Behind Helmet Blunt Trauma Deformation Geometry under Different Helmet Materials

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ABSTRACT

Modern combat helmets improve wearer survivability through preventing ballistic penetration via delamination or deformation of the shell material. However, this deformation may impinge upon the skull and present a risk of behind-helmet blunt trauma (BHBT). While legacy aramid helmets from the late 70s-80s inform current NIJ testing standards, the advent of lower areal density ultra-high molecular weight polyethylene (UHMWPE) and modern suspensions may incur unknown changes that present an unknown effect on BHBT risk. This study investigates whether current standards relying on a peak acceleration threshold and residual clay deformation may not reflect changes in deformation geometry seen in newer shell materials and suspension designs. Thirty-eight helmets categorized into three groups, older aramid, newer aramid (with new suspension), and prototype UHMWPE (with old suspension) were mounted on Hybrid III ATD head-necks and impacted on the temporal surface with 9 mm NATO projectiles at velocities between 388 and 482 m/s. Flash x-ray imaging captured deformation geometry. Deformations were digitized to measure maximum depth, volume, and surface area recruited. Multiple linear regression identified the influence of shell material and suspension on geometry. Results indicated that shell material significantly affected deformation volume and area ($p < 0.05$). Notably, UHMWPE exhibited a qualitatively more "pointed" deformation profile compared to aramid, recruiting material differently as depth increased. In contrast, suspension type and helmet design did not significantly influence deformation geometry. These findings suggest that the BHBT geometry in UHMWPE helmets differs fundamentally from aramid helmets. As UHMWPE helmets encounter higher-energy threats, current acceleration threshold or depth-based standards may not fully capture the risk of skull fracture. To future-proof helmet validation, testing standards should evolve beyond current standards to include area recruitment and other geometric measures.

INTRODUCTION

Helmets are widely used by modern combatants including military and law enforcement to prevent injury to the head. By preventing penetrative injury through delamination and deformation of the armor material helmets greatly increase wearer survivability. However, severe injury or fatality may still occur under non-penetrations from impact of the deforming helmet backface against the head, termed behind-helmet blunt trauma (BHBT)[1]. Though increasing the amount of armor worn may reduce injury risk, a protective but overly heavy helmet would contribute to risks of other injuries such as chronic neck pain[2–4] or performance-decreasing fatigue also increasing injury risk[5–7]. These factors precipitate a need to optimize and balance helmet weight and protection against BHBT and penetration risk. To aid this balance, standards for helmet testing

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enable assessment of injury risk relative to weight. Currently, protection against both penetrating injury and BHBT is evaluated commercially through helmet testing following standards set by the NIJ in 1981 and militarily through military-specific standards in purchase descriptions[8,9]. These standards use peak linear acceleration at the head center of mass and residual deformation depth in plasticine modeling clay (RP-1) respectively. However, both standards do not consider differences in magnitude of deforming helmet shell recruitment across different materials and potential differences in BHBT.

To reduce helmet weight while preserving protection against penetration, since the 2010s ultra-high molecular weight polyethylene (UHMWPE) helmet designs present a lighter areal density alternative to legacy aramid helmets but generally exhibit greater residual deformation depth[10–12]. Given that during the 1970s-80s when the helmet standard was developed UHMWPE helmets did not exist, it is unknown whether these standards remain optimal for balancing UHMWPE helmet protection and weight. Newer helmets also possess substantially different suspension designs, favoring foam pads and an H-nape head harness instead of the webbing suspension used in the 1980s[13]. The difference in suspension material and design may contribute to differences in the BHBT response that are not well-characterized by the current standard threshold. Being derived from standards for thoracic body armor as a thoracic tissue surrogate, the biofidelity of the RP-1 clay model for BHBT head response is also unknown[9,14,15]. To identify whether these material and design differences would be well-characterized by a peak acceleration threshold standard developed originally for a helmet using aramid material and webbing suspension, comparing the older material and suspension against two groups will visualize differences. These groups consist of a UHMWPE shell with a webbing helmet suspension design and aramid shell with modern padded suspension.

METHODS

Thirty-eight helmets of three different types (aramid 1, aramid 2, UHMWPE) were mounted on Hybrid III ATD head-necks and impacted on the temporal surface of the helmet using 124 gr (7.7 g) 9 mm NATO ball projectiles at 388-482 m/s. All helmets were explicitly designed for protection against 9 mm NATO, and no penetrations were present in the test series. Four 150 KVp flash x-ray heads collected 76 flash x-ray images at 70 ns pulse widths from two angles. These were triggered using a frangible impact site surface contact. Projectile velocity was measured by two interleaved Shooting Chrony chronographs and confirmed by high-speed video.

Figure 1: Prototype UHMWPE helmet used. Webbing suspension differs from newer pads often used in modern combat helmets. Adjustment is done by tensioning straps instead of pad removal.

