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ANALYSIS OF COMBAT HELMET PERFORMANCE INTEGRATING BLAST LOADING AND BLUNT IMPACT THROUGH SIMULATION

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Abstract. *The mild traumatic brain injury (mTBI) is one of the most common injuries to service members in recent conflicts. Combat helmets have been designed and evaluated to perform against ballistic and blunt impact threats, but not blast threats. An optimal design of combat helmet considering blunt, ballistic impacts and blast effects is a key requirement to improve the head protection against mTBI. Combat helmets are usually designed based on costly and time consuming laboratory tests. Computational models can offer insights in understanding the force transmission through the head-helmet system into the brain and underlying mechanism of brain injury, and help the development of effective protective design. We developed a design approach integrating the effect of both blast and blunt threats to a helmet system by utilizing multi-physics computational tools and representative human head and helmet models. The high-fidelity computational models were used to capture the dynamic response of the composite shell, suspension pads, retention straps and head. Multiple helmet system configurations subjected to blast and blunt loadings with a combination of loading magnitude and orientation were considered to quantify their influence on brain biomechanical response. Parametric studies were carried out to assess energy absorption for different suspension geometry and material morphology for different loadings. The resulting brain responses in terms of pressure, stress, strain, and strain rate as well as the head acceleration were used with published injury criteria to characterize the helmet system performance through a single metric for each threat type. Approaches to combine single-threat metrics to allow aggregating performance against multiple threats were discussed.*

1 INTRODUCTION

Helmets have been part of the personal protection system for many centuries. Combat helmets have been designed considering the shell to protect against ballistic impact and the suspension to protect against blunt impact; however, none of the design requirements and/or criteria have considered performance against blast and thermal loading [1]. Researchers have been addressing separately the effects of blast, ballistic and blunt impacts, and thermal aspects for helmet systems. From the experiments we have conducted, it has become clear that these sometimes-disparate requirements are all coupled. Thus, a new integrated, multifunctional design approach is expected to lead to improved solutions. Integrating the multiple types of loadings into one design framework with suitable optimization methodologies will help to address the multiple threats into one composite threat and help design helmet systems accordingly.

Many researches have been conducted in the modeling of TBI with helmet protection. Among them, the computational approach have been used to explore how pad configuration affects protection and blast overpressure infiltration, pad materials affect energy absorbing characterization, and novel approach to ballistic impact threat mapping as a tool for helmet shape optimization [2-4]. The computational models have been used to capture the dynamic response of the composite shell, suspension pads, retention straps and human head. The nonlinear material models of brain tissue, bone, suspension pad and composite shell were used to capture the high strain rate and large deformation behavior.

In this work, we used a high-fidelity head model based on the human head anatomic geometry. We employed a coupled Eulerian-Lagrangian approach for the blast induced TBI simulation in which a 3-D high-fidelity CFD model was used to compute the blast explosion field and blast loading on the head and helmet. This allows us to simulate the blast pressure diffraction around the head and helmet and the helmet underwash effect on the brain response. We were exploring how helmet configurations influence brain biomechanical response when subjected to blast and blunt loadings to demonstrate a suitable optimization approach based on the quantitative metrics. Parametric studies described the energy absorption effect for different geometry (i.e., shape, size and placement of helmet pads) and material morphology (i.e., tuned pad material properties) by varying the loading magnitude and orientation. The resulting biomechanical responses of brain tissue pressures, shear stresses, strain rate and corresponding injury thresholds were used to characterize the performance of the helmet system. A single metric was derived for each threat type that distills data for a range of threat parameters (such as blast peak overpressure, impact kinetic energy) into an overall score against blast or blunt loading. Combining these single-threat metrics led to the metric quantifying the aggregate performance against a collection of threats. This lays the foundation for us to explore many other suspension designs through the simulation data to achieve the optimal helmet design accounting for all threats (blunt and ballistic impact, blast effects and thermal loading), which is a key need to the warfighter protection.

2 METHODS

The high-fidelity modeling approach and material models for blast and blunt impact analysis for two different pad suspension configurations are described here, which include the blast analysis and biomechanical modeling of human head with helmet.

