Estimation of Armour Backface Velocity

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Abstract. The velocity of an impact plays a significant role in the response of biological tissue. Current techniques to assess behind-armour blunt trauma (BABT) only measure the static post-test depth in clay and cannot capture the velocity of deformation. Assessments of focal, high-energy impacts that include velocity have been shown to better predict increased injury severity. Previous work has described a technique to estimate the backface velocity (BFV) of armour in clay tests; however, the accuracy of that technique was not reported. To overcome this limitation, experiments have been conducted on ballistic gelatine to measure the BFV of the armour from a subset of the impact conditions previously conducted on clay. The estimates of armour BFV using the conservation of momentum, areal density of the armour, and the area of the clay impression at the impact surface were biased lower than the BFV calculated from high-speed video analysis of ballistic gelatine tests. In other words, the BFV from the gelatine tests tended to be faster than the estimated BFV from clay. Closer inspection of these cases indicated that often many layers of the armour were penetrated, suggesting that the mass of the involved-armour may be overestimated in the calculations. One case exhibited the opposite trend (estimated clay BFV was faster than gelatine BFV). This case involved an impact near the edge of the armour, possibly underestimating the impact area in the clay. This would lead to an underestimation of the mass of the involved-armour, and therefore, an increased BFV estimate. This study begins to identify impact conditions where the BFV of armour can be estimated from clay testing. As velocity may be an important indicator of injury, being able to include a parameter from the backface signature that incorporates it would improve the assessment of injury risk of BABT.

1. INTRODUCTION

Behind-armour blunt trauma (BABT) is the unique blunt injury mechanism resulting from the backface deformation (BFD) of body armour that defeats the bullet or projectile, but still causes injury. That is why before body-armour systems can be purchased or issued, they must be able to pass standards for BFD. However, the current standard [1] used to evaluate BABT does not have a direct relationship to injury and was developed for soft body armour using a low-velocity handgun round [2]. Since the dynamics of BABT loading are not necessarily the same between armour systems or against different threats [3], and the response of human tissue is dependent on strain rate [4], the metric in the standard may not apply to the types of armour and threats currently being evaluated. The current metric is based on a static deformation measurement, but deformation alone, especially for high-rate impacts, does not adequately reflect the viscous properties of the chest and, therefore, injury risk [4]. It then follows that, metrics that include the rate of deformation are better predictors of increased injury severity than ones with just deformation [4-6]. However, current techniques to measure the backface velocity (BFV) requires testing armour with a different methodology than currently used to assess BABT [7-18].

Prather et al. described a procedure to estimate the velocity of the armour deformation from tests similar to the current standard [19]. This method was used to calculate the mass and BFV of the armour in BABT cases re-created on clay to relate the injuries seen to the Blunt Criterion (BC), a metric that considers the rate of deformation and is related to the amount of energy available to cause injury [6]. As BC was better able to predict increased injury severity in those cases than clay depth or clay volume, it might be beneficial to use this metric to evaluate armour systems. However, the accuracy of the Prather method to calculate the BFV of the armour has never been validated. To overcome this limitation, this study will compare the calculated velocity from a subset of the impact conditions previously conducted on clay to the measured BFV from ballistic gelatine experiments at the same impact conditions.

2. METHODOLOGY

This study expanded on previous efforts to re-create cases of real world BABT injuries on Roma Plastilina No. 1 clay [6, 20-21] by re-creating a subset of 10 of these cases on 10% ordnance ballistic gelatine to measure the BFV from the cases. Generally, the gelatine was prepared according to the

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guidelines described in [22]. To obtain the 10% concentration of ordnance gelatine, 10 parts by weight (1,000 g) of gelatine (250 Type A Ordnance Gelatine, available from Kind and Knox) was mixed with 90 parts by volume (9,000 ml) of water. The mixture was allowed to stand for approximately one hour before being poured into a 15.2 cm by 15.2 cm by 40.6 cm (6 inch by 6 inch by 16 inch) aluminium pan. The pan was then placed in an environmental conditioning chamber between 3°C and 5°C (37°F and 41°F) for 30 hours prior to use. To calibrate the gelatine, a 0.177 calibre copper-plated sphere BB was fired at 179 +/- 4.5 m/s (590 +/- 15 fps) from 2 m (6.5 ft) into one block from each batch of gelatine that was made. The resting position of the BB was required to be 8.5 ± 1 cm (2.95 ± .39 inch) for 10% in order for the gelatine to pass and be used for testing.

