AN IMPROVED CYCLING HELMET TECHNOLOGY TO MITIGATE HEAD INJURIES

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This study examined the extent to which cycling helmet paddings made of thermoplastic polyurethane (TPU) material mitigated impact accelerations in a cycling helmet to reduce the likelihood of concussions. The results of this study indicate that the TPU paddings mitigate peak linear acceleration between 8.37% and 25.48%, and reduce the risk of head injury, as measured by the Gadd Severity Index (GSI) scores, ranging 20.97% to 27.62% across helmet impact locations. This information becomes useful for researchers, cyclist and helmet designers because it provides an avenue to improve cycling helmet capabilities in minimizing the risk of traumatic brain injuries due to a head impact.

KEYWORDS: Cycling, concussion, linear acceleration, thermoplastic polyurethane .

INTRODUCTION: Cycling is not only a recreational activity but also a form of human transportation. Cycling injuries to the head occur due to falling or collisions with motor vehicles (Lustenberger et al., 2010). The head is the primary injury site for cyclists with concussions occurring in approximately 38% of hospitalized patients (Haileyesus, Annest, & Dellinger, 2007). These concussions were due to direct impacts to the head or when the torso stopped abruptly during a collision (King et al., 2003). The most frequent head impact locations during cycling collisions were found to be in the front, side, and back regions of the head (Depreitere et al., 2004; Simms & Wood, 2009). Cycling helmets provide a mean to reduce the risk of head injuries during collisions (Ramage-Morin, 2017). These helmets are typically made of expanded polystyrene (EPS) foams designed to dampen and reduce impact forces, as well as, linear and angular accelerations known to cause concussions (McIntosh et al., 2013b). The EPS is housed in a plastic hard shell with ventilation gaps designed for comfort. These helmets adhere to four key design criteria. Firstly, the helmet should not block the rider's vision. Secondly, the helmet should not detach off the head when the rider falls. Thirdly, the straps should not stretch to ensure the helmet does not fall off in an accident. Lastly, the helmet should significantly reduce the force to the rider's head when the helmet hits a hard surface (CPSC, 2012). Despite advancements in helmet technologies, concussions continue to occur during cycling head collisions due to stretches and tears of axon bundles in the white matter, which leads to a breakdown of neuronal signals, and consequently brain damage (Hoshizaki et al., 2016; King et al., 2003; Kleiven, 2013). Based on these limitations in current helmet technologies, the purpose of this study was to determine the extent to which paddings, made of thermoplastic polyurethane (TPU) material, mitigate impact accelerations to reduce the likelihood of concussions. Thermoplastic material exhibits hysteresis and cyclic softening (Qi et al., 2005). The area enclosed by the hysteresis loop represents energy absorbed during a loading-unloading cycle.

METHODS: A medium size National Operating Committee on Standards for Athletic Equipment (NOCSAE) headform instrumented with linear accelerometers was used to simulate dynamic cycling impacts to the head during horizontal collisions. The NOCSAE headform was connected to a mechanical neckform made of neoprene rubber with steel end plates to emulate a human neck. The researchers set the strength of the neck by adjusting the stiffness of the mechanical neckform with a torque of 1.356 N·m (or 12 in·lb), which represents the 50th percentile of adult neck stiffness (Rousseau et al, 2009). The neckform and headform assembly were mounted on a linear bearing table of a pneumatic horizontal impact system, which also contained a main frame and an impacting rod. The main frame consisted of a 3-

gallon pressurized air tank instrumented with a digital pressure gauge. The impacting rod was fitted inside a pressurized chamber. Pressurized air propelled the impacting rod to strike the headform at the front, rear or side locations. This process was accomplished by triggering a solenoid valve so that pressurized air was released from the tank. Before each impact, a new bicycle helmet was placed on the NOCSAE headform. The helmet sat 5 cm from the bridge of the nose on the NOCSAE headform (NOCSAE, 2009). At every location, each helmet was impacted three times without and with TPU paddings, repectively, for a total of 18 impacts. After impact testing without TPU paddings, the TPU paddings were placed between the cycling helmet’s EPS material and NOCSAE headform. Each impact was conducted at the speed of 4.8 m/s based on Consumer Product Safety Commission (CPSC, 2012). The head injury severity index was computed using Equation 1 (Gadd, 1966; Onusic, 1995; Schmitt et al., 2014).

$$\mathrm{GSI} = \int_0^{\tau} a(t)^{2.5}\,dt \qquad (1)$$

where GSI = the Gadd Severity Index; a(t) = linear impact acceleration sampled at a frequency of 20,000 Hz; and τ = impact duration. `A GSI value above 1000 indicates severe head injury (Gadd, 1966).

The percent mitigation of linear impact acceleration for the TPU material across impact locations was determined using Equation 2.

$$\text{\% mitigation} = \left[\frac{(a_{max_{no\,TPU}}) - (a_{max_{TPU}})}{(a_{max_{no\,TPU}})}\right] \times 100 \qquad (2)$$

where a_{max} = maximum acceleration across impact locations with and without TPU.

The percent GSI for the TPU material across impact locations was determined using Equation 3.

$$\text{\% GSI} = \left[\frac{(GSI_{max_{no\,TPU}}) - (GSI_{max_{TPU}})}{(GSI_{max_{no\,TPU}})}\right] * 100 \qquad (3)$$

where GSI_{max} = maximum value of GSI across impact locations with and without TPU.

