Evaluating the Effectiveness of Boxing Headguards in Mitigating Head Impact Accelerations That Cause Concussions by Using a Dynamic Head Model

Tyson R. Rybak, Lakehead University, Canada
Paolo Sanzo, Lakehead University, Canada
Meilan Liu, Lakehead University, Canada
Carlos E. Zerpa, Lakehead University, Canada*

ABSTRACT

Boxing headguards offer a form of head protection to minimize the risk of head injuries for athletes. Existing literature, however, lacks information regarding the protective capabilities of boxing headguards. This study examined the protective capacity of three boxing headguards in minimizing impact accelerations to the head that cause concussions using a dynamic head model. The researchers implemented thermoplastic polyurethane (TPU) inserts in one of the headguards and conducted static tests to examine the material properties of the headguards. The researchers also conducted dynamic testing using a surrogate headform to compare the three boxing headguards in minimizing the risk of concussion for measures of linear and rotational accelerations across different head impact locations. The results of this study revealed that TPU significantly mitigated the magnitude of linear and rotational accelerations when compared to the other headguards. This study offers an avenue to improve athlete safety.

KEYWORDS

Angular Acceleration, Boxing Headguard, Concussions, Headgear, Impact Testing, Linear Acceleration, Static Testing, Thermoplastic Polyurethane

INTRODUCTION

Giza and Hovda (2001) described a concussion as "any transient neurologic dysfunction resulting from a biomechanical force" (p.1). More specifically, a concussion is a "clinical syndrome of biomechanically induced alteration of brain function typically affecting memory and orientation, which may involve a loss of consciousness" (Giza et al., 2013, p. 2250). Concussions or mild traumatic brain injuries (mTBI) that occur while playing the sport of boxing, for example, cause short and long-term traumatic neurologic impairments on athletes and represent one of the major occurrences of head injuries for athletes at the amateur and professional levels.

In the sport of boxing, athletes scores points by landing finishing shots on their opponents with the intention to disable them (World Boxing Association, 2012). Consequently, the magnitude of the

DOI: 10.4018/ijeach.319811
*Corresponding Author

acceleration induced to the athlete's head plays a significant role in the risk of concussions, brain injuries, and the severity of the damage (Rowson et al., 2016).

Boxing headguards provide a mean to reduce the risk of concussion on athletes by mitigating the magnitude of linear accelerations induced to the athlete's head while playing the sport (McIntosh & Patton, 2015). There is a need to understand, however, the behaviour of boxing headguard materials in minimizing not only the magnitude of linear impact accelerations induced to the head but also rotational accelerations caused by oblique impacts to the head. Oblique impacts generate shear forces and consequently rotational accelerations producing a "jarring" effect to the head, which deforms the brain tissue and causes a concussion (Meaney & Smith, 2011). Furthermore, there is a lack of information in the literature regarding the effect of linear and rotational accelerations causing concussions on athletes in the sport of boxing.

Based on the need to further investigate the protective capabilities of boxing headguards, this study examined the static and dynamic properties of two commercial boxing headguards (Adidas→ and Century→ Drive) and a modified TPU liner insert model implemented into a Century→ Drive headguard. The TPU material has become attractive in helmet design for its elastic, high tensile, and flexural strength properties (Lin et al., 2017). The first objective of this study was to determine the energy absorption capacity of boxing headguard materials across different locations during static testing. The second objective was to examine the combined effect of headguard type and impact location on measures of linear and rotational accelerations during simulated dynamic impacts.

BACKGROUND

Meaney et al. (1995) stated that during a head impact, the combination of linear and rotational accelerations causes the brain to accelerate and decelerate inside the skull, which may result in a concussion. Linear accelerations produced during a head impact cause the brain to elongate and deform by putting a stretch on various structures of the brain including neurons, glial cells, and blood vessels. This elongation and deformation of the brain alters membrane permeability and decreases blood flow (Mckee & Daneshvar, 2015), which in turn can lead to a variety of symptoms affecting the physical and cognitive performance of the athlete (Giza & Hovda, 2001). Symptoms of concussion may include confusion, disorientation, unsteadiness, dizziness, headache, and visual disturbances (Giza & Hovda, 2001).

Rotational accelerations, on the other hand, cause shear brain injury. This type of brain injury disrupts the white matter and its connections in the brain, disturbing the axons of the neurons, which may result in a concussion (Rush, 2011). Indeed, several studies have suggested that shear brain deformation resulting from rotational acceleration represents the predominant injury mechanism in concussions (Adams et al., 1982; Gennarelli et al., 1982; Meaney & Smith, 2011; Unterharnscheidt & Higgins, 1969). More specifically, the disturbances of the white matter induced by shear forces result in cell death, causing symptoms related to slow cognitive speed, and decreased motor coordination on the affected individuals (Rush, 2011). Other symptoms related to rotational accelerations may include loss of consciousness due to impact "rotational forces at the junction of the midbrain in the thalamus," which is the region of the brain responsible for all input for motor and sensory information (Mullally, 2017, p. 886).

The location of the impact on the head also plays a role in the cause of the brain injury and the occurrence of concussions (Meaney & Smith, 2011). Impacts to the side, front, or back of the head show significantly different linear and rotational accelerations induced to the brain and consequently, cause different levels of impairment on the athlete (Gennarelli et al., 1982; Meaney & Smith, 2011). Gennarelli et al. (1987), for example, found that impact accelerations induced to the side of the head produced more axonal damage in the brainstem and more frequently a concussion than other head impact locations (Gennarelli et al., 1987). Liao, Lynall, and Mihalik (2016) found that concussed athletes experienced more impacts to the side of the head than non-concussed athletes did. Kerr et al. (2014), on the other hand, found that concussions occurred more frequently from impacts at the front than the side of the head.

In the sport of boxing head impacts may cause, for example, facial lacerations; eye and nose injuries. These head impacts pose a high risk of concussions and acute neurological injuries for amateur and professional athletes (Jordan & Campbell, 1988; McCown, 1959; Zazryn et al., 2003; Zazryn et al., 2009). Acute neurologic injuries in boxing often result from the knockout (KO) punch, which induces linear or rotational acceleration to the cerebellum and brain stem affecting the ability of the athlete to remain standing (Bledsoe et al., 2005). Neurological issues in boxers due to concussions manifest in their resultant speech, gait, cognition, behavior, and personality changes. Boxers who suffer a concussion may also experience a variety of post-concussion symptoms including headaches, balance issues, disrupted sleeping behaviors, and memory problems when recalling information (Johnson, 1969; Mendez, 1995).