The round identified in each case was fired from an appropriately-sized barrel, housed in a universal receiver. The receiver was remotely fired using a computer-controlled pneumatic firing system. The end of the barrel was positioned at the reported standoff distance from the gelatine for each case. Several shots were performed prior to each test to confirm the sighting and projectile velocity. The velocity of each round was recorded with three light screens (Oehler Research Inc., Model 57, Austin, Texas) attached to an Oehler 35P chronograph or by using the Caldwell Ballistic Precision Chronograph (#721122). All velocity measurements were taken with the front screen measuring 0.9 m (3 ft) from the target. Where point-blank contact shots were required for a re-creation, the velocity of the bullet was determined in a "test run"' shooting at a standoff of 1.5 m (5 ft).

The backface response of the armour was obtained using two high-speed cameras: one overhead and one side view, with a sampling rate of 35,000 frames per second. The overhead camera was a Phantom Miro LC310 (Vision Research, Inc., Wayne, New Jersey) with a resolution of 320 × 240. The side camera was a Vision Research Phantom V1212 with a resolution of 512 × 384. The gelatine block was backlit to increase resolution and reduce glare. To calibrate the camera images for calculating the dynamic gelatine deformation and velocity, images were captured by the cameras prior to testing that included scales oriented along the projectile path and plane and placed within the frame of the cameras. The high-speed cameras were triggered by the universal receiver with sufficient duration to capture the whole impact event.

The gelatine block was placed in a specially constructed 1.27 cm (1/2-inch)-thick acrylic enclosure to provide a mounting surface for the armour, as shown in Figure 1. The dimensions of the enclosure were 60.0 cm by 60.0 cm by 45.7 cm (24 inch by 24 inch by 18 inch). The armour was secured using Velcro straps. The impact location on the armour was placed so that it was positioned over the centre of the front face of the gelatine block. All blocks were tested only once per side.

a. **b.**

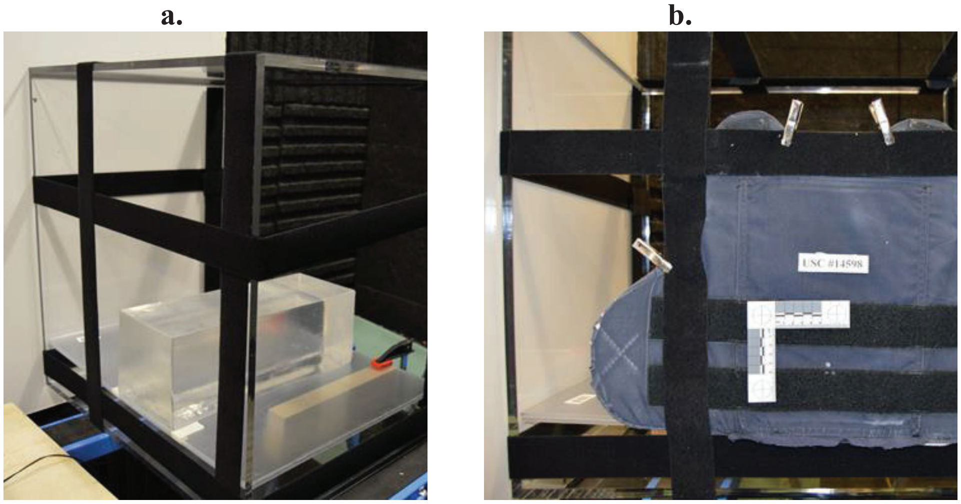

Figure 1. Gelatine test armour mounting fixture: a) acrylic fixture with a representative block of similar size to the ordnance gelatine placed inside and b) example of an armour system mounted to the fixture.

