

Development of a Computational Tool for Assessing the Behind Helmet Blunt Trauma Using 3D Scanning and Impact Analysis

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Abstract. Ballistic helmets are essential defense equipment designed to improve survivability in combat situations. A key factor in evaluating these helmets is back-face deformation, which contributes to behind helmet blunt trauma (BHBT). The larger the BHBT, the greater the risk of traumatic brain injury, brain displacement, and increased intracranial pressure. Currently, standardized parameters and testing methods for accurately assessing this type of damage are lacking. This study developed a computational tool using MATLAB to quantify BHBT in thermoplastic-based ballistic helmets during a ballistic event. The BHBT assessment was performed measuring the indentation caused by the transient deformation of the helmet shell on a metal headform filled with plastiline in the coronal and occipital channels. A 3D laser scanner generated detailed point clouds of the plastiline surface before and after impact. Utilizing the alphaShape function, the tool overlays these point clouds to create a mesh from points within the analyzed region, delineating the deformed area as a closed polyhedron. This provided precise measurements of BHBT depth, area, and volume. The helmets were constructed with para-aramid plain-woven fabric and four different matrices: high-density polyethylene (HDPE), HDPE modified with exfoliated montmorillonite (MMT), HDPE modified with graphene nanoplatelets (GRF), and a hybrid stacking combining GRF and MMT matrixes (GRF/MMT). The ballistic tests were conducted using 9 mm ammunition at a 5 m distance, with a speed range of 426 ± 15 m/s. The results derived from this tool offered a more reliable and precise evaluation of the potential risks associated with BHBT to the equipment user. This, in turn, significantly enhances the assessment of helmet performance and augments user safety.

1. INTRODUCTION

Ballistic helmets are critical protective equipment designed to mitigate the risks associated with high-velocity projectile impacts in combat scenarios. Ballistic helmet performance is fundamentally dictated by the properties of their constituent materials, which must exhibit an optimal balance of strength, energy absorption, and lightweight characteristics. Para-aramid plain-woven fabrics, such as Kevlar®, are widely used in ballistic applications due to their exceptional tensile strength, impact resistance, and ability to dissipate kinetic energy through fiber deformation and fracture mechanisms [1-3]. However, to further enhance the protective capabilities of these helmets, polymeric matrices are often incorporated to improve structural integrity and energy dissipation. HDPE is a popular choice due to its high impact resistance, low density, and ability to absorb significant amounts of energy without brittle failure. Modifications to HDPE with exfoliated montmorillonite (MMT) nanoparticles enhance its mechanical properties by increasing stiffness and thermal stability while improving adhesion between fibers and the matrix [4-6]. Studies have indicated that the integration of graphene nanoplatelets (GRF) into HDPE may lead to enhanced toughness and improved load transfer efficiency, likely due to graphene's exceptional mechanical strength and high aspect ratio [7, 8]. It is also suggested that the hybrid stacking of GRF- and MMT-modified HDPE matrices could combine the advantages of both nanofillers, potentially offering a synergistic improvement in stiffness, toughness, and impact resistance [4].

A critical aspect of ballistic helmet performance evaluation is back-face deformation (BFD), which refers to the extent of deformation occurring on the helmet's inner surface after an impact. Even if the projectile does not penetrate the helmet, back-face deformation can still cause severe injuries to the user [9, 10]. However, its assessment remains challenging due to uncertainties in quantifying energy transfer mechanisms and the complex deformation dynamics involved [11-13]. Additionally, the evaluation of back-face deformation (BFD) and back-face signature (BFS) is crucial, as both contribute directly to behind-helmet blunt trauma (BHBT). BFS, in particular, represents the physical manifestation of BFD caused by ballistic impact, serving as a direct indicator of BHBT risk. It quantifies the deformation by measuring the indentation formed in a backing material, such as clay, which simulates the interface

