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FINITE ELEMENT ANALYSIS OF USER-CENTRED BICYCLE HELMET DESIGN

Helmy Mustafa, Toh Yen Pang, Thierry Perret-Ellena and Aleksandar Subic
School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Bundoora VIC, Australia
E-Mail: helmy.mustafaelbakri@rmit.edu.au

ABSTRACT

Bicycle helmet is currently available to cater to general head sizes, ranging from S/M and L/XL, but there is also a universal model that can fit all sizes through adjustable helmet strap. However, numerous surveys addressed that wearing helmet is not comfortable and the current sizing did not accommodate the range of the user. This is due to the collective report of human anthropometric data that the human head shape and dimension are different according to ethnic groups, age and gender. This paper describes impact attenuation of user-centred design approach of bicycle helmet in accordance to AS/NZS 2063:2008, Australian/ New Zealand Standard for bicycle helmet using validated simulation model of drop impact test. The objective of this paper is to investigate the effect of changing the shape of the liner to improve fit of bicycle helmet, hence the user-centred design approach, on the impact attenuation properties of the helmet. Head scans of 5 participants were taken using Artec3D portable scanner, while bicycle helmets and J head form were scanned using Flexscan 3D scanning equipment. A customized helmet design based on the shape of each participant was developed and tested using validated drop impact simulation model at front, top and side impact locations. The thickness and peak linear acceleration of original helmet and customized user-cantered helmets were also measured. The results revealed that the user-cantered helmet recorded different PLA value compared to the original helmet because liner dimension and thickness was changed to accommodate the head shape of the participants. The finding of this study suggests that the PLA of the helmet depends on the helmet liner thickness. It was also found that generally changing the liner thickness to employ user-centred helmet design would alter the impact performance of the helmet.

Keywords: finite element analysis, impact test, user centred.

INTRODUCTION

Most bicycle helmets that are currently available on the market have been designed to cater for general head sizes, ranging from S/M and L/XL. There are also universal models that can fit all users' head sizes through adjustable helmet strap. However, based on the human anthropometric studies, the human head shape and dimension are different according to ethnic groups, age and gender [1-3]. For example, it was found out from the anthropometric survey that Asian heads were rounder than Caucasian counterparts; Asian heads also generally flatter at the back and forehead. Furthermore, numerous surveys have addressed that wearing helmet is uncomfortable and the current sizing do not accommodate the wide range of the user's head shape, size and dimension [4-7]. Exclusively, it was also reported that Asian users experience poor fit because most helmet are designed according to the anthropometric geometry of Western heads [2, 8]. In order to overcome these helmet fit related problems, several investigations of bicycle helmet have been carried out aiming to improve fit and comfort for a diverse range of user groups. For example, adjustable strap has been introduced by manufacturers to improve fit for all head sizes into one helmet; it has not addressed the gap and fit between the liner and the head. Chang *et al*. (2001) acknowledged the fit problem in regards to helmet safety, but different sizes of head form instead of different shape of liner were used to demonstrate different fit conditions [9]. Therefore, the effect of helmet fit on impact performance of helmet by using improvised helmet liner shape is still unclear. One possible solution to overcome helmet fit problem for each individual is user-centred customization of helmet design approach. The key to facilitate user-centred design approach to bicycle helmet is to change the shape of liner to follow the shape and geometry of the user's head. However, changing liner design and thickness to improve fit would alter the impact performance of helmet. The impact performance of bicycle helmet is indicated by the peak linear acceleration during impact test; the peak deceleration according to Australian Standards cannot exceed 250g to be deemed safe for use. Therefore the objective of this research is to investigate the impact performance of user-customized helmet liner designed according to head shape of five participants and compare the results to the peak linear acceleration of the original helmet model.

MATERIAL AND METHODS

3D scanning and post-processing

Head shapes from 5 participants volunteered for the study were scanned using portable Artec3D scanner. The participants were given one S/M size and another one L size Netti Lightning helmet model, and they were asked to test which helmet size fit them best. All the participants had chosen the size S/M helmet as their preferred size. During scanning, the participants were asked to sit straight and to avoid any movement, and maintain their usual facial expression. They were also required to wear a thin hair cap to compress their hair. The scans of the participants wearing bicycle helmet were also taken afterwards. Figure-1 shows the scanning of participant with and without wearing the helmet using Artec3D handheld scanner.

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Figure-1. Scanning of participant with and without helmet.

