Accident Analysis and Prevention 59 (2013) 109–117

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Angular Impact Mitigation system for bicycle helmets to reduce head acceleration and risk of traumatic brain injury

Kirk Hansen[a], Nathan Dau[a], Florian Feist[b], Caroline Deck[c], Rémy Willinger[c], Steven M. Madey[a], Michael Bottlang[a,*]

[a] Biomechanics Laboratory, Legacy Research Institute, Portland, OR 97232, United States
[b] Vehicle Safety Institute, Graz University of Technology, Graz, Austria
[c] Institut de Mécanique des Fluides et des Solides, Université de Strasbourg, France

ARTICLE INFO

Article history:
Received 8 December 2012
Received in revised form 15 May 2013
Accepted 16 May 2013

Keywords:
Helmet
Bicycle
Traumatic brain injury
Impact mitigation
Rotational acceleration
Concussion

ABSTRACT

Angular acceleration of the head is a known cause of traumatic brain injury (TBI), but contemporary bicycle helmets lack dedicated mechanisms to mitigate angular acceleration. A novel Angular Impact Mitigation (AIM) system for bicycle helmets has been developed that employs an elastically suspended aluminum honeycomb liner to absorb linear acceleration in normal impacts as well as angular acceleration in oblique impacts. This study tested bicycle helmets with and without AIM technology to comparatively assess impact mitigation. Normal impact tests were performed to measure linear head acceleration. Oblique impact tests were performed to measure angular head acceleration and neck loading. Furthermore, acceleration histories of oblique impacts were analyzed in a computational head model to predict the resulting risk of TBI in the form of concussion and diffuse axonal injury (DAI). Compared to standard helmets, AIM helmets resulted in a 14% reduction in peak linear acceleration ($p < 0.001$), a 34% reduction in peak angular acceleration ($p < 0.001$), and a 22–32% reduction in neck loading ($p < 0.001$). Computational results predicted that AIM helmets reduced the risk of concussion and DAI by 27% and 44%, respectively. In conclusion, these results demonstrated that AIM technology could effectively improve impact mitigation compared to a contemporary expanded polystyrene-based bicycle helmet, and may enhance prevention of bicycle-related TBI. Further research is required.

1. Introduction

Bicycle-related head injuries in the United States (US) resulted in an estimated 81,000 emergency room visits in 2011, and 77% of these patients were diagnosed with traumatic brain injury (TBI) (CPSC, 2011). Among children and teenagers, bicycling results in more cases of TBI than any other sport or recreational activity (Gilchrist et al., 2011). The US healthcare costs due to bicycle-related head injuries total over $2 billion annually (Schulman, 2002). The number of bicycle-related TBIs has increased steadily over the past fifteen years, in spite of increased rates of helmet use among cyclists (CPSC, 2011; Karkhaneh, 2006). Mandatory helmet test standards assess linear head acceleration but fail to capture angular head acceleration (BSI, 1997; CPSC, 1998), despite the fact that angular acceleration is also known to cause TBI (Goldsmith and Monson, 2005). Contemporary helmets are designed to meet these linear head acceleration standards, but lack specific mechanisms to mitigate angular head acceleration.

Conventional bicycle helmets consist of three layers: a plastic outer shell, an expanded polystyrene foam (EPS) liner, and an inner layer of comfort foam padding. This design is intended to mitigate skull fracture and focal brain injury. The current safety standards for bicycle helmets in the US and Europe establish limits for peak linear acceleration in response to an idealized normal impact test, in which a helmet is dropped vertically onto a horizontal surface and whereby the head surrogate is constrained to prevent angular acceleration (BSI, 1997; CPSC, 1998). These standards have been effective in driving the design of safer helmets: bicycle helmets have been shown to reduce the risk of head injury by an estimated 31–69% (Abu-Zidan et al., 2007; Amoros et al., 2012; Attewell et al., 2001; Cook and Sheikh, 2003; Thompson et al., 1996).

However, angular acceleration is also recognized as a cause of TBI. Primate studies conducted over thirty years ago demonstrated that angular acceleration can induce a range of traumatic brain injuries, including concussion, diffuse axonal injury (DAI), and acute subdural hematoma (SDH), even in the absence of a direct

* Corresponding author at: Legacy Biomechanics Laboratory, 1225 NE 2nd Avenue, Portland, OR 97215, United States. Tel.: +1 503 413 5457; fax: +1 503 413 4942.
E-mail addresses: mbottlan@lhs.org, mbottlang@biomechresearch.org (M. Bottlang).

