Injury Assessment of Focal Loading Using the Mandible Load Sensing Headform with a Multi-point Thin Film Force Sensor

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ABSTRACT

Military helmets are evolving to improve protection and coverage against fragments, behind armour blunt trauma (BABT), and blunt impact trauma. Providing additional coverage is a challenge due to compromises between human factors requirements and desired coverage and protection. In order to properly assess these trade-offs, it is important to be able to quantify the protection system performance in terms of injury mitigation. However, there are few applicable test methodologies to support product development or acceptance testing. A preliminary injury assessment methodology for evaluating the performance of mandible guard systems has been developed based on the mandible load sensing headform (MLSH) which was designed for the assessment of mouth guards used in American football. The MLSH comprises a Hybrid III 50th percentile headform modified to include an articulating jaw with representation of the upper and lower dentition. Unfortunately the original headform instrumentation was found to be inadequate for distinguishing between unprotected and protected impacts due to the stiffness of the MLSH's jaw and the placement of its measurement load cells in the upper dentition and the temporal mandibular joints. A brief feasibility study using discrete Tekscan FlexiForce® thin film force sensors mounted on the MLSH jaw demonstrated the value of contact force gauges to augment the headform's measurement capabilities. These findings led to the implementation of a custom multipoint sensor which follows the profile of the MLSH mandible and allows mapping of a finer resolution of contact force distribution for arbitrary impact locations. The modified MLSH was subjected to blunt impacts from a falling triangular hazard anvil and to non-perforating ballistic tests on prototype mandible guards. The results show the effectiveness of the gauge at distinguishing between local and distributed loading to the MLSH's mandible from a range of impact orientations. The effectiveness of the mandible guard in mitigating localized loading of the jaw is clearly demonstrated.

1. BACKGROUND

Military helmets are evolving to improve protection and coverage against behind armour blunt trauma (BABT), blunt impact trauma, and blast effects. Providing additional coverage is a challenge due to compromises between human factors requirements, desired coverage and protection but also for performance assessment as there are few applicable test methodologies for development or product acceptance testing.

The Mandible Load Sensing Headform (MLSH) was identified as the most suitable surrogate headform capable of measuring loads transmitted to the jaw from non-penetrating ballistic strike and blunt trauma impacts to a mandibular guard [1]. The MLSH was designed specifically for the assessment of mouth guards used in American football and comprises a Hybrid III 50th percentile headform modified to include an articulating jaw with representation of the upper and lower dentition as seen in Figure 1.

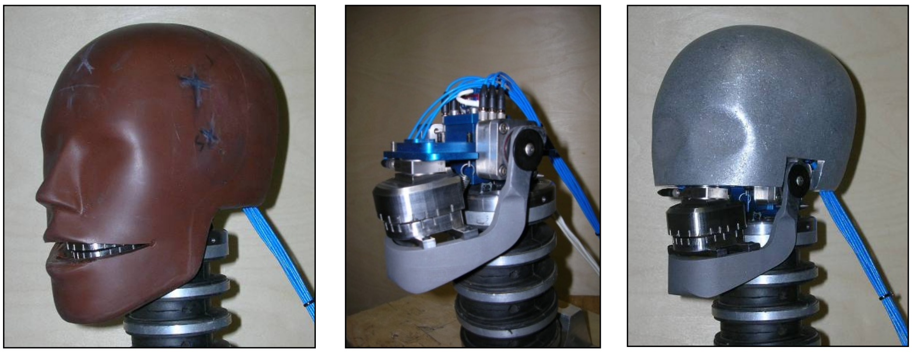


Figure 1: Mandible Load Sensing Headform.

The MLSH has been used in the development of a preliminary injury assessment methodology for evaluating the performance of a mandible guard. Preliminary testing using the MLSH revealed the headform's instrumentation package, which comprises triaxial load cells situated at the temporomandibular joint and in the upper dentition, did not adequately distinguish between potentially injurious behind armour focal loading and distributed loading to the jaw. Similarity, measured loading between protected and unprotected blunt impact tests with similar injury outcome predictions highlighted the limitations in using the global response measured by the headform's instrumentation and the potential for misrepresentation of the benefits of a mandible guard [2]. To address this limitation efforts have been made to advance the measurement capabilities of the MLSH to include localized force measurement on the jaw using thin film force sensors to complement the headform's existing instrumentation.

2. PRELIMINARY THIN FILM SENSOR EVALUATION

Thin film force sensors were applied to the surface of the jaw to measure the localized loading at seven discrete locations along the jaw's midline independently of the reactionary loads measured at the headform's condyles or dentition [3]. The Tekscan FlexiForce® single point 'button' force sensors selected for this application were readily available in three different load ranges 0-4.45 N, 0-111.2 N and 0-444.8 N. For the purposes of our testing the highest capacity gauge was selected and its range was extended to 4448.0 N with the signal conditioning circuitry as per the manufacturer's instructions.

