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Fit, stability and comfort assessment of custom-fitted bicycle helmet inner liner designs, based on 3D anthropometric data

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ABSTRACT

Research has demonstrated that a better-fitted bicycle helmet offers improved protection to the rider during an impact. Nowadays, bicycle helmets in the market that range in size from small/medium to medium/large might not fit the diverse range of human head shapes and dimensions. 3D scanning was used to create 3D head shape databases of 20 participants who volunteered for the study. We developed new custom-fitted helmet inner liners, based on the 3D head shape of two sub-groups of participants, to map their head sizes and contours closely to the conventional Medium (M) and Large (L) sizes as described in from AS/NZS 2512.1: 2009. The new custom-fitted helmet was compared with the helmet available in the market place in a dynamics stability test and from participants' subjective feedback. A significant reduction in the angle of helmet rotation on the headform in the lateral direction was recorded for the custom-fitted helmet. A Wilcoxon signed-rank test was conducted to evaluate participants' feedback on the helmets according to different area definitions. The overall fit and comfort and the top region of the new helmet were significantly improved. However, no difference was found at the significant level of 0.05 for the front and rear region of the new helmet.

1. Introduction

Numerous epidemiological studies (Lee et al., 2006; McIntosh et al., 2013; Richter et al., 2007) demonstrate that bicycle helmets can decrease head and skull injuries as well as brain injury during impact. However, the protection and safety benefit offered by the helmets have been extensively criticised by anti-helmet advocates (Curnow, 2006; Elvik, 2011). This is because a helmet that does not match the morphology of the wearer's head may fail to stay in place during a crash, and thus offers little or no protection (Alemany et al., 2012; Mihora et al., 2007). Understandably, a well-fitting helmet and its ability to stay on the wearer's head will ensure effective protection in a crash.

A recent field study by Thai et al. (2015) examined the effects of different helmet sizes and adjustments for helmet stability. They found that about 30% of recreational and commuter cyclists surveyed often wore helmets that are either too small or too large according to the manufacturers' sizing recommendations. They also found in stability tests that helmets were easily displaced on the wearers' heads at relatively low force. This indicated that bicycle helmet sizes, which are based on the overall head circumference, may be incorrect for different wearers' head shapes. Maw et al. (2012) found that a helmet better fitted to the Styrofoam hemisphere reduces the peak linear decelerations, which could result in less brain injury during impact. Properly fitted helmets, where the shape and size conform as closely as possible to the head shapes they are intended to protect, are crucial to optimize its protection and improve users' perceived comfort and fit (Alemany et al., 2012; Meunier et al., 2000). It has been reported that wearing a wrongly sized helmet could compromise its intended safety performance and lead to feelings of discomfort due to pressure points (Ball et al., 2010; Van den Oord et al., 2012). Therefore, it is of utmost importance to improve the shape and size of a helmet in order for it to be efficient, safe and comfortable (Meunier et al., 2000).

For the past decade, three-dimensional (3D) head scans have provided new opportunities for researchers, sports engineers and designers to evaluate and optimize the size and shape of helmets. 3D data can provide an in-depth description of the size, shape and contour characteristics of the scanned persons, which overcomes the limitation of simple one-dimensional (1D) anthropometric measurements. 1D measurements only provide data on head length, breadth and circumference, which do not adequately describe the shape of a person's head, e.g., round, oval, oblong (Skals et al., 2016; Perret-Ellena et al., 2015; Thai et al., 2015; Ball et al., 2010; Meunier et al., 2000). An early

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study by Meunier et al. (2000) used a stand-off distance (the distance between the inner liner of the helmet and the skull) for the assessment of helmet fit. They specified a minimum stand-off distance of 12.5 mm and suggested that graphical representation provided by the software could assist designers to modify the shape or size of the helmet to accommodate a given population better. Harrison and Robinette (2005) developed a method to determine the minimum number of helmet sizes to accommodate the full anthropometric variability of a military aviator population. They tested the method with 27 participants and found that two helmet sizes would most likely accommodate 99% of the target population. Ball et al. (2010) developed a parameterization technique, an alignment procedure and a 3D landmark technique to compare the 3D shape differences between Chinese and Western heads. They found that Chinese heads are generally rounder, with a flatter back and forehead than Western heads, and they suggested that headgear designed using Western anthropological headforms are not appropriate for the Chinese heads. Alemany et al. (2012) developed a multi-dimensional method to investigate the geometric interaction between the inner liner surface of a helmet and a user's head. They suggested that the morphological characteristics of the target population, pressure distribution over the head and the subjective perception of fit and discomfort need to be considered in establishing criteria that assure a proper fit. Previous studies have also shown that there was significant morphological head shape difference for users from different ethnic/racial backgrounds (Ball et al., 2010; Luximon et al., 2015; Thai et al., 2015). Users may need to shop around to find a headgear that is suitable for their head shape.

