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The effect of motorcycle helmet fit on estimating head impact kinematics from residual liner crush

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ABSTRACT

Proper helmet fit is important for optimizing head protection during an impact, yet many motorcyclists wear helmets that do not properly fit their heads. The goals of this study are i) to quantify how a mismatch in headform size and motorcycle helmet size affects headform peak acceleration and head injury criteria (HIC), and ii) to determine if peak acceleration, HIC, and impact speed can be estimated from the foam liner's maximum residual crush depth or residual crush volume. Shorty-style helmets (4 sizes of a single model) were tested on instrumented headforms (4 sizes) during linear impacts between 2.0 and 10.5 m/s to the forehead region. Helmets were CT scanned to quantify residual crush depth and volume. Separate linear regression models were used to quantify how the response variables (peak acceleration (g), HIC, and impact speed (m/s)) were related to the predictor variables (maximum crush depth (mm), crush volume (cm^3), and the difference in circumference between the helmet and headform (cm)). Overall, we found that increasingly oversized helmets reduced peak headform acceleration and HIC for a given impact speed for maximum residual crush depths less than 7.9 mm and residual crush volume less than 40 cm^3. Below these levels of residual crush, we found that peak headform acceleration, HIC, and impact speed can be estimated from a helmet's residual crush. Above these crush thresholds, large variations in headform kinematics are present, possibly related to densification of the foam liner during the impact.

1. Introduction

Helmets effectively protect heads and reduce both injury risk and severity during motorcycle crashes (Hurt et al., 1981; Rowlands et al., 1996; Liu et al., 2008). Proper fit and alignment of the helmet on the head is important to optimize head protection. Poorly fitting helmets are prone to move out of position or roll off during a crash, and can leave portions of the head unprotected and more vulnerable to injury (Hurt et al., 1998; Rivara et al., 1999; Thai et al., 2014, 2015). A recent study of motorcycle helmet fit found that 40.7% of motorcycle riders wore helmets that were too large and 21.8% wore helmets that were too small (Thai et al., 2014). These researchers considered a helmet to be correctly sized if the wearer's head circumference fell within the range specified on the helmet's label. They also found that the lengths of the riders' heads were between 2.9 cm shorter and 2.1 cm longer, and the widths of the heads were between 2.0 cm narrower and 2.2 cm wider than the International Standards Organization (ISO) headform appropriate for testing the helmets. These findings suggest that motorcycle riders are wearing helmets outside the manufacturer's specified range to accommodate differences in their head length and width.

Current helmet standards prescribe impact attenuation tests using different size headforms for different size helmets; however, differences exist between standards in how to select the appropriate headform size. The Department of Transportation (DOT) standard for motorcycle helmets defines three headform sizes, and prescribes that a helmet be tested with the headform that matches the helmet's specified circumference or with multiple headforms if the helmet's size range falls into more than one headform size category (U.S. Department of Transportation, 2006). The Snell standard for motorcycle helmets includes six headforms (ISO A, C, E, J, M, O) and allows for a helmet to be

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Table 1
Specifications of the helmets and headforms used in this study, including circumference range on the manufacturer's label, initial foam thickness in the forehead region, inner helmet liner circumference after removing the comfort liner, and headform sizes and circumferences. The difference (Δ) between helmet and headform circumferences is specified for the conditions tested.

Helmet size	Manufacturer's labeled size (cm)	Initial foam thickness (mm)	Measured liner circumference (cm)	Mismatch Δ (cm) (N[a])			
				ISO A (50 cm)[b]	ISO C (52 cm)[b]	ISO J (57 cm)[b]	ISO M (60 cm)[b]
XS	48.6–50.8	22.6 ± 0.3	57.60 ± 0.13	7.60 (7)	5.60 (10)	–	–
L	56.2–58.4	23.9 ± 0.3	60.25 ± 0.25	10.25 (6)	8.25 (6)	3.25 (10)	–
XL	58.7–61.0	25.6 ± 0.3	62.01 ± 0.25	12.01 (2)	–	5.01 (6)	2.01 (21)
2XL	61.3–63.5	25.3 ± 0.3	62.25 ± 0.29	–	10.25 (10)	5.25 (6)	2.25 (9)

"–" indicates a helmet/headform combination that was not tested.
[a] N = number of impacts performed at each helmet/headform combination.
[b] Circumference of the headform at the reference line.

tested with any headform that falls within the size range specified by the helmet's manufacturer, or the next smaller size headform (Snell Memorial Foundation, 2015). The British standard includes four headforms (ISO A, E, J, M) and requires that the helmet be tested with the smallest headform appropriate to the size range of the helmet (British Standards Institute, 1985). The Australian/New Zealand standard includes five headforms (ISO A, E, J, M, O) and requires the appropriate size headform be selected based on the inner circumference of the helmet measured 12.7 mm above the headform's reference plane. These differing headform-size selection requirements mean that a single helmet model and size could be tested with different size headforms to comply with these different standards. Perhaps more importantly, helmets may not be tested using the range of headform sizes that represent the riders who are actually wearing the helmets in the field (Thai et al., 2014).