The FlexiForce® gauges were calibrated statically and dynamically, using a compression machine and drop tower, before being applied to the headform. Peak forces correlated very well with those obtained from traditional load cells used during the calibration. A slight lag in response was noted, however, during the drop tower testing highlighting the lower frequency response of the membrane gauges. The gauges were preconditioned prior to their installation on the mandible to achieve optimal response and repeatability of the measurement. The preconditioning comprised applying five cycles of a 4448 N quasi-static load with and an additional five load cycles were used to establish the gauge calibration.

The sensors were glued to the mandible with cyanoacrylate adhesive and covered with a thin 0.007" polyethylene film to reduce the potential for shear loading which adversely affects the gauge's performance. Additionally, petroleum jelly was also applied on the inside of the vinyl headform skin to further minimize shear loads. The installation of the Tekscan gauges is shown in Figure 2 below.

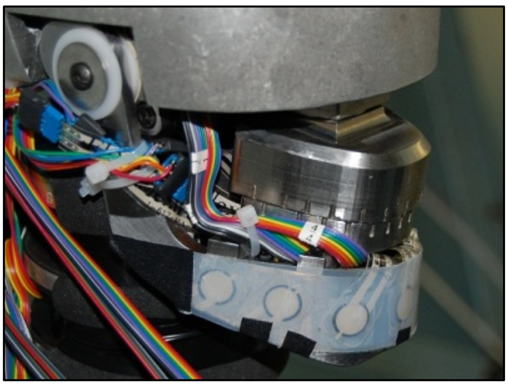
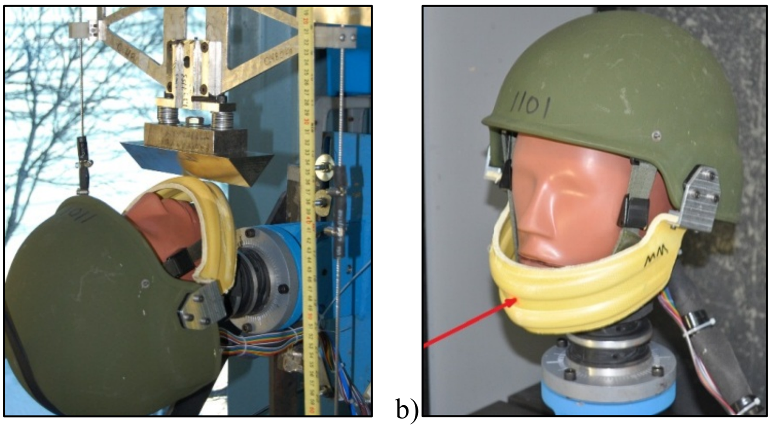


Figure 2: Discrete TekScan FlexiForce® sensors installed on the MLSH jaw.

Impact tests on the fully instrumented MLSH wearing a helmet with a prototype mandible guard comprised of a falling impactor striking the stationary headform supported by a flexible neck. This setup allowed for precise targeting of the thin film sensors. A triangular shape impactor, meeting the geometrical requirements of the ASTM 1446-04 triangular hazard anvil, was used. The stationary head neck assembly was positioned such that the impact point was centred on the FlexiForce® sensor on the chin and aligned normal to the mandible's surface. The head was then rotated 45° about the axis of the neck to achieve a normal impact to the first FlexiForce® sensor to the right of the chin sensor. Masking tape was used to support the headform to prevent neck sag following alignment of the impact site. Upon impact the tape would release or break allowing the neck to flex.

Ballistic tests were also conducted on the same helmet/headform configurations at the same impact locations as the impact tests. A typical test setup is shown in Figure 3 for blunt impact and non-penetrating ballistic strikes to the chin of the mandible guard.



a) b)

Figure 3: Typical impact test configuration for; a) blunt impact, and; b) ballistic strike.

The results of the impact and ballistic tests with the FlexiForce® sensors in place clearly revealed the protective benefits of a mandible guard from localized loading for both frontal and oblique impacts. This was in stark contrast to the measurements with the standard MLSH jaw load sensors where the assessment of the mandible guard performance was inconclusive.

The size and shape of the single point 'button' FlexiForce® sensors limited their application to impacts directly over the sensor, which in practical applications, would be difficult to achieve during impact and ballistic testing due to the relative motion of the facial protection system and the headform during loading and to different mandible guard geometries that might be of interest. Measured contact forces were also sensitive to the impact location relative to the centre of the gauge. And the use of a limited number of discrete sensors limits the number of test locations that can be used.

The use of the FlexiForce® gauges showed promise in being able to assess protection improvement between direct impacts to the jaw and impacts to a protected jaw. However, the discrete gauges used to assess the feasibility of the thin film force sensors did not permit arbitrary impact locations nor did they capture the distribution of loading resulting from the interaction of the back face deformation of the protection system with the face.