This series of helmet impact tests used three different helmets: two aramid helmet types and a prototype UHMWPE helmet (shown in Figure 1). Aramid helmet 1 is an older design that was developed throughout the late 1970s and was officially adopted by the United States military in 1983. This presents the closest approximation of materials and helmet design for which the NIJ 0106.01 helmet standard was developed. Aramid helmet 2 is a newer design that remains in service in the present day, is also an aramid design, and uses similar materials. However, it incorporates a different shell profile and screw-hole location, modern modular foam liner pads, and H-nape suspension. The prototype UHMWPE helmet is essentially an older aramid helmet constructed using UHMWPE, preserving identical webbing suspension with removable headband. This enables comparison of UHMWPE/aramid helmet shell materials directly without the confounding factor of helmet design and vice versa. Therefore, these two newer helmet groups enable visualization of differences attributable to helmet design and material respectively.

Helmet deformation geometry was digitized through manually tracing the edges of the flash x-ray image using ImageJ using similar approaches as previous digitized body armor deformation geometry comparisons[16]. These deformations were characterized by their maximum depth, the volume of the deformation, and the surface area recruited of the helmet shell. These measurements were taken using the assumption that the inflection points of the deformation profile edge represent the maximum extent of the deformed shell surface. A line was drawn between these points such that the maximum value between this axis and the digitized deformation represented peak depth. Assuming that the deformation was evenly distributed and circular, the surface area of the profile was calculated by rotating the line between inflection points to form a circle. Deformation volume was then calculated by rotating the integral area between the profile and the peak depth axis and averaging between the two sides. All flash x-ray images from both angular perspectives were concatenated and assessed independently assuming that the profiles were circular and uniform. Deformation geometry was then compared between helmet suspension type and helmet shell material type using a multiple linear regression model with interactions in R.

RESULTS

The main effect of shell material was found to be significant ($p<0.05$) for both volume and area when predicting deformation depth, indicating and reinforcing that UHMWPE performs differently than aramid under ballistic impact. Significant interactions between helmet shell material and both deformation volume and area were found ($p<0.05$), highlighting that as depth increases the geometric relationship also changes. Figure 2 visualizes the different relationships between UHMWPE and both aramid helmets. UHMWPE shells recruit material differently than aramid, leading to a qualitatively more pointed profile than aramid. Given the more pointed profile and variable recruitment of material, it is likely that the BHBT response assessed in a UHMWPE shell would be different than in an aramid shell for the same threshold standard. Suspension type did not significantly influence deformation geometry. Changes in deformation geometry were dominated almost exclusively by shell material instead of the suspension or helmet design.