between the helmet and the user's head. BHBT occurs when impact energy is transmitted through the helmet, generating internal shell deformation that can lead to cranial injuries even without projectile penetration. The larger the BHBT, the greater the risk of traumatic brain injury, brain displacement, and increased intracranial pressure [14]. Traditionally, the measurement of BFS is performed using calipers. In some cases, the diameter of the impact is measured to estimate an approximate volume for the indentation. However, this method has significant limitations. It is highly imprecise because it generalizes the shape of the indentation, often approximating it as a deformation cone [14], and fails to account for the unique details of each indentation type. This oversimplification can lead to inaccurate assessments of the energy dissipation and the associated risks of BHBT. In this study, BFS was captured using high-resolution 3D scanning, enabling a precise volumetric characterization of the deformation in clay post-impact. This approach provides an accurate assessment of the energy dissipated by the helmet, allowing for a direct correlation between the volume and depth of BFS with the severity of BHBT. By leveraging advanced computational tools and detailed point cloud analysis, this method significantly enhances the reliability and precision of BFS quantification, ultimately improving the evaluation of helmet performance and user safety.

By adopting BFS as a primary metric, this study advances the characterization of BHBT, replacing heuristic measurement methods with precise computational modeling and 3D reconstruction. This approach also overcomes the limitations of traditional methods, including those relying on Finite Element Analysis (FEA). While FEA has been utilized to simulate helmet-head interactions and address some of these challenges [5, 11, 15, 16], its predictive accuracy remains constrained by inherent issues such as mesh dependency and oversimplified material constitutive models. These limitations can lead to discrepancies between simulated and real-world results, reducing the reliability of FEA in accurately predicting BFD and BFS. Furthermore, inconsistencies in ballistic testing parameters, such as fluctuations in projectile velocity, introduce additional variability into BFD and BFS measurements, further impacting the reproducibility and reliability of results. In contrast, this study leverages high-resolution 3D scanning and computational tools to provide a more accurate and detailed assessment of BFS. By capturing the exact geometry of the deformation through point cloud data and volumetric analysis, this method eliminates the approximations inherent in traditional techniques and FEA simulations.

Given these limitations of traditional methods for quantifying BFD, BFS and BHBT, there is a critical need for more advanced assessment tools capable of capturing volumetric deformation with high spatial resolution. One promising alternative is the use of MATLAB's alphaShape function [17], which leverages computational geometry to construct a closed polyhedron mesh from high-density 3D point clouds of plastiline indentations before and after ballistic impacts. This approach provides a more accurate representation of deformation by enabling precise measurements of indentation depth, area, and volume, offering a more reliable metric for BFS and, consequently, potential neurotrauma risk. The alphaShape algorithm, with its ability to detect boundaries more naturally and tolerate noise, mitigates the overestimation and underestimation challenges commonly encountered in boundary detection, even with complex, noisy data [18, 19]. By utilizing the undeformed plastiline surface as a reference, this method correlates deformation volume with impact energy dissipation more effectively than traditional unidimensional measurements. Furthermore, the flexibility of the alphaShape function allows for the evaluation of critical parameters, such as the optimal alpha radius, which directly influences the accuracy of volume calculations [20]. This makes it a powerful tool for enhancing the precision of BHBT assessments, addressing the inherent uncertainties in traditional BFS measurements, and ultimately contributing to improved ballistic helmet design and performance evaluation.

2. EXPERIMENTAL

2.1 Materials

The helmets used in this study were manufactured by hot pressing using 28 layers of aramid (type) and thermoplastic matrices with a thickness of 60 μm . The processing parameters and layup are described in detail in the literature [21]. In this study, the following variations of thermoplastic matrices were tested: HDPE, HDPE/MMT, HDPE/GR, and HDPE/GR/MMT.

2.2 Ballistic Tests

The ballistic tests were conducted at Firing Line number 4 of the Brazilian Army Evaluation Center, LTIV – CAEx. A HPI 9 x 19 mm test barrel, in the premises of LTIV's Fire Line number 4, was used to

fire 9mm ammunition against the target helmets. The distance between the end of the test barrel and the target was 5 meters. NIJ 0106.01 specifies that the ballistic helmet being tested should be positioned five meters from the muzzle of the firearm (test barrel) and must be supported on a head prosthesis (NIJ, 1981). Figure 1 illustrates the complete test setup with the instruments properly identified. It shows the position of the panels connected to the chronograph, referred to as optical barriers HPI 4272, which are responsible for measuring the impact velocity of the test. The distance between the barriers is 1 meter, and it is set up 2 meters away from the target. An aluminum head prosthesis, with 4 entrances, is filled with plastiline (Acrilex 07001 V) and supports the ballistic helmets.