3. DEVELOPMENT OF A MULTIPOINT THIN FILM SENSOR FOR THE MLSH

The promising results obtain during the testing of the FlexiForce® gauges led to the design and fabrication of a custom multipoint sensor that employed the same sensing technology but incorporated a significantly larger array of sensing elements to cover the surface of the mandible guard. Additionally, to maximize surface coverage for measuring behind amour blunt trauma the mandible's surface area was increased to provide support for an extended, multipoint gauge.

The revised mandible geometry is shown Figure 4 below in relation to the original MLSH mandible, and two different human jaws. The mass of the extended mandible is 261 grams, 19% heavier than the original, but it still falls within the MLSH's originally specified design target of 108 grams to 440 grams [4]. The new mandible geometry is compatible with the previous headform without any alterations.

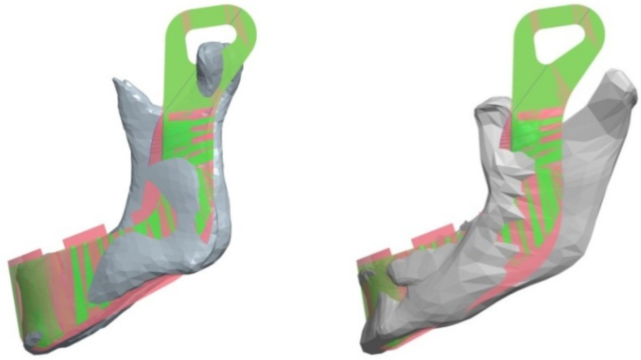
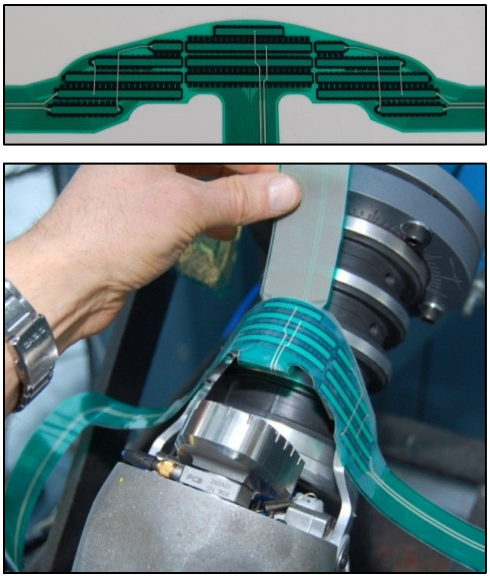


Figure 4: New mandible geometry (pink) compared to the original geometry (green) and two different human mandibles.

Working in conjunction with Tekscan, a new sensor was custom designed to integrate with the MLSH's new mandible and comprises 222 measurement nodes that, when combined with the Tekscan's analog to digital converter and I-Scan® data acquisition hardware and software, is capable of collecting data at a rate of 10 kHz per node. The gauge comprises conductive ink that is printed onto a flexible, flat Mylar substrate that can easily be folded about a simple one dimensional curved surface such as the MLSH's jaw component. These custom gauges are manufactured differently than the FlexiForce® gauges and allow higher speed measurements and, along with the TekScan signal conditioning units, are more suitable for impact testing. The new gauge is show in Figure 5.



a) b)

Figure 5: a) Multipoint sensor, b) sensor installed on MLSH without head skin.

As with the single point FlexiForce® sensors, the new multipoint gauge was statically and dynamically calibrated before being bonded to the jaw with cyanoacrylate adhesive. A thin film of low friction polyethylene was applied between the outer surface of the gauge and the inner surface of the head-skin to minimize shear and related measurement artefacts. To further minimize the potential for shear on the gauge, petroleum jelly was applied to the inner surface of the head skin covering the gauge.

The I-Scan® software displays the force distribution history and a graphical representation of the total force as a function of time. An example of the force distribution and graphical output from I-Scan® is shown in Figure 6 for a blunt impact to an unprotected chin using the ASTM hazard anvil. The first of the pressure maps indicates the pressure distribution at the time of peak force and the subsequent pressure maps show the propagation of the impact upwards towards the dentition as the headform rotates.