Headguards offer a form of head protection to mitigate the risk of head injuries and concussions in the sport of boxing (Dau et al., 2006). The capabilities of boxing headguards to mitigate the risk of concussion, however, depend on the properties of the headguard liner to minimize linear and rotational accelerations induced to the brain during a head punch. McIntosh and Patton (2015), for example, tested the protective capabilities of boxing headguards with the use of linear impactors and surrogate headforms instrumented with linear and rotational accelerometer sensors. The researchers found that with a punch velocity of 8.3 m/s, a bare surrogate headform experienced a mean peak resultant acceleration of 130 g. The use of a boxing headguard, however, reduced the mean peak linear acceleration to 85 g. Dau et al. (2006) also found decreases in linear acceleration from 78.08 g to 51.17 g and rotational acceleration from 9164.10 rad/s^2 to 5534.78 rad/s^2 with the use of a headguard. Although the decrease in peak rotational acceleration exceeded the threshold level of 4500 rad/s^2, the results suggest that the use of a headguard reduces the risk and severity of the concussion.

MAIN FOCUS OF THE ARTICLE

Issues, Controversies, and Problems

The main issue is that the sport of boxing comes with an inherent risk of concussions and head injuries. In particular, concussions that occur while playing the sport of boxing can cause short and long-term traumatic neurologic impairments on athletes, which disrupt the life of the athletes and their families, the functioning of sport organizations, and may also result in an increase in health care costs (Jordan & Campbell, 1988; McCown, 1959; Zazryn et al., 2003; Zazryn et al., 2009). In United States of America (USA), for example, concussions in the sport of boxing represent one of the major occurrences of head injuries for the medical community and are the highest for any individual male sport (Tommasone & McLeod, 2006).

The controversy, however, is that the sport of boxing has different headguard rules by gender and competition levels across different world organizations. Boxing Canada, for example, states that headguard use is mandatory for elite male open boxers, except for National Championship bouts (Boxing Canada, 2017). The International Boxing Association (AIBA) also prohibits the use of headguards in AIBA open boxing men's elite competitions (AIBA, 2019).

The problem lies in that, although the use of boxing headguards reduces the magnitude of linear and rotational accelerations induced to the head during a punch (McIntosh & Patton, 2015), these boxing organizations do not make the use of headguards mandatory at all levels of competition. One of the main reasons for non-mandatory use of headguards is that the literature lacks information regarding the effectiveness of boxing headguards in mitigating the risk of concussion in the sport of boxing. Only a few studies have provided valuable information regarding the behaviours of linear and rotational accelerations during a punch in the sport of boxing (McIntosh & Patton, 2015; O'Sullivan et al., 2016).

As a result, further research is needed to explore the capacity of boxing headguard materials in absorbing energy to minimize linear and shear force impacts to the head. Energy, in the context of mechanics, is the capacity of doing work. The mechanical energy is calculated by the product of force and displacement. When applying the concept of energy absorption to examine the elastic properties of a boxing headguard material during static testing, it involves a loading force over some deformation of the material, and subsequently an unloading force over some restoration of the shape of the material (Marsh et al., 2004, Zerpa et al., 2019). Specifically, the force has a normal component as well as a shear component. The displacement also consists of a compression and shear displacement component. The goal is to be able to examine the extents to which headguard materials absorb compressive and shear energy. As stated by Meaney & Smith (2011), during a boxing punch, shear forces cause rotational accelerations and a "jarring" effect to the head, producing deformation to the brain and consequently a concussion (Meaney & Smith, 2011).

Materials with high tensile and flexural strength such as thermoplastic polyurethane (TPU) provide an avenue to improve helmet design technology and minimize concussion risk (Lin et al., 2017); however, the research on its effectiveness in boxing headguards to reduce linear and rotational accelerations during a punch is still lacking. Based on these issues, controversies, and problems, there is a need to compare the effectiveness of boxing headguard materials in mitigating not only linear but also rotational accelerations to minimize the risk of concussion in the sport of boxing. The following questions guided the current study:

1) Which boxing headguard (Century→ Drive, Adidas→, or TPU-Century→ Drive) absorbed the most energy when loaded with compressive and shear forces across locations (front or side) during static testing?
2) Which boxing headguard (Century→ Drive, Adidas→, or TPU-Century→ Drive) would be more effective in mitigating linear and rotational accelerations at the front, front boss, or side impact locations during dynamic testing?

METHOD

1. Static testing. The researchers used three boxing headguard materials in this study including an Adidas→, a Century→ Drive, and a modified TPU-Century→ Drive, which had TPU inserts placed at the front and side locations of the headguard. All three headguards underwent static testing by using a Chatillon→ force tester to compress the headguards at the front and side locations to analyze the changes in the material properties (VanLandingham et al., 2005) as depicted in Figure 1. The researchers modified the Chatillon→ force tester by adding a pair of 30º wooden wedges. One of the wedges was mounted on top of an AMTI→ force platform. The other wedge was attached to the load cell and the headguards being tested fitted between the inclined surfaces of the wedges. The down and up movements of the load cell with the wedge attached to it caused the headguard to be compressed then restored to its original shape.

The Chatillon→ TCD1100 force tester captured the vertical force and vertical displacement over the duration of the static testing. The AMTI→ force platform, on the other hand, captured the forces in the x and y directions. The researchers added these forces to compute the horizontal force as shown in Equation 1.

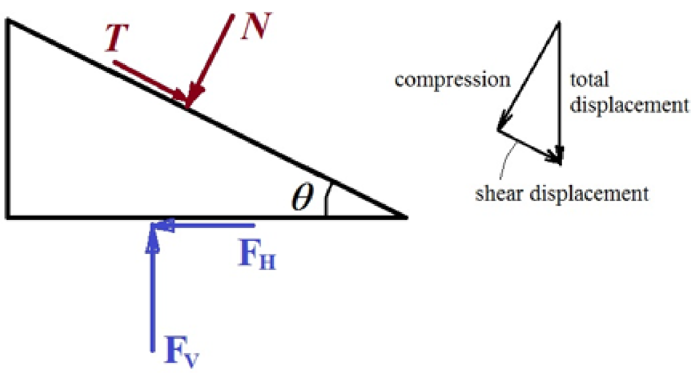
$$F\mathrm{H} = \sqrt{F\mathrm{x}^2 + F\mathrm{y}^2} \quad (1)$$

where F_x is the force in the x direction, and F_y is the force in the y direction.

