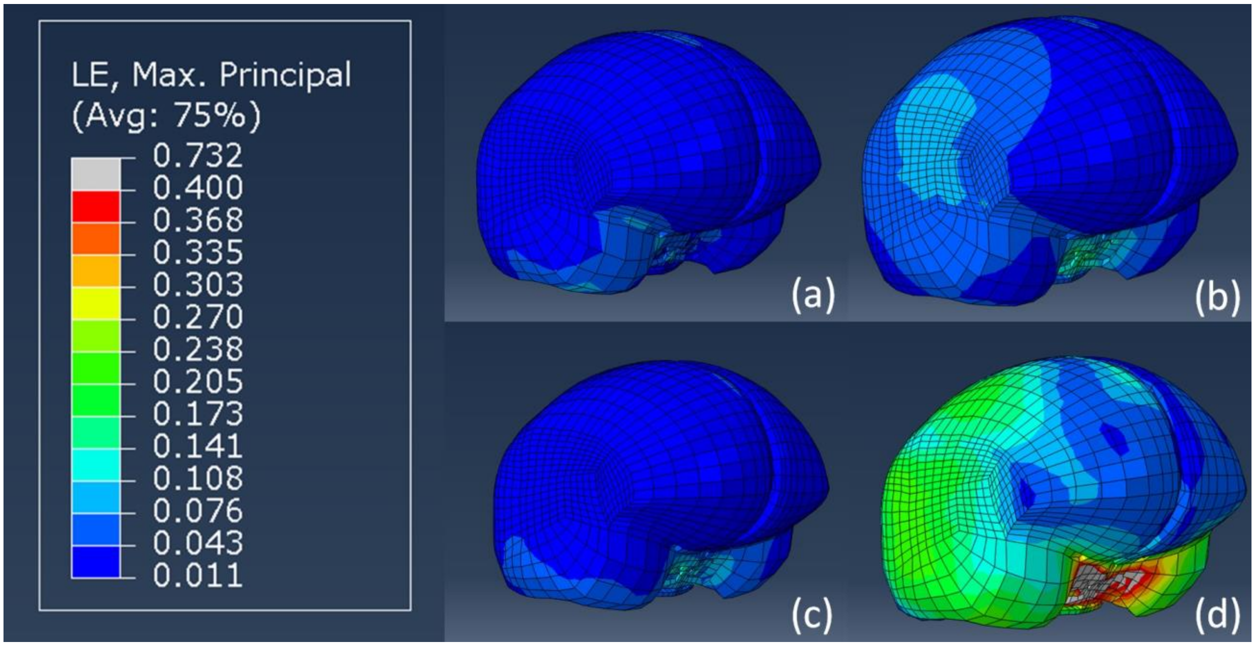

Fig. 2. Strain distribution at maximum (only the cerebrum of the brain model is shown) for one case of: (a) slashing, (b) shoulder collision, (c) ball impact and (d) fall.

Fig. 3 and Table 3 illustrates the influence of the different women's lacrosse striking techniques on maximum principle strain. The results of the Kruskal-Wallis tests for unhelmeted impacts revealed that striking technique had a significant main effect on MPS at all impact locations ($p<.001$). Falls and ball impacts were found to produce significantly higher MPS values compared to all other striking techniques ($p<.05$), except for ball/shoulder collisions for impacts to the side of the headform. One-handed and two-handed slashes result in significantly different MPS responses for front impacts ($p>.05$) but not for side impacts ($p<.05$). There was no significant difference in MPS for either the severe two-handed slash, follow-through slash or shoulder impacts ($p>.05$). Shoulder impacts produced significantly different MPS values compared to one-handed slash, two-handed slash and moderate two-handed slash impact events ($p<.05$), except for moderate two-handed slash for impacts the side of the headform ($p>.05$). One-handed slash and two-handed slash events produced significantly different MPS values than moderate and severe two-handed slashes ($p<.05$). Follow-through slashing was found to lead to significantly higher MPS levels compared to one-handed and two-handed slashing ($p<.05$). Moderate two-handed slashes and severe two-handed slashes resulted in significantly different MPS values for side impacts ($p<.05$), but not for front impact ($p>.05$). A significant difference was found between moderate two-handed slash and follow-through slash for front impact ($p<.05$), whereas they were not significantly different for side impacts ($p>.05$).