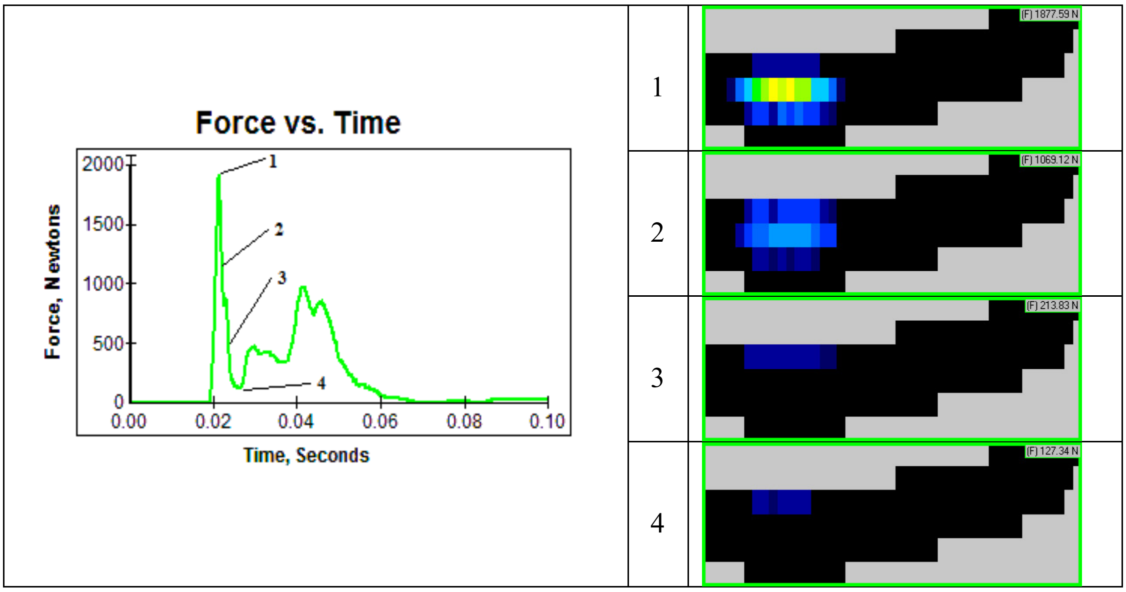


Figure 6: Sample total force and pressure map for an impact to an unprotected chin.

4. EVALUATION OF THE MULTIPOINT SENSOR

The multipoint sensor was evaluated under several blunt impact loading conditions and non-penetrating ballistic strikes.

4.1. Blunt Impacts to the Mandible Front

The MLSH chin was subjected to impacts in the fore-aft direction with and without a mandible guard. The impactor was aligned with the midline of the mandible and, with the headform in the same orientation and alignment, the mandible guard was installed on the helmet and the tests were repeated. For lateral testing the headform was rotated about the vertical axis by 45° to the left and once again the impacts were repeated with the mandible guard installed on the helmet. Additional lateral tests were conducted at 22.5° and 35° of head rotation and 45° rotation to the right to engage the buckle during impact. Typical impact configurations for frontal and 45° lateral impacts are shown in Figure 7.

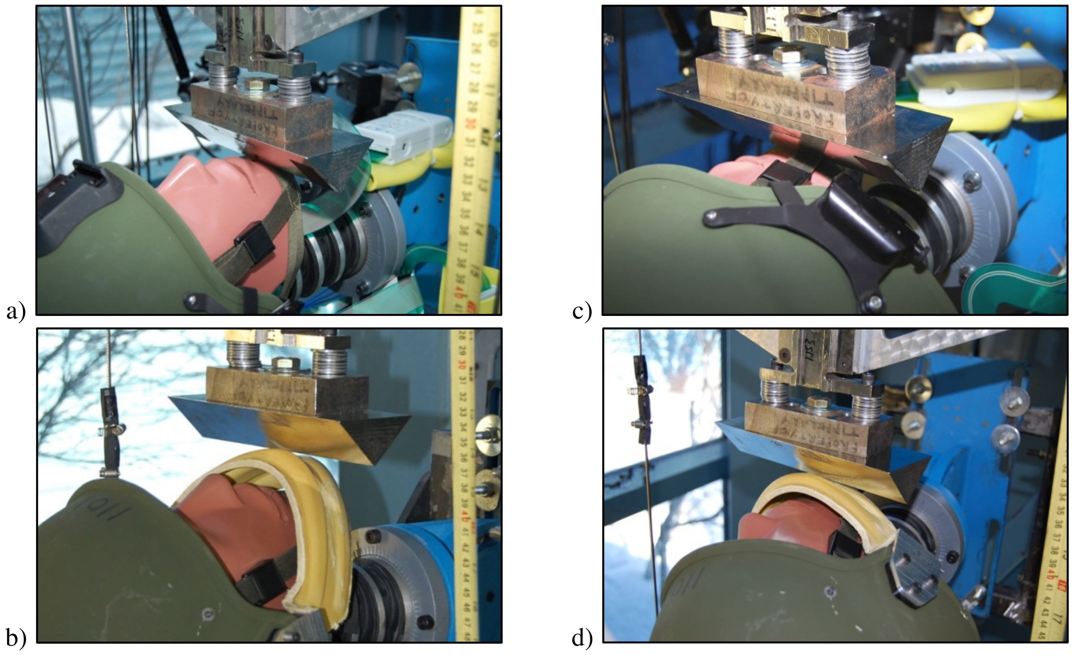
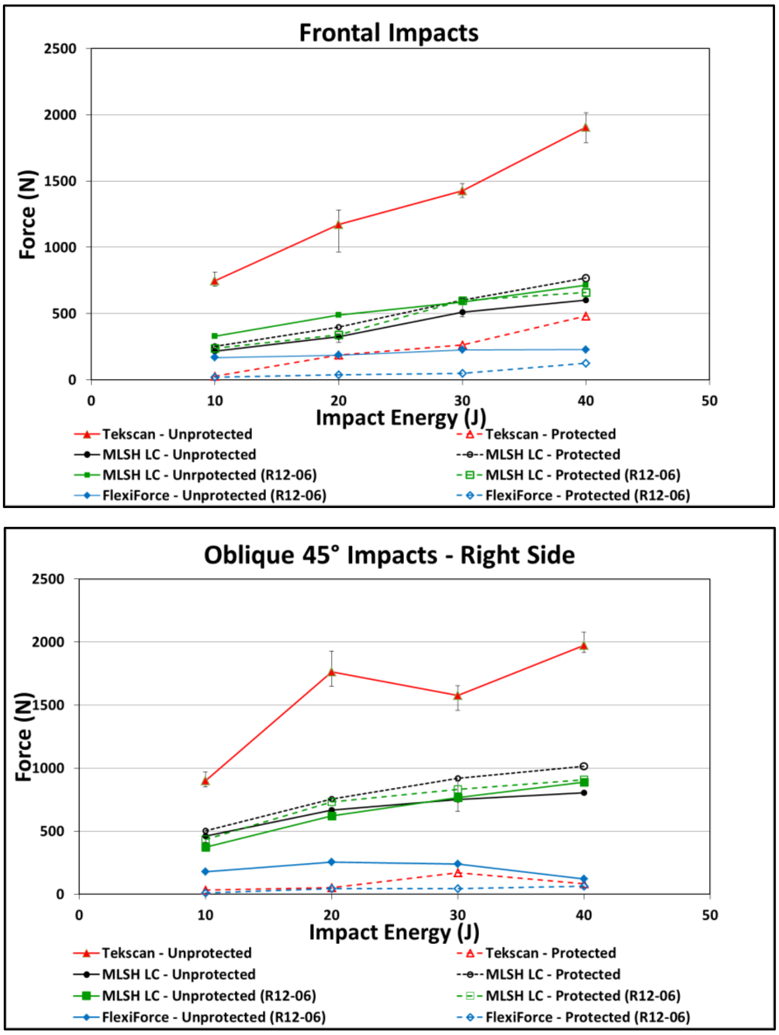


