User Centred Design Customisation of Bicycle Helmets Liner for Improved Dynamic Stability and Fit

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Abstract

In order for bicycle helmets to maintain sufficient coverage and protection of riders, the helmets must be adequately positioned and secured on the head. This research investigates helmet’s dynamic stability parameters in order to determine whether a customised liner can improve the retention and therefore safety. A specialist 3D scanner was used to scan a total of 17 male participants who volunteered for this study. Through 3D scanning the shape and depth of each section of a participant’s head and facial structure was captured. All the heads scanned were orientated with respect to the same co-ordinates based on the Australian and New Zealand Standards in order to customize the liner design to fit the user’s heads. The dynamic stability of the commercially available helmets and the customized helmet were assessed using relevant video and goniometer techniques. The results indicate that for frontal roll-off, the customised helmet liner passed in all simulations of the 160mm drop height. It consistently performed better in the lateral roll-off at height of 40mm and 80mm compared with the commercially available helmets. While the dynamic stability measurements and the design strategies offer the potential to improve fit for different user’s head, further studies should take into consideration a larger population size to draw more accurate conclusions.

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1. Introduction

Bicycle helmets have shown to be effective in providing head protection to riders. However, head injuries are still the cause of death in 69-93% of fatalities in bicycle crashes [1]. Helmet stability and fit are reported as key factors

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that affects its performance in crashes [2]. In order for a helmet to maintain sufficient coverage and protection, whether in cycling, sporting and/or in other work environments, the helmet must be adequately positioned and secured on the head.

Most of the current commercially available helmets are designed and tested on standard manikin headforms, which may not incorporate individual anthropometric measurements such as head geometry and shape that may affect fit and stability [2, 3]. Several studies in the past have used three-dimensional (3D) head scanning methods, to optimise fit and comfort [3-6]. They have found that 3D scan technology can effectively enhance helmet performance through better fit and comfort.

Even with technological advances in helmet design in recent years, U.S and Australia still report high number of cyclist deaths each year [7, 8]. While the Australian and New Zealand Standards [9] have a method of testing the dynamic stability of protective helmets in the forward and rear directions, it is not mandatory for all the bicycle helmets sold in Australia to pass this dynamic test. Lateral roll-off is not part of the requirement for the standards [9]. Previous study [2] has suggested lateral stability should be considered in helmet stability tests. This was done so that more information could be gained on whether or not the liner plays a particular role in reducing the roll-off. Furthermore, the standard does not specify a method to measure the degree of helmet rotation [10].

This research aims to: (i) design and build a test rig for dynamic stability test; (ii) develop a roll-off measurement method for the dynamic stability test, in the forward and rear directions, for three commercially available helmets; (iii) customise the inside liner of bicycle helmets that may influence dynamic stability and fit; and (iv) compare the dynamic stability of commercially available helmet with the customized helmet in forward, rear and lateral directions.

2. Methods

2.1. Volunteered Participants

Seventeen male participants, aged between 18 and 29 years, were recruited for scanning from RMIT University between 3rd March and 3rd July, 2014. The study was approved by RMIT University Human Research Ethics committee. Informed consent was obtained from each participant before any scanning or survey was conducted.

2.2. 3D Anthropometry Data

An Artec Eva 3D scanner was used to capture the anthropometric characteristics of each participant’s head. A similar scanning protocol can be found in a previous study [3], where the posture position and scanning techniques conform to the ISO 20685:2010 3-D scanning methodologies for internationally compatible anthropometric databases. Participants were asked to wear a wig cap to avoid potential hair irregularities in scanned geometry. The initial scanned geometry was ‘cleaned-up’ by removing all unnecessary features or imperfections caused by the wig cap, and missing patches were filled-in to produce a watertight human head model as shown in Fig. 1. A quick scan was also done for the same participant wearing a helmet (Fig. 2). The helmets used in the scanned data are the same helmets used in the dynamic retention test.

