Application of a Test Methodology for Assessing Mandibular Protection System Performance in Mitigating BABT and Blunt Impact: Initial Results and Way Forward

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Abstract

Military helmets are evolving to improve protection and coverage against ever changing threats including behind armour blunt trauma, blunt impact trauma, and blast effects. Providing additional coverage is not only a challenge for design but also for performance assessment as there are few, if any, applicable test methodologies available for development or product acceptance testing. One significant gap is in the area of maxillofacial protection, specifically the assessment of mandibular guards for behind armour blunt impact (BABT) and blunt force impact performance. A screening of the few available surrogate headforms capable of measuring transmitted loads to the face/jaw led to the adoption of the Mandible Load Sensing Headform (MLSH) as a basis for the development of a test standard. The MLSH is based on a modified 50th percentile male Hybrid III headform with an articulated jaw instrumented with triaxial load cells at the left and right condyles and in the upper dentition. A peak resultant jaw load injury criteria has been adopted based on the few published data sets for mandible fracture tolerance levels of post mortem human subject. Mandible guard prototypes from Defence R&D Canada's Advanced Modular Multi-threat Protective Headwear System Technology Demonstration Program (AMMPHS TDP) were used to assess the MLSH based test methodology for non-penetrating impacts by 96 grain steel spheres and blunt impact testing using the ASTM F1446-04 triangular hazard anvil. Drops were also performed with the unprotected headform to establish baselines for the headform response. High-speed video of the drop tower tests showed significant neck extension and rotation. This led to the introduction of a standard Hybrid III headform and instrumented neck (the neck load cell is not compatible with the MLSH headform) to assess neck injury risk as part of the evolving test methodology. Results of the testing have prompted the development of a localized load sensing system to capture focal loading on the jaw in parallel with the resultant loading already measured.

1 INTRODUCTION

Military helmets are evolving to improve protection and coverage against ever changing threats including behind armour blunt trauma, blunt impact trauma, and blast effects. Providing additional coverage is not only a challenge for design due to compromises between human factors requirements and desired coverage and protection but also for performance assessment as there are few, if any, applicable test methodologies available for development or product acceptance testing. One significant gap is in the area of maxillofacial protection, specifically the assessment of mandibular guards for behind armour blunt trauma (BABT) and blunt force impact performance.

Under the Advanced Modular Multi-threat Protective Headwear System technology demonstration project (AMMPHS TDP), Defence R&D Canada explored the feasibility of technologies required for providing scalable ballistic, impact, and blast protection for the head, face, and neck. One of the protective modules of the helmet concept that was developed, built, and tested was a mandible guard which provides protection for the lower face against fragmentation and blunt impact. The design of the guard required the development of an appropriate test methodology which would be able to support the trade-offs being explored in material selection, stand-off, geometry (coverage), human factors requirements, attachment system functionality, etc. by providing an injury-based metric for assessing protection performance.

A screening of the few available surrogate headforms capable of measuring transmitted loads to the face/jaw, reported at PASS 2010 [1], led to the adoption of the Mandible Load Sensing Headform (MLSH) as a basis for the development of the test standard. The results presented here are from a study which explored the headform response to BABT resulting from non-penetrating fragment impacts and low velocity blunt impacts with rigid indentors on a mandible guard. While the focus was on the risk of mandible fracture, some of the test results showed that assessment of mandible guard performance should also include measurement of neck loading. Thus, some of the test conditions were repeated using a standard Hybrid III headform and an instrumented neck because the MLSH is not compatible with the standard neck load cell.

2 MANDIBLE LOAD SENSING HEADFORM

The MLSH (shown in Figure 1) was originally developed by Biokinetics and Associates Limited for the National Football League for the dynamic assessment of mouth guards in the football environment as they relate to brain injury. The headform is based on the 50 percentile Hybrid III crash test dummy head with the lower portion of the skull removed and replaced with an articulating and force-sensing mandible and mechanical teeth. The force transmission through the upper dentition and the left and right temporo-mandibular joints (TMJ) is measured using 3 triaxial load cells. Its biofidelity for low velocity blunt impact has been verified in a series of chin impact experiments with post mortem human subjects [2]. The headform also incorporates three linear accelerometers at the headform centre of gravity (CG) allowing head acceleration-based injury criteria to be assessed at the same time as the risk of jaw fracture. In a typical test configuration, the headform is mounted on the Hybrid III neck assembly however the configuration of the instrumentation for the condyle load cells does not allow the neck load cells to be installed at the same time.

