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Safety Helmet Fit Assessment Using 3D Scanning and Helmet Fit Index (HFI)

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Abstract

Safety helmets, essential in industries like construction, mining, and sports activities, are designed to protect the head from impact and penetration injuries. However, the effectiveness of these helmets is often compromised by issues of poor fit, discomfort, and non-compliance with safety protocols. The primary objective of this research is to evaluate the fit of safety helmets using the Helmet Fit Index (HFI) and 3D scanning. A sample group of 100 male participants aged between 20 and 50 is involved in this study. The methodology includes 3D scanning of participants' heads with and without safety helmets, followed by post-processing. The HFI for safety helmets is typically expressed as a percentage which this index assigns a score ranging from 0 (indicating a very poor fit) to 100 (representing an ideal fit), indicating the proportion of users for whom the helmet adequately fits. The HFI results indicate a poor fit of safety helmet among the selected participants. The average HFI score of 18.62 observed across 100 participants, with scores varying between 7.94 and 47.79. The significant gap at the top for vertical clearance led to high measurements of Gap Uniformity (GU) and the Standoff Distance (SOD), reflecting inconsistencies in the fit. These high values contributed to a lower HFI score, indicating that the helmets were less secure and uncomfortable. Consequently, the helmets' overall performance and safety effectiveness were compromised, underscoring the need for proper internal cushioning and minimal gaps to ensure optimal protection and fit.

1. Introduction

Safety helmets, vital in numerous professional and recreational activities like construction, mining, manufacturing, and sports, protect the head from impact and penetration injuries. However, the effectiveness of these helmets is often compromised by poor fitting. A common issue is the loose fit of helmets, which can lead to inadequate protection in the event of an accident [1-4]. Helmets should fit snugly without causing discomfort or pain, as an ill-fitting helmet increases the risk of accidents. Research indicates that the effectiveness of helmets is significantly influenced by factors like size, fit, and the retention system [4]. Different manufacturers often adopt varied approaches to accommodate a range of head sizes and shapes, leading to inconsistency in fit [5]. Given the significant variations in human head shapes, sizes, and structures, accounting for these anthropometric differences is crucial for accurate fit evaluations. The current market offerings in helmet sizes and designs often fail to cater to the diverse head shapes, leading to issues like gaps between the helmet's inner lining and the head or insufficient coverage in certain areas [4]. This inadequacy in protection is further complicated by the diversity in head dimensions across different ethnic groups, ages, and genders. For instance, Asian heads are generally rounder, with a flatter back and forehead compared to Caucasian heads, resulting in a poor fit for Asian users with helmets designed for Western head sizes [6-8].

The lack of objective and precise metrics to quantify helmet fit makes it difficult to develop standardized fitting guidelines that can accommodate diverse populations [9]. Although safety helmets are known to reduce head and brain injuries, the incidence of head injuries among helmet users points to the potential issue of inadequate helmet fit [10]. Recent advancements in 3D scanning technology have paved the way for more inclusive and comfortable headgear sizing. These technologies allow for the creation of helmets that can accommodate a wider range of head shapes and sizes, promoting better protection and comfort [11]. In Malaysia, there is a lack of comprehensive studies regarding the fit of safety helmets, particularly in various occupational settings and recreational activities. Despite the crucial role of safety helmets in preventing head injuries, insufficient research is dedicated to understanding the adequacy of helmet fit among Malaysian users. This gap in knowledge poses significant concerns for the effectiveness of safety helmets in providing adequate protection and highlights the need for further investigation. Malaysia is characterized by its diverse population with varying head shapes and sizes. A one-size-fits-all approach to safety helmets may not suit the Malaysian population [12]. Therefore, conducting studies on helmet fit that consider the diverse demographics of Malaysia is essential for ensuring that helmets provide adequate protection for all users [12]. Many industries in Malaysia require the use of safety helmets to protect workers from head injuries. However, without proper fit assessments, there is a risk that helmets may not adequately safeguard workers in the event of accidents. Understanding the fit of safety helmets in various occupational settings is crucial for enhancing workplace safety standards [13]. Comprehensive studies on safety helmet fit can inform the development of standardized guidelines and regulations for helmet manufacturers and users in Malaysia [14]. Establishing clear standards for helmet fit can improve the quality and effectiveness of helmets available in the market and promote better adherence to safety practices [15]. The literature indicates a pressing need for helmet designs that accommodate the diverse range of human head shapes and dimensions, particularly for users with Malaysian ethnicity, where the current one-size-fits-all approach is inadequate. This gap in knowledge poses significant concerns for the effectiveness of safety helmets in providing adequate protection and highlights the need for further investigation on the helmet fit index (HFI)[16].