2.1 Computational models of human head with helmet

Figure 1 shows the human head with helmet finite element model. The 3-D human head finite element (FE) model was generated from *in-vivo* magnetic resonance imaging (MRI) scans with 1 mm isotropic resolution of a young adult. The model consists of 29 material components including gray matter, white matter, ventricles, cerebrospinal fluid (CSF), skull, etc. Because of the complex geometry such as the gyrencephalic brain, a tetrahedral mesh was used for the discretization. The head model has approximately 4.5 million tetrahedral elements and approximately 220 thousand triangular elements to describe the head surface [5].

We have constructed the FE model of combat helmet that fits properly with the head (Figure 1a). A large-size combat helmet with pad suspension system and four-point retention strap was used. Hexahedral elements were used to discretize the helmet shell, pad suspension and retention strap and the total number of hexahedral elements is around 20 thousand.

The baseline suspension system consists of seven pads: two trapezoidal pads at the front and rear, four oblong pads placed on two sides of trapezoidal pads, and one cylindrical pad at the crown. Each pad has two layers along its thickness with the stiffer layer is next to the helmet and the softer layer close to the head. To improve the ventilation underneath the helmet and thus mitigate the thermal loading on the head in the hot and humid environment, a 5-pad suspension was also used in which two center pads at the front and rear are removed, as shown in Figure 1c. The meshes for the high-fidelity computational fluid dynamics (CFD) simulations of a human head with helmet for both 7-pad and 5-pad configurations were also constructed, as shown in Figure 1d. An octree mesh was used to discretize the air domain between the human head and helmet and the far-field air flow boundaries. The smaller cell size of 2mm near the head and helmet was used to resolve the curved geometry and the cell size gradually becomes larger away from the head and helmet. The total number of cells for each mesh is over 5 million.

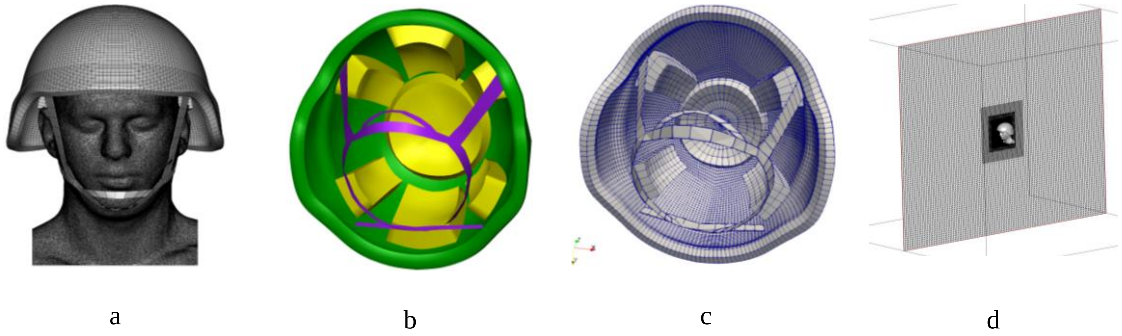

Figure 1: Model of human head with helmet: a) Mesh of FE model, b) helmet (in green) with 7-pad suspension (in yellow) and four-point retention straps (in purple), c) structured mesh for helmet, 5-pad suspension and retention straps, d) cross-sectional view of CFD model.

2.2 Modeling of head and helmet system

The multi-physics solver CoBi [6] was chosen for the simulation of head biomechanics subjected to blast loadings and impact conditions. The gray matter and white matter were modeled as hyper-viscoelastic materials. The CSF layer between the skull and brain and the ventricles inside the brain were modeled as the hyper-elastic solids with a very low shear modulus. The cortical and cancellous bones were modeled as elasto-plastic materials to account for the large permanent deformation at the impact region. The full set of material models and corresponding parameters can be found in [4]. Average nodal pressure (ANP) linear tetrahedral element formulation was used to remedy the parasitic locking problem associated with deformation of nearly incompressible materials, as in the case of soft tissues in blunt, blast and ballistic impacts. The human head model was validated against experimental tests of blunt impact to the head [7]. Recently we have simulated the head impact resulting from a reported pedestrian fall accident, in which the simulation results have been compared with the post-accident medical images of the young male patient's head for the injury correlation [8].