Figure 1. Articulating mandible headform.

The proposed injury criteria are presented in Table 1 below. Resultant jaw forces greater than that shown indicate mandible fracture. It is worth noting that additional work is required in this area to support the selection of appropriate injury criteria, particularly for high rate impacts such as BABT.

Table 1. Proposed mandible fracture tolerance for the articulated mandible headform.

Loading Type	Loading Direction	
	Fore-aft	Lateral
Focal	3916 N	2436 N
Distributed	3916 N	2436 N

3 EXPERIMENTAL STUDY

The first experimental study that explored the use of the MLSH in testing mandibular guards was based on measurements of transmitted force (BABT) and induced head acceleration from non-penetrating ballistic impacts of large fragments and drop tower blunt impacts on a prototype mandible guard.

High-speed video from the low velocity blunt impact tests showed significant neck extension and rotation in many of the impacts. This observation led to a second round of testing and the introduction of a standard Hybrid III headform with the Denton 6 axis neck load cell (Model Number 1716A) to the test methodology. The standard Hybrid III headform included the nine accelerometer package (NAP) allowing rotation acceleration based injury criteria to be evaluated as well. High-speed video, sampling at a rate of 1000 frames per second (fps), recorded each impact event.

3.1 Injury Assessment

Assessments of injury risk using the fracture tolerances in Table 1 were based on the peak resultant jaw loads calculated by first summing the orthogonal fore-aft (X direction), lateral (Y direction) and vertical loads (Z direction) from the left and right condyle load cells and the upper dentition load cell of the MLSH. The resultant load was then obtained by computing the square root of the sum of the squares of these orthogonal loads as indicated in Equation 1.

$$\text{Resultant Jaw Force} = \sqrt{(Force_x)^2 + (Force_y)^2 + (Force_z)^2} \quad (1)$$

where:

$Force_x$ = (left condyle $Force_X$) + (right condyle $Force_X$) + (upper dentition $Force_X$)
$Force_y$ = (left condyle $Force_y$) + (right condyle $Force_y$) + (upper dentition $Force_y$)
$Force_z$ = (left condyle $Force_z$) + (right condyle $Force_z$) + (upper dentition $Force_z$)

The NIJ criteria [3] was use to predict the risk of neck injury based on the forces and shear loads measured with the instrumented neck. Head CG linear acceleration histories were collected for tests using both the MLSH and standard Hybrid III headform. Peak resultant head acceleration, Severity Index (SI) [4], and Head Injury Criterion 15ms (HIC_{15}) [5] were assessed for each impact. Head Impact Power (HIP) [6] was calculated for tests using the NAP in the standard Hybrid III headform

3.2 Mandible guard design

The mandible guard prototype used in the testing presented here was one of 16 geometries/configurations that were explored in the AMMPHS TDP, an indication of the complexity in achieving a functional design that is acceptable to the soldier for the roles for which it is intended. Weapon butt stock compatibility and ability to obtain a repeatable sight picture, stand-off from the face for BABT mitigation and comfort, field of view, range of motion, weight, compatibility with hydration systems, and communications (voice as well as headset/microphone compatibility) are but a few of the constraints on the design that must be balanced.

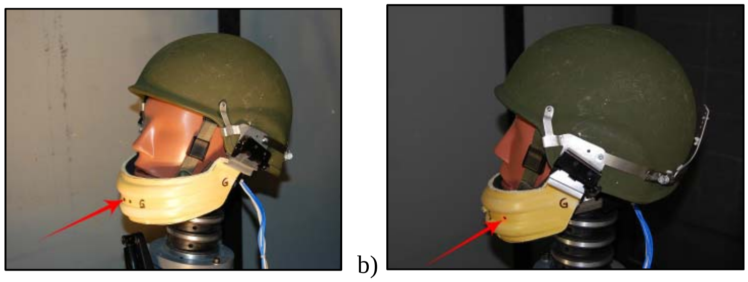
The prototype is a hot pressed woven aramid thermoplastic laminate. The prototype uses a higher matrix content than is typically used in ballistic laminates in order to increase the structural properties to provide resistance to blunt impact, one of the threats the guard is designed to mitigate, and to provide overall durability as the U-shaped geometry of a mandible guard is prone to crushing (e.g. when stowed). Two ribs, running almost the full width of the guard, were also introduced in this design to provide additional bending stiffness with minimal additional weight.

