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Bicycle helmets are highly effective at preventing head injury during head impact: Head-form accelerations and injury criteria for helmeted and unhelmeted impacts

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ABSTRACT

Cycling is a popular form of recreation and method of commuting with clear health benefits. However, cycling is not without risk. In Canada, cycling injuries are more common than in any other summer sport; and according to the US National Highway and Traffic Safety Administration, 52,000 cyclists were injured in the US in 2010. Head injuries account for approximately two-thirds of hospital admissions and three-quarters of fatal injuries among injured cyclists. In many jurisdictions and across all age levels, helmets have been adopted to mitigate risk of serious head injuries among cyclists and the majority of epidemiological literature suggests that helmets effectively reduce risk of injury. Critics have raised questions over the actual efficacy of helmets by pointing to weaknesses in existing helmet epidemiology including selection bias and lack of appropriate control for the type of impact sustained by the cyclist and the severity of the head impact. These criticisms demonstrate the difficulty in conducting epidemiology studies that will be regarded as definitive and the need for complementary biomechanical studies where confounding factors can be adequately controlled. In the bicycle helmet context, there is a paucity of biomechanical data comparing helmeted to unhelmeted head impacts and, to our knowledge, there is no data of this type available with contemporary helmets. In this research, our objective was to perform biomechanical testing of paired helmeted and unhelmeted head impacts using a validated anthropomorphic test headform and a range of drop heights between 0.5 m and 3.0 m, while measuring headform acceleration and Head Injury Criterion (HIC). In the 2 m (6.3 m/s) drops, the middle of our drop height range, the helmet reduced peak accelerations from 824 g (unhelmeted) to 181 g (helmeted) and HIC was reduced from 9667 (unhelmeted) to 1250 (helmeted). At realistic impact speeds of 5.4 m/s (1.5 m drop) and 6.3 m/s (2.0 m drop), bicycle helmets changed the probability of severe brain injury from extremely likely (99.9% risk at both 5.4 and 6.3 m/s) to unlikely (9.3% and 30.6% risk at 1.5 m and 2.0 m drops respectively). These biomechanical results for acceleration and HIC, and the corresponding results for reduced risk of severe brain injury show that contemporary bicycle helmets are highly effective at reducing head injury metrics and the risk for severe brain injury in head impacts characteristic of bicycle crashes.

1. Introduction

Cycling is a popular form of recreation and it is used for commuting and other forms of transportation. It is generally safe and the health benefits of it are clear (Hamer and Chida, 2008; Wen and Rissel, 2008), which is in sharp contrast to motorized transportation of any type. However, cycling is also not without risk. In Canada, cycling injuries are the most common injury occurring from summer sports; over 4300 people were hospitalized due to a cycling

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injury in 2009–2010 (Canadian Institute for Health Information, 2010). According to the National Highway and Traffic Safety Administration (NHTSA), between 600 and 800 cyclists are fatally injured each year in the United States and 52,000 cyclists were injured in the US in 2010 (NHTSA Traffic Safety Facts 2010 Data, 2010). Among cyclists, head injuries account for approximately two-thirds of hospital admissions and three-quarters of fatal injuries (Thompson et al., 1999).

Epidemiological studies show that helmets are highly effective at preventing head and brain injury amongst riders who crash. A case–control study conducted by Thompson et al. (1989) in Seattle over a period of 1 year found that bicycle helmets reduced the risk of head and brain injury by 85% and 88%, respectively. In a second larger case–control study by the same group (Thompson et al., 1996), helmets decreased the risk of head injury by 69%, brain injury by 65%, and severe brain injury by 74%. Helmets were found to be equally effective in accidents involving motor vehicles and those not involving motor vehicles. Furthermore, helmets were found to provide substantial protection from head injuries across all age groups. Amoros et al. (2012) recently conducted a case–control study in France and studied helmet effectiveness over more than 13,500 cyclist injuries. They concluded that helmets were associated with a decreased risk of head injury in cyclist trauma and this decrease seemed to be more pronounced for severe head injuries. Maimaris et al. (1994) studied over a thousand patients that sustained cycling-related injuries who were treated at an emergency department in England. They concluded that helmets reduced the risk of head injury by a factor of more than three. Heng et al. (2006) found that helmet use significantly reduced the risk of head and facial injury in a 2006 study of cycling trauma in Singapore.