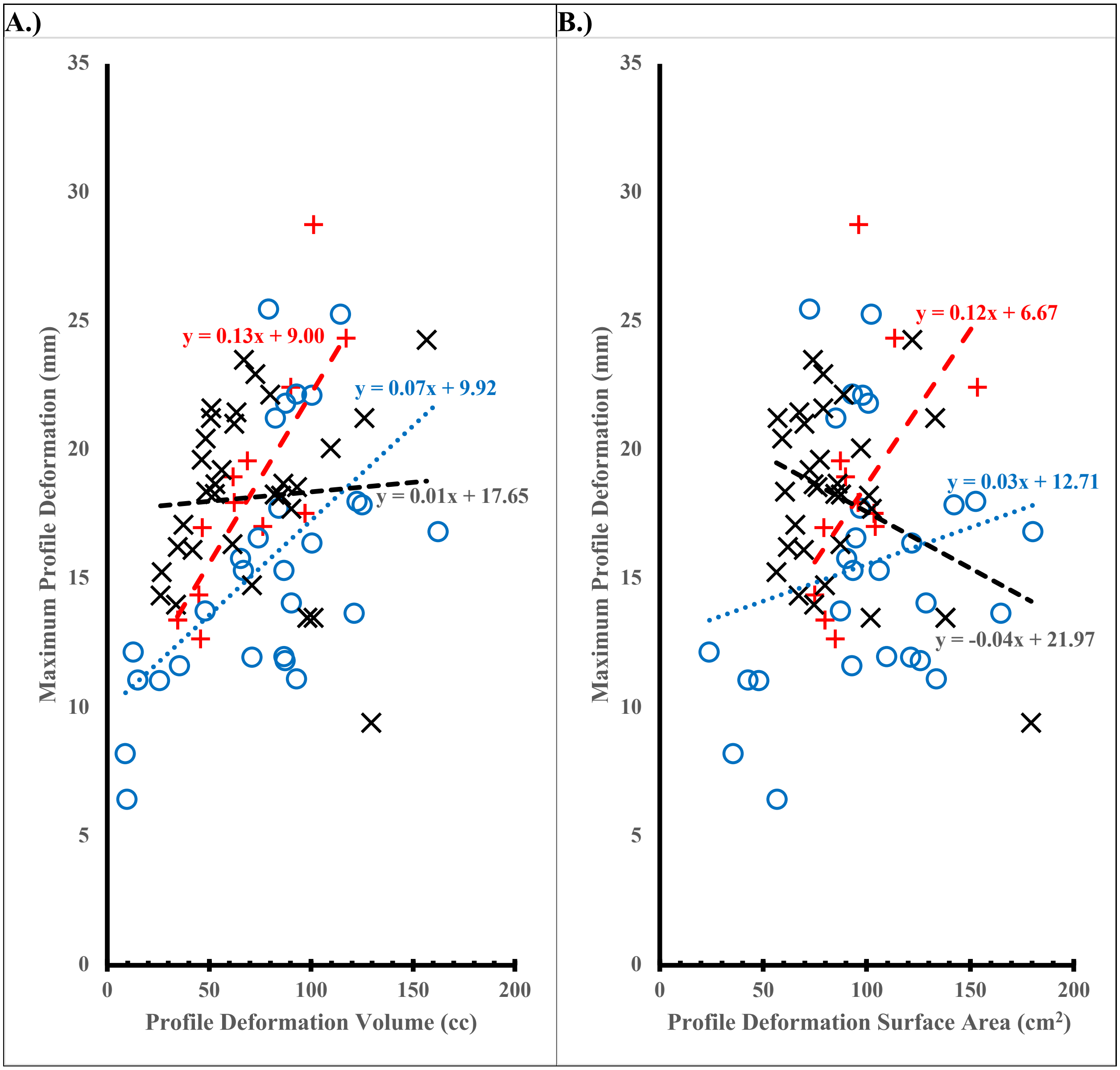

Figure 2: A) Deformation extent over Volume B) Deformation extent over Surface Area.
(O) Aramid 1, (+) Aramid 2, (X) UHMWPE.

DISCUSSION

These findings reinforce previous studies reporting increased deformation depths and qualitatively more pointed deformations in UHMWPE combat helmets. As volume has been correlated with the kinetic energy of the projectile, more energetic threats would likely result in deeper penetrations and more energy transfer to the skull. The advent of rifle-resistant UHMWPE helmets indicates an unprecedented context where highly energetic high velocity threats may be stopped by the material[12]. While less severe than a penetrating injury, risk of BHBT related skull fracture may influence user survivability[1]. To adequately inform and balance injury risk against helmet weight for future designs, a more comprehensive standard able to account for area recruited and encompassed by the capture of the threat projectile in conjunction with different durations and amplitudes of behind-helmet impact would aid futureproofing and augment validation efforts against further advances in helmet material and design.

A number of limitations are present in the current study. Several assumptions were made during digitization of x-ray profiles including the circularity of the deformations used to approximate deformation volume and surface area. The helmet surface struck is not flat and uniform. It is known that ballistic deformations in armor are often not uniform and directionally dependent, e.g. from oblique impacts or yaw of the projectile during travel through the layers of aramid or UHMWPE[17]. The two x-ray angular perspectives were also concatenated in this study. Future work may categorize and assess deformation geometry differences between angular perspectives to more realistically characterize the deformations seen in military helmets. A temporal impact also may not represent all impact cases, such as a frontal impact or apical impact. The modern modular padded suspension used also included the default 7-pad arrangement of helmet pads unlike the commonly custom-configured pad arrangement seen in actual use. Pads are often removed or modified for improved ventilation and reduced thermal burden in warmer climates, which may influence the characteristics of deformation under impact[18,19]. Though no significant differences were attributed to suspension differences in this study, it is unknown if pad removal incurs differences in deformation. Future work may investigate the effects of helmet pad modification or removal on deformation. Though geometry is reported in this study, future work may also quantitatively compare the shape factor or pointedness of deformation to better characterize differences between shell materials.

CONCLUSIONS

This study digitizes backface deformations of ballistic impacts on three different types of military combat helmets using different helmet shell material and suspension configurations. Comparisons are made between modern helmet shell material (UHMWPE) and suspension (foam pads) configurations relative to the older materials (Aramid) and configurations (webbing) the current NIJ 0106.01 (1981) helmet standard was proposed for using quantitative approximation of deformation depth, volume, and surface area. A multiple linear regression model for deformation depth prediction was used for these comparisons such that a significant main effect of helmet shell material was found and significant interactions of shell material and both volume and surface area were identified ($p<0.05$). Qualitatively smaller deformation surface areas were seen at high deformation depths and similar volumes were seen across all depths in UHMWPE. Differences in helmet suspension design were not related to any significant effects. These results indicate that differences between old and modern helmets may pose severe limitations for peak acceleration threshold and residual deformation depth-based standards currently used to evaluate BHBT risk. Future work may investigate including deformation geometry in helmet assessment.

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