Next, the researchers used Equations 2 and 3 to compute the compressive (or normal) force (N) and shear force (T) as shown in Figure 2. The researchers then combined the measures of compressive and shear forces (N and T) with displacement measures (also shown in Figure 2) to compute the compressive, shear, and total energy absorptions of the material using a MATLAB→ script developed by the researchers.

Figure 1. Static testing of Adidas→ headguard at the front location using the Chatillon→ TCD1100 force tester and AMTI→ force platform, showing one wedge and the load cell (right side of the figure)

Figure 2. Free-body diagram showing components of forces (left) and components of displacement (right)



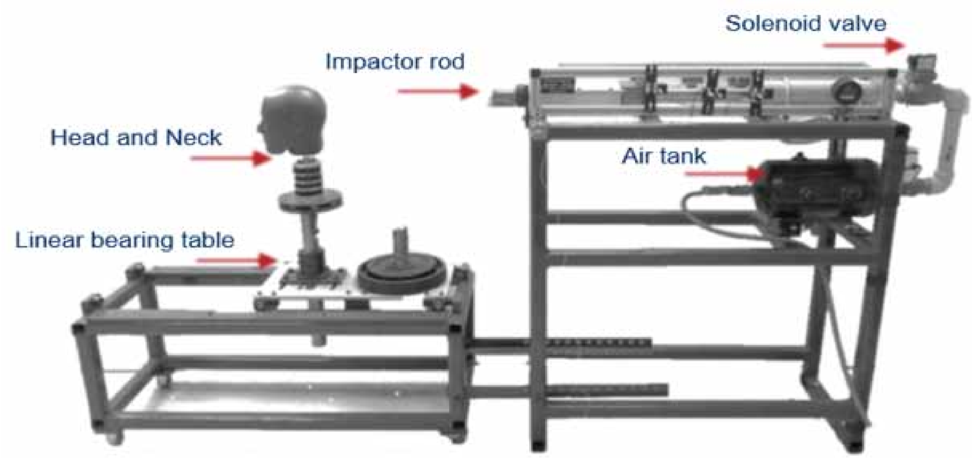
$$N = F_V \cos\theta - F_H \sin\theta \tag{2}$$

$$T = F_H \cos\theta + F_V \sin\theta \tag{3}$$

where F_V is the vertical force captured by the Chatillon→ TCD1100 force tester; F_H is the horizontal force by Equation 1 and θ is the wedge angle.

2. Dynamic testing. The researchers conducted the dynamic impact testing using a pneumatic horizontal impactor. The impactor included a welded steel structure composed of a main frame, a linear bearing table, and an impacting rod as shown in Figure 3. The researchers mounted the headguards on a National Operating Committee on Standards for Athletic Equipment (NOCSAE,

Figure 3. Pneumatic Horizontal Impactor



2019) headform, which was attached to a mechanical neckform as depicted in Figure 3. The surrogate headform and mechanical neck form represented the 50th percentile of a human head and neck.

Each boxing headguard experienced 18 impact velocities at the front, front boss, and side locations, respectively, based on NOCSAE (2018) standards. The front location was situated "in the median plane approximately 25 mm above the anterior intersection of the median and reference plane" (NOCSAE, 2018, pp. 26-27). The front boss was situated as "a point approximately in the 45-degree plane from the median plane measured clockwise and located approximately 25 mm above the reference plane" (NOCSAE, 2018, pp. 26-27). The side location was located "approximately at the intersection of the reference and coronal planes on the right side of the headform" (NOCSAE, 2018, pp. 26-27). The velocities ranged from 2.01 m/s to 5.13 m/s. The researchers achieved these velocities by filling the compressed air tank of the impactor system shown in Figure 3 to a desired air pressure, which was previously calibrated within the velocity range from 2.01 m/s to 5.13 m/s in increments of 2 psi. The researchers released the air pressure from the tank by clicking on a solenoid valve switch to move forward the impactor rod at the desired speed, striking the headguard mounted on the surrogate headform at the respective location. The researchers conducted a total of 162 impacts based on three types of headguards and three head impact locations across 18 different velocities.

The surrogate headform was instrumented with accelerometers and gyroscope sensors to capture the linear acceleration (in g) and angular displacement (in radians) in the x, y, and z directions at a sampling frequency of 20 kHz for each impact. The researchers developed a MATLAB→ script to compute: (a) the angular accelerations (in rad/s^2) from the displacement measures; (b) the peak resultant linear acceleration (PRLA); and (c) the peak resultant rotational acceleration (PRRA).

The researchers conducted two-way ANOVAs for the independent measures to examine the interaction effect between boxing headguard type (Adidas→, Century→ Drive, and TPU-Century→ Drive) and impact location (front, side, and front boss) on measures of PRLA and PRRA. If the results revealed no significant interaction effect, the researchers then used one-way ANOVAs to examine the main effect of headguard and location separately. If the results revealed a significant interaction effect, the researchers explained the interaction by conducting simple main effects analyses to compare the headguard types across each location separately using one-way ANOVAs. Post-hoc analyses and descriptive statistics were implemented using Tukey's test for mean pair comparison regarding the interactions and main effects.

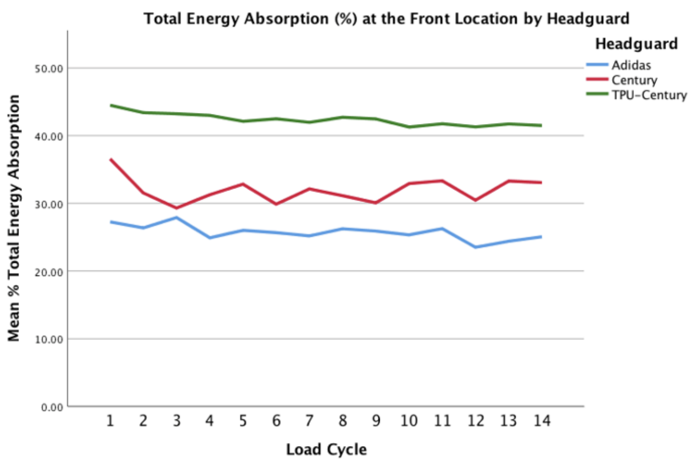
RESULTS

The results of this study addressed each of the research questions separately. The first question aimed at comparing three boxing headgears for the front and side locations during static testing. This analysis included measures of total, compressive, and shear energy absorptions for the front and side locations of the headguards. The second question aimed at comparing three boxing headgears for the front, front boss, and side locations during dynamic testing. This analysis included measures of linear and rotational accelerations for the front, front boss, and side locations of the headguards.