Figure 7: Blunt impact test configurations; a) frontal b) frontal with guard, c) lateral 45°, and; d) lateral 45° with guard.

Three repeat impacts were performed for each orientation and configuration and at each of four energy levels; 10 J, 20 J, 30 J, and 40 J. Data from each transducer, including the upper dentition and TMJ load cells, and each sensing cell of the multipoint sensor were recorded at 10 kHz. High speed video recorded each test at 1000 frames per second.

The peak average forces measured during blunt impact tests, both with and without protection, for the frontal and 45° lateral impacts are presented in Figure 8. Included in the graphs, for comparison purposes, is the data obtained in previous tests with the MLSH and 'button' style FlexiForce® sensors under similar test conditions [3].



a)
b)

Figure 8: Frontal and lateral peak force measured by the MLSH load cells and the multipoint sensor.

The results from these blunt impact tests reveal that:

- The localized load measurements made with the Tekscan multipoint gauge clearly indicate the protective benefits of the mandible guard.
- For a given impact, the localized contact forces measured with the Tekscan multipoint gauge are greater than the resultant reactionary loads measured with the MLSH's load cells. The load cell forces are lower because the mandible guard is free to move to absorb the energy imparted during the impact.
- The FlexiForce® gauges used in the initial thin film gauge evaluations [3] underestimate the localized forces when compared to the force measurements made with the multipoint gauge because they only record the applied loads over a small area of the mandible. A significant portion of the contact load distribution is missed with the single point sensor.
- Similar to the results from the previous test program, the MLHS load cell measurements are higher when a protective mandible guard is installed on the helmet. Although as

indicated these loads are lower than the localized loads measured with the multipoint gauge because the mandible is free to move.

- The MLSH load cell measurements taken during the current test program are similar to previous measurements indicating reproducibility of the test method.
- The cause of the apparently high average Tekscan force measured during the oblique 45°, 20 Joule impacts is unclear but considering the range of force measurements made in that configuration, as noted by the high-low bracket shown in the graph, it is believed to be accurate.

The 45° lateral impacts on the left side differs from the right side 45° impact configuration in two ways: 1) the prototype mandible guard is asymmetrical with larger stand-off on the left side to accommodate the chin strap buckle and, 2) the helmet buckle is situated on the left side and is positioned between the mandible guard and the mandible body. The peak average forces measured during the left 45° lateral blunt impacts are presented in Figure 9.