2. Methodology

2.1 Sampling Size

This study's methodology for determining sample size adhered to the guidelines outlined in the ISO 15535 standard, which outlines procedures for establishing anthropometric databases. Sample size estimation was based on the 5th and 95th percentiles of a parameter with 95% confidence, incorporating the coefficient of variation (CV) and is the ratio between the Standard Deviation (SD) and the mean of a population ($\bar{x}$) (multiplied by 100), α is the percentage of relative accuracy desired, and n is the estimated sample size and a desired percentage of relative accuracy as shown in Eq. 1,2 and 3 [17].

$$n = (1.96 * CV / \alpha)^2 * 1.534^2 \tag{1}$$

$$CV = 100 * SD / \bar{x} \tag{2}$$

$$\alpha = 100 * \bar{x} / \text{precision level} \tag{3}$$

Despite the definition provided by ISO 7250-1 for head circumference measurement, challenges such as aligning landmarks and accounting for hair compression under the tape measure were noted [18]. The anticipated variation in head circumference was estimated at approximately 17 mm, leading to a recommended sample size of 100 participants. This estimation drew upon data from anthropometric surveys of both European and U.S. populations to ensure robustness and relevance to the study's objectives. By following this methodology, the study aimed to establish a statistically sound sample size that would provide meaningful insights into head circumference variability for effective helmet design considerations [19-20].

2.2 3D Scanning and Post-Processing

A sample size of 100 participants took part in this study, and their head shapes were captured using a portable 3D RealSense 2 scanner. Each participant was provided with a universal-sized safety helmet and asked to wear it. During scanning, they were instructed to sit still and upright, maintaining their normal facial expressions. To minimize hair interference, they were required to wear thin hair caps. Scans of the participants wearing safety helmets were also taken. Fig. 1 shows the schematic diagram of the 3D scanning setup using the 3D scanner, both with and without the helmet on. A large screen was also used as a secondary monitor to facilitate visual monitoring during scanning. Maintaining a steady distance between the scanner and the subject was important to ensure high-quality scan results, as the scanner is sensitive to movement and distance variations.