Since the composite material models considering the detailed layup and fiber orientation are computationally costly, simplified homogenized continuum models were often employed in the modeling of the helmet shell. A multi-layer orthotropic elasto-plastic material model was used for each helmet element. In the material model, the large deformation and damage of fiber-reinforced composites were considered by adopting the formulation and corresponding material constants that can be found in [4]. The suspension pad material was modeled using an experimental stress-strain curve-based foam model. The foam model features initial stiffness, a soft plateau region and progressively increasing stiffness at higher strains.

There are several interface conditions in the modeling of dynamic interaction between the helmet system and human head. Since there is no relative motion at the interface between the helmet and pads, the pad surfaces next to the helmet interior were connected to the helmet by the tied interface. Because of its small thickness and bending flexibility, the retention straps were modeled by using the elastic shell elements and connected with the helmet interior by shared nodes. The frictional contact condition was used to model the interactions between the head and pads next to the head, and between the retention straps and head exterior. The proper normal and tangential contact springs were chosen to approximately satisfy the sliding contact conditions between these contact pairs while not over-stiffening the whole numerical system.

2.3 Simulation-based helmet performance metrics

The conventional approach for computational analysis of helmet performance has been utilizing biomechanical measures, such as stresses, strains and pressures, in the head model. These provide a good comparative assessment of equipment performance, but it is difficult to combine responses from multiple modes of loading using such an approach. For blunt impact, we generally use the peak head acceleration to assess the injury probability, while for blast overpressure effects, we generally use pressure in the head and the extent to which the local pressure exceeds the given injury threshold value. For instance, the pressure-based TBI thresholds of 142 kPa and 173 kPa suggested in the reference [9] were used to assess the repetitive blast mTBI and single blast mild TBI (mTBI), respectively. Irrespective of the choice of the criterion we use, combining these into one will require creation of a physics based, non-dimensional parameter that can rank order the extent of each loading type. Here we used an overall performance score considering each threat and showed how they can be combined into a single metric.

We had used the fractional exposure to threat for overpressure loading and blunt impact as such measures [3]. The formal definition of a non-dimensional exposure of external loading was introduced in [4] and is being summarized here. For an externally loaded biomechanical simulation measure q, such as pressure or shear stress in an element e in the brain of the FE model, the exposure can be defined as E(q,e). The associated elemental volume is V(e). If the elemental value equals or exceeds a critical value, such as pressure, stress or strain, usually defined by an injury criteria, E becomes one. The value of E is zero if the pressure in the element does not exceed the injury threshold. Considering the whole brain, we can construct an exposure fraction, $EF(q,E_{tot})$, for the entire brain with E_{tot} elements as

$$EF(q, E_{tot}) = \frac{\sum_{e=1}^{E_{tot}} E(q,e) \times V(e)}{\sum_{e=1}^{E_{tot}} V(e)} \tag{1}$$

$EF(q,E_{tot})$ is therefore the sum of all measures exceeding a specified injury threshold, weighted for the volume of each element and normalized for the total brain volume.

The overall performance of a protective equipment design (or configuration), S, is a weighted combination of the performance metric for each individual loading. The performance metric for each loading type can be created based on its unique aspects and the non-dimensionality of the metric will allow integration with the metrics for the other loadings. The performance score for overpressure loading, S_{blast}, can be defined as a pressure exposure fraction PEF calculated from Eq. (1). The PEF is defined as the peak overpressure computed when the head subject is exposed to the overpressure from a blast while wearing a helmet, with respect to a baseline for the critical pressure exposure fraction, PEF_0 for a no-helmet peak overpressure. The score for blast loading can be calculated from the PEF as below

$$S_{blast} = (1- PEF / PEF_0) \times 100 \tag{2}$$

For blunt impact loading, the score is calculated based on the peak head acceleration A as below