For the purposes of the initial tests on the mandible guards, they were rigidly fixed to a standard combat helmet using a machined aluminum adapter plate bonded and bolted to the ends of the mandible guard and attached to the helmet using three machine screws on either side.

3.3 Ballistic Testing Configuration

Ballistic testing using the articulated mandible headform focused on assessing the risk of BABT for non-penetrating impacts of large fragments, in this case the 96 grain steel sphere (11.5 mm dia. Salem Specialty Ball, Material C/S, grade 25), were launched using a smooth bore barrel chambered for a .460 Weatherby Magnum cartridge. The target striking velocity for these tests was 280 m/s.

Three impact locations were selected: centred on the chin, offset 45° to the left of the chin (approximately over the chin strap buckle), and offset 45° to the right of the chin (flattest portion of the guard). In most cases, the impact was centred between the upper and lower ribs although a limited number of tests were performed directly on the rib. The headform was oriented such that the shot line was normal to the strike face of the mandible at the desired impact location. Each mandible guard was struck once at each of the three impact locations. Previous tests had shown that the guards were sufficiently durable to take up to five impacts, spread across the surface of the guard, without a significant loss in structural integrity.



a) b)

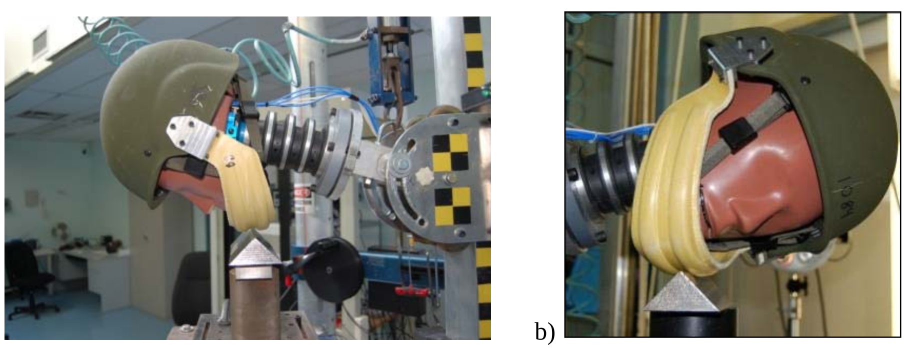
Figure 2. Behind armour blunt trauma test set-ups; a) strike to the chin; b) strike to the mandible body.

A 1 cm minimum offset was enforced between the inner face of the guard and the skin of the mannequin. All the mandible guards in these tests were lined with 3.2 mm (1/8 inch) VN 740 Vinyl Nitrile foam to replicate a possible end use configuration where foam would be used for comfort and to aid in impact attenuation. Once the helmet liner was adjusted appropriately for the shape and size of the headform size, the angle of the helmet on the head was set by fixing the distance between the front lower rim of the helmet and the tip of the nose of the headform. The helmet straps were then cinched and the offset of the mandible guard from the chin verified.

The individual load cell and accelerometer histories were sampled at a rate of 50 kHz. The load cell data was filtered using a 4 pole Butterworth Filter meeting the SAE J211 CFC 600 filter specification while the acceleration data was filtered using a CFC 1000 filter.

3.4 Impact Testing Configuration

The blunt impact testing was based on the same three orientations used in the ballistic testing. The headform and neck were installed on the monorail drop carriage of an impact tower (see Figure 3a) such that the angle of impact was normal (90°) to the surface of the mandible guard. The neck was angled upwards by 18° from the horizontal to achieve this. Side impacts were performed with the headform rotated 45° about the axis of the neck, as shown in Figure 3b. The same procedure described above for the ballistic testing was used to position the helmet and mandible guard on the headform.



a) b)

Figure 3. Setup for the blunt impact tests; a) frontal and b) oblique impact.

The ASTM F1446-04 triangular hazard anvil, shown in Figure 3, was adopted for the impact geometry. Aside from significantly challenging the performance of the mandible guard, the geometry was thought to be representative of potential threats that may be encountered, in particular for vehicle occupants (e.g. hatch rings, episcopes, etc.). The anvil was oriented such that the edge was parallel with the width of the mandible, striking between the two ribs of the guard for each impact location. Impact energies were between 10 J and 50 J.

The load cell and accelerometer histories were sampled at a rate of 10 kHz. The load cell data was filtered using a 4 pole Butterworth Filter meeting the SAE J211 CFC 600 filter specification while the acceleration data was filtered using a CFC 1000 filter.