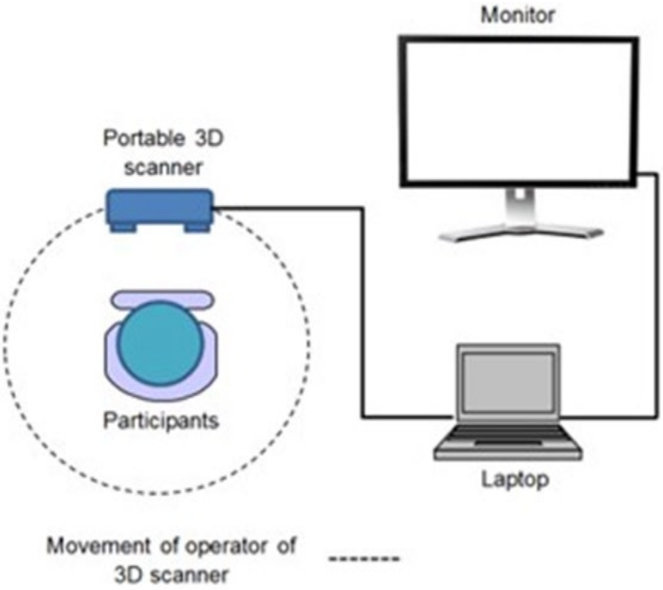

Fig. 1 *Schematic diagram of 3D scanning setup*

This study utilized the Geomagic Wrap application to post-process head scan images. Initially, the scans displayed several imperfections, which were addressed through various corrective measures. The scans were first smoothened to eliminate irregularities. Large holes in the scans were carefully repaired individually, while smaller holes were automatically filled using the application's fill tools. The regions affected by the creases from the hair cap, which participants wore to compress their hair during scanning, posed significant difficulties. In Fig. 2, these were precisely removed and seamlessly reconstructed using the tangential holes fill and defeature tools. The mesh doctor tool rectified other issues like non-manifold edges, self-intersections, highly creased edges, spikes, and small disconnected components. Due to the scanner's inability to accurately detect human hair, participants' requirement to wear thin hair caps during scanning led to additional surface glitches at the interface between the hair cap and the head. These unwanted areas were modified using the defeature tool. An automated fill hole function was applied for smaller imperfections like minor holes, whereas larger holes required more intricate editing using partial fill and bridge fill-up tools. Fig. 3 showcases the processed head scan images of the participants involved, illustrating the effectiveness of these post-processing techniques in creating clean and accurate 3D head models.

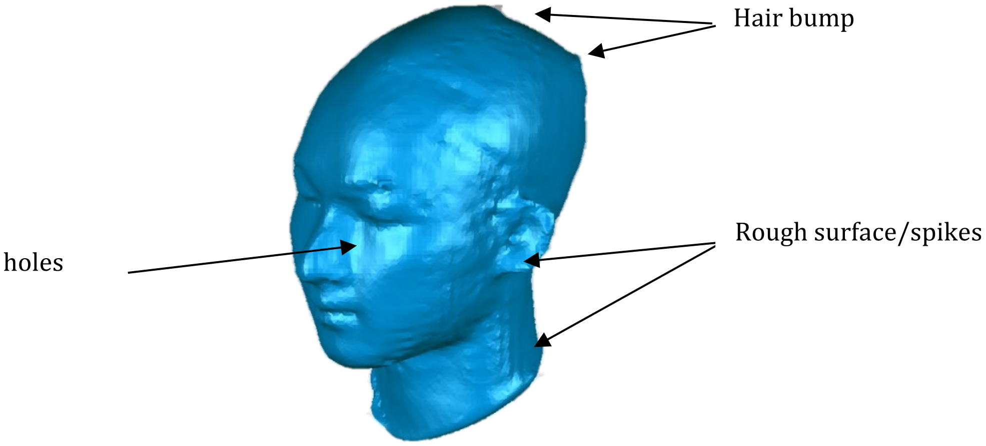

Fig 2 *Raw 3D scans*

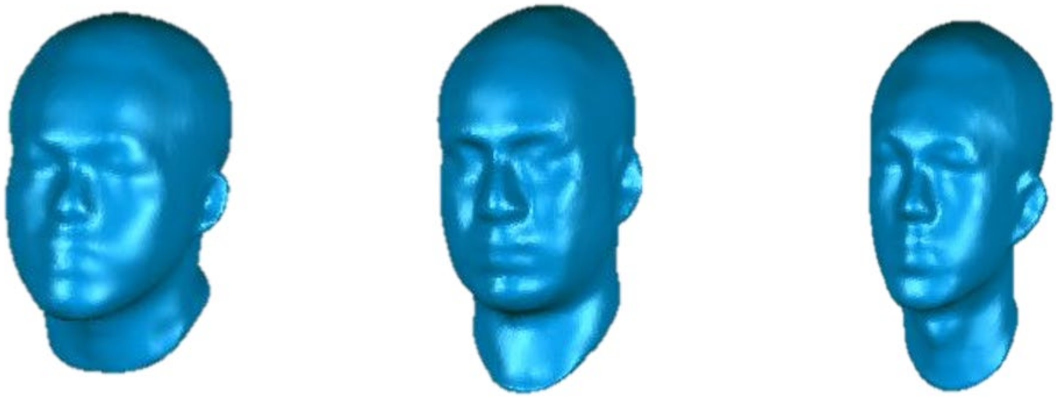

Fig. 3 *Isometric view of head scans of some participants involved in the study after cleaning*