Fig. 1. 3D watertight human head model

Fig. 2. 3D scan of a human head with helmet
2.3. Scanned Data Alignment

Scanned data were aligned using two methods: (1) the n-point manual alignment; and (2) a global registration method in the Geomagic Studio 12® [3]. The ‘cleaned’ head scans were first merged with the rough scan of participant and helmet (Fig. 3). Merging was done through manual registration method, which involved selecting six specific feature points present in both scans. These points included the inside and outside of both eyes, nose and the right side of the bottom lip.

Fig 3. (a) 3D Watertight head scan, (b) rough scan of participant with helmet, (c) merged scan of cleaned head and partial helmet on head.

A similar manual alignment process was applied when merging the complete helmet scan to that of the rough scan of the participant wearing the same helmet (Fig. 4). In addition to the manual alignment process, a global registration was performed to improve the accuracy of the merged scans.

Fig. 4. (a) Complete helmet scan, (b) rough scan of participant with helmet, (c) manual registration of merged cleaned helmet and participant with helmet.

2.4. Helmet Liner Design

In order to customise the liner design, the twenty head scans produced in this research were grouped into medium (M) and large (L) sizes based on the guidelines of the Australian and New Zealand Standards (AS/NZS 2512.1:2009) [11]. The outline and boundary of the head shape were aligned to the AS/NZS Standards, and all the scanned heads were orientated to face the same x,y,z co-ordinates. To assist with the merger of the head scans, two anatomy planes were used: (a) a sagittal plane, which goes down the centre of the forehead and nose, to outline the head in half; and (b) a coronal plane drawn from the centre of the ear to the underneath of the eye socket.

Fig. 5. (a) Reference of the AS/NZS headform, (b) head scan aligned to AS/NZS standards, (c) anatomy planes.

A total of seven head scans were within the range of the medium size headform. They were merged and a section of the top of the head was smoothed out to produce one uniform surface. This uniform surface was used to
customise the inside liner shape (Fig. 6). The manually registered helmet of the participant scans was aligned with the inside liner profile. This allowed the inside liner profile to sit directly underneath the helmet as if a user was wearing it. The inside liner of the helmet was removed and replaced by the uniform surface of the combined head scans. A 5mm offset allowed for hair thickness. It is important to note that the outer contours of the helmet remain unchanged. The final customized helmet was based on the seven selected head scan data.

Fig. 6. (a) Merged inside liner of the seven selected heads, (b) inside liner with participant scan (c) final design of the customized helmet

2.5. Dynamic Stability Test Rig Design

A test rig able to simulate the rolling off of a helmet on a rig headform was designed and fabricated (Fig. 7). The test rig was designed in accordance with Australian and New Zealand Standards AS/NZS 2512.7.2:2009 [9].

Fig. 7. Dynamic Stability Test Rig

Fig. 8. Test helmets, (a) H1, (b) H2, and (c) H3

2.6. Dynamics Stability Testing Procedure

The test rig comprised of a standard headform (size F with circumference of 550mm diameter), and a ten-kilogram drop weight and hook. A nylon strap was used to attach the drop weight to the hook, which was placed on the back of the helmet and aligned with the centre of the helmet. A 4.5Kg weight rested on the apex of the helmet before testing to make sure the helmet was sitting adequately on the headform. Four helmets were tested: customized helmet, and three different commercially available helmets of medium size (generally between 520mm-570mm) (Fig. 8).

The drop height varied between 80mm and 240mm, with an increment of 40mm for frontal and rear roll-off. The test was stopped when the helmet was fully displaced from the headform. Each test was repeated three times for statistical reasons.

Fig. 9. Prototype customized helmet for testing
3. Results

3.1. Customized liner

The shape and the size of the inside liner of helmet H1 was customized on the seven selected head scan data, which fell within the medium size headform. A customized prototype was manufactured for the dynamic stability test (Fig. 9).

3.2. Helmet rotation

The angle of rotation of the helmet, which did not become detached from the headform, was measured using two different approaches: (i) visual analysis using a goniometer; and (ii) through video analysis with a camera (Fig. 10 and Fig. 11). Results were provided by visual measurement and video analysis.

