THE EFFECTIVENESS OF BOXING HEADGUARDS WITH THERMOPLASTIC POLYURETHANE INSERTS IN MITIGATING LINEAR AND ANGULAR IMPACT ACCELERATIONS TO THE HEAD USING A DYNAMIC HEAD MODEL

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The purpose of this study was to examine the capacity of commercial boxing headguards and an experimental thermoplastic polyurethane (TPU) liner to mitigate the risk of concussions. Headguards were tested dynamically across a range of impact locations using simulated head impacts with a pneumatic horizontal impactor to explore the behavior of the headguards. This study showed differences between headguard types in mitigating concussion risk resulting from linear and angular accelerations of the head. The results demonstrated that introducing TPU into a headguard reduces concussion risk most prominently by decreasing peak resultant linear acceleration (PRLA) and peak resultant rotational acceleration (PRRA) of the head. This study provides information about the performance of commercial headguards and suggests an avenue for further TPU research.

KEYWORDS: headgear, concussions, linear acceleration, angular acceleration, impact testing, static testing, thermoplastic polyurethane

INTRODUCTION: Boxing is a combat sport that comes with inherent injury risk. Mild traumatic brain injuries (mTBI) and long term traumatic neurologic impairments represent the major occurrences of injuries for the medical community. The aim of boxing is often to incapacitate the opponent; As such, an emphasis is placed on scoring head blows (Canadian Medical Association, 2001). The magnitude of the acceleration of the head plays a significant role in the risk of brain injuries and the severity of the damage (Rowson et al., 2016). Concussions more often occur when an impact generates an acceleration of the skull, but the brain lags behind due to inertia leading to the strain on the neural tissue and the development of various symptoms (Rowson et al., 2016). The rates of concussion in boxing are the highest of any individual male sport (Tommasone & McLeod, 2006). In Canada, the sport of boxing has different headguard rules by gender and competition levels to minimize concussion risk. Boxing Canada states that headguard use is mandatory for elite male open boxers, with the exception of National Championship bouts (Boxing Canada, 2017). The International Boxing Association (AIBA), however, prohibits the use of headguards in AIBA open boxing men's elite competition (AIBA, 2019). Previous research has shown headguards to be generally useful for reducing concussion risk, including reductions in linear and angular accelerations (Mcintosh & Patton, 2015). Despite these research findings, there are several gaps in the existing literature regarding the effectiveness of boxing headguards in mitigating the risk of concussion due to their material properties. The current research aimed to address some of these gaps by examining the effectiveness of thermoplastic polyurethane (TPU) material in mitigating the risk of concussion when used as a liner in boxing headguards. The TPU material has high tensile and flexural strength, and it has been recently introduced into helmet designs for other sports (Lin et al., 2017). Therefore, this study examined the material properties of commercial boxing headgear (Adidas® and Century® Drive) and innovated TPU liner inserts in mitigating linear and angular impacts using a surrogate headform. The researchers hypothesized that the TPU-Century® Drive model would mitigate more linear and angular accelerations when compared to the Adidas® model and Century® Drive model during simulated head impacts across different locations.

METHODS: Three headguards were tested in this study, an Adidas® model, a Century® Drive model, and a modified TPU-Century® Drive model with TPU inserts placed at the front, front boss, and side locations. To insert the TPU, the original inner foam padding was cut out of the

Century® Drive headguard at each location and replaced with the TPU liner inserts. Dynamic impact testing was completed using a pneumatic horizontal impactor. The impactor included a large welded steel structure composed of a main frame, a linear bearing table, and an impacting rod. The headguards were mounted on a National Operating Committee on Standards for Athletic Equipment (NOCSAE, 2017) headform, which was attached to a mechanical neckform. The head and neck were designed to represent the 50th percentile of a human male. Hits to the headguards were imparted by directing the pneumatic horizontal impacting rod at a desired impact location and velocity. Impacts were conducted across 18 velocities ranging from 2.01 m/s to 5.13 m/s to simulate the boxers' impacts to the head and these velocities were achieved by filling the compressed air tank of the pneumatic horizontal impactor to a desired air pressure corresponding to a certain impact velocity. Impact locations were determined according to NOCSAE (2018) standards for front, front boss, and side locations. One impact was recorded for each combination of headguard and impact location across 18 different impact velocities, which represented the boxing simulee conditions for a total of n=162 impacts overall. Results for peak resultant linear acceleration (PRLA) were analyzed and displayed in LabChart® using the data obtained from PowerLab® via accelerometers positioned in the headform. A magnetometer integrated with a gyroscope sensor was used to measure and compute the peak resultant rotational acceleration (PRRA). To analyze the data, 3 impact locations (front, side front boss) x 3 headguard types (Adidas®, Century® Drive, and TPU-Century® Drive) two-way independent measures ANOVA tests were performed for each dependent variable (PRLA, PRRA) respectively. For the ANOVA tests, if an interaction effect was found, the interaction was explained using simple main effects via one-way ANOVAs. If no significant interactions were found for a respective dependent variable, the main effects for each independent variable were analyzed separately. 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 a two-way independent measures ANOVA showed that there was not a significant interaction, $F(4,153)=1.087$, $p=.365$, between headguard type and impact location on the measure of PRLA. When examining the main effects, however, the results showed statistically significant differences, $F(2,153)=17.066$, $p<.05$, $\eta^2=.182$ between headguard types on the measure of PRLA as shown in Figure 1. The TPU-Century® Drive performed the best in mitigating PRLA (M=104.61g, SD=48.39), when compared to the Century® Drive (M=182.93g, SD=99.58) and Adidas® (M=184.94g, SD=92.27) at $p<.05$. There were statistically significant differences, $F(2,153) = 4.237$, $p=.016$, $\eta^2=.052$, between impact locations (front, front boss, side) on the measure of PRLA for all headguards. The PRLA experienced by the headform was significantly lower for front boss impacts (M=138.30g, SD=75.43) when compared to side impacts (M=182.73g, SD=108.91) at $p<.05$.