Static Measures

a. **Front location static test**. The results for the static tests conducted at the front headguard location indicated that the TPU-Century→ Drive absorbed the highest amount of total energy of the three headguards in terms of mean percentage (M=42.38%), followed by the Century→ Drive headguard (M=31.98%), and then the Adidas→ headguard, which absorbed the lowest amount of total energy (M=25.71%). Figure 4 shows a representation of the percentage of total energy absorption when comparing the three headguards at the front location across 14 loading and unloading cycles.

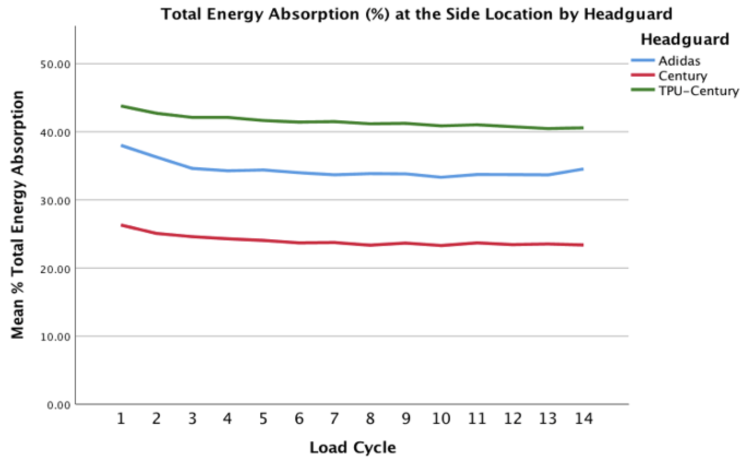
Figure 4. Percentage of total energy absorption for the Adidas→, Century→ Drive, and TPU-Century→ Drive headguards at the front location during static testing



When separating the total energy into compressive and shear energies, the TPU-Century→ Drive had the highest mean percentage of compressive energy absorption (M=46.25%), followed by the Century→ Drive (M=36.39%), and then the Adidas→, which absorbed the lowest amount of compressive energy (M=30.13%). Similarly, the TPU-Century→ Drive absorbed the highest amount of shear energy (M=35.08%) when compared to the Century→ Drive headguard (M=22.85%), and the Adidas→ headguard (M=17.63%).

b. **Side location static test.** The results of the static tests conducted at the side location indicated that the TPU-Century→ Drive had the highest mean percentage of total energy absorption (M=41.52%) when compared to the Adidas→ (M=34.42%), and Century→ Drive (M=24.01%) headgears. Figure 5 shows a representation of the percentage of total energy absorption when comparing the three headguards at the side location across 14 loading and unloading cycles.

Figure 5. Percentage of total energy absorption of the Adidas→, Century→ Drive, and TPU-Century→ Drive headguards at the side location during static testing



When separating the total energy into compressive and shear energies, the TPU-Century→ Drive had the highest mean percentage of absorbed compressive energy (M=48.48%), when compared to the Adidas→ (M=40.10%), and Century→ Drive (M=28.66%) headgear. Similarly, for the shear energy, the TPU-Century→ Drive absorbed the highest percentage of shear energy (M=29.15%), when compared to the Adidas→ headguard (M=22.48%), and the Century→ Drive headgear (M=13.51%).

Dynamic Measures

a. **Linear impact acceleration.** The results of the two-way independent measures ANOVA showed no significant interaction effect, F (4,153) =1.087, p=.365, between headguard condition (Adidas→, Century→ Drive, and TPU-Century→ Drive) and impact location (front, front boss, and side) for the measures of PRLA. When examining the main effects, however, the results of the one-way ANOVA showed statistically significant differences, $F(2,153)=17.066$, $p<.05$, $\eta^2=.182$ with a large effect size between headguard types (Adidas→, Century→ Drive, and TPU- Century→ Drive) for the measures of PRLA. The Tukey's post-hoc analysis revealed that the TPU-Century→ Drive performed the best in mitigating PRLA (M=104.61 g, SD=48.39), when compared to the Century→ Drive (M=182.93 g, SD=99.58) and Adidas→ (M=184.94 g, SD=92.27) at $p<.05$ as shown in Figure 6. The differences in performance between the Century→ Drive and Adidas→, however, were not statistically significant at $p<.05$ as shown in Figure 6.

The one-way ANOVA main effect analysis also showed statistically significant differences, F (2,153) = 4.237, p=.016, $\eta^2=.052$, with a small effect size between impact locations (front, front boss, and side) for the measure of PRLA. The Tukey's post-hoc analysis showed statistically significant lower PRLA measures for the front boss impacts (M=138.30 g, SD=75.43) than the side impacts (M=182.73 g, SD=108.91) at $p<.05$. The Tukey's post-hoc analysis, however, revealed no statistically significant differences in PRLA measures for the front impact location (M=151.45 g, SD=80.21) when compared to the front boss and side impact locations as shown in Figure 7.

b. **Angular Acceleration.** The results of the two-way independent measures ANOVA showed a statistically significant interaction effect, $F(4,153)=4.103$, $p=.003$, $\eta^2=.097$, with a medium effect