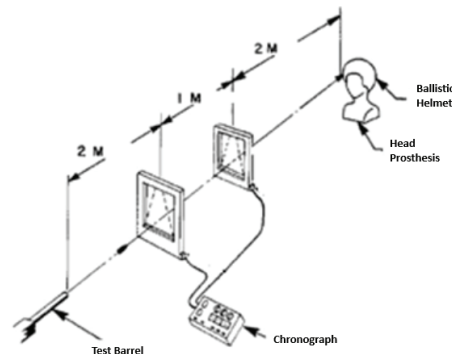


Figure 1. Schematic of the ballistic test setup for a helmet (adapted from NIJ 0106.01)

The tests were conducted using 9 mm FMJ ammunition at a velocity of 426 ± 15 m/s. Impact positions on the helmets were determined in accordance with the AR-PD 10-02 standard [22]. In the coronal plane, impacts on the right and left sides were positioned 50 mm above the ear protector. In the mid-sagittal plane, the frontal impact was placed 85 mm from the helmet's lower edge, while the rear impact was positioned 75 mm from the lower edge.

2.3 3D Scanning and Point Cloud generation

3D scanning has become a standard tool in various fields due to its ability to create highly accurate digital representations of real-world objects. Recent advancements have significantly improved its accuracy, speed, and overall results, making it indispensable for modern product development and analysis [23, 24]. In this study, the FARO Freestyle 2 3D scanning technology was employed to capture the deformation of a ballistic plastiline-filled headform before and after a ballistic impact. By utilizing this technology, the study ensures precise measurement of the headform's deformation, which is critical for evaluating the helmet's protective performance. The resulting point clouds were saved in .xyz format, a widely used file format for storing 3D point data, which ensures compatibility with various analysis and modeling software tools.

2.3 Data Processing with MATLAB

2.3.1 Preprocessing

The initial step in the analysis of the back-face signature (BFS) involved processing the raw point clouds to remove noise and irrelevant data points outside the region of interest (ROI). A bounding box was defined in the x, y, and z coordinates to isolate the points corresponding to the plastiline-filled headform, ensuring that only the relevant area was retained for further analysis. This step is crucial to focus the computational effort on the region of indentation depth and avoid distortions caused by extraneous data.

The alignment of the undeformed and deformed point clouds was performed using the Iterative Closest Point (ICP) algorithm, a widely used method for fine registration of 3D point clouds. The ICP algorithm iteratively minimizes the Root Mean Squared Error (RMSE) between corresponding points in the two clouds. The stopping criteria for ICP were set to an RMSE threshold of 10^{-5} , ensuring precise

alignment of the point clouds. Accurate alignment is essential for reliable analysis of the indentation depth, as even minor misalignments can lead to significant errors in volume calculations.

2.3.1 Volume Calculation using traditional method

To quantify the back-face signature (BFS) in the plastiline, a mesh variation analysis was conducted. This method calculates the point-to-mesh distance between the deformed point cloud and the reference (undeformed) point cloud. By measuring the deviation of each point in the deformed cloud relative to the reference mesh, the maximum indentation depth was determined. This indentation depth corresponds to the BFS, which is a critical parameter for evaluating helmet performance under ballistic impact. The BFS represents the height of the deformation cone used in the traditional volume calculation method, where the deformation is approximated as a cone. The base of the cone was estimated directly from the point cloud analysis, ensuring that the traditional method provides the closest possible approximation to the actual deformation geometry.

The traditional method, which approximates the deformation volume as a cone, relies on the BFS as one of its key parameters. While this approach provides a representation of the deformation, it inherently lacks the ability to capture the complex geometry and fine details of the deformation distribution. In this study, the BFS was calculated not only to enable the traditional volume calculation but also to establish a baseline for comparison with the more advanced alphaShape method. By comparing the results obtained from both methods, we can highlight the limitations of the traditional approach and demonstrate the advantages of using alphaShape for precise analysis of the indentation depth and deformation geometry.