Perret-Ellena et al. (2014) and Ellena et al. (2016) developed a Helmet Fix Index (HFI) to analyze the fit between a helmet model and a human head. They suggested that the HFI provides an accurate and efficient measure to analyze, compare and improve bicycle helmet fit for the targeted cyclist population. More recently, Luximon et al. (2015) developed 3D head templates to allow the creation of better fitting products for the head and face of Chinese population. By incorporating the 3D head templates with computer-aided design (CAD) tools, designers can visualize, evaluate and correct product fit on screen during the development process.

Despite these previous investigations, a user's subjective feeling of comfort or discomfort when wearing a mass customised helmet remains unmeasured. Therefore, research with 3D scans and assessments via experimental testing as well as human participants' feedback are necessary to provide better knowledge on how helmets should be improved in order to reduce wearer discomfort and improve fit and stability.

We conducted the present research with the following specific objectives to:

1. Design and custom fit the inner liner of a helmet model based on 3D anthropometric head scans that correspond to the conventional Medium (M) and Large (L) headform sizes, as described in AS/NZS 2512.1: 2009 respectively
2. Evaluate the dynamic stability of the new custom-fitted inner liner helmet, and
3. Evaluate the fit and comfort of the new custom-fitted inner liner helmet.

2. Materials and methods

2.1. Participants

The study was conducted between March and November 2014 at the School of Aerospace, Mechanical and Manufacturing Engineering, at RMIT University in Melbourne, Australia. Two rounds of recruitment were conducted (Fig. 1). The first round was conducted between March and May 2014 to scan the participants' heads and to customize the design of the inner liner of a selected helmet. The second round was

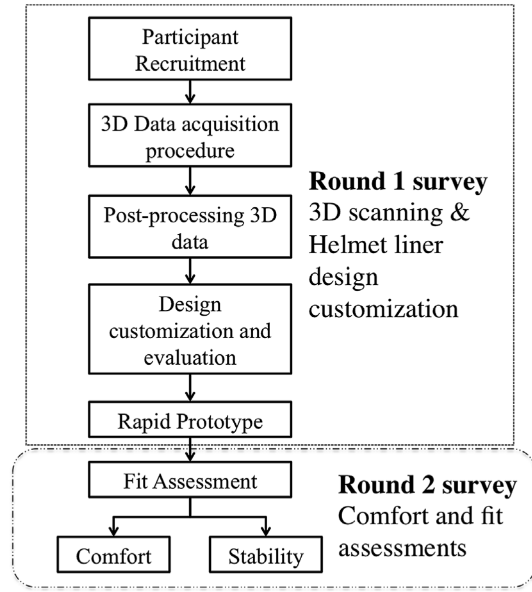

Fig. 1. Overview of research framework.

conducted between October and November 2014 for the comfort and fit assessment. The fit assessment survey required a more extensive procedure, where participants were asked to fill in the fit assessment form on a ten point rating scale. The aim was to record the subjective rating comparing the fit and comfort of a commercially available helmet, namely MET Kaos, with the new custom-fitted inner liner helmet. In the second round survey, participants' head were also scanned to capture their sizes and shapes, but their scan data were not used to customize the design of the inner liner. They were also asked to provide additional comments in an open-ended question.

All of these volunteer participants were students at RMIT University. They were randomly approached by the researchers with a flyer that explained the purpose of the survey and what participants would be asked to do. All participants gave their written informed consent prior to the scanning and survey in accordance to the guidelines approved by the RMIT University ethics committee.

2.2. Design and customization of helmet liner

The design and customization process of the new custom-fitted inner liner started with the 3D scanning of the volunteer participants' heads and a commercially available helmet, namely, the MET Kaos, which is readily available in local stores (Fig. 1). The MET Kaos helmet was used as reference point to produce a new custom-fitted helmet inner liner design.

2.2.1. 3D data acquisition

A Flexscan 3D scanner was used to scan the commercially available helmet. This helmet was placed on a rotating table and scanned from eight different positions in order to capture its entire profile and geometry, especially the ventilation holes (Fig. 2). All scans from these different positions were aligned and combined using the Flexscan 3D software.

An Artec Eva handheld 3D scanner was used for scanning of the participants' head shapes. Prior to the scanning, participants were asked to fill a self-administrated questionnaire on their age, gender, height, mass, ethnic/ancestral background, and helmet use. The participants were asked to try on the MET Kaos helmet, which available in Australia in two sizes (Medium and Large), and select the size that they thought was the most comfortable to fit their head size. The participants were asked to wear a thin wig cap to compress their hair and to reveal their head shapes prior to the scanning process. Fourteen participants