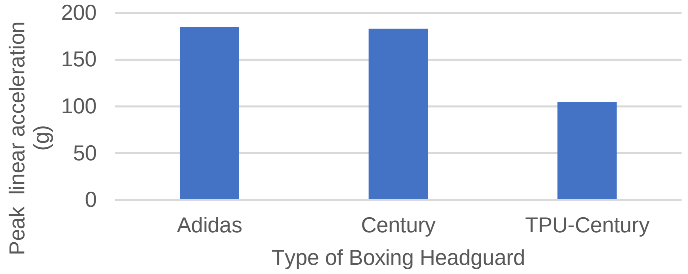

Figure 1. Comparison of boxing headguards for measures of peak linear acceleration in g

The results of the two-way independent measures ANOVA, however, showed a significant interaction effect, $F(4,153) = 4.103$, $p=.003$, $\eta^2=.097$, between headguard type and impact location on the measure of PRRA. As shown in Table 1, for the front impacts, measures of

PRRA were the lowest for the TPU-Century® Drive headguard (M=588.15 rad/s^2, SD=108.47), at p<.05 compared to the Adidas® headguard (M=1209.99 rad/s^2, SD=840.99) and the Century® Drive headguard (M=713.06 rad/s^2, SD=431.40). When comparing the PRRA results across locations for the TPU-Century® Drive headguard, impacts to the side location (M=1224.07 rad/s^2, SD=831.74) were significantly higher (p<.05 for both) compared to front boss (M=600.30 rad/s^2, SD=105.65) and front impacts (M=588.15 rad/s^2, SD=108.47). For the Adidas® headguard, however, PRRA results were the lowest for front boss impacts (M=585.74 rad/s^2, SD=89.57), when compared to front impacts (M=1209.99 rad/s^2, SD=840.99), at p<.05. Whereas, for Century® Drive headguard impacts, PRRA results were significantly higher (p<.05 for both) for impacts at the side (M=1135.95 rad/s^2, SD=730.42) compared to 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).

Table 1. Means and standard deviations for measures of rotational accelerations in rad/s^2

	Front location		Side location		Front boss location	
	Mean	SD	Mean	SD	Mean	SD
Adidas	1202.99	840.99	925.98	481.02	585.75	89.57
Century	713.06	431.40	1135	730.42	579.57	144.01
TPU-Century	588.15	108.47	1224.07	831.74	600.30	105.65

DISCUSSION: This study expands on previous boxing headguard research by investigating a modified headguard incorporating TPU material as a headguard protective technology. The results of this study revealed that 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's (2016), commercial headguards tested according to the American Society for Testing and Materials (ASTM) protocols failed to pass the resultant linear acceleration threshold value of 150g. In the current study, the Adidas® and Century® Drive headguards failed this threshold as well, but the TPU-Century® Drive performed the best (M=104.61g, SD=48.39) and passed the threshold requirement with a value 30% below the ASTM recommendation. This outcome expands on previous TPU research, showing it to be effective across locations and impact velocities when used in boxing helmets to reduce PRLA, which is considered a good predictor of peak pressure occurring within the brain due to a head impact (Meaney & Smith, 2011).

The literature also suggests that rotational acceleration correlates highly with the occurrence of concussions as this type of acceleration produces more deformation to the brain than linear acceleration would produce in other tissues of the body, making it 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 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. 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 threshold of 4500 rad/s^2 of angular acceleration noted by Ommaya et al. (2002), the current study found that no impacts resulted in angular acceleration that came close to meeting this threshold. This outcome is a good sign in terms of commercial boxing headguards mitigating concussion risk due to rotational accelerations. Nonetheless, the use of TPU in the headguard showed promise in reducing concussion risk, specifically in mitigating PRLA across all locations and PRRA at the front location when compared to commercial headguards.

This study builds on the research work of Mcintosh and Patton (2015) who showed the benefits of boxing headguards in reducing concussion risk. This study builds on their research work by providing positive evidence that the TPU material can be used in future research to further demonstrate its effectiveness across a wider range of impact conditions. The benefits of TPU material shown in this study also resembled the research work presented by Zerpa et al. (2020), which showed the benefits of TPU in head protection from impacts. As such, the findings of this study provide positive evidence in support of the use of TPU in boxing headguards as an effective material to decrease concussion risk.

CONCLUSION: The findings of this study display the differences in commercially produced headguards and new innovated TPU material in mitigating concussion risk occurring from linear and angular accelerations in the sport of boxing. The positive effects of TPU material highlight the need for further research incorporating TPU in the design of boxing headguards. Future research should explore the use of TPU of different sizes and shapes in headguards to further determine how it can be most effective across locations and impact conditions. Finally, the information presented in this study is also beneficial for researchers, equipment manufacturers, and boxing organizations to better understand the effectiveness of boxing headguards for mitigating concussion risk.

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