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Fit Assessment of Safety Helmets among Female Engineering Students in UTHM Pagoh Campus

Nurul Athirah Sharudin[1], Helmy Mustafa El Bakri[1]*

[1] *Department of Mechanical Engineering (Manufacturing) Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Kampus Pagoh, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: helmy@uthm.edu.my
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Abstract

Wearing personal protective equipment (PPE) is essential to ensure the health and safety of workers and personnel at work. Safety helmets are an essential component of personal protective equipment (PPE) designed to reduce the risk of head injuries caused by falling objects, collisions, and other occupational hazards. However, many safety helmets that are sold commercially don't suit all user demographics well, especially among female users. This study evaluates the global and local Helmet Fit Index (HFI) of standard safety helmets worn by female engineering students at Universiti Tun Hussein Onn Malaysia (UTHM), Pagoh Campus. 3D scanning and post-processing techniques in Geomagic were used to capture and analyse the geometric relationship between the head and helmet's inner surface. A total of thirty participants were involved. Global HFI and local HFI values for five head regions (front, top, left, right, and back) were determined based on standoff distance (SOD), gap uniformity (GU), and head protection proportion (HPP) that interpreted by using CATIA. The results indicate that the overall helmet fit is relatively low, with very low Global Helmet Fit Index (HFI) values and large negative standoff distances, particularly at the top and front regions, where the widest gaps and poorest gap uniformity were observed, while the left, right, and back regions exhibited comparatively smaller gaps and better conformity to the head shape. These findings highlight the limitations of current helmet designs in accommodating female head morphology and provide valuable input for future helmet design improvements.

1. Introduction

Personal Protective Equipment (PPE) is recognized as the last line of defence in preventing occupational injuries, illnesses, and fatalities when higher-level control measures cannot fully eliminate workplace hazards (NIOSH, 2015). Among all PPE, safety helmets play a critical role in protecting workers from head injuries, which are among the most severe and potentially fatal types of occupational injuries. Head protection is therefore mandatory in many industrial environments, particularly in construction, manufacturing, and heavy industries. Safety helmets are designed to protect the wearer from impacts caused by falling or moving objects, accidental head strikes against fixed structures, and, in some cases, electrical hazards. A typical safety helmet consists of a hard outer shell and an internal suspension or liner system that absorbs and distributes impact energy, thereby reducing the force transmitted to the skull and brain during impact events (OSHA, n.d.; ILO, 2023).

Despite meeting established safety standards such as EN 397 and ANSI Z89.1, the protective performance of a safety helmet is strongly influenced by how well it fits the user's head. In industrial environments, workers are required to wear helmets for prolonged periods, often while performing physically demanding tasks in confined or hazardous spaces. Poor helmet fit can lead to instability, discomfort, and improper positioning, exposing critical head regions such as the crown, forehead, and occipital areas. Previous studies have shown that inadequate helmet fit significantly reduces protection effectiveness and may increase the risk of head injury, even when the helmet satisfies impact resistance requirements (Winder & Stacey, 2002).Recent research has highlighted limitations in conventional helmet sizing and fit evaluation methods, which often rely on two-dimensional measurements, manual fitting assessments, or subjective user feedback. These approaches are insufficient for capturing the complex three-dimensional geometry of the human head and its interaction with the helmet's inner surfaces.

In contrast, three-dimensional (3D) head scanning technology provides a precise and non-invasive means of capturing detailed head geometry, enabling accurate assessment of head shape, size, and surface contours. This technology has been increasingly adopted in ergonomic and anthropometric studies to overcome the limitations of traditional measurement techniques (Perret-Ellena et al., 2014). The integration of 3D scanning with computational analysis allows for objective evaluation of helmet fit by quantifying the spatial relationship between the helmet inner surface and the wearer's head. Using 3D scanned head and helmet models, deviation analysis can be performed to identify gap distribution, contact regions, and coverage areas with high spatial resolution.

This approach enables the detection of critical mismatch regions that are not visible through conventional inspection methods. Furthermore, 3D scanning facilitates repeatable and reproducible measurements, reducing human error and improving the reliability of fit assessments (Ellena et al., 2016). Advanced fit assessment frameworks, such as the Helmet Fit Index (HFI), have been developed based on 3D scanning and computational analysis. The HFI integrates key geometric parameters, including standoff distance, gap uniformity, and head protection proportion, to provide a quantitative measure of helmet-to-head compatibility.