The entire process, including noise removal, alignment, and BFS calculation, is illustrated in Figure 2. This figure provides a visual representation of the steps involved in preparing the point clouds for further analysis, ensuring that the data is accurate and reliable for both traditional and advanced methods.

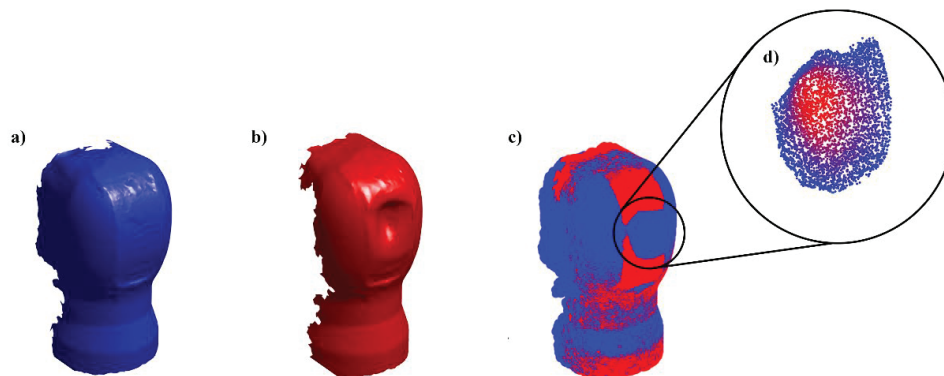


Figure 2. STL meshes generated from the point cloud: a) Without deformation, b) With deformation. c) Point clouds with deformation (red) and without deformation (blue) after ICP alignment. d) In blue, non-deformed regions and in red, deformed regions

2.3.1 Volume Calculation using alphaShape

The computational tool for calculating deformation volume was developed using MATLAB. The tool leverages MATLAB's alphaShape function, which constructs a 3D mesh from the point clouds of the plastiline before and after ballistic impact. The alphaShape function works by connecting points within a specified radius, known as the alpha radius, to create a polyhedral surface. The alpha radius controls the level of detail and smoothness of the resulting mesh, making it a critical parameter for accurate deformation analysis.

The alphaShape method is particularly useful for reconstructing surfaces from 3D point clouds, such as those captured by scanners. It works by connecting points to form triangles or lines, creating a surface that approximates the shape of the object. However, the choice of the alpha radius is crucial. If

the alpha radius is too small, the resulting mesh may contain gaps or disconnected regions, failing to fully enclose the point cloud. Conversely, if the alpha radius is too large, the mesh may oversimplify the shape, losing fine details and merging separate features. A good visualization of how the alpha radius works is shown in Figure 3.

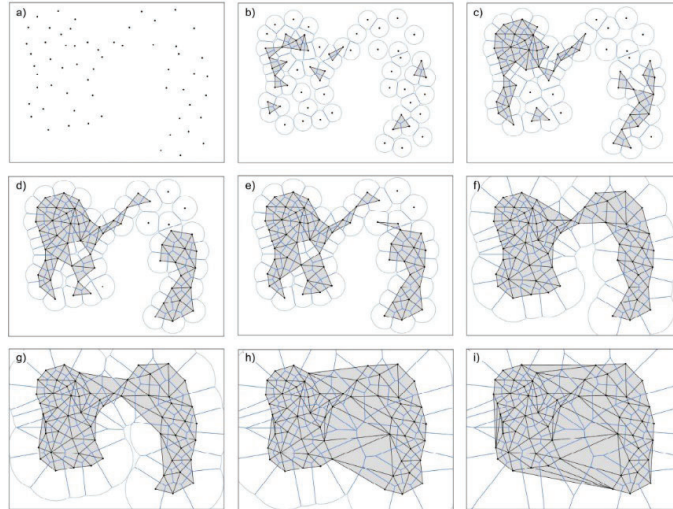


Figure 3. (a) a zero Alpha Radius producing an empty Alpha Shape; (b–h) an increase in Alpha Radius from left to right, and top to bottom, respectively; (i) an infinite Alpha Radius producing the Convex Hull [25]

Therefore, the critical alpha α_c is the smallest alpha radius that creates a fully enclosed shape without gaps or disconnected regions. It represents the point at which the mesh transitions from fragmented patches to a cohesive surface. Determining the critical alpha is essential because it ensures that the mesh accurately captures the deformation geometry while preserving fine details. In this study, the critical alpha was determined iteratively by testing a range of alpha values and selecting the smallest value that produced a fully enclosed shape.