0001-4575/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.aap.2013.05.019

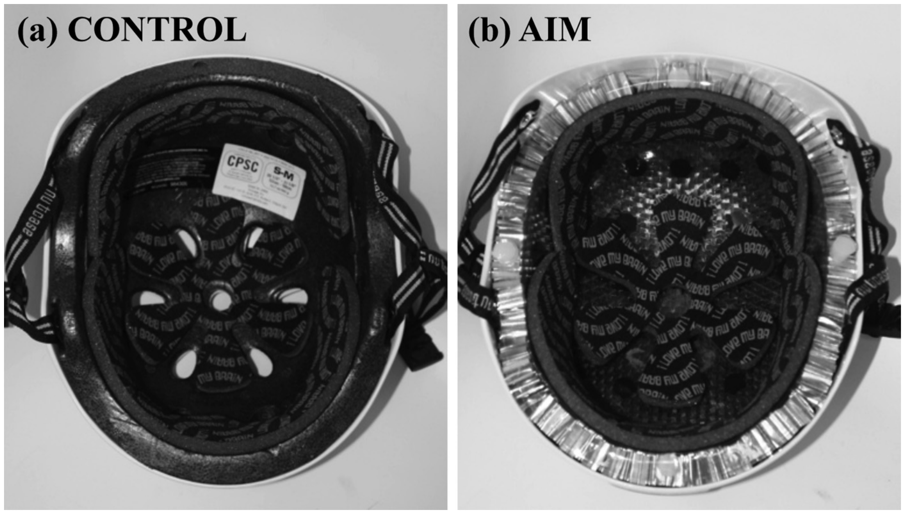

Fig. 1. (a) Commercially available CONTROL helmet, consisting of ABS outer shell, EPS energy-absorbing liner, and polyurethane comfort padding. (b) Prototype Angular Impact Mitigation (AIM) helmet, with EPS liner replaced by suspended aluminum honeycomb.

impact to the head (Gennarelli and Thibault, 1982; Gennarelli et al., 1982; Ommaya and Hirsch, 1971). The mechanism for these injuries has been further investigated through physical models (Bottlang et al., 2007; Margulies et al., 1990), cadaver studies (Hardy et al., 2007), and computational simulations (Deck et al., 2007; Takhounts et al., 2008; Weaver et al., 2012; Willinger et al., 1999; Zhang et al., 2004), which have demonstrated that the brain is highly susceptible to shear strain induced by angular head acceleration.

The increased awareness of the connection between angular acceleration and TBI has sparked research to determine angular head accelerations in realistic impact scenarios. Physical tests and finite element models have been developed to measure the angular accelerations induced in oblique impacts that account for the tangential as well as normal forces that are typically present when a helmeted bicyclist contacts an impact surface (Aare and Halldin, 2003; Ivarsson et al., 2003; Mills and Gilchrist, 2008a,b; Pang et al., 2011). These angular accelerations have been shown to exceed the thresholds expected to cause TBI, even while linear accelerations remained below the limits established in helmet safety standards (BSI, 1997; CPSC, 1998; Pang et al., 2011). Moreover, a recent proposal was made to introduce tangential impact and improved brain injury criteria into future bicycle helmet test standards (Deck et al., 2012).

To reduce the risk of TBI among helmeted bicyclists, a novel bicycle helmet was developed with an Angular Impact Mitigation (AIM) system capable of reducing both linear and angular head acceleration. The AIM system is comprised of an aluminum honeycomb liner that is elastically suspended between an inner liner and outer shell. The aluminum honeycomb material provides a highly effective crumple zone, while the innovative suspension method mitigates angular acceleration by permitting elastic translation of the outer helmet shell relative to the head.

This study was designed to compare the impact mitigation performance between standard bicycle helmets with and without AIM technology, based on improved brain injury criteria. It was hypothesized that the AIM system would provide improved mitigation of linear and angular acceleration, and a reduction in TBI risk.

2. Methods

Bicycle helmets with and without AIM technology were subjected to impacts in a vertical drop test stand to compare the resulting head acceleration levels. First, linear head acceleration was measured in response to normal impact tests onto a horizontal surface. Second, angular head accelerations were captured in response to oblique impact tests onto a surface angled 30° from horizontal. Finally, acceleration histories of oblique impacts were implemented into a validated computational head model to predict the resulting TBI risk.

2.1. Helmets

For the CONTROL group, 10 identical commercially available bicycle helmets (Street Solid size S-M, Nutcase Helmets, Portland, OR) (Fig. 1a) were tested. These helmets consisted of a 3 mm thick acrylonitrile butadiene styrene (ABS) outer shell, a 17 mm thick, 85 kg/m^3 density expanded polystyrene (EPS) liner, and 8 mm thick polyurethane comfort padding. These hard shell bicycle helmets were chosen because they enabled the EPS liner to be replaced by an Angular Impact Mitigation (AIM) system, with no modification of the outer shell, retention system, or fit.

For the AIM group, 10 additional CONTROL helmets were modified by replacing their EPS liners with an AIM system, while retaining the outer shell, comfort padding, and retention straps (Fig. 1b). The AIM system consisted of a 17 mm thick aluminum honeycomb liner (5052/F40-0.0019 Flex-Core, Hexcel, Stamford, CT) of 50 kg/m^3 density that was elastically suspended between the outer shell and an inner liner. The unique cell structure of this particular honeycomb allowed forming the liner into a spherical shape inside the helmet shell while retaining a regular cell geometry. For mitigation of linear acceleration, this honeycomb served as a non-elastic crumple zone to absorb the normal component of the impact force that was directed perpendicular to the outer helmet shell. For mitigation of angular acceleration, the honeycomb was suspended between the outer ABS shell and an inner polymer liner, which was thermoformed from 0.8 mm thick polyethylene terephthalate (PETG). To enable elastic translation between the outer shell and inner liner, the honeycomb was attached at discrete fixation points to the crown of the outer shell and to the periphery of the inner liner by means of a permanent adhesive (Surebonder 707, FPC, Wauconda, IL) (Fig. 2a). Adhesive felt pads at the interior and exterior surfaces of the honeycomb facilitated sliding between the honeycomb and the adjacent layers. In this configuration, the honeycomb acted as an elastic spherical bearing between the outer shell and inner helmet liner to absorb the impact force component that acted tangential to the helmet shell, mitigating angular head acceleration