The safety helmet was digitally captured using the GOM 3D scanner. Before scanning, components like the helmet's strap were removed to ensure a clean scan. Due to the helmet's glossy surface and round shape, dotted stickers were applied to it to prevent any error during the 3D scanning process. The helmet was placed on a flat table for a comprehensive capture, as shown in Fig. 4. The scanning process involved the GOM 3D scanner's projector and camera setup, with the helmet being scanned from many different angles as the scanner rotated around the safety helmet.

This method was particularly crucial for accurately capturing the helmet's complete profile and geometry, especially the area around the holes and curves. Subsequently, the scans of these various positions were meticulously aligned using the Geomagic Wrap software. A general post-processing step was also undertaken to eliminate any background elements from the scans, as in Fig. 5. Similarly, it was created following the same scanning and post-processing procedures in Geomagic Wrap software. The final digital models of the safety helmet are showcased in Fig. 6, demonstrating the detailed and precise nature of the scanning process.

Fig. 4 *3D scanned helmet using GOM scanner*

Fig. 5 *General post-processing*

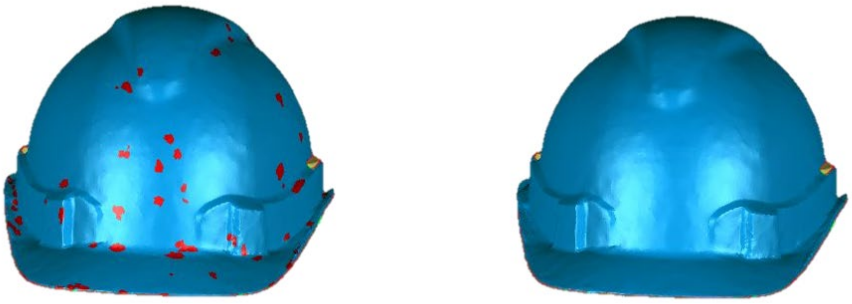

Fig. 6 *Digital model of safety helmet (L) before meshed process (R) after meshed process*

The process of creating the helmet shell involved several steps. Initially, the internal portion of the scanned helmet was removed, leaving only the section representing the shell. To account for the assumption that the shell is marginally larger than the harness inside the helmet, a 2.7 mm inner offset was applied to all its surfaces, effectively enlarging the shell's size as the standard safety helmet thickness [25]. The thickness of just the shell of a safety helmet can vary depending on the design and materials used. Typically, the shell thickness ranges from around 1.5 mm to 4 mm. This shell is the outermost layer of the helmet and is responsible for distributing and absorbing impact energy. Referencing the manufacturer's specifications is crucial for determining the exact shell thickness of a specific safety helmet model [25]. The edges of the shell scan were then smoothed out using the single fill tool, eliminating any sharp or rough edges. The *Mesh Doctor* tool came into play to address and rectify spikes, non-manifold edges, self-intersections, small holes, and creased edges. Finally, all scans were converted into surface data and saved as *.stl* files.