4 RESULTS AND DISCUSSION

4.1 Blunt Impact

An example of the force histories collected from the three MLSH mandible tri-axial load cells, in this case for a 30J impact to the right side of a mandible guard, is shown below in Figure 4.

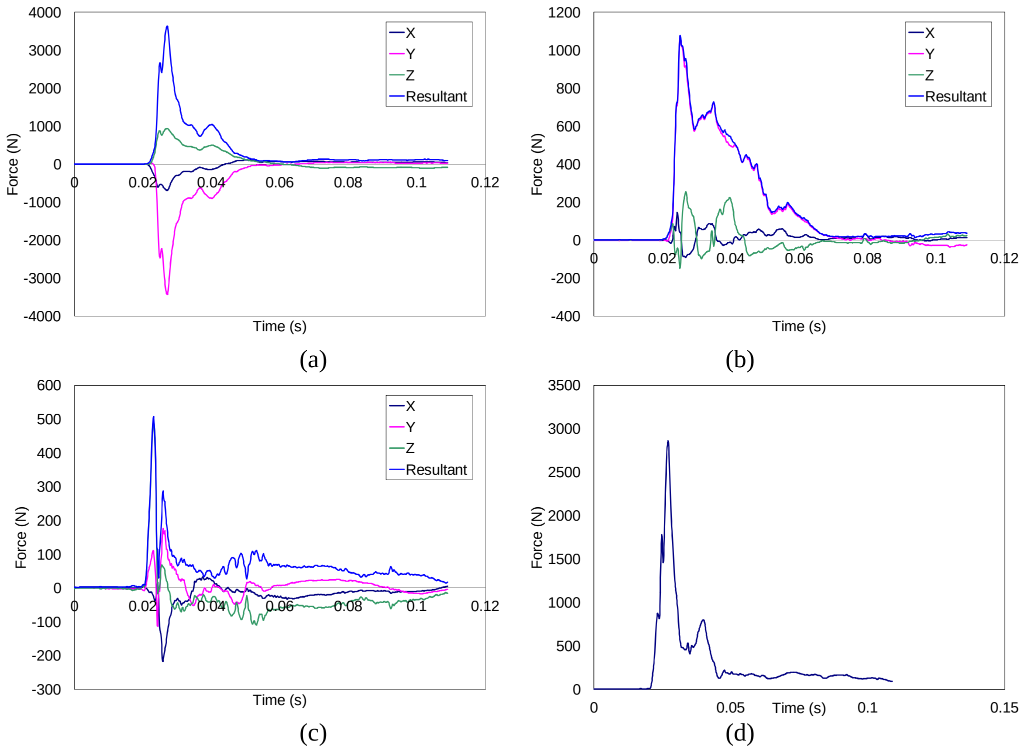


Figure 4. Example of force histories for an impact on the right side of a mandible guard: (a) left condyle, (b) right condyle, (c) upper dentition, and (d) the resultant force on the MLSH mandible.

Peak resultant forces in the MLSH mandible are shown in Figure 5 for chin impacts and Figure 6 for impacts to the side of the headform. The trends for unprotected impacts predict loading that exceeds the tolerance values for approx. 35 J frontal impacts and 45 J oblique impacts. Interestingly the results for the protected cases show little difference in transmitted loading versus the unprotected cases, albeit with a fair bit of scatter in the results, and therefore little difference in predicted injury outcome. This is somewhat contrary to what might be expected given the highly localized loading from the edge of the triangular anvil and highlights that the measurement of the global reaction of the mandible is not sufficient on its own to properly assess the protection provided by a mandible guard. It is not that the injury risk predicted for the protected case is incorrect (at least in as much as the tolerance values are valid), but rather that the injury risk from highly focal loading in the unprotected cases is not captured by the MLSH used in this testing.

Of note is one of the protected data points for the chin impact where the retention buckle of the helmet chin strap failed. This appears (albeit there is only one data point) to result in a marked increase in transmitted force which may be due to increased rotation of the helmet on the head.

Also shown on the two graphs are results for mandible guards with a thin foam liner fixed to the inner surface of the guard. The foam was inserted in the first tests that were performed on this particular mandible guard with the expectation that it would provide at least a minimal level of additional energy absorption. The measured resultant forces in the MLSH mandible are consistently higher than those measured for mandible guards with no foam. These results would imply that the foam actually amplified the loading to the jaw. It is thought that this increased loading is due to increased coupling (friction) between the mandible guard and the face of the headform. The load histories measured at the condyles showed increased forces that would be consistent with this hypothesis.