Helmets are not generally tested with mismatched headform sizes and therefore the effect of this mismatch on impact performance is not well understood. Chang et al. (2001) found lower peak accelerations and head injury criteria (HIC) with increasingly smaller headforms within a fixed helmet size; however, this finding was based on a finite element (FE) model and was not validated against physical testing. In contrast, Rivara et al. (1999) postulated that the gap between the head and the liner of an oversized helmet may undermine the liner's ability to absorb the impact and thus increase the risk of brain injury. To date, there is no systematic study of the effect of helmet size mismatch on headform kinematics or the impact performance of motorcycle helmets.

During a helmet impact, the energy-absorbing liner reduces peak head acceleration by increasing the displacement and time over which the impact occurs. Energy-absorbing liners are typically made of expanded polystyrene (EPS) foam that crushes during the impact and then partially rebounds after the impact. This residual deformation can be quantified using parameters such as maximum crush depth or crush volume, and can then be used to estimate impact energy and peak head or headform acceleration (Mcintosh and Patton, 2012; Bonin et al., 2016). This relationship, however, may not be accurate either at low impact severities where there is little residual crush or at high impact severities where the foam bottoms out, i.e., densifies, and head acceleration increases rapidly with small increases in impact speed (Demarco et al., 2010; Kroeker et al., 2016). Moreover, the previously observed relationship between residual crush and head/headform kinematics was based on appropriately sized helmets (Bonin et al., 2016). The effect of helmet/head size mismatch on this relationship remains unknown.

The goal of this study is to understand how a mismatch in headform and motorcycle helmet size affects headform kinematics and the residual damage to the liner of a single helmet model at a single impact location. More specifically, we sought to quantify how peak acceleration, HIC and impact speed vary with different combinations of headform and helmet sizes, and to determine whether these kinematic variables can be estimated from maximum residual crush depth or residual crush volume. We first hypothesized that for a given impact speed, both peak acceleration and HIC would decrease as the relative helmet size increased. We then hypothesized that peak acceleration, HIC, and impact speed could be estimated from maximum residual crush depth and crush volume, and explored over what region this relationship was valid. To test these hypotheses, we focused our study on a single helmet model to control for variability in liner density, liner thickness and shell properties, and we used only one impact location on this helmet to control for shell/liner geometry and minimize edge effects. We recognize that these narrow test conditions limit the generalizability of our results, but we sought to first establish whether the hypothesized relationship existed at a single impact location within a single helmet before proceeding to other impact locations and other helmets.

2. Methods

Four sizes of helmets (XS, L, XL, 2XL) (Skull Cap, Daytona Helmets, Ormond Beach, FL) were tested on four sizes of ISO half headforms (A, C, J, M) (Cadex Inc., Quebec, Canada). A hat-size measuring tool (Guangzhou Capable Machinery, Guangdong, China) was used to measure the inner circumference of the EPS liner in the reference plane of 14 new untested helmets (3 of sizes XS, XL and 2XL, and 5 of size L) with the 4.5 mm thick (uncompressed) low-density comfort liners removed (Table 1). The circumference of each headform was measured at the reference line and these measurements matched the circumference specified in the standard governing the ISO headforms (International Standards Organization, 1983). The difference (Δ) between the measured liner circumference and the headform circumference was used to represent the degree of helmet/headform mismatch (Table 1).

The Skull Cap helmet is a DOT-approved half-face or shorty-style helmet with an EPS energy absorbing liner and a 5 mm thick acrylonitrile butadiene styrene (ABS) shell. Some of the helmets were equipped with three male studs for attaching a visor at the front edge of the helmet shell, but these studs did not interfere with the impacts. All helmets were tested with the visor removed. The chinstrap was secured snugly over a custom-made chin bar attached to the underside of the headform.

A 3.2 m tall monorail and trolley assembly guided the helmets during the drop tests. A uni-axial ± 2000 g accelerometer (7264B-2000T, Endevco, San Juan Capistrano, CA) was located at the headform's center of mass and oriented vertically. The total mass of the trolley, ball arm and each headform was about 5 kg (ISO A = 4.977 kg, ISO C = 4.981 kg, ISO J = 4.999 kg, ISO M = 5.000 kg). Impact speed was measured with a speed trap located within 40 mm of impact, and impact speed accuracy was better than ± 0.5% at 10 m/s. Speed trap and accelerometer signals were simultaneously acquired at 100 kHz. Accelerometer data were digitally low-pass filtered at 1650 Hz using an 8th-order zero-lag Butterworth filter (SAE Channel Class 1000). Peak acceleration was extracted and HIC_{15} was computed from the filtered