Assessment of Less Lethal Impact Munitions Using the Facial and Ocular CountermeasUre for Safety (FOCUS) Headform

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Abstract
Recent social protests and gatherings in the USA have prompted law enforcement agencies to increase their use of less lethal impact munitions (LLIMs) for crowd control. Media reports and firsthand accounts have indicated that many of the LLIMs are impacting individuals in the head and neck regions. There is very little data available on the risk of injury (ROI) from LLIM impacts to these body regions. The Facial and Ocular CountermeasUre for Safety (FOCUS) surrogate headform was used to assess the ROI (fracture) from LLIM impacts. LLIMs were fired at the FOCUS headform to determine the ROI to the frontal and maxilla bones. Sixteen different LLIMs were assessed which included 12-gauge, 37-mm, and 40-mm caliber projectiles from five manufacturers. The LLIMs included bean bag style, rubber, and foam/sponge projectiles. Each LLIM was tested multiple times to determine the average ROI. The average peak resultant frontal bone force ranged from 2.0 to 7.6 kN which represented ROIs from ~30% up to 95%. The average peak resultant maxilla bone force ranged from 1.0 to 4.4 kN which represented ROIs from ~30% up to 99%. In general, 12-gauge LLIMs had a lower ROI than the larger caliber LLIMs and the rubber projectiles had a lower ROI than the bean bag style projectiles. Due to the relative thickness, the maxilla has a much lower fracture force than the frontal bone, and this was borne out in the ROIs from the maxilla impacts. Impacts to both bones showed a positive correlation between normalized energy and resultant force ($p < 0.01$). The slope of the plotted resultant force against the normalized energy for the 12-gauge munitions was significantly smaller compared to larger calibers for both impact sites, frontal ($p = 0.031$), and maxilla ($p < 0.001$).

Keywords FOCUS headform · Less lethal · Impact · Munition · Face

Introduction
The deployment of less lethal impact munitions (LLIMs) during times of civil unrest has occurred in multiple countries [1–4]; however, widespread use was not common in the USA until the summer of 2020. After the death of George Floyd and the ensuing protests, law enforcement agencies from several municipalities deployed these rounds as a means to control the crowds. As part of their deployment, serious injuries were reported with the most common being impacts to the head and face [5].

Although commonly referred to as “rubber bullets,” LLIMs can be made from a variety of materials including rubber, fabric filled with lead shot, bagged silica sand, foam rubber, and wood. Each of these materials come in a variety of shapes and sizes and are designed to be deployed through 12-gauge shotguns or 37/40-mm launchers. The number of submunitions within each LLIM can vary from a single projectile to multiple smaller projectiles. Most of the multiple projectile rounds are designed to be used for crowd control with the single projectile rounds being designed for use on an individual. The majority of LLIMs being produced are direct-fire although some rounds are designed to be fired at a low trajectory or skip-fired.

The underlying goal of LLIMs is pain compliance, and impact to the body with a relatively hard object has prompted research into the risk of injury associated with their deployment. Previous research into the injurious effects has focused on the torso and abdomen since these are the recommended points of impact [6–8]. This research has
included the development of testing methods and biomechanical surrogates to evaluate the risk of injury prior to deployment [9–11]. The use of biomechanical surrogates to predict the risk of injury has been seen in a variety of areas including automotive [12], sports (www.NOCSAE.org), and even ballistics. These surrogates allow for various impact scenarios to be studied in a laboratory setting, prior to their use in the real world. Current NATO standards [10, 11] have used a Ballistic Load Sensing Headform (BLSH) (Biokinet-ics) and a 3-Rib Ballistic Impact Device (3-RBID) for the evaluation of LLIMs to the head and thorax respectively. However, to date, there is limited literature on standardized testing methodologies and recommended surrogates to determine the effects of LLIMs facial impacts.