Previous studies have demonstrated that 3D scanning–based HFI analysis is effective in differentiating helmet fit performance across helmet types, designs, and user populations, including gender- and ethnicity-related variations in head morphology (Ellena et al., 2016; Azman et al., 2022). Therefore, the application of 3D head scanning combined with quantitative fit metrics offers a robust and objective approach for evaluating safety helmet fit. This method is particularly important for populations that are underrepresented in conventional helmet design databases, such as female and Asian users. By enabling detailed analysis of helmet–head conformity, 3D scanning supports the development of improved helmet designs that enhance fit, comfort, and protection, ultimately contributing to increased safety and compliance in industrial environments.

2. Methodology

2.1 Helmet Scanning and Post-Processing

Fig 1 (a) shows that a light coat of matting spray should be applied to the helmet to reduce glare and improve scan accuracy. A reference point marker should be placed on the surface of the helmet as shown on Fig 1 (b). These markers help the software align multiple scans accurately by providing consistent reference points throughout the scanning process. Before starting the actual scan, it is important to adjust the camera lenses and sensor angles as shown in Fig 1 (c) of the GOM ATOS III Triple Scan to match the size and shape of the object being scanned. During scanning, rotate the helmet incrementally to capture the full surface, typically requiring about 15 captures to complete the scan of the entire helmet. Finally, save the scanned data as an STL file for further processing or analysis.

(a) (b) (c)

Fig. 1 *Helmet scanning (a) Applying matting spray on the safety helmet (b) Applying reference point on the safety helmet (c) Adjust the camera lenses and sensor angles.*

The scanning was first cleaned and fixed. The 3D helmet scan mesh was loaded into the Geomagic Studio program for further processing. First up in the post-processing process is mesh repair, which includes edge repair, spike removal, and hole filling. Fig 2 shows the illustration of the helmet scan condition before and after editing.

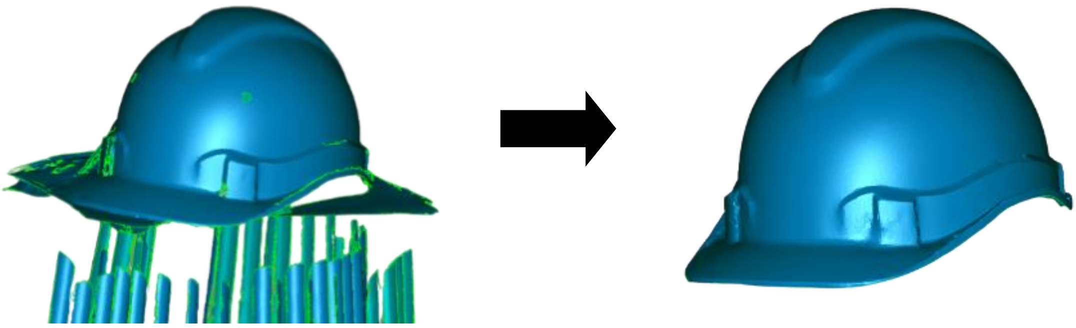

Fig 2 *Helmet scan before and after editing process*

2.2 3D Scanning of participant

Thirty female engineering students from UTHM Pagoh Campus were selected as participants. Each participant wore a standard wig cap to minimize hair-related irregularities during scanning. A portable 3D scanner was used to capture the head geometry while participants remained seated and maintained a fixed posture to reduce motion errors. The scanner operator carefully moved around each participant within a defined scanning radius, following a circular scanning path as illustrated in Figure 3(a), to ensure full coverage of the head geometry. The scanning distance was maintained between 0.5 m and 2.0 m, as shown in Figure 3(b), in accordance with the scanner's optimal operating range to achieve adequate resolution and minimize data noise. Multiple overlapping scans were captured to ensure complete surface coverage, particularly at complex regions such as the crown, forehead, and occipital areas. Two sets of scans were performed for each participant which is bare-head scans and helmeted-head scans, where participants wore the selected safety helmet in a standard wearing position. The helmet was positioned according to manufacturer guidelines, with the suspension system adjusted to a comfortable fit before scanning. Capturing both conditions allowed direct comparison between the head geometry and the helmet inner surface for subsequent deviation and fit analyses.