All scanned files were opened in Geomagic Studio 12 software for further image post-processing. The 3D scans were smoothed and cleaned up using smooth features. All small holes were filled in automatically using fill up tools, while the big holes were patched carefully one by one. The area affected by the folded hair cap were removed and patched up again using tangential holes fill up and defeature tools. Non manifold edges, self-intersection, highly creased edges, spikes and small components were also processed using *Mesh Doctor* tool.

Figure-2. Scanned models of five participants used in this research.

An S/M size Netti Lightning bicycle helmet model was scanned using the Flexscan 3D scanner. The strap, velcro stickers, visor and paddings were removed from the helmet before the scanning. The whole helmet was scanned and assumed as helmet liner because the shell cannot be easily removed from the helmet due to glue application and in-mould bonding. The helmet was placed onto a rotating table and scanned using projector and camera setup of Flexscan 3D scanner as shown in Figure-3. The helmet was scanned from 8 different angles in order to capture its entire profile and geometry, in particular the ventilation holes area. All scans from different positions of helmet were aligned and combined using the Flexscan 3D software. General post-processing job to remove the background scans was also conducted. The 3D model of J-headform used in experimental drop test was also obtained using the same procedure involving 3D scanning and post processing in Geomagic Studio 12 software. The completed digital model of Netti Lightning helmet and headform J are presented in Figure-4.

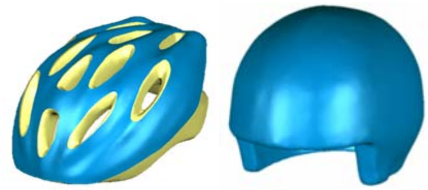

Figure-3. Digital models of bicycle helmet consisting of liner and shell, and half headform J.

When creating the shell geometry for each helmet, the internal part of scanned helmet was removed and only the area representing the shell was retained. The edges of the remaining scan representing the shell were repaired using single fill tool to remove sharp edges. Mesh doctor tool was used to remove spikes, non-manifold edges, self-intersections, small holes and creased edges. All scans were converted to surface data and saved as a universal .igs file format.

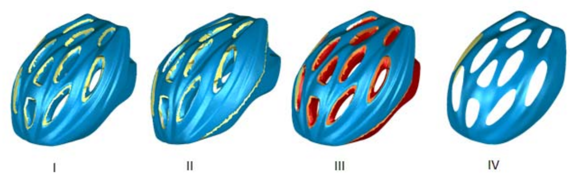

Figure-4. Process of creating helmet shell from the scanned image of helmet.

Designing user-centered helmet

The helmet, the participant head and the helmeted head scanned models were imported into Geomagic Studio 12 to create a customized user-centred helmet design for each participant. First, the helmeted head scan and head scan were aligned using n-points manual registration tool. 7 registration points were placed on each scans to align the helmeted head scan and head scan. Then, global registration tool were later used to improve the alignment of the two scans. The same procedures were adopted to align the helmeted head scan and helmet scan. As a result, the helmet and the head scan were aligned to the position to those in the helmeted head scan.

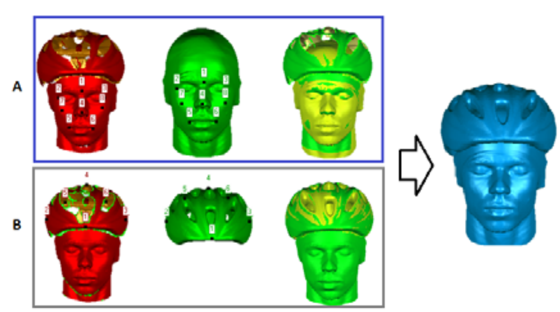

Figure-5. Aligning helmet and head scans to helmeted head scan**.**

To create the user-centered liner, the areas below the helmet line on the head scan were removed. The

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remaining area was expanded 10mm using offset function. This 10mm offset represents the thickness of the comfort padding used in the helmet. Boolean operation was used to subtract head scan that intersected with the liner. Then, the areas inside the liner were removed except for the ventilation holes. After that, the head scan and helmet liner was combined using Boolean operation called union. Holes were created at the head scan (inner part of the helmet) and patched using fill tools to reconstruct the ventilation holes. Gaps between the liner and combined head scan were filled up carefully to retain its original shape. Figure-6 shows the new user-centred helmet and the original helmet model with the head scan. In comparison to the original helmet scan, it is clear that the gap between the head scan and the new user-centred helmet are constant.

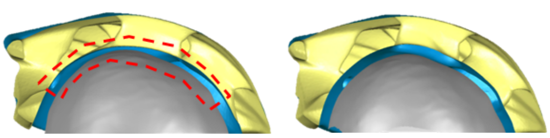

Figure-6. Comparison between the original helmet and user-centered helmet models.