3. RESULTS AND DISCUSSION

3.1 *AlphaShape* (AS) on Volume Calculations

To better understand the effects of the alpha radius on the reconstruction of meshes, Figure 4 presents a side-by-side comparison of the deformed point cloud region (shown in red) and the reference region (shown in blue) for the HDPE, MMT, GRF, and GRF/MMT helmets. Each row in the figure corresponds to a specific helmet material, while the sequence of images from left to right illustrates the reconstructed surface for different alpha radius values: the critical alpha α_c , $3 \alpha_c$, $100 \alpha_c$ and the convex hull (CH). This sequence clearly demonstrates how the alpha radius influences the level of detail and smoothness of the reconstructed surface.

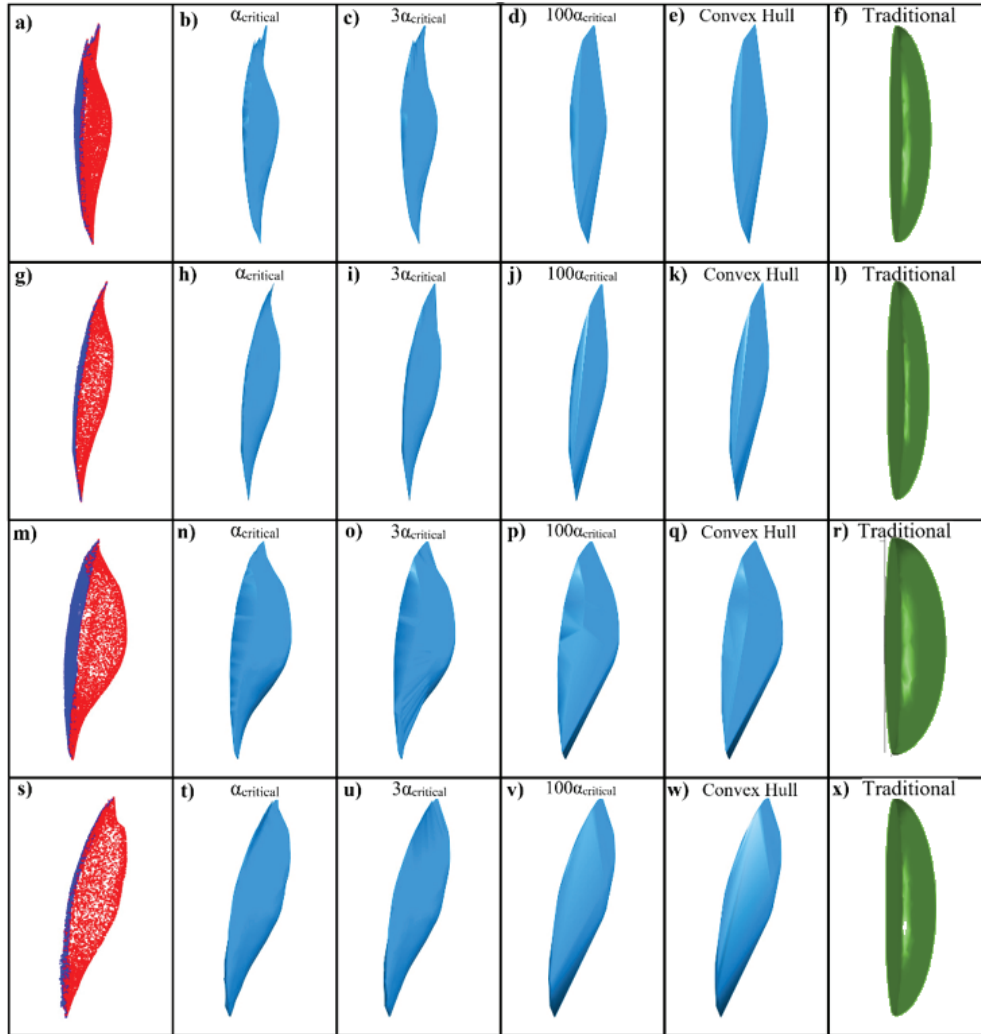


Figure 4. Side view of the deformed point cloud region (red) compared to the reference region (blue) for the HDPE, MMT, GRF, and GRF/MMT helmets (a, f, k, p, respectively). (f, l, r, x) are the respective solids if the calculation method used was the traditional method from the literature

Beyond the critical alpha, further increases in the radius lead to progressive smoothing of the surface. At $\alpha = 3 \alpha_c$, the surface begins to lose some of the finer details, and at $\alpha = 100 \alpha_c$, the surface approaches the convex hull (CH), which represents the outermost boundary of the point cloud. The convex hull provides a robust but oversimplified representation of the deformation, as it ignores concave features and local variations.