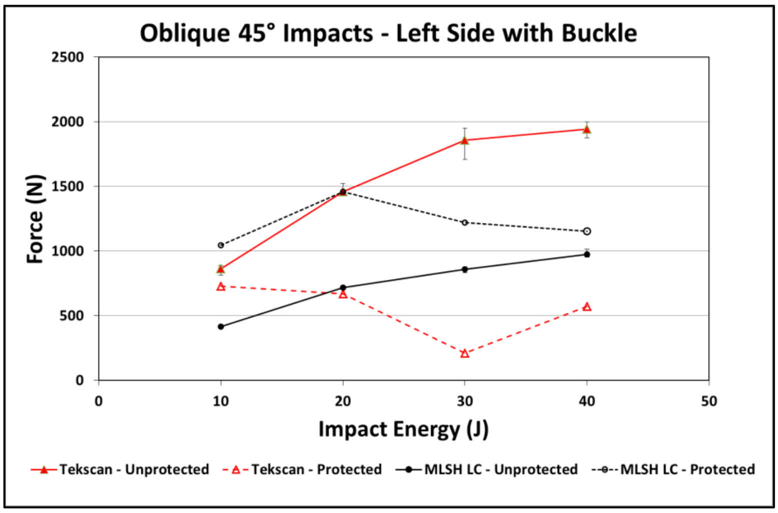


Figure 9: Oblique left 45° blunt impact test results (buckle side).

Generally, the MLSH forces from the left 45° unprotected impacts are similar to those measured on the right side, however the forces are much higher for the protected impacts. This is likely due to the reduced clearance and altered load transmission path to the mandible caused by the presence of the helmet buckle located between the mandible guard and the jaw. For ease of caparison, the forces measured with the Tekscan multipoint gauge for both the left and right 45° impacts are presented in Figure 10.

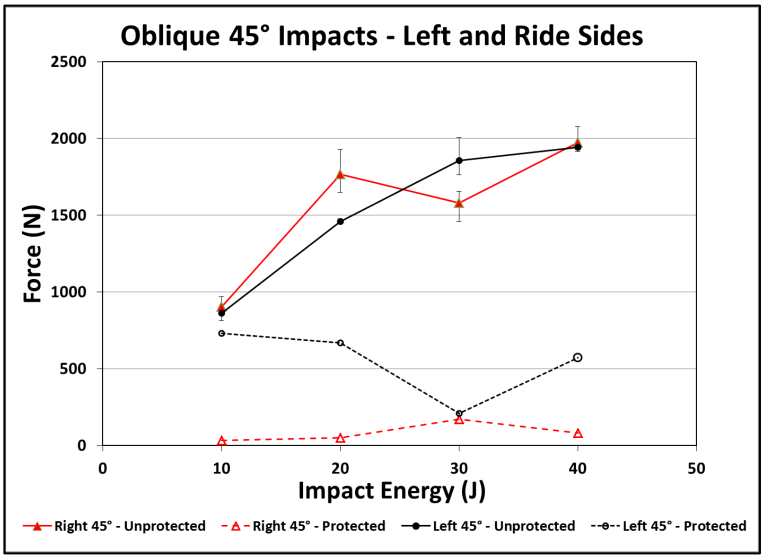


Figure 10: Tekscan multipoint sensor force measurements from left and right 45° impacts.

The forces measured during the unprotected impacts are somewhat similar because the point of initial contact for left side impacts is forward of the buckle and is similar to the point of contact on the right side with little influence from the buckle. The initial point of contact for both the left and right 45° lateral configurations are shown side-by-side in Figure 11 for a 40 Joule impact.

a) b)

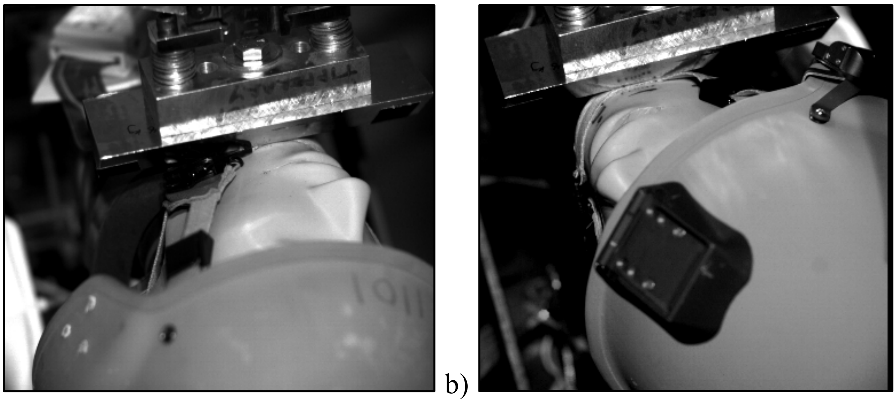


Figure 11: Initial point of contact for both; (a) left, and; (b) right 45° lateral impacts.

With the prototype mandible guard installed, the contact forces for the left, buckle side impacts, are larger than those measure on the right side. Without the buckle, the mandible distributes the impact load over a larger area whereas the presence of the buckle results in focal loading at the chin and under the buckle.

The results of the impacts to the additional lateral test sites are presented in Figure 12.