2.3 Alignment of Helmet and Head for Each Participant

The digital models, including the helmet, participant head, and helmeted head scans, were uploaded into Geomagic Wrap to develop tailored helmet designs for each participant. Initially, the scans of the helmeted head and the participant's head were synchronized using the n-points manual registration tool, as depicted in Fig. 7 [12]. This involved strategically placing several registration points on both scans to ensure precise alignment of the helmeted head scans with the head scan. Subsequently, the global registration tool was employed to refine and perfect the alignment between these two scans. The same alignment process was also applied to the helmeted head scan and the helmet scan. Consequently, this methodical approach ensured that the final alignment accurately represented the position of the helmet on the participant's head as in the helmeted head scan, laying the groundwork for a highly customized and precise helmet design for each participant. Fig. 8 in the study illustrates the images of a participant wearing the helmet, displayed in isometric, front, and side views, showcasing the precision and effectiveness of this customization process.

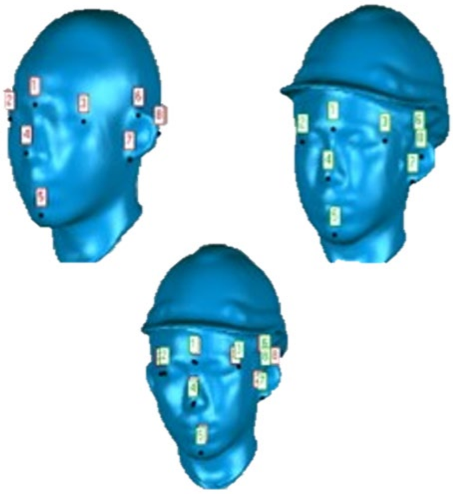

Fig. 7 *Aligning helmet and head scans to helmeted head scan*

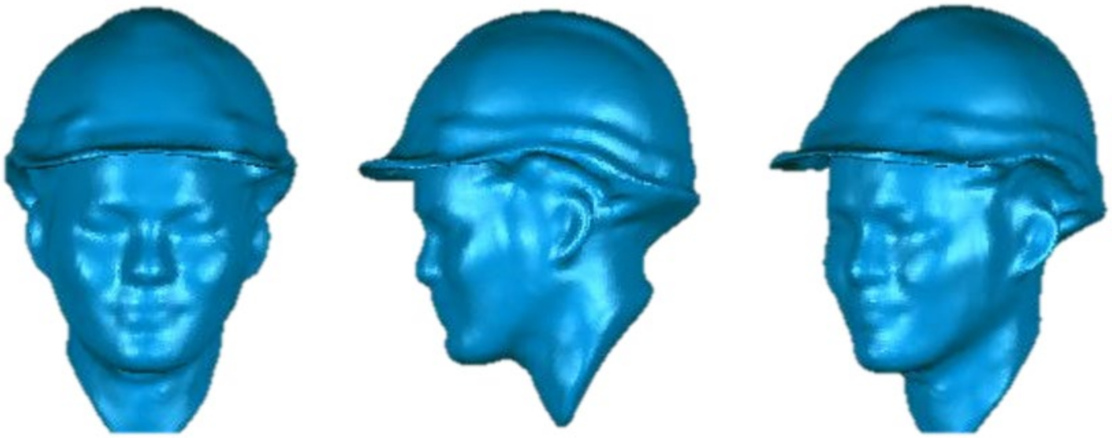

Fig. 8 *Scanned images of participants wearing helmets in isometric, front, and side view*

2.4 Helmet Fit Index (HFI)

The Helmet Fit Index (HFI) was used to evaluate the fit between the custom-fit helmet and the head scan [22]. HFI is designed to assign a 'score' reflecting the compatibility between a particular helmet model and an individual's head. This index operates on a scale ranging from 0, indicating an extremely poor fit, to 100, representing an ideal, perfect fit [22]. The formula for calculating the Helmet Fit Index (HFI) is as Eq. 4 follows:

$$x = \{a * (| SOD - 6 | - 2) + \frac{b * GU}{HPP}, for\ 4 > SOD > 8 \tag{4}$$

$$\frac{b * GU}{HPP}, for\ 4 \leq SOD \leq 8$$

$$\therefore where, a = \frac{2}{3}\ and\ b = \frac{6}{5}$$

This analysis involved calculating the gap distribution between the mesh of the head and the helmet's interior. Two key parameters were established: (i) Standoff Distance (SOD), defined as the mean of the shortest distances from each point on the liners inside the mesh to the head shape, and (ii) Gap Uniformity (GU), which is the standard deviation of these gap distances, indicating how much the individual gaps deviate from the average. To accurately measure the gap between the trimmed head mesh and the interior liner mesh, a distance analysis tool from CATIA V5R21 was employed.