The effects of a men's lacrosse helmet on the level of MPS produced by the different women's lacrosse striking techniques are presented in Fig. 3 and Table 3. Comparing helmeted and unhelmeted conditions revealed significant differences in the levels of MPS for follow-through slash, ball impacts and falls ($p<.05$). No significant difference in MPS was found between helmeted and unhelmeted impacts for one-handed slash, two-handed slash, moderate two-handed slash and severe two-handed slash events ($p>.05$), except for two-handed and moderate two-handed slashes to the front impact location ($p<.05$).

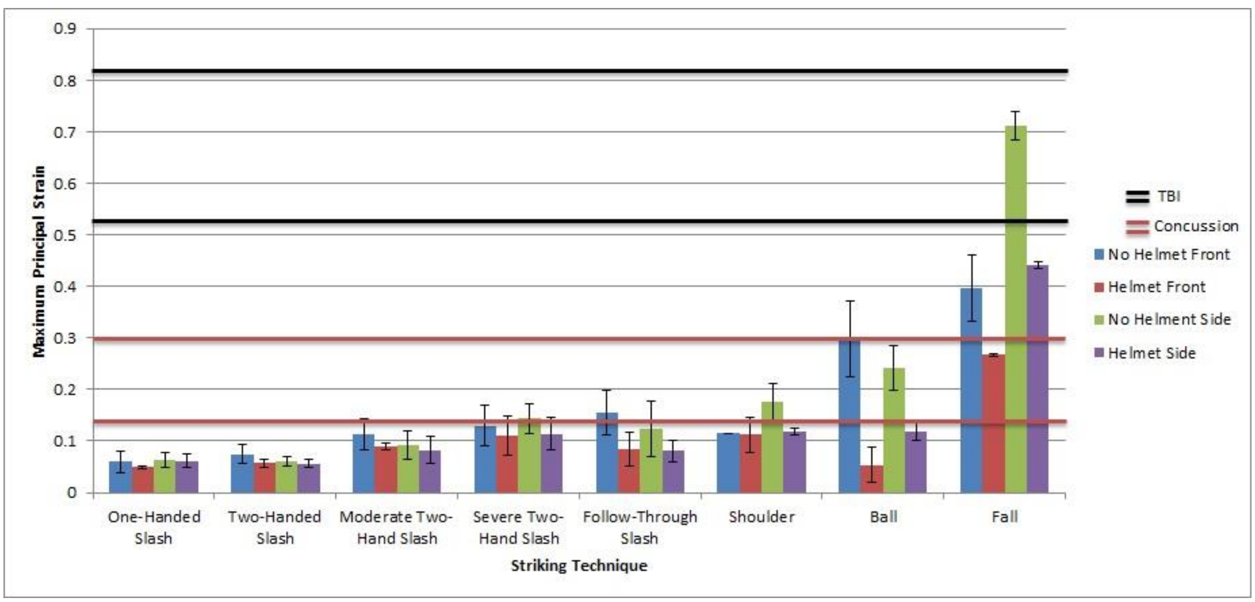

Fig. 3. Maximum principal strain across all impact conditions. The two black lines represent the reported range of reported traumatic brain injury (TBI) (Doorly, 2007; Doorly and Gilchrist, 2006; Post et al., 2015b) and the two red lines represent the range of reported concussions (Kendall, 2016; Oeur et al., 2015; Rousseau, 2014; Zanetti et al., 2013).

Table 3: Mean maximum principal strain for all impact conditions (±1 standard deviation).