Given the high percentage of impacts to the head/neck/face (40%), and resulting injuries reported [5], it is critical that there is an ability to evaluate these munitions prior to deployment. This will allow for a proper risk/benefit assessment to be determined to guide use of force policies. The BLSH was developed to evaluate high-rate loading to the head during a threat against a ballistic helmet. This headform has an array of seven load cells in the frontal region which can be relocated to the temporoparietal region. Although it has been evaluated for use in LLIM testing in the past [10, 13], this surrogate cannot be used to assess injuries to the facial bones, nor the eyes.

Additional research in the less lethal field has assessed both facial and temporoparietal impacts [14–17]. In one of these previous efforts, impacts with a blunt ballistic impactor, used to represent the mass and velocities of LLIMs, were conducted to determine the threshold of facial fractures in six post-mortem human subjects (PMHS) [15]. It was reported that peak forces of $3.5 \pm 0.9$ kN and $3.0 \pm 1.0$ kN did not cause fractures in the frontal bones and mandible respectively; however, a peak force of $2.3 \pm 0.5$ kN on the zygoma created anterior maxilla fractures. Another study conducted impacts on eleven (11) PMHS to determine both injury risk and the biomechanical response of the frontal and zygoma bones of the face from LLIM impacts [14]. However, the use of PMHS to determine risk of injury for a specific LLIMs is not feasible for financial and ethical reasons. Therefore, the use of a biomechanical surrogate to evaluate these munitions is desired.

One surrogate that has the ability to evaluate the risk of facial fracture and eye injury is the Facial and Ocular CountermeasUre for Safety (FOCUS) headform [18]. This surrogate was developed with funding from the US army to specifically evaluate the capability of protective equipment to decrease the risk of eye and facial injuries [19]. The headform has ten load cells, each representing a different region of the face including the eyes. The facial load cells are bolted to a steel skull, and each has a loading platen shaped to the contour of the bone it represents. The eye load cells are bolted to the steel skull and have a spherical rubber “eyeball” glued to the eye load cell loading platen representing the back of the eye socket. The entire skull is covered with a synthetic skin (Fig. 1).

The original validation focused on loading from a seven (7) pound impactor that was dropped at velocities from 1 to 6 m/s [18]. Although this headform has been used to evaluate a variety of impact conditions including projectile shooting toys [20], infield softball masks [21], and BB projectiles [22], it has not been used to evaluate LLIMs. Therefore, the goal of the current research is to evaluate the risk of injury from a variety of LLIMs using the FOCUS headform and determine its viability as a surrogate for future LLIM risk of injury assessment.

Methods

A total of sixteen (16) different rounds were tested from five (5) manufacturers (see Table 1). The rounds were made from a variety of materials including rubber, fabric with lead shot (bean bag), and foam (sponge). Nine of the rounds were 12-gauge rounds, fired from a universal receiver (HS Precision Model UR-01), five (5) rounds were 37 mm and were fired from a single-shot 37-mm launcher (Defense Technology, LLC, model 1315), and the remaining two (2) rounds were fired from a single-shot 40-mm launcher (Penn Arms model L140-1). The 37-mm and 40-mm rounds were fired by a certified firearms instructor. The goal was to obtain data for both the frontal and maxilla regions of the FOCUS headform. At least five (5) shots of each round were fired at each location with a minimum of three acceptable shot placements obtained. No more than eight shots were taken for any given round/location combination.

The FOCUS headform (Fig. 1) (Humanetics, 575–1000) was installed on a Hybrid III 50th percentile neck (Humanetics, 78,051–336-H) and attached to a linear trolley to allow for motion post-impact. A total of 38 channels of data were

Fig. 1 FOCUS headform with part of the skin removed to reveal load cell locations (from the FOCUS headform user manual [24])
collected including the ten load cells in the face, six accelerometers (3 linear and 3 angular) at the CG of the head, and one six-channel upper neck load cell. Of the ten facial load cells, all were tri-axial with the exception of the two eye load cells. These load cells only collected force along the anterior to posterior loading path. Data were collected at 20,000 samples per second using a SLICE Pro data acquisition system (DTS, Inc). The load cell data were filtered as recommended using a CFC 300 filter [23].