3. Results

Table 1 shows the Helmet Fit Index (HFI) and associated parameters for each of the 100 participant's heads when wearing the original commercial helmet model. The lowest HFI was observed in participant P51, with a score of 7.94 %, while the highest was seen in participant P96, scoring 47.79 %. It's noteworthy that the majority of participants registered HFIs below 50. The average values for Standoff Distance (SOD), Gap Uniformity (GU), and HFI across participants P1-P100 were 18.98 mm, 6.43 mm, and 18.62, respectively. These findings point to a generally poor fit between the original helmets and the participants' heads, primarily attributed to the uneven gaps and distances between the helmet's inner surface and the varying shapes and sizes of the participants' heads. The difference in Standoff Distances, which ranged from 10.6 mm to 25.1 mm, further underscores the diversity in human head profiles and sizes as highlighted in prior studies [23][24].

Previous research by Ellena et al. on bicycle helmets found that the fit was optimal due to the proper alignment between the helmets and the participants' heads. In terms of similarity with this research, the method used is the same. The result shows that the HFI of bicycle helmets is far higher than that of safety helmets. This is because bicycle helmets do not have a strapped helmet, but safety helmets have a strap that indicates user gaps. The safety helmets used in this study did not have an EPS liner (polystyrene foam) around the interior as in bicycle helmets, resulting in a considerable gap at the top of the head for vertical clearance. This design flaw led to higher measurements of gap uniformity (GU) and the standoff distance (SOD), indicating inconsistencies in fit. The large vertical clearance and lack of cushioning contributed to a lower Helmet Fit Index (HFI), which signifies a less secure and comfortable fit. As a result, the helmets' overall performance and safety effectiveness were compromised, underscoring the need for proper cushioning and minimal gaps to ensure optimal protection for safety helmet users. Conversely, a significant fit issue arises in the case of safety helmets due to the gap between the helmet and the user's head falling within the helmet straps.

Table 1 *Helmet Fit Index (HFI) and related parameters of average mean and standard deviation on participants with original helmet (P1-P100)*

	Positive maximum deviation	The standoff distance (SOD)	Gap uniformity (GU)	Test area of the head	Actual helmet protection area	Head protection proportion (HPP)	Fit parameter(X)	Helmet fit index (HFI)
Average mean	38.63	18.98	6.43	66077.40	50808.41	0.77	17.46	18.62
Std. dev	5.83	2.85	1.50	2887.43	3121.81	0.04	3.63	6.94