$$S_{blunt} = (1-A/A_{cr}) \times 100 \tag{3}$$

where the critical head acceleration A_{cr} uses an appropriate acceleration threshold for head injury. The overall performance score by integrating effects due to multiple loading types, such as blast overpressure and blunt impact, can be represented as follows

$$S = S(S_i, w_i), \quad i=1, 2 \tag{4}$$

where S_i represents the performance score and w_i represents the weighting factor for loading type i, respectively. The exact function for integrating the effect of different loadings will have to be established through experimentation and considering the possible cross-coupling between the causes of the loadings. In our case, performance of a helmet system due to blunt impact and blast overpressure loadings do not appear to be mutually dependent. For example, the helmet wearer may be subjected to blunt impact when entering a vehicle or a building even without any overpressure loading. If the weighting factors are approximately equal, the equation for the performance score S in (4) becomes

$$S = (S_{blast} + S_{blunt})/2 \tag{5}$$

As we better understand the interdependence of loading types on performance of the helmet system, and learn how the performance varies with respect to loading conditions, and other external factors, such as usage factor, we can adjust these weighting factors.

3 RESULTS

The head without helmet and with helmet of two pad configurations subjected to blast loading and blunt impact were simulated. In our computational models, frontal, side and rear loadings were considered, although blast and blunt threats in the combat theater can be from any orientation. The simulation results were used for the helmet performance analysis integrating blunt impact and blast loading.

3.1 Head with helmet subjected to blast loading

The blast pressure loading on the head with and without helmet from a free-field explosion in air was simulated utilizing high-fidelity CFD analysis. A bare spherical high explosive TNT charge was detonated at 1.5 m from the head surface at the forehead level on the transverse plane of the head. The peak incident overpressure near the head location was 15.0 psi (103.4 kPa). The propagation of the shock front from the explosion to the head with the helmet (the target) was represented as a one-dimensional (1-D) simulation considering the symmetry around the explosive (i.e., without considering the effect of ground bounce). The details of the 1-D spherical model using the Jones-Wilkins-Lee (JWL) equation of state simulated the initial explosion stage before the shock front reached the head were described in [6]. Subsequently, the 1-D solution, including pressure, velocity and temperature fields, was used as the initial condition at 1.8 milliseconds to carry out a full three-dimensional (3-D) simulation of the shock front loading on the target.

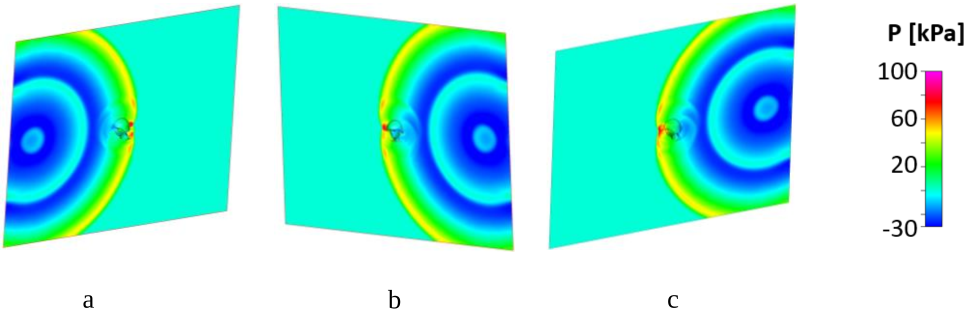

Figure 2: Selected snapshots of blast simulation of explosion on head and helmet at 1 ms for a) frontal blast, b) blast from left side, c) rear blast.