Striking Technique	Location	Helmet (Yes/No)	Maximum Principal Strain
One-Handed Slash	Front	No	0.060 (0.021)
		Yes	0.049 (0.003)
	Side	No	0.062 (0.014)
		Yes	0.061 (0.014)
Two-Handed Slash	Front	No	0.075 (0.018)
		Yes	0.057 (0.007)
	Side	No	0.061 (0.009)
		Yes	0.056 (0.007)
Moderate Two-Handed Slash	Front	No	0.112 (0.031)
		Yes	0.090 (0.007)
	Side	No	0.092 (0.028)
		Yes	0.082 (0.026)
Severe Two-Handed Slash	Front	No	0.130 (0.038)
		Yes	0.111 (0.039)
	Side	No	0.143 (0.028)
		Yes	0.114 (0.032)
Follow-Through Slash	Front	No	0.156 (0.043)
		Yes	0.085 (0.032)
	Side	No	0.123 (0.054)
		Yes	0.080 (0.021)
Shoulder	Front	No	0.115 (0.001)
		Yes	0.112 (0.034)
	Side	No	0.175 (0.036)
		Yes	0.118 (0.006)
Ball	Front	No	0.230 (0.074)
		Yes	0.053 (0.034)
	Side	No	0.242 (0.043)
		Yes	0.118 (0.017)
Fall	Front	No	0.397 (0.064)
		Yes	0.267 (0.003)
	Side	No	0.711 (0.027)
		Yes	0.441 (0.006)

Discussion

The purpose of this study was to describe head impacts experienced in women's lacrosse and to quantify the level of protection afforded by a men's lacrosse helmet. Unhelmeted impacts revealed significant differences in the level of MPS arising from different striking techniques. Stick impacts and shoulder collisions were found to produce lower MPS values when compared to falls and ball impacts. These results are consistent with the linear and rotational acceleration results found by Rodowicz et al. (2015) and (Clark and Hoshizaki, 2016) as fall and ball impacts are seen to produce a higher head response than stick impacts and shoulder collisions. Falls were found to have the highest MPS values compared to the striking techniques examined in this study. Falls were found to produce MPS values within the range of persistent concussive syndrome (PCS) and TBI (Doorly, 2007; Doorly and Gilchrist, 2006; Oeur et al., 2015; Post et al., 2015b, c), consistent with linear and rotational accelerations reported by Clark and Hoshizaki (2016). Ball impacts produced the second highest MPS values and these were within the range associated with concussion (0.14–0.3) (Kendall, 2016; Oeur et al., 2015; Rousseau, 2014; Zanetti et al., 2013). The reported linear and rotational acceleration findings of Rodowicz et al. (2015) and Clark and Hoshizaki (2016) also reflected values within the range of concussion (61–144 g and 4186–12832 rad/s2, respectively). For the most part, stick and shoulder impacts were below reported MPS ranges for concussion. However, severe two-handed slash and shoulder collisions to the side of the headform and follow-through slashing to the front of the headform did produce MPS values within the range associated with concussion (Kendall, 2016; Oeur et al., 2015; Rousseau, 2014; Zanetti et al., 2013). This highlights the importance of enforcing major fouls such as Rough/Dangerous Check, Check to the Head, Slash, Obstruction of the Free Space to Goal (shooting space), Illegal Shot and Dangerous Follow-Through in order to protect players from such potentially injurious events (Clark and Hoshizaki, 2016).

Additionally from Fig. 1 it can be noted that among the different striking techniques the peak MPS commonly occurs in the auditory association area. These results are consistent with (Kendall, 2016) who found peak strains to be located in the auditory association area for a wide range of impact events (i.e. falls, punches and shoulder collisions). High levels of stain in this region of the brain could be caused by the resistance to rotation by the falx and tentorium (Li et al., 2006). As a result this region of the brain may be susceptible to high levels of strains associated with brain injuries.

Maximum principal strain identified shoulder collisions within the range of concussion (Kendall, 2016; Oeur et al., 2015; Rousseau, 2014; Zanetti et al., 2013) whereas both peak linear and rotational acceleration reported by Clark and Hoshizaki (2016) were below reported ranges of concussion. This difference is due to the high compliance of shoulder impacts, which result in lower magnitudes of peak linear and rotational accelerations but longer duration acceleration response curves (Clark, 2015; Clark et al., 2015; Rousseau, 2014). Long duration impacts have been reported to cause high brain stress and strain (Gilchrist, 2003; Willinger et al., 1994). The shoulder impacts were found to produce similar MPS values to those of severe two-handed and follow-through slashing.