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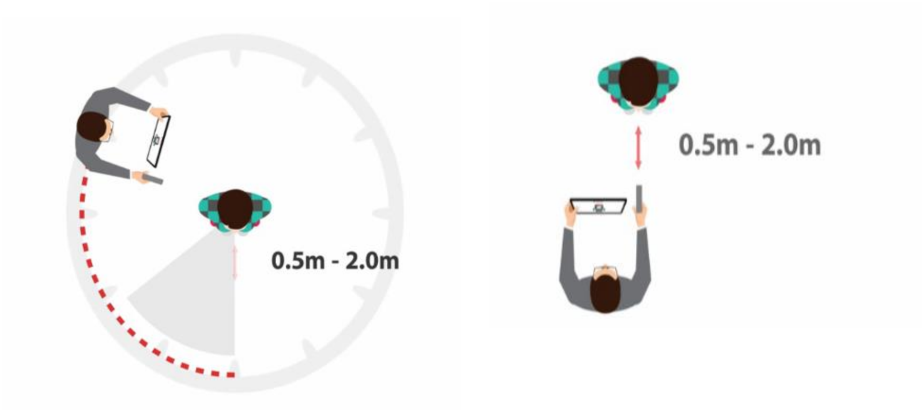

(a) (b)

Fig 3 *(a) Illustration of scanner operation moves around the participants (b)*

After the scanning process, the captured 3D mesh undergoes several post-processing steps to ensure accuracy and clarity using Geomagic software. The first step is mesh cleaning, which involves repairing edges, removing spikes, and filling any holes in the scan to produce a continuous and clean surface. Next, a defect removal process is applied to eliminate artifacts, such as wig cap bumps, that may have been captured during scanning. These bumps are removed, and the holes left behind are filled in a way that restores the true contour of the participant's head. Finally, the mesh is smoothed to refine key facial features such as the cheekbones and chin, ensuring that the resulting model accurately reflects the actual head shape for reliable analysis, as shown in Fig 4 and Fig 5.

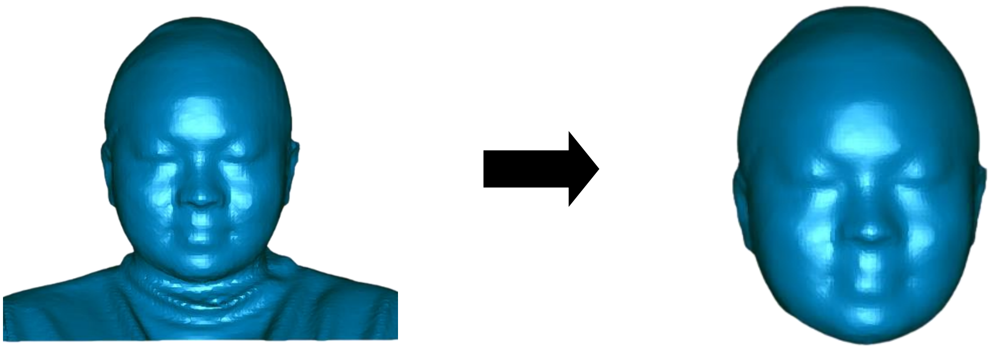

Fig 4 *Participants' head scans before and after the editing process*

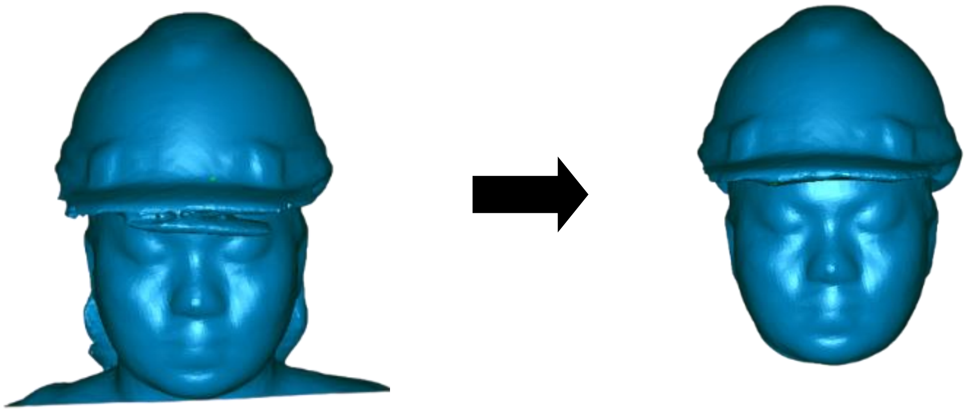

Fig 5 *Participants' heads with helmet scans before and after the editing process*