The line graph in Fig. 9 illustrates the relationship between the Helmet Fit Index (HFI) and the fit parameter (X). Each point on the line represents an observation from the dataset, with the line itself connecting these points to show the trend of HFI as the fit parameter changes. This visual can be used to analyze the trend and potentially identify a pattern or correlation between the fit parameter and the HFI score. It seems that there is a trend indicating that as the fit parameter (X) increases, the HFI score decreases, which could suggest that helmets with a higher X value (potentially representing a looser fit) have a lower fit index, indicating a poorer fit. In earlier research conducted by Ellena et al., the findings indicated a parallel outcome regarding fit between bicycle helmets and safety helmets. For example, if a safety helmet exhibited a (HFI) of 90%, it indicated a satisfactory fit for 90% of the tested users, leaving 10% with potential fit concerns. This correlation also held true for bicycle helmets. However, without further context on what the X parameter precisely measures, more detailed conclusions would be speculative, as shown in Fig. 10 and Fig. 11. Fig.10 shows that the highest value of the HFI results for this study is 47.79%. The positive maximum deviation point was 30.74 mm. The standoff distance (SOD) is 17.53 mm, and the gap uniformity (GU) is 6.67. Hence, Fig. 11 shows the lowest value of HFI, which results in 7.94 %. The positive maximum deviation point was 41.7 mm. The standoff distance (SOD) was 17.7, and the gap uniformity (GU) was 6.37 mm, further emphasizing the poor fit, indicating larger gaps and less consistent contact between the helmet and the wearer's head. These findings underscore the importance of considering multiple fit parameters in evaluating helmet fit and effectiveness. While the HFI provides a summary measure of overall fit, examining specific parameters such as maximum deviation, standoff distance, and gap uniformity allows for a more nuanced understanding of fit quality. By addressing these specific fit issues, helmet manufacturers can enhance their products' safety and comfort, ultimately improving user satisfaction and reducing the risk of head injuries.

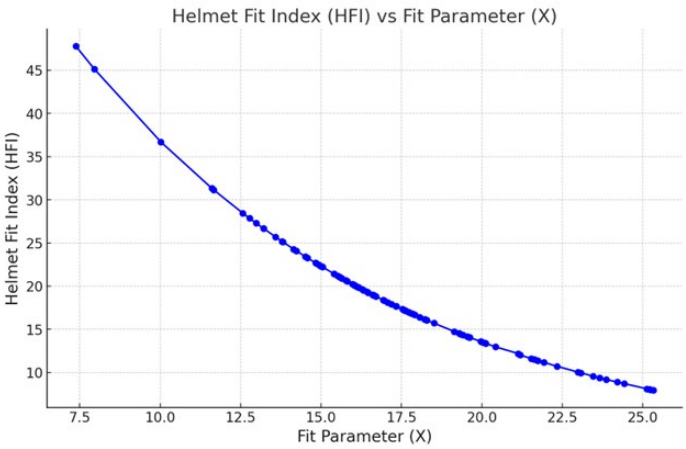

Fig. 9 *Line graph of the relationship between Helmet Fit Index (HFI) vs Fit Parameter (x)*