Wearing men's lacrosse helmets was found to be effective at reducing MPS for fall and ball impacts. In the case of falls, a helmet lowered the level of MPS from values that were within the range of PCS and TBI (Doorly, 2007; Doorly and Gilchrist, 2006; Oeur et al., 2015; Post et al., 2015b, c) to levels that were associated with concussion (Kendall, 2016; Oeur et al., 2015; Rousseau, 2014; Zanetti et al., 2013). However, for ball impacts, wearing a helmet was seen to decrease MPS values to below the concussive ranges (Kendall, 2016; Oeur et al., 2015; Rousseau, 2014; Zanetti et al., 2013). These results are consistent with those reported by Rodowicz et al. (2015) and Clark and Hoshizaki (2016) as men's lacrosse helmets proved to be effective at decreasing the head response in high risk situations for falls and ball impacts. This can prove to be an effective method for managing brain strain for such high risk events.

Helmets were effective in decreasing MPS for follow-through slashing but not for the remaining stick impacts. This supports the findings of Rodowicz et al. (2015) and Clark and Hoshizaki (2016) for follow-through slashing and less severe stick impacts. However, these results are different from Clark and Hoshizaki (2016) for more severe stick impacts such as severe two-handed slashing. It has been suggested that the shape of the resulting acceleration-time curve is a better measure of the actual of brain injury, rather than peak resultant accelerations (Post et al., 2012). In addition to peak, other factors of the acceleration-time curve which have previously been measured to describe brain injury including duration, time to peak, slope to peak, integral of curve and x, y and z components of the acceleration-time curve (Kendall, 2016; Post et al., 2014a, b, 2015a). The amount of variance each variable can account for can vary depending on the impact event (Kendall, 2016) and as such no one components of the acceleration-time curve has proven to be the best predictor of brain injury for all situations. Rather it has been suggested that a combination of variables used to characterize a specific impact event would provide higher correlations due to the complexities that describe brain injuries (Kendall, 2016). Researchers have suggested that the use of finite element model metrics such as MPS can be a more informative solution for brain injury as these metrics allow for the interpretation of all aspects of the linear and rotational acceleration curves (Forero et al., 2011; King et al., 2003; Post et al., 2012; Post and Hoshizaki, 2012). As a result MPS has been found to be a better predictor of concussion than kinematics variables such as peak resultant accelerations and Head Injury Criterion (HIC) (Kleiven, 2002; Willinger and Baumgartner, 2003; Zhang et al., 2004; Zhou et al., 1995).

Consistent with earlier studies, shoulder collisions were not effectively managed by men's lacrosse helmets, with no decrease in the level of MPS (Clark et al., 2017; Clark et al., 2016).

The inability of helmets to decrease the MPS response due to shoulder collisions may be explained by the high compliance of the human shoulder to absorb most of the impact energy instead of the helmet (Clark et al., 2017, 2016). The men's lacrosse helmet is effective at reducing MPS values for falls, ball impacts and follow-through slashing.

Limitations

The current study was intended to study men's lacrosse helmets and does not represent the ability of soft headgear to reduce MPS. American Society for Testing and Materials (ASTM) has proposed a standard for woman's lacrosse headgear (ASTM F08.51) and, in the event the standard is adopted, future work should assess the ability of certified woman's lacrosse headgear to reduce MPS. The range of MPS levels used to represent injurious levels are based on reconstructions on a wide variety of sporting and everyday head injuries (Doorly, 2007; Doorly and Gilchrist, 2006; Kendall, 2016; Oeur et al., 2015; Post et al., 2015b, c; Rousseau, 2014; Zanetti et al., 2013) and may not accurately reflect head injuries in women's lacrosse. The response of the model is dependent on the material characteristics associated with each part of the head/brain complex. Further the geometry of the current model was extracted from MRI and CT scans of a male cadaver. Differences between the anatomy of male and female brain (Luders and Toga, 2010) may affect the strain response of the brain. As such, the response of the UCDBTM is intended to be a representation of how the brain may respond under the modelled loading scenarios and may not represent the exact motion of the brain.

Conclusion

This study is the first to describe eight types of women's lacrosse head impacts using finite element modelling and the ability of a men's lacrosse helmet to decrease the subsequent level of MPS. It was found that falls and ball head impacts resulted in highest MPS values and were within the range of response associated with concussion and TBI. When comparing helmeted and unhelmeted impacts, it was found that men's lacrosse helmets were effective at reducing MPS for follow-through slashing, falls and ball impacts. These results demonstrate that for high risk events, MPS can be significantly reduced by implementing the use of helmets if the rules of the sport do not effectively manage such situations.

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