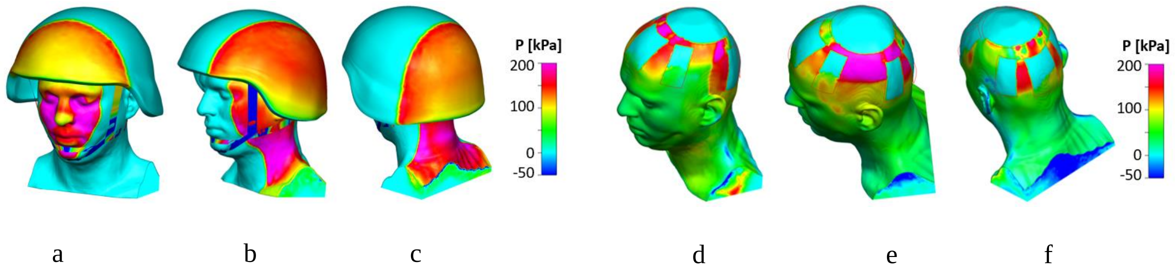

Figure 3: Selected snapshots of overpressure on head and helmet with 7-pad configuration at 0.2 ms for a) frontal, b) left side, and c) rear blasts. Selected snapshots of overpressure on head underneath helmet with 7-pad suspension system at 0.6 ms for a) frontal blast, b) blast from left side, and c) rear blast.

The overpressure fields at the middle planes at 1 millisecond from 3-D CFD simulations of frontal, side and rear blasts are shown in Figure 2. The shock wave reflection at the near end of the head and the wave confluence by the diffraction at the far end of the head are clearly seen. Figure 3a-c shows the pressure loading on the head and helmet with the 7-pad configuration at 0.2 milliseconds for three orientations. The pressures at the face for the frontal blast and the neck for the side and rear blasts are high than the one on the helmet surface because of their local concave curvature. The pressure underneath the helmet with 7-pad suspension system at 0.6 milliseconds is shown in Figure 3d-f. The high pressure builds up between the pads, especially for the case of side blast. The overpressure on the head and helmet in the 5-pad configuration is similar to the 7-pad one shown in Figure 3 and thus are not shown here.

Figure 4 shows the pressure at middle planes of the head and helmet with the 7-pad configuration at 0.6 milliseconds for three blast orientations. The blast loads transmit from helmet, pads, and head surface into the skull and brain. The pressure wave forms coup and contrecoup patterns in the brain. The maximum and minimum pressures in the brain for the three blast directions are shown in Figure 5 and 6, respectively. When the head has a 7-pad suspension system, there are fewer regions of extreme pressures in the brain than those with a 5-pad suspension system. Such difference can be related to the removal of frontal and rear pads in the 5-pad configuration, in which the larger uncovered head surface allows greater blast overpressure infiltration to load the head and the brain.

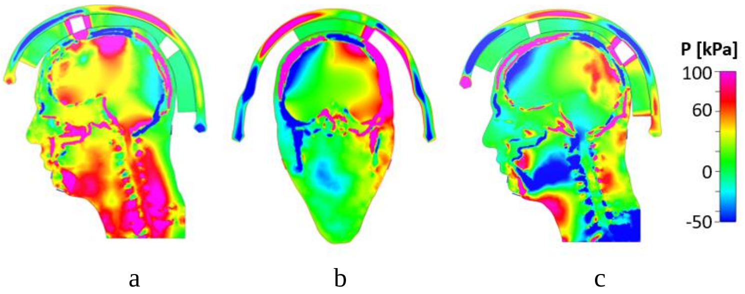

Figure 4: Selected snapshots of pressure at middle plane with 7-pad suspension system at 0.6 ms for a) frontal blast, b) blast from left side, and c) rear blast.

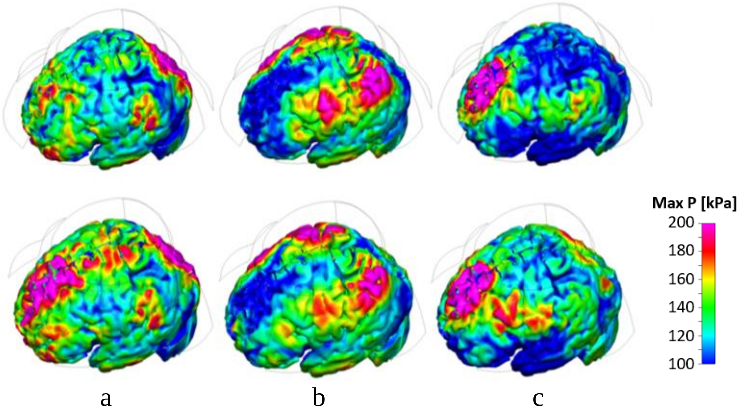

Figure 5: Selected snapshots of maximum pressure on brain for a) frontal blast, b) blast from left side, and c) rear blast. Top row shows for 7-pad suspension in helmet and bottom row shows for 5-pad suspension in helmet.