The muzzle to target distance was kept constant at 3.1 m. A triple-screen chronograph (Oehler Skyscreen, model 57) was placed 0.9 m from the target to measure the projectile velocity. High-speed video of the events was captured from an angle above the target (Vision Research, model Phantom Miro 310) at 3600 frames per second to determine exact shot placement. A second high-speed camera (Vision Research, model Phantom V1212) was positioned perpendicular to the line of impact and captured video at 10,000 frames per second. The second camera allowed for the angle of impact to be determined and provided a secondary means of calculated impact velocity.

Given the design of the headform, the load cell data were examined to establish if the measured data was a true signal or one generated due to inertial loading. Any load cell output that was generated due to inertial loading was identified and eliminated. For all remaining load cells, resultant forces were calculated and summed to give an overall total resultant force.

A shot was considered valid if the point of impact was at the point of aim (verified with high-speed video); the resulting load cell data indicated that ≥60% of the measured force was on the load cell being targeted (verified during data analysis). For each valid impact, the following variables were determined: impact energy, normalized energy, impulse, impulse duration. Impact energy was based on the reported mass of the round and the resulting target velocity. The normalized energy was calculated using the theoretical maximum possible diameter of the rounds divided into the calculated impact energy. Impulse was calculated from the area under the force curve between 5% of the peak force and the onset of global head motion with the impulse duration being the time difference between these points.

The distribution of the loading between multiple load cells was calculated to determine if the majority of the load was seen by the region of interest; frontal, and maxilla “bones”. Those cases where less than 60% of the total load was seen by the regions of interest were eliminated from the Risk of Injury (ROI) assessment where an injury is considered to be a fracture of the specific bone. This assessment was based on a Weibull distribution to estimate the survival function reported by Weisenbach et al. [23]. This function is as follows:

\[ ROI = 1 - e^{-\left(\frac{F}{\mu}\right)^\gamma} \]  

(1)

where \( F \) = maximum resultant force calculated for the load cell, \( \lambda = \text{scale} \), and \( \gamma = \text{shape} \). The scale and shape values are specific to each load cell representing the various facial bones. Those for the frontal load cell and maxilla load cell were used in the current effort (Table 2).

For rounds of the same caliber and material, a Student’s \( t \)-Test was performed to determine significant differences in the ROI. A full factorial linear regression that included normalized energy, round caliber, and round material was used to model the relationship between the variables.

### Table 1: Less lethal impact munitions tested.

| Manufacturer         | Round | Caliber | Material | Mass (g) | Velocity (m/s) |
|----------------------|-------|---------|----------|----------|----------------|
| ALS                  | 1202  | 12 gauge| Rubber   | 9        | 152            |
| ALS                  | 1212  | 12 gauge| Bean bag | 40       | 83             |
| ALS                  | 3702  | 37 mm   | Bean bag | 100      | 66             |
| ALS                  | 3704  | 37 mm   | Bean bag | 150      | 55             |
| CTS                  | 2581  | 12 gauge| Bean bag | 40       | 85             |
| CTS                  | 3580  | 37 mm   | Bean bag | 40       | 91             |
| CTS                  | 4557  | 40 mm   | Sponge   | 60       | 76             |
| Defense technology   | 3021  | 12 gauge| Rubber   | 5.8      | 152            |
| Defense technology   | 3027  | 12 gauge| Bean bag | 40       | 82             |
| Defense technology   | 6225  | 37 mm   | Bean bag | 75       | 67             |
| Defense technology   | 6325  | 40 mm   | Sponge   | 27       | 99             |
| Lightfield less lethal| LMRS | 12 gauge| Rubber   | 8.4      | 152            |
| Lightfield less lethal| LSSL | 12 gauge| Rubber   | 4.9      | 198            |
| MK Ballistics        | 4900  | 12 gauge| Rubber   | 6.8      | 152            |
| MK Ballistics        | 4023  | 12 gauge| Bean bag | 40       | 75             |
| MK Ballistics        | 2275  | 37 mm   | Bean bag | 150      | 55             |
| MK Ballistics        | 2910  | 37 mm   | Rubber   | 75       | 55             |
also conducted to determine whether these variables could predict resultant force to the frontal and/or zygoma regions. Normalized energy was considered a covariate, while caliber and material type were factors.