Figure 6. Measures of PRLA for each helmet type

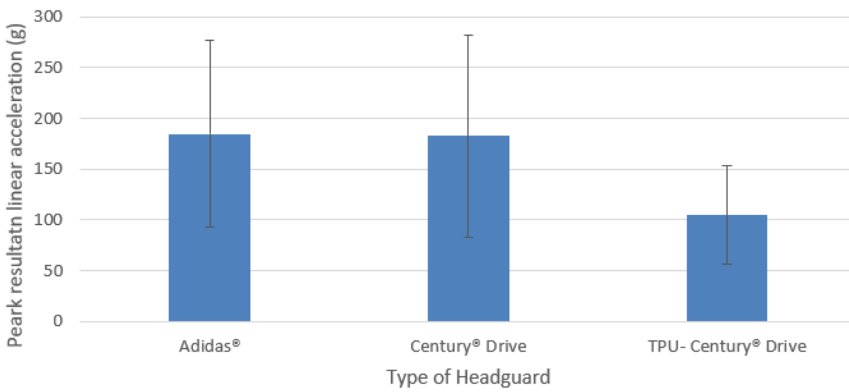
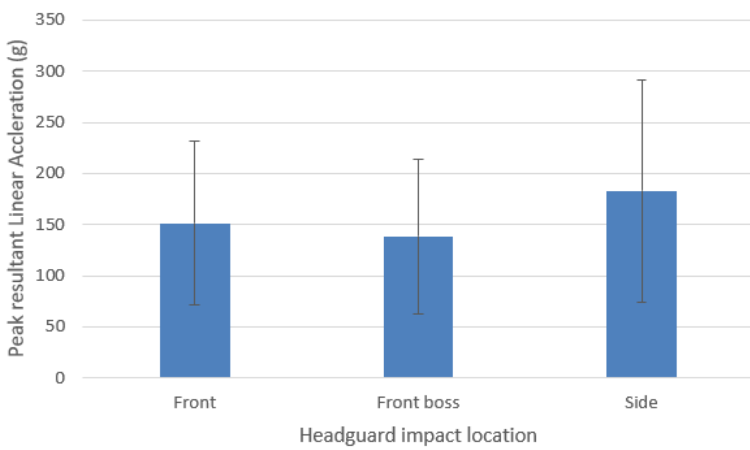


Figure 7. Measures of PRLA for each impact location

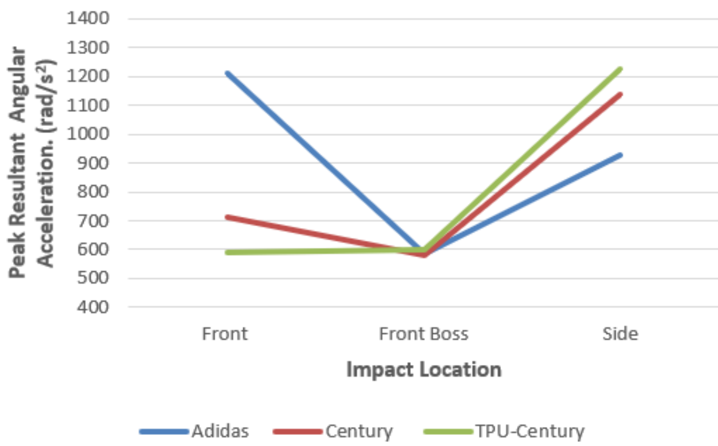


size between headguard conditions (Adidas→, Century→ Drive, and TPU-Century→ Drive) and impact locations (front, front boss, and side) for the measures of PRRA. Figure 8 displays a representation of this interaction.

The researchers then conducted simple main effect analyses to further explain this interaction. The results of the one-way ANOVA showed statistically significant differences in measures of PRRA, F (2, 51) = 6.456, p=.003, η^2=.202, with a large effect size among the three headguard types at the front location. The Tukey's post-hoc analysis revealed that the Adidas→ headguard (M=1209.99 rad/s^2, SD=840.99) had significantly higher measures of PRRA than the Century→ Drive headguard (M=713.06 rad/s^2, SD=431.40) and the TPU-Century→ Drive headguard (M=588.15 rad/s^2, SD=108.47) for the front location, at p<.05 as shown in Figure 8.

For the one-way ANOVA conducted by headguard types, the Adidas→ headguard revealed significant differences in measures of PRRA across impact locations, F(2, 51)=5.572, p=.006, η^2=.179, with a large effect size. The Tukey's post-hoc analysis revealed significantly lower measures of PRRA for the front boss location (M=585.74 rad/s^2, SD=89.57), than the front location (M=1209.99 rad/s^2, SD=840.99) at p<.05. The differences in measures of PRRA for the side location (M=925.98 rad/s^2, SD=481.02) were not statistically significant when compared to the front and front boss impact locations at p<.05.

Figure 8. Interaction effect of headguard type and impact location on measures of PRRA



The Century→ Drive headguard revealed significant differences in measures of PRRA across impact locations, F (2, 51) = 6.154, p=.004, η^2=.194, with a large effect size. The Tukey's post-hoc analysis showed that the PRRA was significantly higher for impacts at the side (M=1135.95 rad/s^2, SD=730.42) than impacts at the front (M=713.06 rad/s^2, SD=431.40) and front boss (M=579.57 rad/s^2, SD=144.01) locations, p<.05. The differences between front and front boss locations were not statistically significant for measures of PRRA.

The TPU-Century→ Drive headguard also revealed statistically significant differences in measures of PRRA across impact locations, F (2, 51) = 9.993, p<.05, η^2=.282, with a large effect size. The Tukey's post-hoc analysis showed that the PRRA measure for the TPU-Century→ Drive headguard was significantly higher (p<.05 for both) for impacts at the side location (M=1224.07 rad/s^2, SD=831.74) than at the front boss (M=600.30 rad/s^2, SD=105.65), and front (M=588.15 rad/s^2, SD=108.47) locations. The differences between the front and front boss locations were not statistically significant at p<.05 for measures of PRRA.

CONCLUSION

This study explored the effectiveness of boxing headguards to absorb energy during static testing and their capacity to reduce head impact accelerations during dynamic testing. Particularly, this study built on previous boxing headguard research by investigating the effectiveness of a modified TPU headguard as a protective technology to mitigate head impact accelerations responsible for causing concussions (McIntosh & Patton, 2015).

The static analysis provided valuable information regarding the material properties of the TPU-Century→ Drive, Century→ Drive, and Adidas→ boxing headguards in term of their capacity to load, unload, and absorb energy. Across 14 loading and unloading cycles at the front and side locations of the boxing headguards, the TPU-Century→ Drive provided the highest compressive, shear, and total energy absorptions when compared to the Century→ Drive and Adidas→ boxing headguards. This outcome supported the notion that the elastic, high tensile, and flexural strength properties of the TPU material improved the performance of the Century→ Drive headguard to distribute the loading energy over a larger area and, consequently, expanded the energy absorption capacity of the headguard (Barth et al., 2001; Lin et al., 2017).