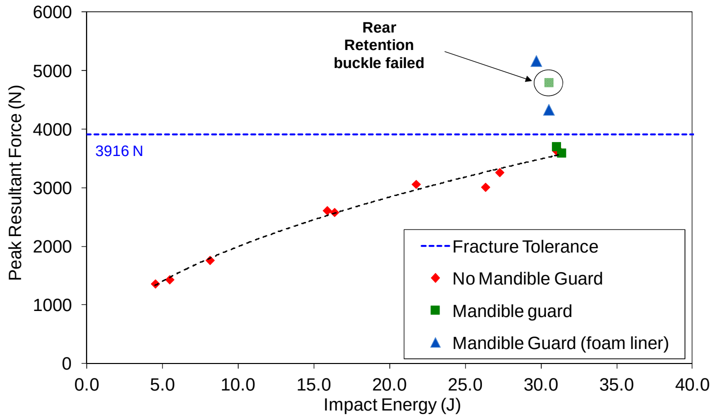


Figure 5. Peak resultant force for protected and unprotected impacts to the chin.

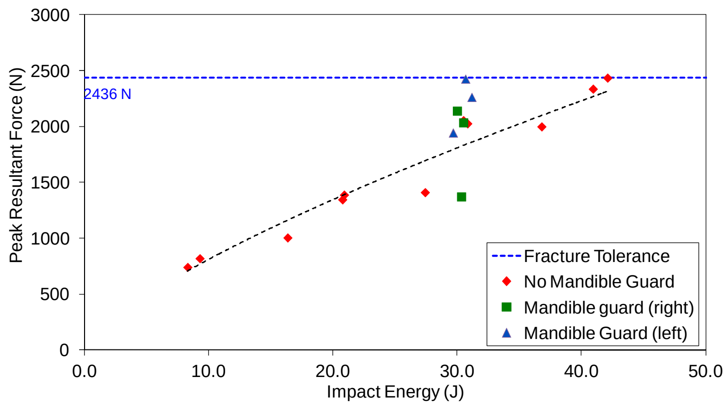


Figure 6. Peak resultant force for protected and unprotected impacts to the side of the jaw.

Selected frames from high-speed imagery of unprotected and protected impacts to the chin of the MLSH are shown below in Figure 7 and Figure 8, respectively.

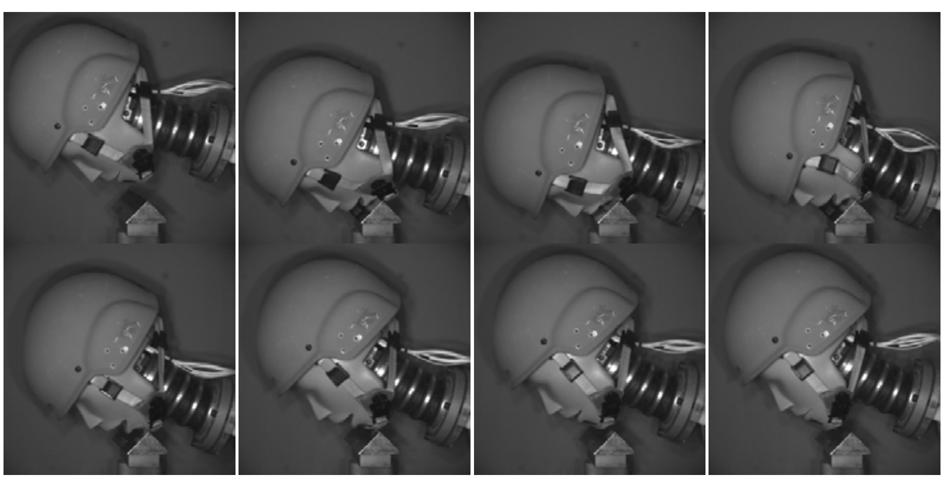


Figure 7. High-speed imaging of a 30 J blunt impact on the chin of the unprotected MLSH head.