RESULTS: Descriptive statistics shown in Table 1 indicates that with TPU paddings, more linear acceleration was mitigated across all helmet impact locations at the speed of 4.8 m/s when compared to the without TPU conditions. The descriptive statistics also indicates that, without TPU paddings, the side location experienced a higher acceleration value when compared to the front and back locations. Yet, when impacting all the locations at the same speed with the TPU paddings, the linear acceleration was reduced for all the locations, although the acceleration value remained higher for the side location when compared to the other two locations. The data also revealed more variability across impact trials for the front location without TPU paddings. The side location, on the contrary, contained more variability across trials for the TPU paddings. Finally, the back location had more consistent results across trials for both conditions, with and without TPU paddings.

The results in Table 2 indicate that, with the TPU paddings, more linear impact acceleration was mitigated in the back location (25.48% reduction) as compared to the side and front locations (8.37% and 17.33%, respectively). The reductions in GSI scores, however, ranged 20.97% to 27.70%. Overall, the reductions in GSI scores, and in linear accelerations (with the exception of linear acceleration at the side location) were significant as they were well above 10%, with some above 25%.

The percent reductions for acceleration and GSI scores were computed using Equations 2 and 3. The trial with the highest acceleration values or GSI scores across impact locations was selected to compute the percent reductions instead of the mean values to ensure more consistency due to the high variability experienced by some locations across trials for the with and without TPU conditions as shown in Table 1.

Table 1: Descriptive statistics of acceleration measures (in gravitational acceleration g = 9.81 m/s^2) with and without TPU.

	N	Minimum	Maximum	Mean	Std. deviation
Front without	3	90.78	95.27	92.76	2.29
Front_TPU	3	78.62	78.76	78.71	0.78
Back without	3	78.18	80.21	79.38	1.06
Back_TPU	3	59.77	62.32	61.29	1.34
Side without	3	103.85	106.71	104.98	1.52
Side_TPU	3	88.91	97.78	94.16	4.65

Table 2: Percentage of mitigation and reduction in GSI scores for TPU inserts.

	Impact locations		
	Front	Back	Side
% mitigation of linear acceleration	17.33	25.48	8.37
% reduction in GSI scores	27.70	27.62	20.97

DISCUSSION: This study aimed to determine the extent to which thermoplastic polyurethane (TPU) paddings mitigate impact accelerations in a cycling helmet to reduce the risk of head injury, and consequently the likelihood of concussions during collisions. As stated in the literature, the most frequent head impact locations during cycling collisions happen in the front, side, and back regions of the head (Depreitere et al., 2004; Simms & Wood, 2009). Despite advancements in cycling helmet technologies to reduce the likelihood of head injuries, concussions continue to occur during cycling collisions (Attewell et al., 2001). Researchers, however, found that the use of innovated insert liners helps improve cycling helmet technology to mitigate the risk of head injury (Hoshizaki et al., 2016). The outcome of the current study supports these research findings and shows that it is possible to improve the performance of a cycling helmet to mitigate impact acceleration and reduce the risk of head injury. This result can be achieved by adding TPU paddings at the front, side and back locations of the cycling helmet. The front location, for example, demonstrated a reduction of 17.33% in linear acceleration and a reduction of 27.70% in GSI with the TPU paddings. The back impact location had reductions in peak linear acceleration and GSI score of 25.48% and 27.62%, respectively. Similarly, the side location showed a reduction of 8.37% in linear acceleration and 20.97% in GSI with the TPU paddings. Both the front and side impact locations share a similar characteristic that the highest peak linear acceleration also generates the highest GSI value; however, the back location does not follow the same trend. This outcome may be related to the differences in the geometry of the helmet across locations, which seem to affect the capability of the helmet to mitigate the impact and reduce the risk of injury. This outcome, however, is similar to previous research in which differences across locations on measure of acceleration and GSI scores were found to be related to the geometry of the helmet (Zerpa et al., 2019). Furthermore, when estimating the probability of head injury based on the outcome of the data and the work of Schmitt et al., (2014), the present results indicate lower probability of head injury for the impact locations with TPU than without TPU paddings. Finally, probability differences in percent reduction with and without TPU paddings were also observed across helmet locations. For the back location, for example, the GSI scores suggest that the probability of sustaining a severe head injury is approximately 17.4% without TPU paddings and 12.7% with TPU paddings. For the side location, the GSI scores suggest that the probability of sustaining a severe head injury is 37.7% without TPU paddings and 29.7% with

TPU paddings. These outcomes indicate that TPU paddings reduce the probability of head injury in some locations more than in other locations due to the geometry of the cycling helmet.

CONCLUSION: This study shows that TPU paddings in cycling helmets seem to provide an avenue to improve the performance of the helmets in reducing head injury during collisions. Improving cycling helmets' capabilities in reducing the severity of head injuries can potentially reduce hospitalizations, disabilities, fatalities, and health care costs. Future research will aim to test different brands of cycling helmets and further examine measures of shear forces, rotational accelerations, and energy absorptions to improve the design of the TPU paddings in reducing risk of head injury.

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