For comparison, closed semi-ellipsoidal surfaces were also generated for each point cloud, representing the best approximation of the deformation using the traditional method. The semi-ellipsoid method, employed for the traditional method, provides a simplified representation, it fails to capture the intricate details of the deformation distribution, such as localized depressions, ridges, or asymmetries. Besides, this method produces a much larger deformation area than what occurs in reality. In contrast, the alphaShape method, particularly at the critical alpha value, preserves these fine details, offering a more accurate and realistic representation of the indented geometry. Figure 4(f, l, r, x) highlights the limitations of traditional methods and underscores the importance of using advanced computational tools like alphaShape for precise deformation analysis.

The relationship between the alpha radius (α) and the calculated deformation volume was analyzed across four impact positions (frontal, rear, left lateral, and right lateral) for the four helmet materials (HDPE, HDPE/MMT, HDPE/GRF, and GRF/MMT). The resulting curves, shown in Figure 5, exhibit a characteristic sigmoidal profile. Initially, for small alpha radius ($\alpha < \alpha_c$), the deformation volume

increases sharply, reflecting the transition from fragmented surface patches to a cohesive polyhedron. This phase is marked by a steep slope, indicating rapid volumetric growth as the alpha shape begins to enclose the point cloud.

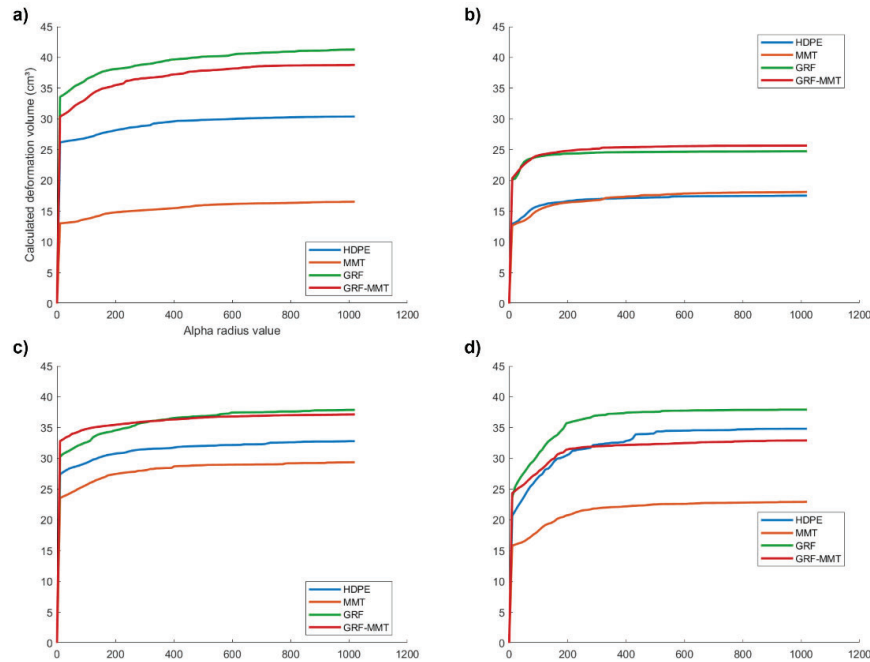


Figure 4. Deformation volume as a function of alpha radius: a) Frontal impact, b) Rear impact, c) Left lateral impact, d) Right lateral impact