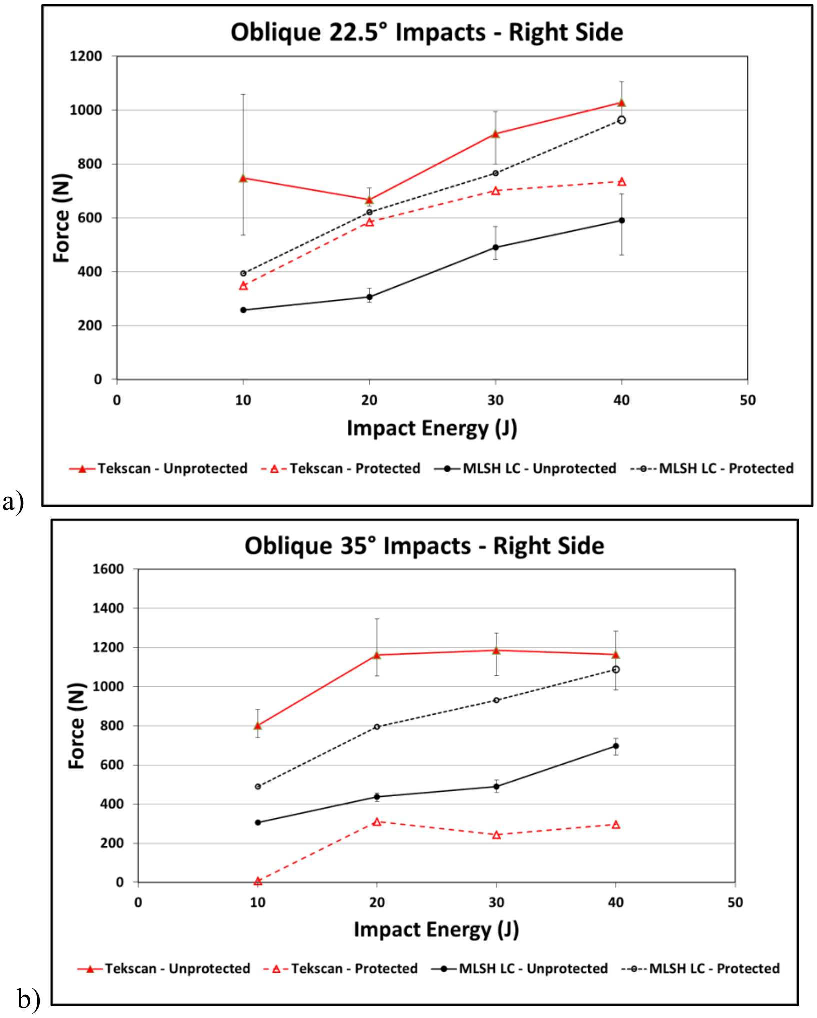


Figure 12: Lateral right 22.5° and 35° right blunt impact test results.

The MLSH load cell's force measurements and the Tekscan multipoint sensor's force measurements for the 22.5° and 35° oblique impacts behaved similarly to the tests conducted at the other impact locations and the observations made previously apply. However, in the oblique 22.5° configuration the multipoint sensor's load measurements are comparatively much higher than those seen in the other impact configurations. The reason for this is not clear but it is suspected that geometrical effects affecting the interaction between the chin and the asymmetrical prototype mandible guard are the cause.

4.2. Ballistic Strike to the Mandible

To assess the multipoint gauge's ability to measure BABT from non-penetrating ballistic strikes, the prototype mandible guards were shot with 6.22 g (96 grain) spheres at a nominal non-penetrating V_{trauma} velocity of 275 m/s. The mandible guards were conditioned in a hot environment (50° C) for a minimum of twelve hours. Shot placement was established prior to the installation of the protective system. Once installed, the helmet was positioned such that the strike location was between the stiffening ribs of the prototype mandible guard. The setup for these tests is shown in Figure 13.

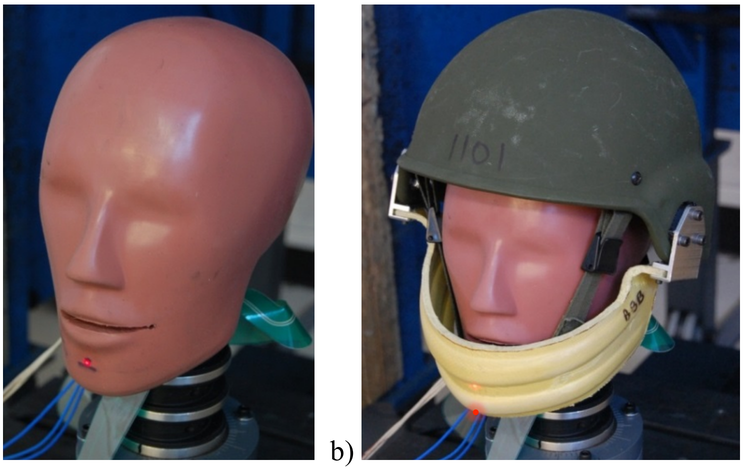


Figure 13: Ballistic test configuration; a) targeting (red dot); b) protection installed.