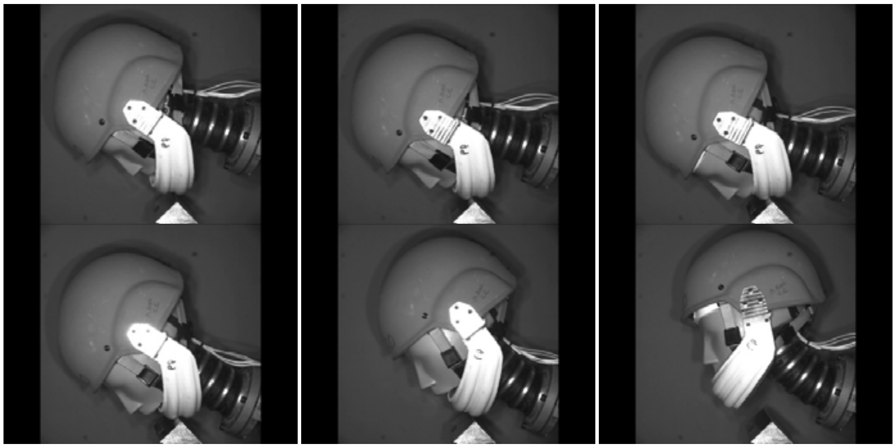


Figure 8. High-speed imaging of a 30 J blunt impact on the chin of the mandible guard.

It is interesting to note the difference in the late time response of the headform and neck. The protected impacts show significant extension of the neck compared to the unprotected impacts. This is thought to be related to the geometry of the mandible guard used in these tests. The ribs on the guard catch the edge of the indentor during the impact, constraining the movement of the mandible guard, helmet, and therefore the head. When the head begins to rebound from the impact, the rib disengages from the anvil and the rebound is accentuated by the unloading of the neck. Interestingly no difference in injury risk is predicted based on the Nij criteria for protected or unprotected impacts to the chin up to 26 J (Figure 11 below). Above that energy level, there is a sharp increase in injury risk for the unprotected case. The mandible guard continues to provide protection up to 50 J. Note that the more significant effect of the ribs is the prevention of an edged contact surface sliding up or down the guard potentially impacting the face or neck directly.

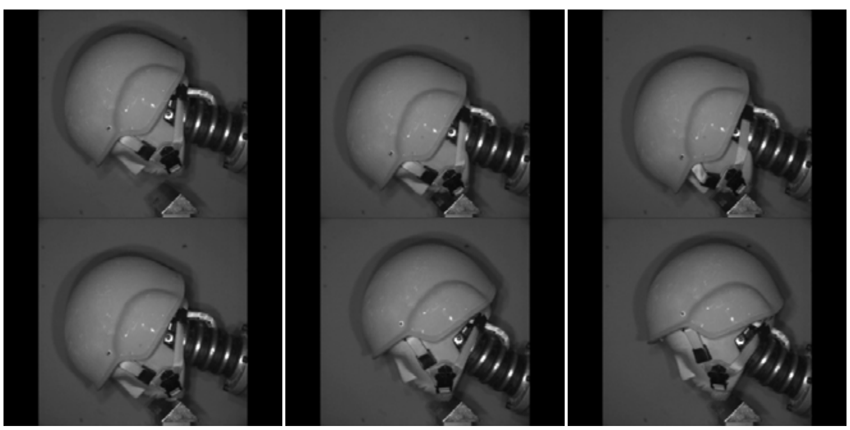


Figure 9. High-speed imaging of a 30 J blunt impact on the chin of the unprotected Hybrid III head.

Figure 9 shows the response of the bare Hybrid III headform for comparison with that of the MLSH in Figure 7. Apart from the local deformation associated with the articulated jaw of the MLSH, the dynamic response of the headforms and flexion/extension of the necks appears to be very similar.

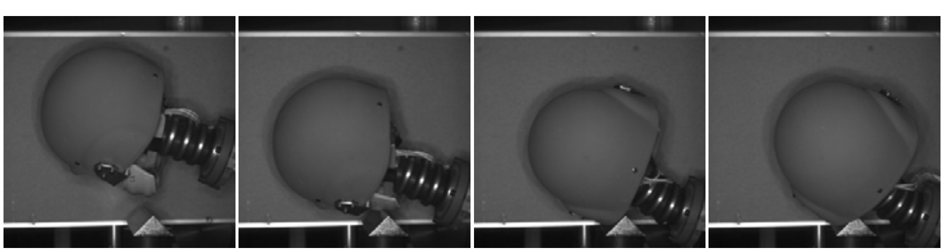


Figure 10. Example of torsional loading on the neck from a 30 J oblique impact to the mandible guard.

Figure 10 shows the equivalent headform and neck response for an oblique impact. In this case, the mandible guard slides along the anvil, rotating the headform about its axis. The presence of the mandible guard results in an increase in injury risk across the impact energies tested (Figure 11) but the neck loading is less than for the chin impacts, and even at 50 J a low risk of neck injury is predicted.