Both strain and strain rate in the brain due to the blast loadings are very small. The maximum strain rates in the brain for the 7-pad configuration, and are mostly below the 50 s^{-1}. Similar results of low-level of strain and strain rate were obtained for the 5-pad configuration and thus not shown here. Table 1 shows the pressure exposure fraction using Eq. (1) for the head without helmet and head with helmet when the pressure injury threshold of 142 kPa was used. The helmet with 7-pad configuration gives the lowest PEF while the head without helmet has the highest PEF.

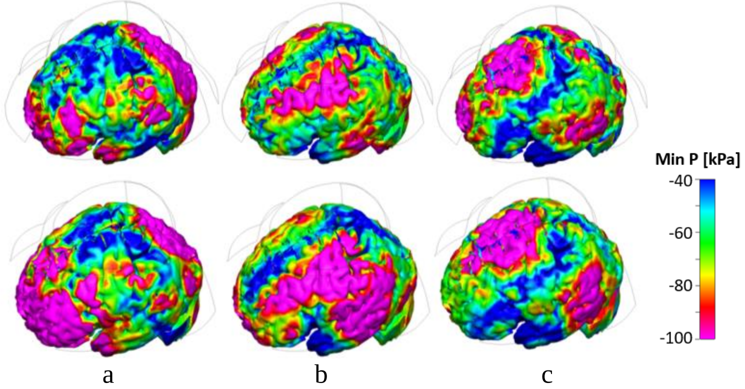

Figure 6: Selected snapshots of minimum pressure on brain for a) frontal blast, b) blast from left side, and c) rear blast. Top row shows for 7-pad suspension in helmet and bottom row shows for 5-pad suspension in helmet.

Table 1: Pressure exposure fraction (%) for all cases with blast loads.

Pad configuration	Frontal	Side	Rear	Mean
No helmet	12.2	31.6	27.9	23.9
7-Pad	4.1	6.2	2.5	4.3
5-Pad	7.7	5.4	3.1	5.4

3.2 Head with helmet subjected to blunt impact

In the analysis of blunt impact of the head with helmet, we compare the helmet performance between 7-pad and 5-pad configurations. Given that 5-pad configuration with frontal and rear energy-absorbing pads removed provides less protection, it is important to check if there is a concerning reduction in the protection capability against the frontal, side and rear impacts with the 5-pad configuration.

In the simulations, it is assumed that before hitting the ground the head is rotating around the first thoracic vertebra (T1). The distance between T1 and the center of mass of the head is approximately 0.2 m. Following the helmet drop test standard, the initial angular velocity ω of head around T1 is set to be 20 rad/s and the resulting head velocity is about 4 m/s (~ 13 ft/s). To account for the uneven ground, we assume that the head hits a rigid hemisphere object with radius of 2 cm on the ground, as shown in Figure 7a for the side impact.

Figure 7b shows the corresponding deformation of head and helmet system at 5 milliseconds. During the side impact, the head was moving towards the right side of helmet shell and sliding on the pad surfaces, as shown in Figure 8a. The maximum and minimum pressures experienced in the brain are shown in Figure 8b and 8c, respectively. Again, the coup-contrecoup pattern can be seen where the maximum pressure occurs in the brain near the impact site and the minimum pressure at the opposite side. The magnitudes of maximum strain rate shown in Figure 8d and maximum shear stress in Figure 8e are small. In contrast, the maximum effective strain in Figure 8f shows the high values on part of the brain. The corresponding contours of pressure, strain rate, shear stress and effective strain for the 5-pad configuration are similar and not shown here. Table 2 shows the head peak accelerations for both pad configurations at three impact orientations. Overall the 5-pad configuration produces to a smaller peak acceleration compared to the 7-pad one for the aforementioned impact conditions.