**Results**

Data were collected on a total of 202 impacts that were performed during the testing. Thirteen impacts were eliminated due to errors including data acquisition, video trigger failure, or errant rounds that did not impact the head. Another six impacts were removed due to a greater than 33% discrepancy from the manufacturer’s reported velocity. The remaining data were analyzed to determine the average energy, normalized energy, impulse, and impulse duration (Table 3 and Table 4).

The remaining 183 impacts were then divided based on which load cell measured the highest percentage of load. Based on this analysis, 77 were frontal, 75 were maxilla, 24 were nasal, 6 were eye, and 1 was a zygoma impact. The data for frontal and maxilla were then further analyzed to determine risk of injury. Based on the criteria of at least 60% of the load being measured by the load cell in the region of interest, 67 of the frontal impacts and 66 of the maxilla impacts were analyzed for risk of injury. Impact locations can be seen in Figs. 2 and 3.

**Frontal Risk of Injury (ROI)**

The nine 12-gauge rounds tested were divided by material type into rubber and bean bag-type rounds. A total of five rubber rounds were investigated which included those that were a solid rubber projectile and those that were rubber filaments radiating from a central point to form a spheroid. The total resultant force measured in the frontal load cells with these rounds ranged from a low of $2.0 \pm 0.7$ kN for the DT3021 to a high of $3.7 \pm 0.4$ kN for the ALS 1202. This resulted in three rounds (DT3021, LLLSSL, and MK4900) with between a 25% and 50% risk of frontal bone fracture and two rounds with above 50% risk (ALS1202 and LLLMRS) of fracture (Fig. 4).

There were four 12-gauge bean bag type rounds investigated; all were a “sock” design and not a square stitched bag. These rounds, as a group, resulted in significantly higher loads than the rubber rounds ($p < 0.001$). The range of forces was from $4.0 \pm 0.8$ kN (MK4023) to $5.0 \pm 0.1$ kN (CTS 2581). All four rounds (ALS1212, CTS 2581, DT3027, and MK 4023) resulted in average resultant forces that would predict a greater than 50% risk of fracture.

There were eight LLIMs that were 37-mm or 40-mm rounds. These rounds were either rubber (MK2910), bean bag (ALS 3072, ALS 3074, CTS 3580, DT 6225, and MK 2275), or sponge (CTS 4557, DT 6326) materials. The MK