3.3. Roll-off test

Fig. 12 shows that the average differences between angles of rotation measured using the two methods were within ± 5° for the three commercially available helmets (H1, H2, and H3).

![Fig. 10. Visual analysis of roll-off using goniometer](image)

![Fig. 11. Video analysis of roll-off to measure initial and final angle](image)

![Fig. 12. Forward roll-off tests using visual and video analyses](image)

![Fig. 13. Comparison of results between helmet H1 and customised liner helmet (a) front and rear roll of at 160mm, (b) lateral roll-off](image)
Furthermore, we made a comparison between helmet H1 and the customised liner in the front, rear and lateral roll-off. Results show that the customised liner helmet performed worse compared to helmet H1 in the frontal and rear roll-off at a drop height of 160mm. However, the customised liner performed marginally better in lateral roll-off for heights of 40mm and 80mm (Fig. 13).

4. Discussion

This research used a novel approach to create a customized liner for a bicycle helmet. The customized liner was based on accurate anthropometric characteristics of seven volunteer participants. The participants’ head sizes were all a medium headform’s size, which is analogue to the size F in the Australian and New Zealand Standards [11]. The customized liner design and development process was achieved using the computer aided design (CAD) software, by superimposing the scanned participants’ data on to the customised liner. The liner’s geometry, design and fit were assessed before manufacturing. Modification of the geometry and design can easily be made so that any style of helmet can be generated using the developed method.

Although the participants were asked to wear a wig cap to compress their hair, it is impossible to make sure the hair thickness is perfectly compressed. Hair thickness will vary depending on individual, and it may have irregularities and may not uniformly distribute throughout the human head [3, 4]. Hence, when designing the customized liner profile, we adopted a uniform 5mm offset to account for hair thickness, which may introduce some error.

The dynamic stability of the helmets were performed in accordance to the requirements of Australian Standards/New Zealand Standards [9]. We adopted two different approaches to measure the degree of helmet roll-off subjected to dynamic stability tests. The methods were: (i) physical measurement using a goniometer; and (ii) video analysis using a camera. We made comparisons between these two measurement approaches and found that the average angle of roll-off recorded between these two measurements were within 5 degrees. The differences in measurements can be attributed to human error. In particular, the main error may be attributed to the parallax error, which occurs when viewing the measurements at slightly different angles to the background. However, we were confident that with meticulous adjustments the measurement methods were acceptable and reasonable results were obtained.

At the drop height of 80mm, the average helmet rotation angles were 22° and 34° for the forward and rear tests, respectively. In those tests, the mean force was 7.8 N, which is similar to the mean tensile force (7N) as reported by Thai et al. [2]. At such a relatively low force, the helmet was retained on the headform, but its large angle of rotation on the headform suggested that the helmet may not fit well, thus exposing the entire frontal and rear region of the head to direct impact in a crash.

In this study, only helmet H1 and the customised liner helmet were tested for lateral roll-off. The customized liner helmet underperformed in the forward and rear roll-off at 160mm compared with helmet H1. However, it consistently performed better than helmet H1 in the lateral roll-off at heights of 40mm and 80mm. From the video analysis, we found that the design and geometry of chinstrap plays an important role in retaining the helmet on the headform. The chinstrap that adequately hugged the back of the head will reduce the forward roll, and stop the helmet from rolling off.

5. Conclusions

This research presented a novel method of using the scanned participants’ head geometry data to establish size requirements, and to customize liner designs. The prototype for the customised liner was manufactured and subjected to dynamic stability tests that are analogue to the requirements of AS/NZS standards. Two different approaches were adopted to measure the degree of helmet roll-off. The methods were: (i) physical measurement using a goniometer; and (ii) video analysis using a camera. The average differences between angles of rotation measured using the two methods were within ± 5°, which were considered acceptable. Findings of this research highlight customised liner consistently performed better than the commercially available helmets, especially in the lateral roll off. The design strategies for improving fit reported here can also be used for different head sizes and
other protective helmet design applications. The design of the customised helmet was developed using a small number of volunteered participants, a further research with a larger participants are needed to improve the fit and stability especially for the forward and rear roll-off tests.

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