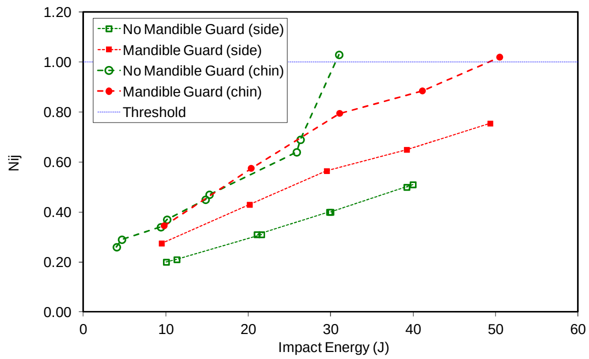
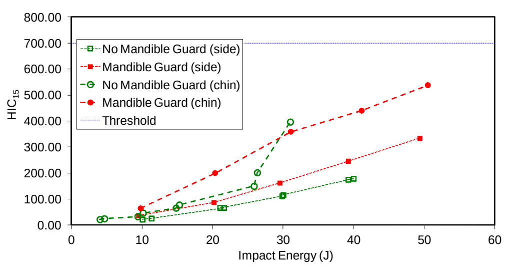
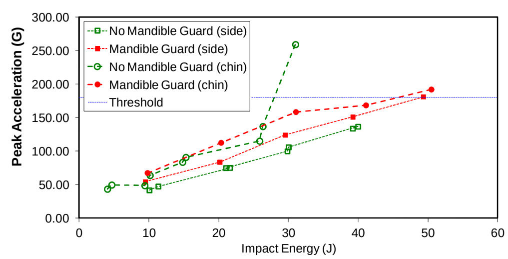


Figure 11. Neck injury risk as a function of impact load for protected and unprotected impacts to the chin and side of the headform.

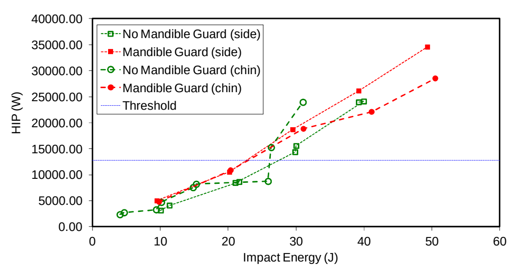
Head injury risk based on HIC_{15} is lower than the threshold across the range of impact energies tested (Figure 12a). Injury risk based on head CG peak linear acceleration (Figure 12b) is higher with impacts over 50 J predicted to result in significant head injuries for the protected cases. However, injury risk based on rotational and linear acceleration using HIP (Figure 12c) is predicted to be high above only 20 J.



(a)



(b)



(c)

Figure 12. Head injury risk for protected and unprotected impacts to the chin and side of the headform: (a) HIC_{15}, (b) CG peak resultant linear acceleration, and (c) HIP.

Comparing the protected and unprotected cases, the addition of the mandible guard results in an increase in injury risk based on HIC for most of the impact energies tested for both chin and side impacts. Similarly the addition of the mandible guard increases slightly the injury risk but only for side impacts for HIC_{15}, CG peak linear acceleration, and HIP.

Interestingly, the same sharp increase in injury risk observed in the neck for unprotected chin impacts are paralleled in all of the acceleration based head injury criteria.

4.2 Non-Penetrating Ballistic Impact

Selected images from high-speed video of a non-penetrating impact over the chin are show in Figure 13. Results of the ballistic testing are summarized in Table 2.

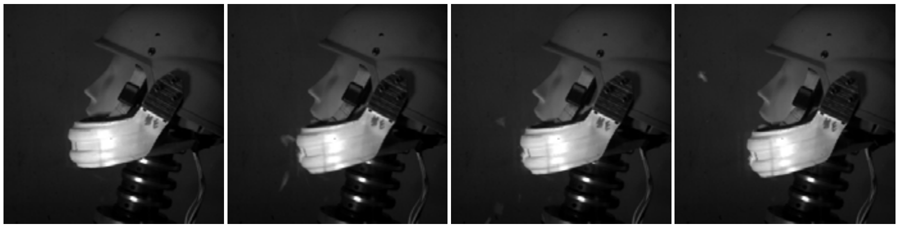


Figure 13. High-speed imaging of a ballistic impact over the chin.