The time history of the BFD of the re-created cases was digitised using frames taken from the high-speed video of the top view (Figure 2). The leading edge of the deformation was traced (green line) to capture the deformation profile at discrete times for the entire loading phase of the impact event for each of the re-created cases.

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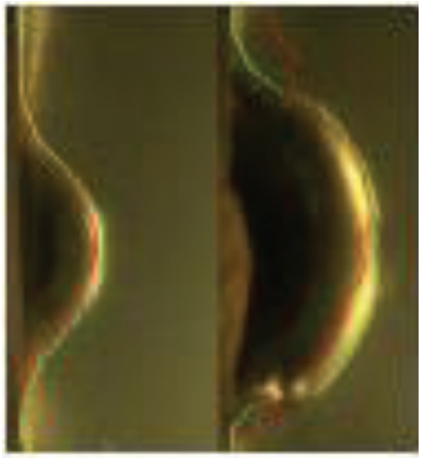

Figure 2. Representative high-speed video images used to calculate the time history of the BFD of the armour. Green line demonstrates the deformation profile determined in each frame.

To estimate the BFV from the re-created BABT cases on clay, the method to estimate the mass and velocity of the armour backface described by Prather et al. was used [19]. In this method, it is assumed that mass and velocity of the projectile at impact is equal to the mass and velocity of the armour and projectile after impact because momentum should be conserved. Standard procedures during the ballistic tests involve weighing the projectile making it easy to obtain the mass of the projectile. The velocity of the projectile in the re-creations was measured using a chronograph as described in the work by Hewins et. al. [20] or by the method described above. To estimate the mass of the armour involved in the BABT impact, the areal density of the armour was multiplied by the area of the armour involved in the impact. The areal density of the armour systems was obtained via manufacturers' and retailers' catalogues, or directly from the manufacturer. To get the amount of the armour involved, it was assumed that the number of penetrated layers of the armour is negligible, and that the area of the crater in the clay from the previously-conducted tests represents the area of the armour involved in the impact. Since the projectile did not fully penetrate the armour, its mass should also be included in the post-impact mass. In summary, the calculation of the effective mass of the armour backface is described by Equation 1,

$$\mathrm{m}_{eff} = \rho_A A_{crater} + m_{bullet} \tag{1}$$

where ρ_A is the areal density of the armour, A_{crater} is the area of the crater along the initial plane of the clay box, and m_{bullet} is the mass of the projectile. Once the effective mass is determined, using the conservation of momentum, the effective velocity of the armour (v_{eff}), or BFV, can be calculated using Equation 2.

$$v_{eff} = \frac{m_{bullet} v_{bullet}}{\mathrm{m}_{eff}} \tag{2}$$

A Bland-Altman plot analysis was performed to assess the agreement between the measurement of BFV in gelatine tests and the calculation of BFV from the clay tests [23]. A Shapiro-Wilk test was used to evaluate the normality of the differences in BFV [24]. As it is expected that the BFV measured in the gelatine tests would be more accurate than the calculation from the clay tests, a percentage similarity analysis was evaluated using Equation 3 [25]. The analysis was carried out using JMP, version 12.0.1, statistical software (SAS Institute, Inc., Cary, NC, 2015).

$$\%_{sim} = \left(\frac{\frac{BFV_{gelatine} + BFV_{clay}}{2}}{BFV_{gelatine}} \right) \times 100 \tag{3}$$

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3. RESULTS

A total of 10 case studies were included in the analysis. Table 1 provides a summary of the peak BFVs determined from the measurements of the gelatine tests and from the calculations from the clay tests for each case.