2.3 Alignment

The head scan was conducted using a pristine helmet mesh. The purpose is to measure the separation between the head and the inner surface of the helmet lining. We used both manual and global positioning, the "Manual Registration" and "Global Registration" options in Geomagic Wrap to precisely align the helmet with the participant's head. We selected the n-point for the scans between a helmet and the head wearing one to overlap and align together using the manual registration method. Figures Fig 6 and Fig 7 show the illustration of the alignment process.

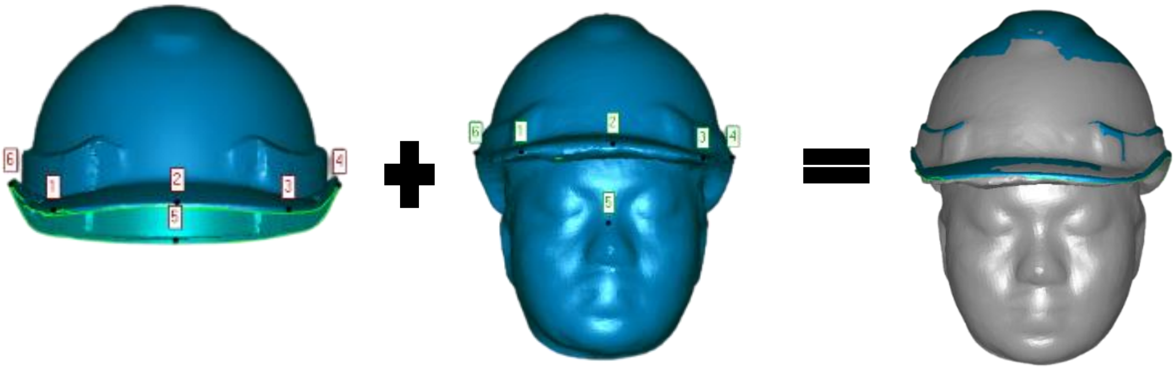

Fig 6 *Participants' heads with helmet and helmets allignment scans before and after the process*

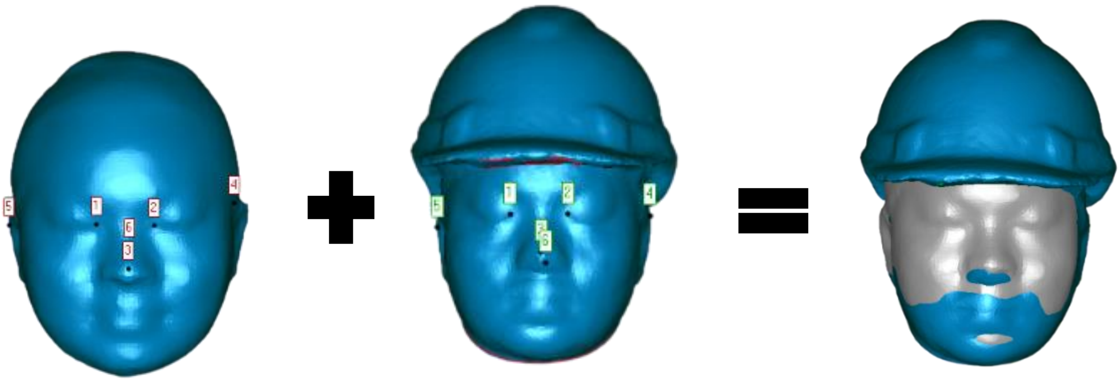

Fig 7 *Participants' heads and participats heads with helmets and alignment scans before and after the process*

This technology also employed a head scan to align the head of the person wearing a helmet. After finishing the alignment using 'Manual Registration', we used 'Global Registration' to refine the registration of two or more roughly registered points or polygon objects. Fig 8 shows the final alignment result.