As with the blunt impact testing, the response of the MLSH/helmet/prototype mandible guard system was recorded with high-speed video but a rate of 3000 frames per second.

The results of the non-penetrating ballistic tests are presented in Figure 14 below. Included are the average peak loads for the Tekscan multipoint sensor, the MLSH's load cell measurements and the limited FlexiForce® force measurements obtained in a previous test program [3]. Where possible, the range of forces measured is also included.

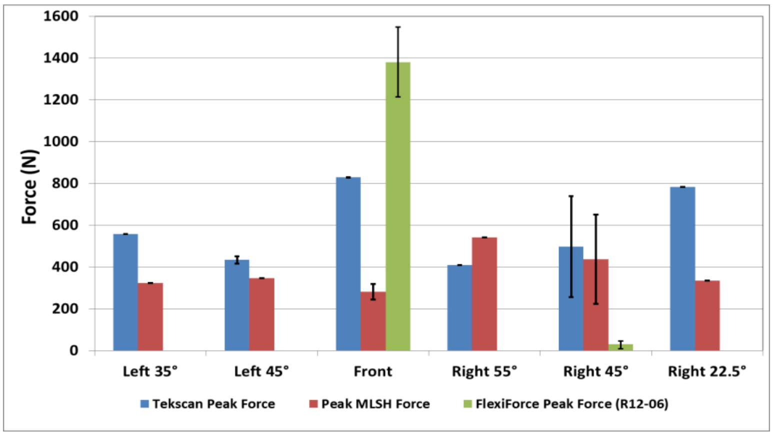


Figure 14: Results of non-penetrating ballistic impacts.

In all configurations, except for the oblique right 55°, the peak forces measured with the Tekscan multipoint gauge exceeded the peak reactionary forces determined by the MLHS's load cell measurements. The right 55° test was one of the last of the tests conducted and it is believed that prior damage to the gauge resulted in non-responsive sensing node which would provide an underestimation of the total force applied.

A frame from the I-Scan® pressure map for this test is shown in Figure 15 where a large number of blank cells can been seen. Note that due to the gauge design, which is divided into three regions, left, right and centre, the damage or loss of capability on the right side region does not affect the functionality of the centre or left side.

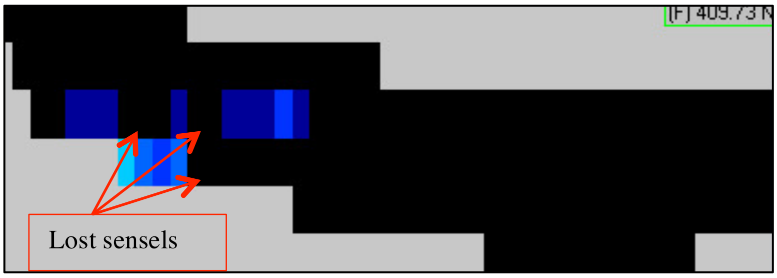


Figure 15: Oblique 55° non-penetrating ballistic test showing lost sensels.

5. CONCLUSION

The potential for thin film force gauges to enhance the measurement capability of the MLSH to include localized load measurements was demonstrated with a Tekscan FlexiForce® gauges. However, due to their size and shape, their usefulness was limited to impacts directly over the sensor. Using similar technology as that employed by the FlexiForce® gauge, a custom gauge with significantly greater spatial resolution was developed. The multipoint gauge provides 222 sensing locations over the surface of the mandible compared to the 7 locations that were measured with the FlexiForce® gauges.

A marginal increase in surface area of the MLSH's mandible was incorporated to provide a supporting surface for the custom multipoint gauge and to increase the measurement area for assessing facial protection systems. The extended mandible has a mass of 261 grams which is 19% heavier than the original design but still falls within the original design target of 108 grams to 440 grams. Minimal effect on the measurement of the condyle and bite loads is expected due to the increase in mandible mass. The mandible geometry remains compatible with the headform and with the Hybrid III neck.

Both blunt impact and ballistic tests were conducted with the multipoint force gauge installed on the MLSH. The results of the tests showed a marked increase in the spatial resolution to measure applied forces onto the mandible whether it was from direct blunt impact, behind armour blunt loading, or backface deformation from non-penetrating impacts to a prototype mandible guard.

The force measurements made with the multipoint sensor clearly indicated the protective benefits of a mandible guard during blunt impact testing in all configurations and locations tested. However, until an injury criterion is defined for focal, high rate loading of the mandible, the level of protection or injury reduction cannot be quantified in absolute terms. Further research is needed in this regard.

The multipoint gauge demonstrated good durability during the blunt impact testing although some lost cells were observed as the testing proceeded. The gauge was more susceptible to damage during the ballistic testing where cracking of the substrate was observed. However, because the gauge is divided into three regions it is possible for testing to continue with the undamaged regions of the sensor.

References

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