Ideally, a boxing headguard liner would absorb most, if not all, of the loading energy of an impact and then dissipate it during the unloading phase at any impact location of the headguard (Zerpa et al., 2019). As stated by Barth et al. (2001), a higher energy dissipation value translates to a lower rebound velocity, reducing the risk of a contrecoup injury, where the brain collides with the skull because of the impact.

In the current study, the addition of a single TPU insert to the front location of the Century→ Drive headguard resulted in a 10% increase in the capability of the headgear to absorb compressive, shear, and total energies than the other headguards examined in this study. Similarly, for the side location, the addition of a single TPU insert to the Century→ Drive headguard yielded 50% more shear energy being absorbed and 15% more compressive and total energies absorbed than the other boxing headguards. These were promising results, suggesting the use of TPU insert liners as an avenue to improve the protective capabilities of current boxing headguards as the sport of boxing poses a high risk of concussion during amateur and professional competitions (Pellman et al., 2003). In the sport of boxing, the loss of consciousness very often results from hook punches to the side of the mandible, which cause high levels of rotational movement and increase the magnitude of trauma in all areas of the brain (Cournoyer and Hoshizaki, 2019). Consequently, increasing the protective capacity of boxing headguards with the use of TPU may provide an avenue to minimize the risk of concussion for amateur and professional boxers.

The results from the static testing also seemed to suggest that the Adidas→ headguard absorbed energy less effectively at the front location, while the Century→ Drive absorbed energy less effectively at the side location. These outcomes pointed to the need to improve the protective capacity of these commercial boxing headguards in the front and side locations to reduce the impact loads placed on the head during a punch and therefore, minimize the risk of concussion (Di Landro et al., 2002). As stated by Kerr et al (2014), concussions occur primarily from impacts at the front and side locations of the head.

The inclusion of the TPU material in the Century→ Drive headguard marked an improvement in shear, compressive, and total energy absorptions across the front and side locations. These findings support the research conducted by Bates et al. (2019) and Rizzo et al. (2021) regarding the usefulness of TPU material in energy absorption.

The dynamic analysis, on the other hand, provided valuable information regarding the capacity of the boxing headguards in mitigating linear and rotational accelerations responsible for causing concussions due to head impacts occurring in the front, front boss, and side locations of the head while practicing the sport of boxing (Jordan & Campbell, 1988; McCown, 1959; McIntosh & Patton, 2015; Zazryn et al., 2003; Zazryn et al., 2009).

In the current study, the TPU performed the best at mitigating PRLA when compared to the tested commercial headguards. This finding supports the need to improve the performance of existing commercial boxing headguards in minimizing concussion risk. As stated by O'Sullivan and Fife (2016), commercial headguards tested according to the American Society for Testing and Materials (ASTM) protocols (ASTM, 2015) failed to pass the resultant linear acceleration threshold value of 150 g. In the current study, the Adidas→ and Century→ Drive headguards also failed this threshold, but the TPU-Century→ Drive performed the best (M=104.61 g, SD=48.39) and passed the threshold requirement with a value of 30% below the ASTM recommendation. This outcome expands on previous TPU research by showing the effectiveness of TPU in reducing PRLA, which is considered a good predictor of peak pressure occurring within the brain due to a head impact (Bates et al., 2019; Meaney & Smith, 2011; Rizzo et al., 2021).

The literature also suggests that rotational acceleration correlates highly with the occurrence of concussions as this type of acceleration produces more deformation in the brain tissue than linear acceleration does, making rotational acceleration a strong predictor of concussions (Meaney & Smith, 2011). In the current study, the TPU-Century→ Drive performed the best at mitigating rotational accelerations at the front location as compared to the commercial headguards. This outcome indicates a need for improved and more durable materials located at the front location of current commercial boxing headguards and, more specifically, the Adidas→ headguard, which was less effective in mitigating angular accelerations at the front location than the Century→ Drive headguard. The TPU-Century→ Drive and commercial Century→ Drive, however, showed consistently worse performance at the side in mitigating angular accelerations in comparison to other locations of the headguards, which may be explained by the thin side padding of the commercial Century→ Drive headguard. When comparing these results to the concussion threshold of 4500 rad/s^2 of angular acceleration noted by Ommaya et al. (2002), the current study found that all the boxing headguards performed below these threshold values. This outcome is encouraging in terms of the capabilities of commercial boxing headguards to mitigate the occurrence of concussions due to rotational accelerations. Nonetheless, the use of TPU in combination with a Century→ Drive headguard material showed promise in reducing PRLA across all locations and PRRA at the front location when compared to commercial headguards.

In summary, from the theoretical perspective, the research findings of this study build on the existing literature by implementing TPU insert liners in boxing headguard technologies as an avenue to mitigate linear and rotational accelerations responsible for causing concussions on athletes in the sport of boxing (Bates et al.,2019; Meaney & Smith, 2011; Rizzo et al., 2021). From the practical perspective, the method and research findings of this study provide an avenue for helmet designers and researchers to improve the performance of current boxing headgears to protect athletes' heads in the sport of boxing against concussions. The inclusion of multiple impact locations, a wide range of impact velocities, and the use of accelerometers and gyroscope sensors in the current study allowed the researchers to create a closer replication of impacts that occur in real boxing matches to evaluate the performance of boxing headguards in protection against concussion. Future research will include different ranges of neck strengths for the male and female populations and different impact angles to further examine the performance of boxing headguards. Finally, future research will include information on the risk of injury measures and energy absorption capabilities of boxing headguards during dynamic impacts.

ACKNOWLEDGMENT

Conflict of Interest

The authors of this publication declare that there is no conflict of interest.