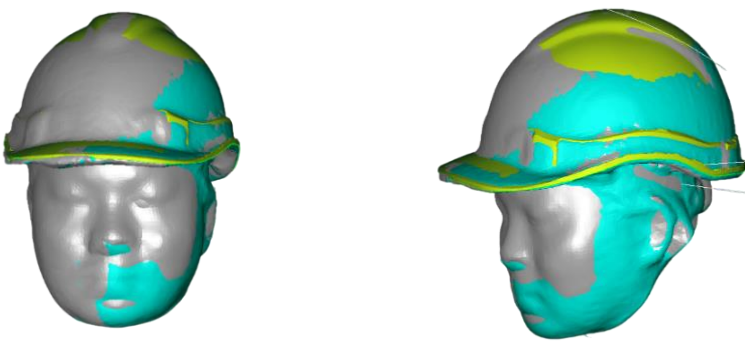

Fig 8 *Final alignment results*

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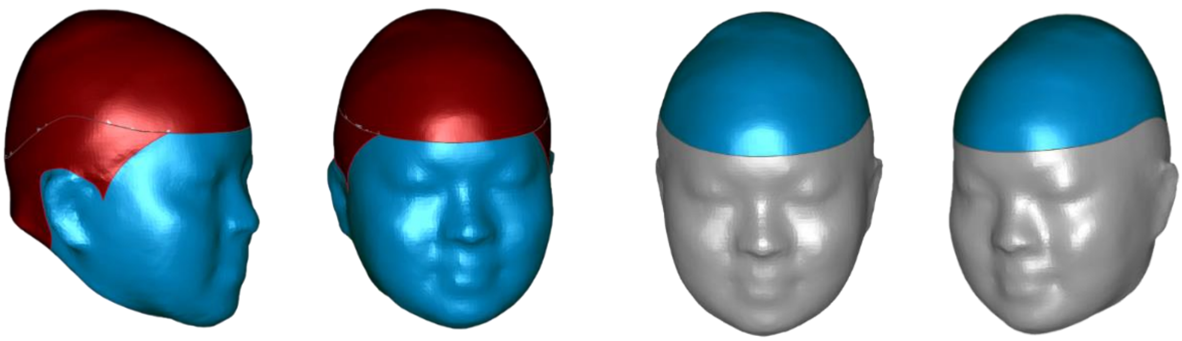
2.4 Global Helmet Fit Index (HFI)

Helmet fit was evaluated using the Helmet Fit Index (HFI), which quantifies the geometric relationship between the helmet inner surface and the wearer's head. The HFI assigns a numerical score that reflects the compatibility between a specific helmet model and an individual head shape, operating on a scale from 0, indicating an extremely poor fit, to 100, representing an ideal and perfect fit. This index has been widely adopted in previous helmet fit studies as an objective method for evaluating helmet–head compatibility using three-dimensional geometric analysis (Perret-Ellena et al., 2014; Ellena et al., 2016). Three key parameters were considered in the HFI calculation: standoff distance (SOD), which represents the average separation between the helmet and head surface; gap uniformity (GU), which indicates the consistency of the gap distribution; and head protection proportion (HPP), which quantifies the proportion of the head area covered by the helmet. The SOD and GU parameters were obtained through deviation analysis using CATIA, while the HPP was determined using Geomagic software. This approach is consistent with methods reported in previous studies on helmet fit assessment using computational and 3D scanning techniques (Perret-Ellena et al., 2014; Ellena et al., 2016; Azman et al., 2022).

The Global HFI represents the overall helmet fit across the protected regions of the head, including the front, top, left, right, and back areas. Deviation analysis was conducted to determine the average gap distribution and surface coverage between the helmet inner surface and the wearer's head, enabling an objective evaluation of helmet fit performance based on three-dimensional geometric compatibility, as recommended in earlier helmet fit and design studies (Ellena et al., 2016; Azlan et al., 2024).



(a) (b)

Fig 9 (a) *Test Area (b) Actual Test Area*

The gap between the inner surface of the helmet liner and the participant's head was measured using the deviation analysis tool in CATIA. This analysis was conducted for each head region and for the entire helmet interior. Two values were obtained, which are Standoff Distance (SOD), which represents the average distance between the helmet and the head, and Gap Uniformity (GU), which shows how evenly the helmet fits around the head. The percentage of the head surface covered by the helmet was also considered in the Helmet Fit Index (HFI) calculation. This value, called the Head Protection Proportion (HPP), was calculated by projecting the helmet liner boundary onto the head scan to determine the protected area. To perform the analysis, the helmet liner was set as the reference surface, and the head scan as the measured surface after alignment in Geomagic Wrap. CATIA then calculated the gap between the helmet and the head. In the deviation maps, red areas indicate regions with the largest gaps, as shown in Fig 11.