Beyond the critical alpha value (α_c), the growth rate of calculated deformation volume decays exponentially, with the volume asymptotically approaching that of the convex hull (CH). At this stage, further increases in the alpha radius primarily smooth finer details of the deformation, leading to minimal residual variation in volume beyond $\alpha = 100 \alpha_c$. This behavior aligns with theoretical predictions from Edelsbrunner's alpha-shape formalism [26], where $\alpha < \alpha_c$ represents the percolation threshold at which disconnected components merge into a single enclosed volume.

The α_c was determined through the intersection of linear regression lines fitted to the ascending and plateau phases of the α -V curve. This method improves upon traditional "elbow point" detection by incorporating material-specific deformation mechanics, ensuring that α_c corresponds to the smallest alpha radius that fully encloses the point cloud while preserving local curvature features [17]. This approach was validated through cross-correlation with micro-CT reference volumes, demonstrating high accuracy and reliability. The critical alpha value provides an optimal compromise, ensuring that the deformation geometry is accurately represented while preserving the necessary level of detail. For all helmets analyzed, the critical alpha values obtained were approximately $\alpha_c \cong 10$, with minor variations depending on the material and impact position.

Selecting an inappropriate alpha radius can lead to significant inaccuracies in volume calculations. If the alpha radius is too small, the surface may fail to fully enclose the point cloud, resulting in underfitting and underestimation of the deformation volume. Conversely, an excessively large alpha radius can over-smooth the deformation, leading to the loss of fine details and overestimation of the volume. The critical alpha value ensures that the mesh accurately represents the deformation geometry while preserving the necessary level of detail, providing a robust foundation for further analysis of deformation patterns and energy absorption in ballistic helmets.

These findings align with prior studies, such as those by Wilson et al. (2009), who utilized the critical alpha value for precise molecular volume calculations [27], and Liang et al. (1998), who applied alpha shape analysis to compute molecular surface areas and volumes, demonstrating its effectiveness in capturing the complex geometries of macromolecules [28]. By leveraging the critical alpha value, our

volume calculations are both precise and reliable, enabling a detailed evaluation of helmet performance and material effectiveness.

The analysis of four different helmet materials across multiple impact positions reveals substantial discrepancies between the volumes calculated using the alphaShape method and those obtained through traditional techniques, as shown in Figure 5. The relative errors range from as low as 0.11% to as high as 107.25%, with an average error of approximately 47%.

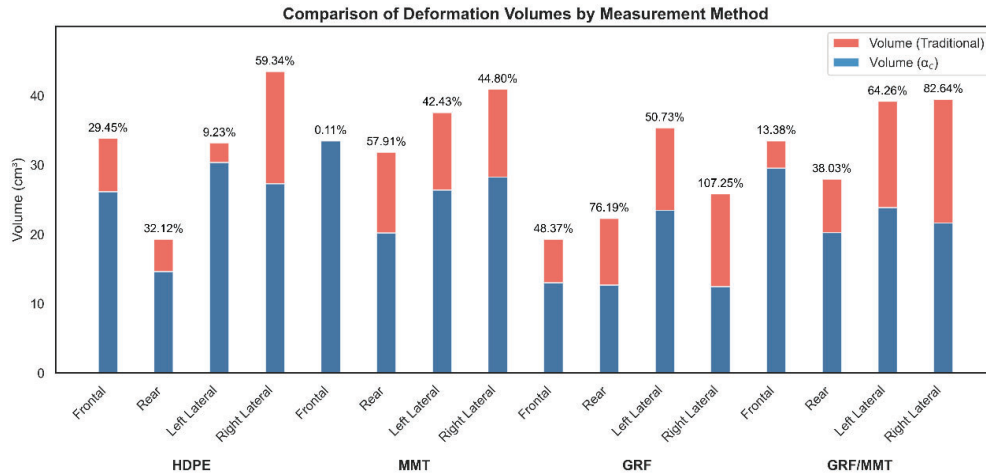


Figure 5. Comparison between volume values obtained with alphaShape and the most accurate traditional method in the literature