Table 1. Summary of cases

Case	$BFV_{gelatine}$ (m/s)	BFV_{clay} (m/s)
BABT ID 029	64.4	62.1
BABT ID 031	68.1	26.8
BABT ID 019	91.6	85.1
BABT ID 043	101.5	91.1
BABT ID 010	111.4	25.6
BABT ID 036	122.7	94.9
BABT ID 046	123.8	131.1
BABT ID 004	128.7	136.7
BABT ID 017	133.7	202.5
BABT ID 027	202.2	30.3

Figure 3 compares the BFVs determined from clay and gelatine to the unity line, or the line that indicates when the BFVs calculated from each method are the same. The plot indicates that there are a number of cases where the two methods are equivalent and roughly 4 cases where they deviate from the unity line. The regression analysis of these parameters did not indicate a strong correlation between the two BFV methods, with an R^2 of only 0.018.

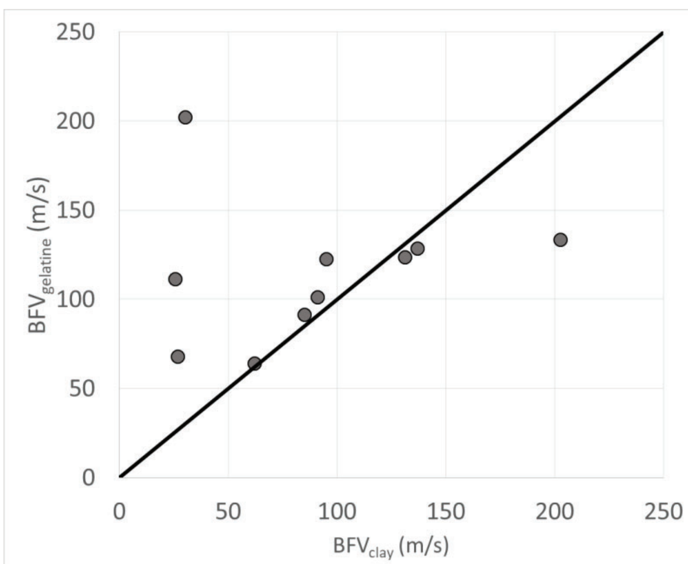

Figure 3. The BFV determined from the gelatine and clay tests compared to the line of equality.

To better identify the differences between the BFV methods, Figure 4 plots the differences between the methods and the average of the peak gelatine and clay BFVs for each case. The distribution of the difference data was determined to be normal. The mean difference between the methods is 26 m/s ± 65 m/s, indicating that the BFV calculated from the clay is generally less than the peak BFV measured from the gelatine tests. The differences are normally distributed, so about 95% of the differences between the two methods will be between the mean difference ± 2 times the standard deviation (SD). In other words, the BFV calculated from the clay could be 155 m/s above or 103 m/s below the peak BFV measured from the gelatine tests.

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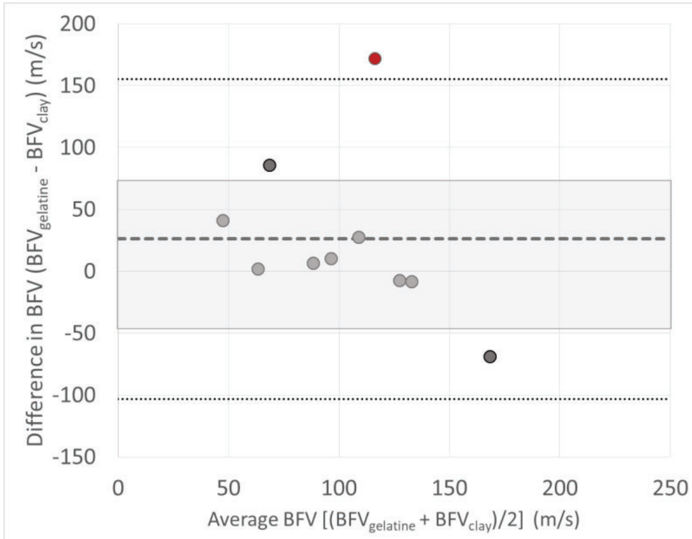

Figure 4. The difference in BFV against the average BFV of the two methods for each case. The bold dashed line indicates the mean difference between the methods. The finer dashed lines demonstrate the mean ± 2SD. The datapoint highlighted in red is considered an outlier. The light grey box indicates the 95% confidence interval (CI) for the mean difference. The 95% CI for the agreement limits are wider than the scale of the plot.