When the parameters are added together, the values of x are in Eq. 1, and the formula for calculating the Helmet Fit Index (HFI) is Eq. 2.

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

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

$$\therefore where, a = \frac{2}{3}\ and\ b = \frac{6}{5} \tag{1}$$

$$HFI \begin{cases} 100 * \exp\left(0.13 - \frac{|SOD - 6|}{15} - \frac{0.12Gu}{HPP}\right), & 4 > SOD > 8 \\ 100 * \exp\left(\frac{0.12GU}{HPP}\right), & 4 \leq SOD \leq 8 \end{cases} \tag{2}$$

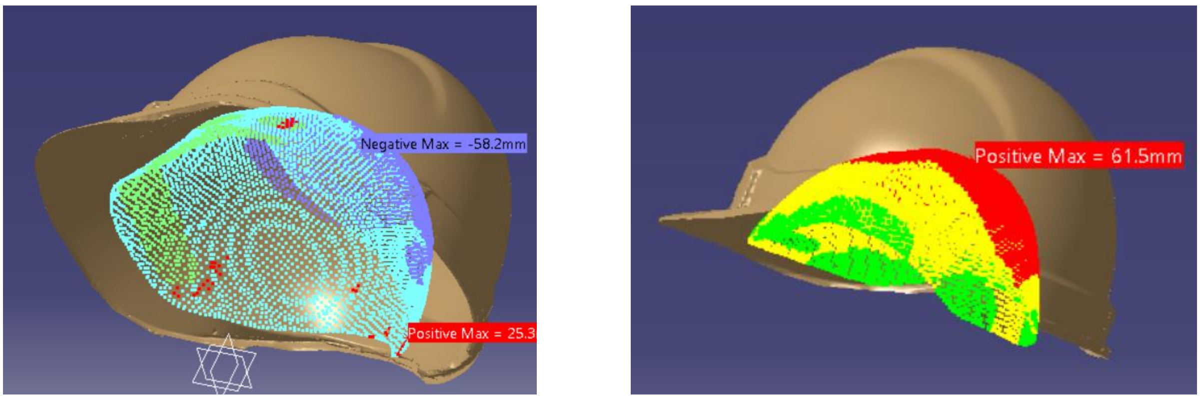
3. Results and Discussion

The results show that the mean Global HFI value for the participants indicates a generally poor helmet fit. Large gap distances were observed in certain regions, suggesting insufficient contact between the helmet liner and the head surface. Local HFI analysis revealed that the front and top regions exhibited lower fit scores compared to the left, right, and back regions. This uneven distribution of gaps suggests that current helmet designs may not adequately match the head shape of female users, particularly in critical impact-prone areas. These findings are consistent with previous studies that reported reduced helmet fit among populations not considered during the initial design stage. Improving helmet geometry to accommodate female anthropometric characteristics better could enhance both comfort and protective performance.

Table 1 ***Global Helmet Fit Index (HFI) Score***

Parameters	SOD (mm)	GU (mm)	HPP	Test Area (mm^2)	Actual Area (mm^2)	x	HFI
Lowest (P-12)	-29.90	20.30	0.63	62,926.11	39,601.66	49.48	0.22
Highest (P-7)	-31.10	11.50	0.79	61,538.34	48,485.30	40.92	1.67
Mean Dev.	-27.83	15.82	0.69	67,911.91	46,819.05	41.48	0.82
Std. Dev.	2.41	1.94	0.07	4,334.51	3,426.37	4.43	0.36

From this analysis, the average Global Helmet Fit Index (HFI) calculated for thirty female participants is 28.2057. The minimum value for Global HFI is 0.22, and the maximum is 1.67 as shown in Fig 10 (a) and (b).