| Round   | Caliber | Material | Average peak resultant force (kN) | Average energy (J) | Normalized energy (kJ/m²) | Impulse (s*N) | Impulse duration (ms) |
|---------|---------|----------|-----------------------------------|--------------------|--------------------------|--------------|-----------------------|
| ALS1202 | 12 gauge | Rubber   | 4.2                               | 118.1              | 439.1                    | 3.5          | 1.57                  |
| ALS1212 | 12 gauge | Bean bag | 3.8                               | 72.0               | 267.5                    | 3.1          | 1.79                  |
| ALS3702 | 37 mm   | Bean bag | 7.8                               | 178.8              | 656.6                    | 6.6          | 1.64                  |
| ALS3704 | 37 mm   | Bean bag | 6.9                               | 173.9              | 161.0                    | 7.5          | 2.34                  |
| CTS2581 | 12 gauge | Bean bag | 5.0                               | 144.7              | 538.0                    | 4.2          | 1.72                  |
| CTS3580 | 37 mm   | Bean bag | 5.7                               | 134.4              | 124.5                    | 5.8          | 2.20                  |
| CTS4557 | 40 mm   | Sponge   | 7.2                               | 121.9              | 96.7                     | 7.2          | 1.90                  |
| DT3021  | 12 gauge | Rubber   | 2.2                               | 64.1               | 238.1                    | 1.8          | 1.60                  |
| DT3027  | 12 gauge | Bean bag | 4.6                               | 165.3              | 614.4                    | 3.9          | 1.73                  |
| DT6225  | 37 mm   | Bean bag | 5.6                               | 97.5               | 90.3                     | 5.2          | 1.86                  |
| DT6325  | 40 mm   | Sponge   | 3.2                               | 113.3              | 90.0                     | 2.8          | 1.87                  |
| LL LMRS | 12 gauge | Rubber   | 3.3                               | 80.1               | 297.7                    | 2.7          | 1.57                  |
| LL LSSL | 12 gauge | Rubber   | 2.3                               | 79.4               | 295.1                    | 1.9          | 1.67                  |
| MK4900  | 12 gauge | Rubber   | 2.3                               | 49.0               | 182.1                    | 1.8          | 1.50                  |
| MK4023  | 12 gauge | Bean bag | 3.7                               | 63.1               | 234.6                    | 3.2          | 1.75                  |
| MK2275  | 37 mm   | Bean bag | 8.0                               | 228.7              | 211.8                    | 8.0          | 2.59                  |
| MK2910  | 37 mm   | Rubber   | 5.1                               | 101.5              | 93.9                     | 5.1          | 1.89                  |
2910 was the only rubber 37-mm or 40-mm LLIM tested and resulted in an average frontal load of 5.1 ± 1.0 kN with an average fracture risk of 84.9%.

There were several types of 37-mm bean bag rounds: stitched and sock rounds. Two were circular in nature with stitching along the perimeter (ALS 3702 and MK 2275). Two were tail stabilized with ALS 3704 being stitched and CTS 3580 being of the sock nature. DT 6225 was a rectangular bag with stitching on the ends. For two (2) of the rounds (CTS 3580 and DT 6225), there was only one (1) impact that had a correct shot placement and resulted in greater than 60% loading on the frontal load cell. One round (ALS 3702) resulted in an ROI of over 95% with an average frontal resultant force of 7.6 ± 0.6 kN. Four of the remaining rounds had risks of injury above 75%. The risk of fracture for the final round (DT 6225) was between 50% and 75% with an average frontal resultant force of 3.6 ± 0.1 kN.

The final two 40-mm rounds (CTS 4557 and DT 6325) were designed with sponge tipped impactors. These rounds resulted in average frontal resultant forces of 5.6 ± 0.4 kN for the CTS 4557 and 2.5 ± 0.5 kN for the DT 6325. The difference was statistically significantly (p < 0.001) with the ROI being 89.7% for the CTS 4557 and 50.2% for the DT 6325.

**Maxilla Risk of Injury (ROI)**

The total resultant force measured at the maxilla load cells from the five 12-gauge rubber rounds ranged from 1.0 ± 0.1 kN for the DT3021 to 1.8 ± 0.2 kN for the ALS 1202. The ALS 1202 resulted in the highest average ROI at 82.6%. The LMRS had a ROI of 56.0%, while the remaining three rounds (DT 3021, LL LSSL, MK4900) predicted between a 25% and 50% risk of fracture to the maxilla bone (Fig. 5).

The four 12-gauge bean bag type rounds investigated (ALS1212, CTS 2581, DT3027, and MK 4023) once again resulted in significantly higher loads than the rubber rounds (p < 0.001). The range of forces was from 2.2 ± 0.4 kN (MK4023) to 2.6 ± 0.1 kN (CTS 2581). All four rounds resulted in average resultant forces that would predict greater than a 75% risk of fracture.