Despite the protection provided by helmets, as demonstrated by the epidemiological studies above, the safety benefits offered by helmets are not universally accepted. Many cities, towns, states and provinces do not have helmet laws and many cyclists do not wear helmets (Page et al., 2012). Anti-helmet groups state that helmets are not effective and that, in some cases, due to the increased size of a helmeted head compared to a bare head or due to the compliance of the shell or presence of vent holes, helmets can cause "rotational" injuries such as diffuse axonal injury (DAI). In the lay press, some groups claim that helmets cause injuries by obstructing vision or blocking sound. Researchers have also published articles, critical of the many epidemiological studies (cited above) that show that helmets are highly effective at preventing head injuries, accusing them of bias and conflicts of interest (Curnow, 2006; Elvik, 2011). Curnow argued that bicycle helmets are not as effective as claimed because previous epidemiological studies have not considered rotational injury (Curnow, 2003). There is considerable debate on the merit and limitations of the epidemiological evidence (Curnow, 2006, 2003; Elvik, 2011; Hagel and Barry Pless, 2006). One limitation of the epidemiological approaches is that it infers helmet performance during the impact from evidence collected after the impact and thus the severity of the head impact under study is never known. It is not our purpose to debate the merit of the epidemiological literature. Here we aim to explore the extent to which the epidemiological evidence of helmet efficacy can be supported or contradicted by a biomechanical study that allows study of helmet performance *during* the impact.

Biomechanical investigations of helmet efficacy, and indeed helmet certification standards, simulate helmeted head impact by dropping helmeted headforms onto prescribed impact surfaces. In helmet certification standards, the primary metric to assess impact management efficacy is linear headform acceleration measured during a drop test; helmets are considered to have met the certification criteria if the helmeted headform acceleration is below a prescribed threshold. The threshold varies from standard to standard (Table 1), and is not directly correlated to established risk curves. The standards generally require that helmets be certified using a magnesium headform. The range of drop heights associated with these standards is from 1.5 m (EN1078) to 2.2 m (Snell B95A) (Table 1).

In biomechanical investigations, linear and rotational head accelerations are measured during the impact and helmet efficacy is determined by comparing these accelerations, and other derived metrics such as the Head Injury Criterion (HIC), to injury risk functions. For example, Mertz et al. have established head injury probability curves, in terms of HIC and linear acceleration, for the Hybrid III headform which was originally developed for automotive crash testing (Mertz et al., 2003). Because injury tolerances exist for this headform, the Hybrid III is increasingly applied in biomechanical helmet and head impact studies (Beckwith et al., 2012; Kendall et al., 2012; Pang et al., 2011; Pellman et al., 2003; Scher, 2006; Scher et al., 2009; Viano and Halstead, 2012; Viano and Pellman, 2005). Overall, the biomechanical studies indicate that helmets significantly reduce head accelerations relative to unhelmeted impacts (Benz et al., 1993; Hodgson, 1990; Mattei et al., 2012; Scher, 2006) or to impacts with thin uncertified novelty helmets (DeMarco et al., 2010; Scher et al., 2009). Furthermore, because linear head acceleration is known to be monotonically correlated to concussion and skull fracture risk (Greenwald et al., 2008; Mertz et al., 2003; Pellman et al., 2003) they are therefore known to reduce the risk of sustaining head injury.

The biomechanical comparison that best matches the epidemiological studies, and thus that would be best able to augment the debate in that field, is a comparison of helmeted and unhelmeted head impact under identical impact conditions. Unfortunately, these tests are difficult to perform because of limitations of the magnesium head forms that are mandated in bicycle helmet standards and that have thus most often been used in bicycle helmet impact tests. The magnesium head forms are at high risk of damage if they are tested with no helmet and they have not been validated to match the expected human response for bare head impacts. Thus there is no test series available to our knowledge that contrasts helmeted and unhelmeted impacts for contemporary bicycle helmets under direct matched impact. Hodgson contrasted early 1990s era helmets with an unhelmeted impact using a "small humanoid headform", Benz et al. dropped an unhelmeted Hybrid II headform from a lower height than their helmeted impacts and Mattei et al. dropped human cadaver skulls with and without helmets from six and nine inch drop heights (Benz et al., 1993; Hodgson, 1990; Mattei et al., 2012). All of these studies demonstrated a dramatic decrease in head accelerations for the helmeted compared to the

Table 1
Comparison of several bicycle helmet standards.

Standard	Reference	Drop height (m)	Drop height (feet)	Criteria (g's)
Consumer Product Safety Commission (CPSC)	16 CFR Part 1203	2	6.6	300
Snell Memorial Foundation (Snell)	BF95 (1998 Revision)	2.2	7.2	300
American Society for Testing and Materials (ASTM)	ASTM F1447F12	2	6.6	300
Canadian Standards Association (CSA)	CSA D113 2FM89 (Reaffirmed 2004)	1.6	5.2	250
European Standards (CEN)	EN 1078	1.5	4.9	250