(a) (b)

Fig 10 Deviation analysis *(a) Minimum value (b) Maximum value*

3. Discussion

Table 1 shows that the overall fit between the safety helmet and the participants' head shapes is poor. The low Global Helmet Fit Index (HFI) values are mainly caused by very large standoff distances (SOD), ranging from approximately −23 mm to −32 mm, and high gap uniformity (GU) values between 11 mm and 20 mm. These values are far from the recommended fit criteria reported in previous studies, where an ideal helmet fit should have an SOD of 4 to 8 mm and a GU value close to zero. The Global HFI combines SOD, GU, and Head Protection Proportion (HPP) to represent overall helmet-to-head fit on a scale from 0 to 100. When compared with previous studies, bicycle helmets generally show moderate fit performance, while industrial safety helmets show very low scores. Ellena et al. (2016) reported global HFI values between 48 and 56 for bicycle helmets, which were associated with near-optimal SOD and low GU values. In contrast, Azlan et al. (2024) reported a mean global HFI of 18.62 for a universal safety helmet worn by Malaysian males, mainly due to large top gaps and limited internal cushioning. In this study, the fit was even worse for Malaysian female engineering students. The global HFI value was approximately 0.82, with a very large negative SOD (−27.83 mm) and high GU (15.82 mm). These results indicate severe looseness and poor helmet stability, especially in the top and back regions. Fig 10 (a) shows the deviation analysis for the participant with the lowest Global HFI. Large red regions can be seen, especially at the top and front of the head, indicating very large gaps between the helmet and the head. This shows that the helmet does not sit properly and has poor contact with the head. Fig 10 (b) presents the deviation analysis for the participant with the highest Global HFI. This finding is consistent with anthropometric research showing that female head dimensions are generally smaller, shorter, and rounder than those of males, especially in Asian populations (Zhuang et al., 2010; Lee et al., 2018; Azman et al., 2022). Since most industrial safety helmets are designed based on Western male anthropometric data, this mismatch further exacerbates fit problems for female users. Compared to Fig 10 (a), the gaps are smaller and more evenly distributed, indicating a relatively better fit, although gaps are still present. The comparison with previous studies clearly shows that universal safety helmets provide a much poorer fit than bicycle helmets, particularly for Malaysian female users. The very low HFI values are mainly caused by excessive vertical gaps, uneven contact, lack of EPS liners, and limited adjustability. These design limitations are not suitable for rounder Asian and female head shapes. As a result, poor helmet fit may increase discomfort, instability, and reduce impact protection during industrial accidents.

4. Conclusion

These findings highlight the need for improved safety helmet designs, particularly for female users, to enhance comfort and protection. The very low HFI values clearly show that current universal, one-size-fits-all safety helmets are not suitable for users with different head shapes, especially Malaysian females. This study provides important insights that can guide the development of better-fitting helmets and support improvements in future helmet design standards. Firstly, safety helmet manufacturers should incorporate energy-absorbing liners such as expanded polystyrene (EPS), like those used in bicycle helmets. The inclusion of EPS liners can reduce excessive vertical gaps, improve gap uniformity, and increase head protection proportion (HPP), especially at the top and back regions where the largest mismatches were observed. This improvement would enhance both helmet fit and impact protection. Secondly, helmet designs should move beyond purely suspension-based systems and adopt hybrid fit systems that combine adjustable harnesses with internal cushioning. Adjustable height and circumference mechanisms would allow helmets to better conform to different head shapes, reduce uneven gaps, and improve stability during movement and impact. This is particularly important for female users, whose head shapes often differ from the Western head models commonly used in helmet design. Thirdly, manufacturers and regulatory bodies should develop gender- and region-specific helmet sizing systems based on updated Asian anthropometric data. Providing multiple shell sizes and adjustable internal configurations would reduce fit mismatches and improve safety performance. In addition, helmet standards should include fit-based evaluation methods such as local and global Helmet Fit Index (HFI), alongside conventional impact tests. Finally, future studies should evaluate redesigned safety helmets using 3D head scanning and HFI analysis across diverse populations, including different genders, ethnic groups, and occupations. Combining objective fit measurements with user-reported comfort and stability assessments would further support the development of safer and more ergonomic industrial safety helmets.

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Conflict of Interest

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

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nurul Athirah Sharudin, Helmy Mustafa El Bakri;* ***data collection:*** *Nurul Athirah Sharudin;* ***analysis and interpretation of results:*** *Nurul Athirah Sharudin, Helmy Mustafa El Bakri;* ***draft manuscript preparation:*** *Nurul Athirah Sharudin, Helmy Mustafa El Bakri. All authors reviewed the results and approved the final version of the manuscript.*

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