Table 2. Summary of BABT tests of a mandible guard on an MLSH

Sample ID	Impact Location	Impact Velocity (m/s)	Peak Resultant Force (N)	Peak Resultant Accel. (G)	SI	HIC_{15}
D	Chin	266	535.5	24.3	*	*
E	Chin	282	1097.3	64.3	18.5	12.9
F	Chin	274	458.5	24.8	*	*
I	Right	285	645.4	108.0	84.5	50.6
J	Right	285	879.9	138.6	147.2	87.8
K	Right	277	795.8	120.2	109.3	64.9
I	Left	276	682.4	118.7	104.3	70.8
J	Left	276	269.4	24.0	*	*
K	Left	245	221.3	17.4	*	*
* The low accelerations resulted in very low SI and HIC values (less than 3).						

The peak resultant forces measured in the mandible were well below the thresholds of 3916 N and 2436 N for the front and lateral loading directions, respectively, for all of the tests performed despite the small stand-off used. This included tests on the left side of the mandible over the chin strap buckle where the buckle was shattered by the impact of the deforming back face of the mandible guard. An example of the typical backface deformation is shown below in Figure 14. In view of the results for the impact testing where the inability of the current test methodology to capture the difference between highly focal loading and more diffuse loading of the mandible, it is clear that the results measured here give only part of the picture as far as injury risk. The addition of instrumentation which can capture the local load distribution under the site of the impact, and the associated injury criteria, is necessary in order to properly assess injury risk and the protection provided by facial protection systems.

Previous ballistic testing of the mandible prototypes showed very good repeatability so it is likely that the significant variability observed in the results in Table 2 are related to the challenges in reproducing the alignment of the mandible guard/helmet on the headform for each test.

Figure 14. Typical residual backface deformation of the mandible guard (in this example, the strikes on the left and right sides were at lower velocity than over the chin).

Peak resultant CG acceleration, SI, and HIC values were all well below accepted tolerance levels. The relative motion of the helmet on the headform was small. A test performed as part of another trial showed resultant forces and induced accelerations were similar with and without the chin strap buckled so the helmet retention systems may play a secondary role in the helmet/mandible response for non-penetrating ballistic impacts. This hypothesis will have to be verified with different helmet liners. It is certain that a higher striking velocity on a heavier mandible guard would impart more force/acceleration but there seems to be a reasonable margin of safety in this regard.

5 CONCLUSION

The similarity of the loading for the protected and unprotected blunt impact tests and the resulting prediction of similar injury outcomes highlight the limitations in using a global response measure. While the MLSH was able to highlight the effect of the mandible guard, as well as features of the design of the mandible guard, on injury risk, the global response of the mandible assessed using the total resultant force does not appear to be appropriate as the sole measure of performance for highly dynamic and localized loading. Additional instrumentation is required to assess the local contact force, or ideally force distribution, at the point of impact to improve the prediction of injury outcome. Only then can the differences between a highly focal loading (e.g. the triangular anvil on the unprotected jaw or the behind armour signature of a non-penetrating ballistic impact) and the redistribution of that loading by a facial protection system be properly assessed.

Work is already underway to add this instrumentation to the MLSH and is showing promising results, at least as far as the instrumentation goes. However, while quantitative measurements of local load distribution to the jaw will be possible, no predictions of injury outcome can be made until more injury data is collected and new injury criteria developed based on fractures from highly dynamic focal loading. As was noted in the original screening of headforms for maxillofacial injury assessment [1], data on injury tolerance for facial bones, including the mandible, are rare and what is available was not developed using the loading rates and loading distributions representative of the threats of interest for combat helmet systems. More work is urgently needed in this area to support the further development and validation of an injury metric based test methodology for design, testing, and acceptance of facial protection systems

Mandible guard performance in mitigating injuries to the face and head from blunt impacts is not only a function of the risk of jaw fracture. While the continued development of the MLSH is important to fill the gap in current surrogate technologies to capture that injury mechanism, the rotational accelerations and the neck loads induced by frontal and lateral impacts to the protected jaw are of sufficient magnitude to require the inclusion of the more traditional standard Hybrid III headform and neck with appropriate instrumentation as part of the assessment of mandible performance.

The variability in the results for the transmitted force for the ballistic testing appears to underscore a high sensitivity to the alignment of the mandible guard/helmet on the headform for each test. More work will be required to identify the specific source of this variability and to put in place controls in the test methodology to allow repeatable assessments of performance. However, these results also highlight the potential impact that the way each soldier wears his or her helmet and the variability in facial anthropometry across the user population can have on actual performance in mitigating trauma.

Acknowledgements

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