These findings highlight several critical aspects:

- 1. Precision of Measurement:** The alphaShape method consistently produces lower volume measurements compared to traditional approaches. This suggests that conventional techniques may overestimate deformation volume, potentially due to simplifying assumptions regarding the deformation shape.
- 2. Variability Across Impact Locations:** The discrepancies between methods vary considerably depending on the impact location. Lateral impacts, for instance, exhibit higher relative errors compared to frontal impacts. This variability underscores the importance of accounting for the complex geometry of helmet shells in deformation analysis.
- 3. Material-Dependent Effects:** The degree of discrepancy between methods appears to be influenced by the helmet material. The HDPE/GRF composite, for example, exhibits smaller relative errors on average compared to other materials, indicating that material properties may affect the accuracy of traditional measurement techniques.
- 4. Implications for BHBT Assessment:** The significant differences in volume calculations have direct implications for BHBT evaluation. Overestimation of deformation volume by traditional methods could lead to excessively conservative assessments of helmet performance, potentially resulting in unnecessary design modifications or the rejection of effective protective solutions.

The ability of the alphaShape method to capture the nuanced geometry of deformation is particularly relevant in the context of modern helmet designs. Previous studies, such as Tan et al. (2012), have indicated that traditional cone approximations can underestimate actual deformation volumes by 15-30%, particularly for non-symmetric deformations [29]. The present findings confirm that in some cases, this underestimation may be even more pronounced.

4. CONCLUSION

The alphaShape method has proven to be a critical tool for achieving precise and reliable measurements of back-face signature (BFS) and, consequently, behind-helmet blunt trauma (BHBT). Traditional methods, such as the semi-ellipsoidal approximation, fail to capture the intricate details of deformation geometry, leading to significant inaccuracies in volume calculations, with relative errors reaching up to 107.25% compared to the alphaShape method. These discrepancies directly impact the assessment of helmet performance and BHBT risks, as overestimated volumes may result in overly conservative design decisions, while underestimated volumes may understate the severity of potential injuries.

By employing the critical alpha (α_c) value, the alphaShape method strikes an optimal balance between preserving fine details and ensuring a cohesive representation of the deformation. It accurately reconstructs the surface geometry, capturing localized depressions, ridges, and asymmetries that traditional techniques often overlook. The sigmoidal relationship between the alpha radius and deformation volume further validates the method's robustness, with the critical alpha ensuring the mesh fully encloses the point cloud while maintaining essential detail. This precision is vital for evaluating the energy absorption capabilities of different helmet materials and their effectiveness in mitigating BHTB.

The study also highlights the limitations of traditional methods, which rely on generalized assumptions about deformation shape and fail to account for material-dependent and impact-location-specific variations. In contrast, the alphaShape method adapts to the complex geometry of helmet shells and the unique deformation patterns resulting from different impact scenarios. This capability is particularly relevant for modern helmet designs, where non-symmetric deformations are common and require detailed analysis for accurate performance assessment.

The findings align with prior research in fields such as molecular volume calculations, where the alphaShape method has proven effective in capturing complex geometries. By applying this method to ballistic helmet evaluation, we have established a more reliable framework for quantifying BFS and BHTB, enhancing the assessment of helmet performance and user safety. The precision of the alphaShape method not only improves deformation volume calculations but also provides valuable insights into energy dissipation mechanisms, guiding the development of more effective protective solutions.

In conclusion, the alphaShape method represents a significant advancement in ballistic helmet evaluation. Its ability to accurately reconstruct and analyze deformation geometry offers a superior alternative to traditional techniques, ensuring a more precise assessment of BHTB risks and helmet performance. This approach enhances the reliability of BFS measurements and contributes to ongoing efforts to improve helmet design and user safety in combat scenarios. Future studies should continue to explore advanced computational tools like alphaShape to further refine our understanding of helmet mechanics and traumatic brain injury prevention.

Acknowledgments

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