Similar design methods were adopted to create another four customized bicycle helmet based on the head shape of other four participants.

Thickness measurement of helmet

Intersection points of the curve projected from feature planes were used to measure the thickness of the helmet at side, top and front impact locations. To create intersection point at front location, planes A and B were created at 15˚ and -15˚ from xz plane and around y-axis. Curves were projected from plane A, plane B and yz-plane using create section tool for side point. For front points, plane C was created at 20˚ angle from xy-plane and around x-axis. Curves were projected from plane C and yz-plane. For top point, curves were projected from xz-plane and yz-plane. Digital measure distance tool in the software were used to measure distance between the two intersection points, as illustrated in Figure 7. The same procedures were used to measure the thickness of the original helmet and the other 5 customized user-centered based helmets.

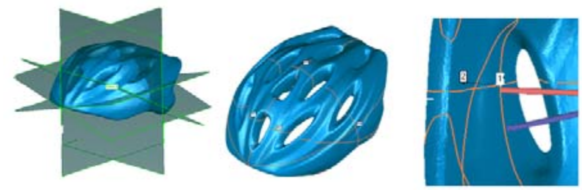

Figure-7. Thickness measurement of helmet at points defined using curves generated from planes.

Numerical simulation of helmet impact test

Geometry images of helmet liner, shell, headform and flat anvil were imported to Abaqus 6.11. Helmet shells were meshed with triangular S3R linear shell elements with 3-5 mm element spacing, while all liners were meshed with C3D10M modified quadratic tetrahedral elements with 8-10 mm element spacing. Distortion control was also applied to all elements of helmet liners to avoid excessive distortion. Meanwhile, C3D10M tetrahedral elements with 8-10 element size were used to mesh J-headform, and C3D8R an 8-node linear brick element was chosen for flat anvil. Helmet liner was modelled as deformable isotropic Crushable foam material with element size between 5 to 8mm. Volumetric hardening parameters such as the ratios of the initial yield pressures in hydrostatic tension and compression and the uniaxial compressive data of EPS were taken from literature[10, 11]. The density of Expanded Polystyrene (EPS) used as helmet liner was obtained by measuring the dimension and weighing several samples of EPS foam from each helmet model.

Table-1. Samples for different helmet.

Models	Material	Density (kg/m^3)	Young Modulus (MPa)	Poison Ratio
Liner	EPS foam	63.4	20	0
Helmet shell	Glued PC	1200	2.2	0.37
Strap	Nylon web			
Flat anvil	Rigid body	-	-	-
Headform J	Rigid body	-	-	-

An isotropic linear elastic model was chosen to simulate the mechanical behaviour of PC. It was assumed that all helmet models have the same shell material properties because the in-mould bonding between helmet shell and liner prevents proper removal of shell without damaging the helmet. The density, Young's modulus and Poison ratio of PC used in all material model of shell was 1200 kg/ m^3, 2.2 GPa and 0.37 respectively [10].

Penalty contact property with friction coefficient of 0.4 was adopted for interactions between all surface

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contacts in this simulation. Meanwhile, tie contact was applied between inner surface of shell and outer surface of liner to simulate in-mould bonding between helmet shell and liner [11]. Homogenous shell section with corresponding thickness of 0.40-0.45mm was assigned to helmet shell. The anvil and headform were defined as rigid bodies while the bottom face of the anvil was fixed in every degree of freedom (DOF). The velocity of helmet upon impacting flat anvil was set at 5.44 ms^{-1} as obtained from the drop impact test. The peak linear acceleration of the helmet was measured at the centre of gravity (COG) of the headform.

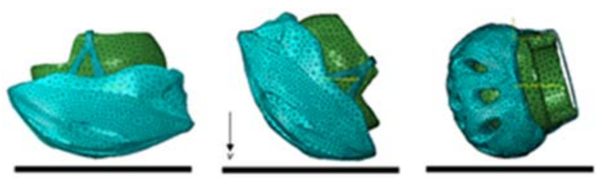

Figure-8. Velocity of helmet upon impacting flat anvil.