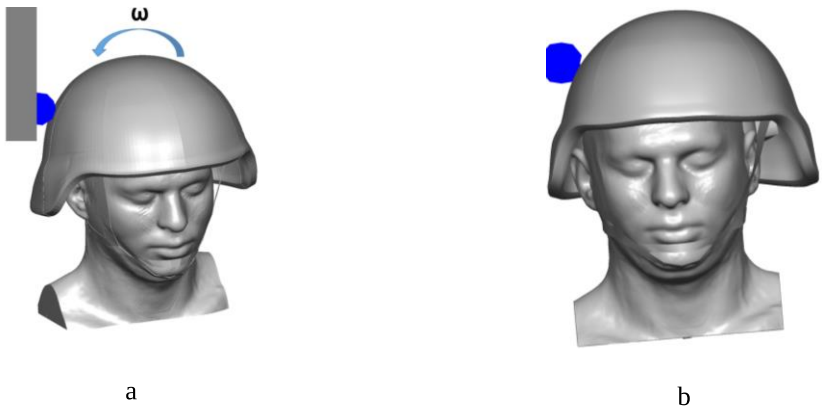

Figure 7: FE analysis of head with helmet. a) hitting a hemisphere object of radius of 2 cm on the ground with initial angular velocity of 20 rad/s around t1, b) deformation of head and helmet at 5 ms.

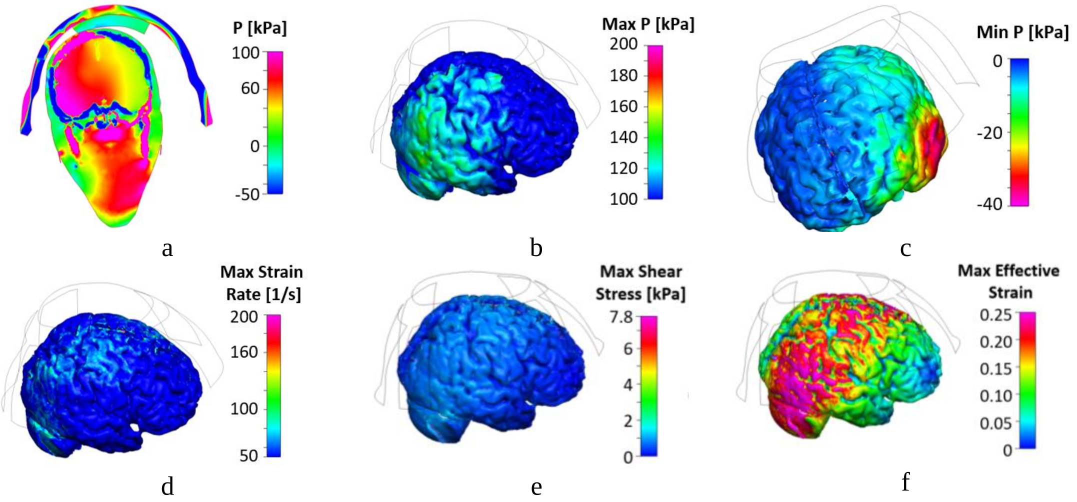

Figure 8: a) Pressure at coronal plane through impact site, b) maximum pressure on the brain, c) minimum pressure on the brain, d) maximum strain rate, e) maximum shear stress, f) maximum effective strain on the brain for helmet with 7-pad suspension system subjected to the side impact.

Table 2: Head peak acceleration (g) for all cases with blunt impacts.

Pad configuration	Frontal	Side	Rear	Mean
7-Pad	37	67	124	76
5-Pad	28	70	61	53

3.3 Integration of overpressure, blunt impact for helmet system

As described in the previous section, as a first order approximation, we used the weighted scoring method to evaluate the helmet performance of different pad configurations with respect to multiple threats. Table 3 shows the scores from individual threat and the overall scores of 5-pad and 7-pad configurations – S_{blast} in Eq. (2) was calculated with respect to the 142 kPa peak pressure-based brain injury criterion, compared to the no-helmet case in Table 1, S_{blunt} in Eq. (3) was calculated with respect to the 150 g average peak acceleration of the helmet, using the results of Table 2. For the calculation of the overall score, the weighting factor for each threat was set to be the same. The overall score shows that the 7-pad configuration on the helmet provides an overall lower score than the 5-pad configuration using Eq. (5).