Within Figure 4, the datapoint highlighted in red indicates an outlier in the dataset. Inspection into that test, BABT ID 027, revealed that this case involved an impact near the edge of the armour to represent the real world case. As a result, portions of the armour exhibited a significant amount of extrusion along the edge, as shown in Figure 5. This extrusion caused the clay to have a deformation crater wider than the armour. As a consequence, the estimated amount of armour involvement, i.e., effective mass of the armour, was overestimated for this test, thereby reducing the estimated BFV in the clay test. Since testing procedures for armour do not involve tests so close to the edge, even for the so-called "edge shots", the outlier was removed from further analysis in this study.

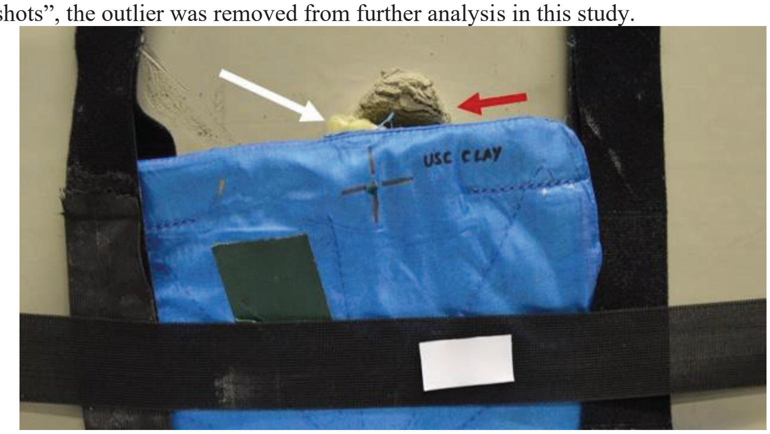

Figure 5. A picture of the armour panel on the clay block post-impact demonstrating the extruded fibres of the armour panel (white arrow) and the crater diameter exceeding the edge of the armour (red arrow).

Another analysis of the differences between the methods and the average of the $BFV_{gelatine}$ and BFV_{clay} for each case was done after removing the outlier, as displayed in Figure 6. The distribution of the difference data was still determined to be normal, even after the outlier was removed. The mean difference dropped from 26 m/s to 10 m/s when the outlier was removed. The mean difference is also a positive value, indicating that the BFV calculated from the clay is generally less than the peak BFV measured from the gelatine tests. With the outlier removed, the BFV calculated from the clay could be 94 m/s above or 74 m/s below the peak BFV measured from the gelatine tests.

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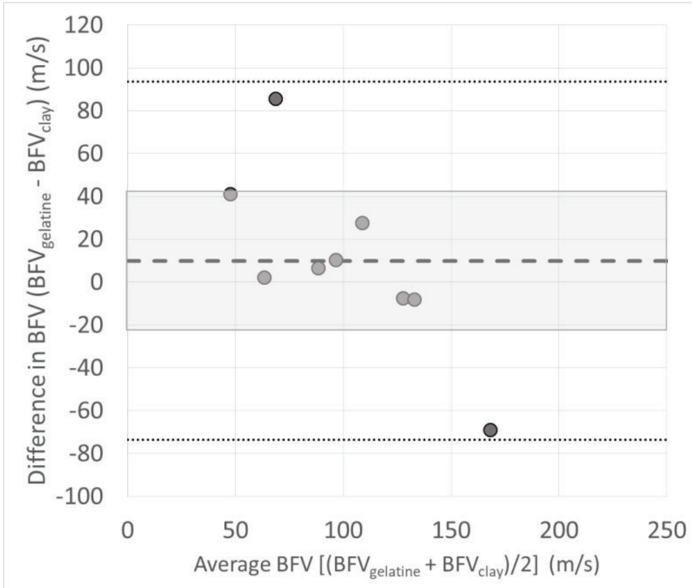

Figure 6. The difference in BFV against the average BFV of the two methods for each case with the outlier removed. The bold dashed line indicates the mean difference between the methods. The finer dashed lines demonstrate the mean ± 2SD. The light grey box indicates the 95% CI for the mean difference. The 95% CI for the agreement limits are wider than the scale of the plot.