RESULTS AND DISCUSSIONS

Thickness of helmet

Table-2 described the thickness of original helmet model and customized user-centred helmet P1-P5. The thickness was measured at three different landmarks such as front, top and side of all helmets. The thickness of helmet P1-P5 varies from 21.8-23.8mm at side location, compared to 22.7mm of the original helmet. The largest difference measured were between helmets P5 and P1 in comparison to the original helmet at +1.0mm and -1.4mm. This can be explained that the thickness of the helmet was reduced to fit participant P5 and was increased to fit participant P1. For top location, the thickness of all helmets P1-P5 is in the range of 32.5-36.7mm. The thickness of all helmets P1-P5 at top location is greater than the thickness of original model at 30.0mm. This indicates that the helmet thickness was increased at top location of all helmets P1-P5 to fit the participants. Meanwhile for front impact location, the thickness difference between customized helmets P1-P5 to original helmet model is between +2.5 and -1.7mm. Thickness of the original helmet was reduced for 3.9mm for participant P3 and was increased 2.6mm for participant P2. Based on the thickness comparison between the original helmet and the customized helmets P1-P5, it is clear that there is a change of helmet thickness at top, front and top location. This change is necessary to implement the helmet user-centered design approach because the helmet liner was designed to fit and follow the shape of each participant.

Peak linear acceleration

A validated numerical simulation of drop impact test of Netti Lightning helmet model was used to determine the peak linear acceleration (PLA) of user-centered helmet P1-P5 and original helmet at front, top and side impact locations. Figure-9 illustrates the recorded PLA of all helmets at side, front and top impact location. It is apparent from this figure that all curves have similar pattern, indicating that the simulation model are consistent for all helmets. This finding also highlights the comparison of PLA recorded by the user-centered helmets in comparison to those obtained from the original helmet. Based on the graphs, it is clear that the PLA registered by the user centered helmet differs to the original model. This suggests that the results are in good agreement with the hypothesis that changing the liner dimension to implement user-centred design approach would alter the impact performance of a helmet.

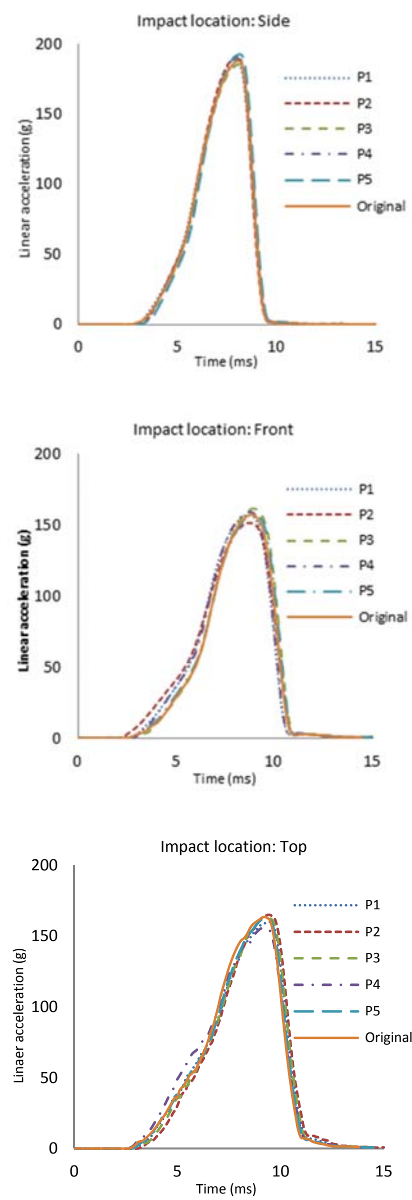

Figure-9. Presents the PLA of all user-centered helmets P1-P5 and the original helmet model.

For side impact location, the biggest difference of PLA value was recorded by helmet P5 at 192.6g, +5.2g

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more than the original helmet model. Meanwhile, the lowest change of PLA value was registered by helmet P4 at 189.6g, +1.6 more than the original helmet model. These results are consistent with the measured liner thickness of both helmets at side location, where helmet P5 has the biggest thickness difference and helmet P4 has the lowest thickness difference. It is also can be seen from the table that helmet P1 and P3 have lower PLA and helmet P2, P4 and P5 have higher PLA than the PLA recorded by the original helmet model. Again, these results are also consistent with the thickness measured at side location of the helmet. The thickness of helmet P1 and P3 was more than the original helmet, while the thickness of helmet P2, P4 and P5 were less than the original helmet and conditions that the researcher to deal in order to solve the problems.