Once again, the MK 2910 was the only rubber 37 mm LLIM tested and resulted in an average maxilla load of 3.2 ± 0.6 kN with an average risk of fracture of 99.3%. The 37-mm bean bag rounds also resulted in high fracture risk with all being above 95%. The range of average resultant forces seen in the maxilla load cell with these rounds was from 2.9 ± 0.3 kN (CTS 3580) and 4.4 ± 0.7 kN (MK2275).

For impacts to both the frontal and maxilla regions, there was a positive correlation between normalized energy and resultant force (p < 0.01). For impacts to the frontal region, the slope for the 12-gauge munitions was significantly smaller (p = 0.031) compared to larger calibers (Fig. 6) regardless of material type. The slope for the bean bag

| Round    | Caliber | Material | Average peak resultant force (kN) | Energy (J) | Normalized energy (kJ/m²) | Impulse (s*N) | Impulse duration (ms) |
|----------|---------|----------|-----------------------------------|------------|---------------------------|--------------|-----------------------|
| ALS1202  | 12 gauge| Rubber   | 2.2                               | 121.8      | 452.7                     | 1.7          | 1.47                  |
| ALS1212  | 12 gauge| Bean bag | 2.4                               | 68.2       | 253.5                     | 2.0          | 1.66                  |
| ALS3702  | 37 mm   | Bean bag | 5.3                               | 221.4      | 705.0                     | 4.6          | 1.66                  |
| ALS3704  | 37 mm   | Bean bag | 4.4                               | 192.4      | 178.1                     | 4.6          | 2.23                  |
| CTS2581  | 12 gauge| Bean bag | 3.6                               | 134.6      | 500.5                     | 3.1          | 1.98                  |
| CTS3580  | 37 mm   | Bean bag | 3.2                               | 146.2      | 135.4                     | 3.2          | 2.64                  |
| CTS4557  | 40 mm   | Sponge   | 4.4                               | 139.0      | 110.3                     | 4.2          | 1.90                  |
| DT3021   | 12 gauge| Rubber   | 1.4                               | 68.1       | 253.3                     | 1.2          | 1.93                  |
| DT3027   | 12 gauge| Bean bag | 3.5                               | 132.1      | 490.9                     | 3.0          | 1.87                  |
| DT6225   | 37 mm   | Bean bag | 4.5                               | 135.1      | 125.1                     | 4.5          | 2.12                  |
| DT6325   | 40 mm   | Sponge   | 3.0                               | 111.8      | 88.8                      | 2.6          | 1.68                  |
| LL LMRS  | 12 gauge| Rubber   | 1.3                               | 63.9       | 237.4                     | 1.1          | 1.45                  |
| LL LSSL  | 12 gauge| Rubber   | 1.4                               | 79.5       | 295.5                     | 1.2          | 1.65                  |
| MK4900   | 12 gauge| Rubber   | 1.1                               | 70.8       | 263.3                     | 0.9          | 1.51                  |
| MK4023   | 12 gauge| Bean bag | 2.6                               | 63.5       | 236.0                     | 2.1          | 1.93                  |
| MK2275   | 37 mm   | Bean bag | 6.4                               | 234.2      | 216.9                     | 5.9          | 1.99                  |
| MK2910   | 37 mm   | Rubber   | 4.0                               | 98.9       | 91.6                      | 4.0          | 1.96                  |
material was also significantly smaller \( (p=0.012) \) compared to other materials regardless of caliber. For impacts to the maxilla, the slope for the 12-gauge munitions was significantly smaller \( (p<0.001) \) (Fig. 7).