Figure 7 displays the distribution of the data of the percentage similarity values for the analysis with the outlier removed. The mean percentage similarity value for this data is 93.5%, which indicates that the BFV calculation from the clay tests has a mean bias of 6.5% less than the BFV measurements from the gelatine tests. The coefficient of variation, a metric that reflects accuracy and precision, is 20.3%.

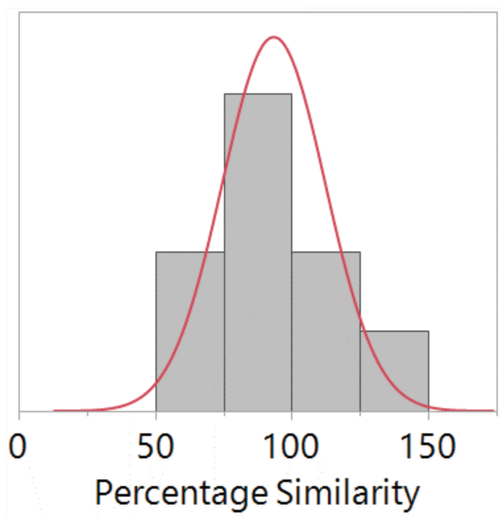

Figure 7. A histogram of the percentage similarity comparing the clay-calculation method for determining BFV with the more accurate gelatine method. A percentage similarity value of 100% indicates that the two methods give the same results, whereas a value of 0% indicates that the results of the two methods are not similar. The red line illustrates the normal distribution.

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4. DISCUSSION

This study has measured the peak BFV of the armour for various BABT impact events, a potentially important parameter to consider in the injury risk from BABT impacts. Current methodologies to evaluate body armour for BABT do not currently consider the velocity of the BFD. The method to estimate the BFV from the common clay tests used in the evaluation of BABT is advantageous because it can easily be implemented into the current methodology and would not add a significant cost to testing. However, the accuracy of that technique had never been explored. Therefore, the calculated BFV from the clay tests were compared with the peak BFV measured from tests on gelatine using high-speed cameras to visualize the dynamic BFD. The analysis revealed important differences in the BFVs determined between the two methods.

On average, the BFV calculated from the clay tests underestimated the peak BFV measured from the gelatine tests by 10 m/s. For the BFV to be underestimated in the clay tests, the effective mass for those tests must be overestimated. Investigating the cases more deeply, it was revealed that the cases that have a large deviation above the unity line in Figure 3 (Cases BABT ID 010 and BABT ID 031) have numerous layers of the armour fully penetrated. If fewer layers of the armour system were deforming into the clay, then the areal density used to calculate the effective mass would not represent the actual areal density of the armour involved, leading to an overestimate of the mass. Figure 8 shows how the layers separated within the armour panel in Case BABT ID 010 suggesting the raised layers were not significantly contributing to the mass of the armour during the impact, leading to an underestimate of the BFV.

a.

b.

Figure 8. An example of the separation of layers within the armour panel for Case BABT ID 010 after the impact, as demonstrated by the elevation of the panel from the clay surface. a. A front view of the armour on the clay block post-impact. b. A side view of the elevation of the armour panel post-impact.

There was one case, BABT 017, that had a relatively large deviation such that the BFV from the clay test was estimated to be greater than the peak BFV measured on gelatine. This case was also near the edge of the armour, approximately 3.5 cm from the edge. For this case, it was observed that the area of clay residue left behind on the back side of the armour was greater than the area of the crater in the clay. Since the impact location was near the edge of the armour, it is possible that the armour along that edge could collapse, or fold, into the crater since there is limited resistance on the free edge of the armour. If more armour was involved during the impact than estimated from the area of the crater, then the effective mass for this case would be underestimated, thereby calculating a higher BFV. Case BABT ID 004 demonstrated a combination of factors that might affect the estimate of the effective mass of the armour. This case demonstrated many layers of armour penetration, but this impact location was also near the edge. Considering the difference between the two methods was not very large, it is likely that these two effects cancelled each other out with regards to over- and underestimating the effective mass