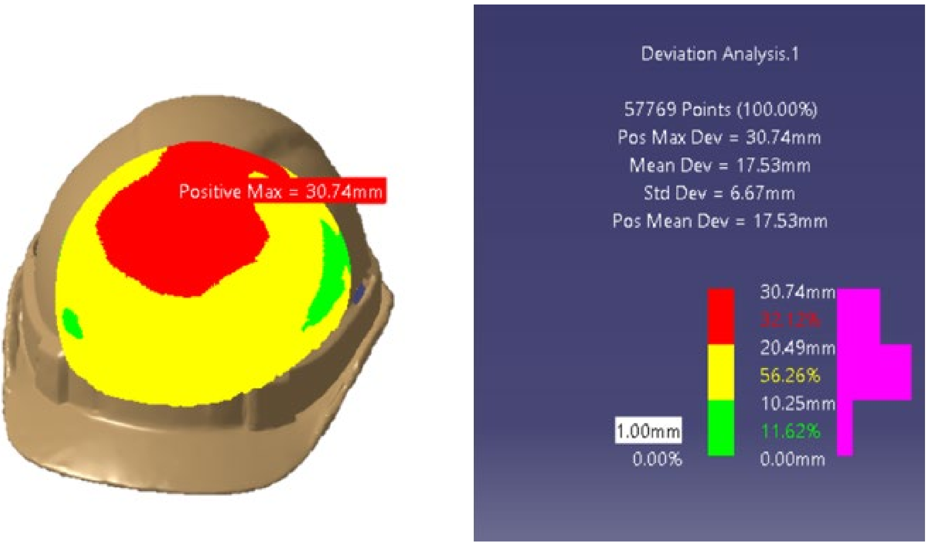

Fig. 10 *The lowest value of HFI results*

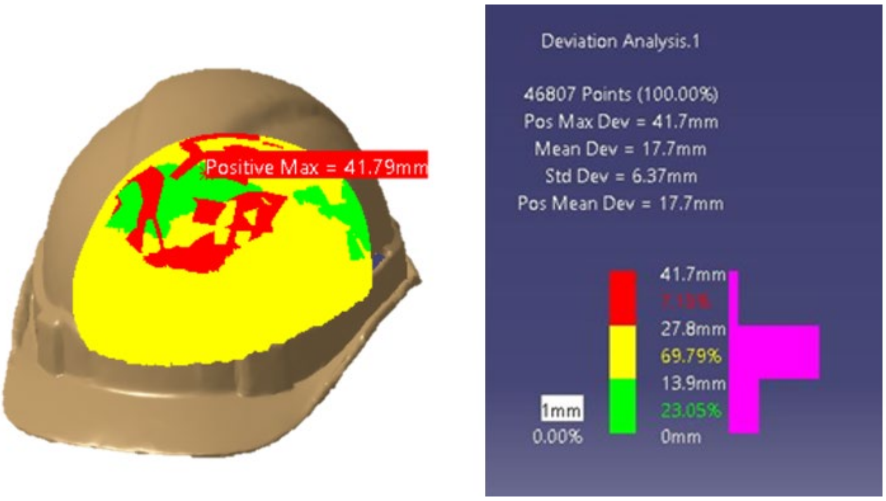

Fig. 11 *The highest value of HFI results*

4. Conclusions

This study significantly contributes to understanding helmet fit and its impact on safety in various activities. The comprehensive analysis using the Helmet Fit Index (HFI) revealed a prevalent issue of poor fit in standard commercial helmets among the participants. Of particular significance is the average HFI score of 18.62 observed across 100 participants, with scores varying between 7.94 and 47.79. This highlights a prevalent deficiency in helmet design, as it fails to accommodate the diverse range of head shapes and sizes adequately. This indicates that most helmets tested in the study exhibited suboptimal fit, potentially compromising the safety and comfort of users. The wide range of HFI scores underscores the need for improved helmet design that considers the variability in head morphology to ensure optimal protection for all individuals. The analysis also highlighted the critical role of individualized helmet design, as evidenced by the varying Standoff Distances (SOD) and Gap Uniformities (GU) among participants. The study's use of 3D scanning and post-processing techniques to create custom-fit helmets marks a significant advancement in personal protective equipment design. The line graph analysis's notable correlation between the fit parameter (X) and HFI further emphasizes the need for helmets that meet safety standards and poorly fit with individual head dimensions for optimal protection and comfort.

Conclusively, this research emphasizes the necessity for continuous innovation in helmet design and manufacturing. It advocates for a more user-centric approach, accommodating the unique head profiles of diverse populations, particularly in regions like Malaysia where current one-size-fits-all models prove insufficient. This study covers the way for future research and development in helmet technology, aiming for a higher standard of safety and comfort in protective headgear. To improve helmet fit and performance, consider redesigning the adjustable harness to better accommodate differences in head circumference. Instead of just relying on the fixed shell size, an adjustable harness can provide a more precise fit. Additionally, exploring MIPS technology for impact resistance could be beneficial for future studies. This technology can enhance safety by reducing rotational forces during impacts.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Syahrizan Azlan, Helmy Mustafa El Bakri, Salwa Mahmood;* ***Data collection:*** *Syahrizan Azlan;* ***Analysis and interpretation of results:*** *Syahrizan Azlan, Hannan Hamimi Hasmadi, Nur Fitrah Najiha Muhamad Dzahir, Helmy Mustafa El Bakri, Salwa Mahmood;* ***Draft manuscript preparation:*** *Syahrizan Azlan, Helmy Mustafa El Bakri. All authors reviewed the results and approved the final version of the manuscript.*

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