Table 3: Overall helmet performance score calculation.

Pad configuration	S_{blast}	S_{blunt}	Helmet Performance Score, S
7-Pad	82.0	49.3	65.7
5-Pad	77.4	64.7	71.1

4 DISCUSSIONS

The performance scores in Table 3 above represent each of these loadings, with the premise that the higher the score, the better the performance of the helmet. Several factors can influence the individual loading performance scores as well as the overall performance of a helmet system as discussed below.

For the blast loading performance, the helmet system with 7-pad suspension provides better performance for blast overpressure loading, compared with the 5-pad system. This can be explained by considering the infiltration of pressure in the underwash (the gap between the inside surface of the helmet shell and the skull surface) as a result of the shock front being partially blocked by the 7 pads. The lower underwash pressure reduces the loading on the head and thus reduces the intracranial pressure. The 5-pad helmet provides more spacing between the pads and thus allows higher underwash pressures, resulting in a higher pressure in the brain, thus providing reduced protection. Thus, morphology of the pads and their arrangement may influence the overpressure peak pressure and pressure time history in the underwash, and thus determine the protection from this threat offered by a helmet system. Notably, most helmets are not designed for the blast protection, consideration of a more distributed helmet pad system may provide improved performance for blast overpressure loading.

For the blunt impact loading performance, the two pad suspensions suggested notionally that overall the 7-pad configuration works worse considering all likely positions considered. A main contributor of this difference in performance score is due to the higher head acceleration of the 7-pad system from rear impact. This difference with the 5-pad suspension could be due to design of the helmet shell, with the larger mass at the back, as well as perhaps a tighter coupling between the head and the helmet for the rear impact. The other impact directions do not show such a big difference in the head acceleration between the two suspension designs. At the same time, the presence of the extra pad in the front (Figure 1b) may explain the slightly higher acceleration of the 7-pad suspension for the frontal impact. The absence of the pads seems to confirm this hypothesis by both suspension designs producing almost the same head acceleration for a side impact. Again, the impact performance of the helmet system can be refined by considering both an on-pad and off-pad locations on the front, sides and rear to get a better resolution of the role of impact location on the overall performance score.

Based on the overall performance score for helmet suspension designs, the 5-pad design performs better than the 7-pad design. The use of equal weightage for two loading types, has benefited the 5-pad design from a slightly higher blunt impact performance score. However, if the blast overpressure is the more likely scenario, the weightage between these two may need to be reallocated, resulting in a different design decision.

Another key parameter has been the shape and materials used for the pad suspension. In the case of the blast overpressure, the shape and distribution of the foam pads and their materials will determine if/how the pads can block the shock front and reduce the peak pressure through the skull. Likewise, the pad materials, shapes and their distribution will alter the overall dynamics of the helmet shell and its deformation pattern in both the blunt impact and ballistic impact. For blunt impact loading, more simulations will need to be carried out at different locations on the helmet and with different obliquities to create a composite performance score for blunt impact. The overall problem for design of helmets will therefore become a trade space problem with multiple variables.

5 CONCLUSION

Integrating the blast loading and the blunt impact into a design framework to facilitate a trade space analysis for helmet design has been presented. The high-fidelity modeling approach was used to analyze the helmet performance in both the blast loads and blunt impact. Biomechanical parameters such as pressure, shear stress, effective strain and strain rate as well as the head acceleration were considered to relate the helmet protection performance with the mild traumatic brain injury assessment. Both loadings were used for multiple configurations of notional helmet suspension systems as representative cases. The results from the simulations were integrated in a framework to assess helmet system design for multiple loading conditions. The results from this case study were analyzed, and techniques for extending these concepts to designing helmet system for multiple threats were discussed. Future work will include the consideration of more parametric simulations in a wider range of field conditions and the identification of optimal helmet design based on of its overall performance score.

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