For top impact location, it is apparent from Table-3 that all helmets P1-P5 recorded PLA between 160.1g and 164.9g, all of them less than the PLA of the original helmet measured at 165.5g. This result reflects the thickness of the helmet because the thickness of all helmets P1-P5 is greater than the thickness of original helmet at top location. The lowest PLA was recorded by helmet P4 at 155.9g. This is also in line with the previous result that thickness of helmet P4 is greater than other helmets. These findings are also in good agreement that the PLA of helmet reduces when the helmet thickness increases and vice versa. At front impact location, the highest PLA were recorded by helmet P3 at 16.7g and the lowest were recorded by helmet P1 at 157.3g. It also appears that Helmet P3, P4 and P5 registered PLA more than the PLA of the original model and PLA of helmet P1 and P2 was less than those recorded by the original model. From this data we can see that the results are also consistent with the measured helmet thickness in Table-2. As Table-2 shows, helmet P1 and P2 are thicker and helmet P3, P4 and P5 are thinner than the original helmet.

Table-2. Comparing helmet thickness P1, P2, P3, P4 and P5.

Helmet model	Thickness (mm)					
	Side	**Thickness difference**	**Top**	**Thickness difference**	**Front**	**Thickness difference**
Original	22.7	-	30.0	-	34.0	-
Helmet P1	23.8	+1.0	35.7	+5.7	34.2	+0.2
Helmet P2	21.8	-0.9	32.5	+2.5	36.5	+2.3
Helmet P3	23.5	+0.8	34.0	+4.0	32.0	-2.0
Helmet P4	22.0	-0.7	36.7	+6.7	32.5	-1.5
Helmet P5	22.3	-1.4	34.4	+4.4	33.7	-0.3

Table-3. Comparing helmet P1, P2, P3, P4 and P5.

Helmet model	Peak linear acceleration (g)					
	Side	**PLA difference**	**Top**	**PLA difference**	**Front**	**PLA difference**
Original	187.8	-	165.5	-	157.6	-
Helmet P1	185.3	-3.0	160.1	-5.4	157.3	-0.3
Helmet P2	190.9	+3.4	164.9	-0.6	151.5	-6.1
Helmet P3	185.5	-2.6	163.2	-2.3	161.7	+4.1
Helmet P4	189.4	+1.6	155.9	-9.6	159.4	+1.8
Helmet P5	192.6	+5.2	162.5	-3.0	157.9	+0.3

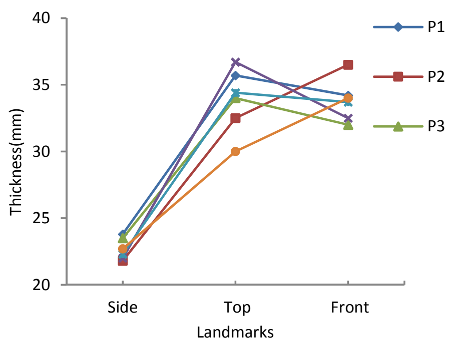

Figure-10. Graph for thickness of helmet.

The thickness and PLA of user centered helmet P1-P5 and original helmet at side, top and front locations are presented in Figure-10. From the graph 11(a) we can see that the thickness of helmet liner at side location is the lowest at around 20-25mm range, while the thickness at top and front location in between 30-35mm. Data from Figure-10(a) can be compared to the data in Figure-(b), which shows the highest PLA value of helmet were recorded at side location, while PLA at top location is slightly higher than front location. This result is in good agreement with the thickness of the helmet presented in Figure-10(a).

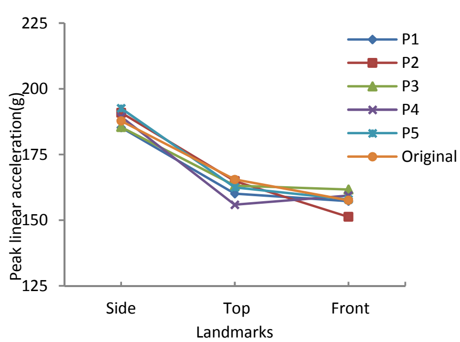

Figure-10a. Graph that shows PLA value.

CONCLUSIONS

This study set out to determine the effect of customized user-centred helmet design on the impact attenuation of the helmet. 5 user-centred helmet liner models were designed to follow the shape of the head shape of representing 5 participants. The head shape of participants and the helmet were scanned using handheld Artec3D scanner and Flexscan 3D camera respectively. The thickness and peak linear acceleration of original helmet and customized user-centered helmets were measured and compared. This study has found that user-centered helmet recorded different PLA value compared to the original helmet because liner dimension and thickness was changed to accommodate the head shape of the participants. The finding of this study also suggests that the PLA of the helmet depends on the helmet liner thickness, the PLA increases when the helmet thickness is reduced and vice versa. In conclusion, this study confirms that changing the liner thickness to employ user-centered helmet design would alter the impact performance of the helmet.

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