**Discussion**

The use of LLIMs increased significantly during the protests in the summer of 2020. This increase resulted in injuries from a variety of LLIMs being reported across the USA [5, 25] with several of these injuries being to the head, neck, and face. In one report [25], over 13% of the cases resulted in moderate to severe injuries with surgical intervention being required in 8% of the cases and another 18% sustaining a traumatic brain injury. This is in contrast to what has been previously report by Beatty et al. [26], where only 3% of injuries over a 9-year period were considered clinically significant. The exact location of impact was not reported in Beatty et al. [26]; therefore, this difference could be due to certain impact locations requiring less clinical intervention.

The current effort demonstrates that the likelihood of a severe injury due to a facial impact with an LLIM is quite high. The lowest ROI was seen with the 12-gauge rounds impacting the frontal bone load cell. Of note, the mass of the 12-gauge rounds was ≤40 g, while all but two of the larger caliber impactors had masses ≥60 g.

The 37-mm and 40-mm rounds were divided into three categories based on materials of design: rubber, “bean bag,” and sponge. Only one round made of rubber was tested: MK 2910. This round was similar to the 12-gauge MK 4900 but had a mass over 10 times larger at 75 g versus 6.8 g.
However, the velocity of this round was slower at 55 m/s versus 152 m/s for the MK 4900. Therefore, the overall kinetic energy of this round was less than twice that of the 12-gauge round at 113 J and 79 J respectively. The 37-mm version, with between 2 and 4 times the impulse, created a higher risk of injury when compared to comparable 12-gauge rounds at both impact locations.

The differences in measured load between the two 40-mm sponge rounds, which were statistically significant for the frontal impacts and trending toward significant for the maxilla, are likely due to the difference in the mass of the two rounds. The CTS 4557 is more than twice the mass of the DTS 6325. While the predicted ROI was nearly the same for the maxilla, it was considerably different for the frontal bone (89.7% vs. 50.2% for the CTS 4557 and DT 6325 respectively). This difference is likely because the frontal bone has a higher tolerance to fracture and therefore is more sensitive in the loading range of LLIMs.

In comparing the 12-gauge and 37/40-mm rounds, the slope of the predicted force versus the normalized energy was significantly lower for the 12 gauge. This indicates that the normalized energy may increase resultant force more quickly in 37 mm or 40 mm rounds compared with 12 gauge. However, this model does not predict the risk of penetration which may be more prevalent in the 12-gauge impacts, especially in anatomical regions with mainly soft tissue present.

**Limitations**

The current study only assessed the risk of injury to two (2) bones of the face. Data from media reports indicate that impacts to the face are not limited to these two bones, so additional testing at other facial bones would provide additional insights into the risks of injury to those bones. There is very limited data available on the exact type and

![Fig. 3 Impact locations for 37/40-mm projectiles to the a Frontal bone(s) and b maxilla bone](image)
manufacturer of LLIMs being used by law enforcement agencies across the USA, so the rounds used in this study were based on what is reported in the media and what was currently available for purchase. Assess to LLIMs was significantly limited during the 2020–2021 timeframe due in part to the high demand from local law enforcement and limited production during COVID-19. Assessment of additional LLIMs would provide end-users with additional information which could prove useful for procurement decisions.

While the FOCUS headform has instrumentation that makes it appropriate for use in this study, it is clear that the skin used on the headform cannot withstand the mechanical stress of repeated impacts from LLIMs. As such, during testing, it was observed that the skin had become abraded/lacerated in several locations. Additionally, it became clear during testing that removal of the skin to assess and re-tighten load cell platens provides an opportunity for design improvements.

**Conclusion**

The current study demonstrates that there is no one variable (size, material, mass, velocity, shot location) that solely predicts the risk of injury from LLIMs. Indeed, most of the rounds tested present a fairly high risk of injury when the facial region is impacted. Therefore, it is recommended that the head and face be avoided when deploying these rounds in the future.
Fig. 5  Forces in suborbital impacts, risks of Injury indicated

Fig. 6  Scatter plot of predicted values by normalized energy, caliber, and material type for the frontal
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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Declarations

Conflict of Interest The authors declare no competing interests.

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