Funding Agency

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

REFERENCES

Adams, J. H., Graham, D. I., Murray, L. S., & Scott, G. (1982). Diffuse axonal injury due to nonmissile head injury in humans: An analysis of 45 cases. *Annals of Neurology*, *12*(6), 557–563. doi:10.1002/ana.410120610 PMID:7159059

AIBA. (2019). *Technical and competition rules*. Retrieved from https://www.iba.sport/aiba-technical-competition-rules/

ASTM. (2015). *Standard specification for protective headgear used in martial arts*. Retrieved from https://www.astm.org/f2397-09.html

Barth, J. T., Freeman, J. R., Broshek, D. K., & Varney, R. N. (2001). Acceleration-deceleration sport-related concussion: The gravity of it all. *Journal of Athletic Training*, *36*(3), 253–256. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC155415/ PMID:12937493

Bates, S. R., Farrow, I. R., & Trask, R. S. (2019). Compressive behaviour of 3D printed thermoplastic polyurethane honeycombs with graded densities. *Materials & Design*, *162*, 130–142. doi:10.1016/j.matdes.2018.11.019

Bledsoe, G. H., Li, G., & Levy, F. (2005). Injury risk in professional boxing. *Southern Medical Journal, 98*(10), 994-998. doi:10.1097/01.smj.0000182498.19288.e2

Canada. (2017). *Articles and rules*. Retrieved from https://boxingcanada.org/wp-content/uploads/2017/10/Rules-and-Articles-October-2017.pdf<ALIGNMENT.qj></ALIGNMENT>Boxing

Cournoyer, J., & Hoshizaki, T. B. (2019). Head dynamic response and brain tissue deformation for boxing punches with and without loss of consciousness. *Clinical Biomechanics (Bristol, Avon)*, *67*, 96–101. doi:10.1016/j.clinbiomech.2019.05.003 PMID:31082637

Dau, N., Chien, H. C., Sherman, D., & Bir, C. (2006). *Effectiveness of boxing headgear for limiting injury*. Retrieved from https://www.researchgate.net/publication/267790987_Effectiveness_of_Boxing_Headgear_for_Limiting_Injury

Di Landro, L., Sala, G., & Olivieri, D. (2002). Deformation mechanisms and energy absorption of polystyrene foams for protective helmets. *Polymer Testing*, *21*(2), 217–228. doi:10.1016/S0142-9418(01)00073-3

Gennarelli, T. A., Thibault, L. E., Adams, J. H., Graham, D. I., Thompson, C. J., & Marcincin, R. P. (1982). Diffuse axonal injury and traumatic coma in the primate. *Annals of Neurology*, *12*(6), 564–574. doi:10.1002/ana.410120611 PMID:7159060

Gennarelli, T. A., Thibault, L. E., Tomei, G., Wiser, R., Graham, D., & Adams, J. (1987). *Directional dependence of axonal brain injury due to centroidal and non-centroidal acceleration.* SAE Technical Paper Series. paper no. 872197. Retrieved from https://www.sae.org/publications/technical-papers/content/872197/

Giza, C. C., & Hovda, D. A. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training*, *36*(3), 228–235. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC155411/ PMID:12937489

Giza, C. C., Kutcher, J. S., Ashwal, S., Barth, J., Getchius, T. S. D., Gioia, G. A., Gronseth, G. S., Guskiewicz, K., Mandel, S., Manley, G., McKeag, D. B., Thurman, D. J., & Zafonte, R. (2013). Summary of evidence-based guideline update: Evaluation and management of concussion in sports: Report of the Guideline Development Subcommittee of the American Academy of Neurology. *Neurology*, *80*(24), 2250–2257. doi:10.1212/WNL.0b013e31828d57dd PMID:23508730

Johnson, J. (1969). Organic psychosyndromes due to boxing. *The British Journal of Psychiatry*, *115*(518), 45–53. doi:10.1192/bjp.115.518.45 PMID:5305282

Jordan, B. D., & Campbell, E. A. (1988). Acute injuries among professional boxers in New York State: A two-year survey. *The Physician and Sportsmedicine*, *16*(1), 87–91. doi:10.1080/00913847.1988.11709407 PMID:27427106

Kerr, Z. Y., Collins, C. L., Mihalik, J. P., Marshall, S. W., Guskiewicz, K. M., & Comstock, R. D. (2014). Impact locations and concussion outcomes in high school football player-to-player collisions. *Pediatrics*, *134*(3), 489–496. doi:10.1542/peds.2014-0770 PMID:25113292

Liao, S., Lynall, R. C., & Mihalik, J. P. (2016). The effect of head impact location on day of diagnosed concussion in college football. *Medicine and Science in Sports and Exercise*, *48*(7), 1239–1243. doi:10.1249/MSS.0000000000000896 PMID:26871990

Lin, T., Lou, C., & Lin, J. (2017). The effects of thermoplastic polyurethane on the structure and mechanical properties of modified polypropylene blends. *Applied Sciences (Basel, Switzerland)*, *7*(12), 1254. Advance online publication. doi:10.3390/app7121254

Marsh, P., McPherson, M., & Zerpa, C. (Eds.). (2004). Proceedings from 22nd *International Symposium on Biomechanics in Sport*. Academic Press.

McCown, I. A. (1959). Boxing injuries. *American Journal of Surgery*, *98*(3), 509–516. doi:10.1016/0002-9610(59)90545-8

McIntosh, A. S., & Patton, D. A. (2015). Boxing headguard performance in punch machine tests. *British Journal of Sports Medicine*, *49*(17), 1108–1112. doi:10.1136/bjsports-2015-095094 PMID:26175022

Mckee, A. C., & Daneshvar, D. H. (2015). Chapter 4 - The neuropathology of traumatic brain injury. Handbook of Clinical Neurology: Traumatic Brain Injury, Part I, 127, 45-66. doi: doi:10.1016/B978-0-444-52892-6.00004-0

Meaney, D. F., & Smith, D. H. (2011). Biomechanics of concussion. *Clinics in Sports Medicine*, *30*(1), 19–31. doi:10.1016/j.csm.2010.08.009 PMID:21074079

Meaney, D. F., Smith, D. H., Shreiber, D. I., Bain, A. C., Miller, R. T., Ross, D. T., & Gennarelli, T. A. (1995). Biomechanical analysis of experimental diffuse axonal injury. *Journal of Neurotrauma*, *12*(4), 689–694. doi:10.1089/neu.1995.12.689 PMID:8683620

Mendez, M. F. (1995). The neuropsychiatric aspects of boxing. *International Journal of Psychiatry in Medicine*, *25*(3), 249–262. doi:10.2190/CUMK-THT1-X98M-WB4C PMID:8567192

Mullally, W. J. (2017). Concussion. *The American Journal of Medicine, 130*(8), 885-892. doi: 10.1016/j.amjmed.2017.04.016

NOCSAE. (2019). *Standard pneumatic ram test method and equipment used in evaluating the performance characteristics of protective headgear and face guards*. Retrieved from https://nocsae.org/wp-content/uploads/2018/05/ND081-18am19-005.pdf

NOCSAE. (2018). *Standard test method and equipment used in evaluating the performance characteristics of headgear/equipment*. Retrieved from https://nocsae.org/standard/standard-test-method-and-equipment-used-in-evaluating-the-performance-characteristics-of-headgear-equipment/

O'Sullivan, D. M., & Fife, G. P. (2016). Impact attenuation of protective boxing and taekwondo headgear. *European Journal of Sport Science*, *16*(8), 1219–1225. doi:10.1080/17461391.2016.1161073 PMID:26999564

Ommaya, A. K., Goldsmith, W., & Thibault, L. (2002). Biomechanics and neuropathology of adult and paediatric head injury. *British Journal of Neurosurgery*, *16*(3), 220–242. doi:10.1080/02688690220148824 PMID:12201393

Pellman, E. J., Viano, D. C., Tucker, A. M., Casson, I. R., & Waeckerle, J. F. (2003). Concussion in professional football: Reconstruction of game impacts and injuries. *Neurosurgery*, *53*(4), 799–814. doi:10.1093/neurosurgery/53.3.799 PMID:14519212

Rizzo, F., Dagostino, T., Cuomo, S., Pinto, F., & Meo, M. (2021). High-velocity impact investigation on thermoplastic polyurethane/CFRP T-stiffened panel. *Materials Today: Proceedings*, *34*, 164–170. doi:10.1016/j.matpr.2020.02.163

Rowson, S., Bland, M. L., Campolettano, E. T., Press, J. N., Rowson, B., Smith, J. A., Sproule, D. W., Tyson, A. M., & Duma, S. M. (2016). Biomechanical perspectives on concussion in sport. *Sports Medicine and Arthroscopy Review*, *24*(3), 100–107. doi:10.1097/JSA.0000000000000121 PMID:27482775

Rush, B. (2011). Shearing injury, shear strain. Encyclopedia of Clinical Neuropsychology, 2285-2286. doi:10.1007/978-0-387-79948-3_277

Tommasone, B., & McLeod, T. C. V. (2006). Contact sport concussion incidence. *Journal of Athletic Training*, *41*(4), 470–472. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1748409/ PMID:17273475

Unterharnscheidt, F., & Higgins, L. S. (1969). Traumatic lesions of brain and spinal cord due to nondeforming angular acceleration of the head. *Texas Reports on Biology and Medicine*, *27*(1), 127–166. https://pubmed.ncbi.nlm.nih.gov/4976573/ PMID:4976573

VanLandingham, M. R., Chang, N.-K., Drzal, P. L., White, C. C., & Chang, S.-H. (2005). Viscoelastic characterization of polymers using instrumented indentation. I. Quasi-static testing. *Journal of Polymer Science. Part B, Polymer Physics*, *43*(14), 1794–1811. doi:10.1002/polb.20454

World Boxing Association. (2012). *Some common injuries in boxing*. Retrieved from https://www.wbaboxing.com/box-medical-articles/some-common-injuries-in-boxing#.YuWxDYTMK70

Zazryn, T. R. (2003). A 16 year study of injuries to professional boxers in the state of Victoria, Australia. *British Journal of Sports Medicine*, *37*(4), 448–451. doi:10.1136/bjsm.37.5.448 PMID:12893717

Zazryn, T. R., Mccrory, P. R., & Cameron, P. A. (2009). Neurologic injuries in boxing and other combat sports. *Physical Medicine and Rehabilitation Clinics of North America*, *20*(1), 227–xi. doi:10.1016/j.pmr.2008.10.004 PMID:19084773

Zerpa, C., Carlson, S., Przysucha, E., Liu, M., & Sanzo, P. (2019). Energy measures across hockey helmet impact locations, *ISBS Proceeding Archive, 37*(1), 443-446. Retrieved from https://commons.nmu.edu/isbs/vol37/iss1/109/

Paolo Sanzo is an Associate Professor in the School of Kinesiology at Lakehead University and at the Northern Ontario School of Medicine University and the Director and Physiotherapist at Active Potential Rehabilitation Services. He is also an instructor and chief examiner for the Orthopedic Division of the Canadian Physiotherapy Association. Dr. Sanzo was the elected past Member Organization Delegate for Canada and elected as the Vice President of the International Federation of Orthopaedic Manipulative Physical Therapists in October 2020. His research interests are in the area of rehabilitation and sports medicine. More specifically, his research integrates the clinical, biomechanical, and physiological aspects of human movement and gait analysis. It also includes the exploration of the medical and clinical uses and effects of extracorporeal shockwave therapy as it applies to failed tendon and bone healing responses; the clinical application and rationale for the use of therapeutic taping and bracing as an adjunct to rehabilitation and sport performance measures; the biomechanical analysis of concussion and clinical trials exploring various assessment and treatment techniques; manual therapy and length tension testing and the relationships between muscle and myofascial tissues in various musculoskeletal disorders; and the integration of medical technologies for both assessment and treatment purposes. He has published articles in several peer-reviewed journals, authored four books on length tension testing techniques in the upper and lower quadrants, and serves as a reviewer for several journal titles.

Meilan Liu is an Associate Professor in the Department of Mechanical Engineering at Lakehead University (Thunder Bay, Ontario, Canada). She began teaching in the Department of Mechanical Engineering soon after obtaining her Ph.D. Her main research interests include finite element analysis of structures, nonlinear mechanics, dynamics of complex systems, biomechanics, and injury prevention. She is licensed professional engineer in the Province of Ontario, Canada. In more recent years, she has served on a few Professional Engineers Ontario committees, at both the local and provincial levels.

Carlos Zerpa is an Associate Professor in the School of Kinesiology at Lakehead University. He has a PHD in the field of measurements with a focus on the assessment and evaluation of human physical and cognitive performance. He teaches and researches in the field of biomechanics- injury reconstruction for head collision causing concussions. He also researches on evaluating the effectiveness of helmets in preventing head injuries and concussions in sports using measures of linear and rotational acceleration as well as energy dissipation. His research expands to measures of gait symmetry for antalgic gait patterns on transtibial amputee populations and the implementation of heel lift prosthetics to mitigate disruptions of gait patterns. He has developed and evaluated the effectiveness of numerous technologies to assess human performance by combining biological and mechanical systems for clinical and research applications.