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of the armour. The rest of the cases demonstrated very little to no penetration of layers. If the cases BABT ID 027, BABT ID 010, BABT ID 031, BABT 017, and BABT ID 004 are removed from the analysis, that leaves a sample size of only 5. With a sample size so small, it is difficult to properly evaluate that the distribution of the differences is normal, an assumption in Bland-Altman analysis, since normality tests have little power to reject the null hypothesis with small sample sizes [26]. Small sample sizes also typically expand the confidence intervals since sample sizes are included in the calculation of those intervals. Yet, in this study, removing the cases associated with indeterminate armour involvement, improved the limits of agreement and the confidence intervals in the Bland-Altman analysis for the remaining cases (Figure 9). Considering the limited sample size, caution should be exercised when applying these results, but the mean difference, now 8 m/s, still indicates a bias towards an underestimate of the BFV in the clay tests.

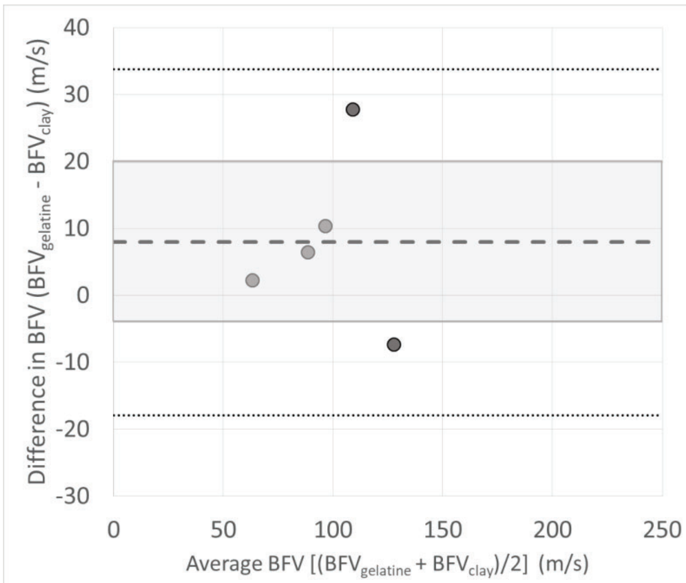

Figure 9. The difference in BFV against the average BFV of the two methods for each case with the cases having suspect effective masses removed. The bold dashed line indicates the mean difference between the methods. The finer dashed lines demonstrate the mean ± 2SD. The light grey box indicates the 95% CI for the mean difference. The 95% CI for the agreement limits are wider than the scale of the plot.

Even with the improvements in the limits of agreement and confidence intervals, the range of the limits of agreement in the velocity are greater than the velocity deviations allowed within armour testing (±9.1 m/s). More comparison testing will likely improve the confidence intervals and the limits of agreement, but increasing the number of samples will not address the unique contributions the specific armour systems played in the calculation of the BFV in the clay tests. Additional analysis to identify the necessary armour parameters post-impact to improve the determination of the effective mass of the armour is required for this method to be able to be incorporated in a testing environment. For example, a potential source of error in the estimation of the mass in the clay tests could be from using the manufacturer-provided areal density. There are several methods to calculate areal density that do not provide equivalent values [27], and it is not clear which method was utilised for each armor system. Future estimates of BFV from clay tests should include experimentally determining the areal density of the armour systems. Furthermore, the added complexity of obtaining those armour parameters during the testing will have to be evaluated for feasibility and financial and time costs. The method to calculate the BFV from the clay tests does show promise for conditions in which the armour witnesses limited penetration and the impact locations are an adequate distance from the edge.

5. CONCLUSION

This study has measured the peak BFV of body armour for 10 re-created BABT impact events, a potentially important parameter to consider in the injury risk from BABT impacts, using a clay-based

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method and a gelatine-based method. Armour testing on clay is more common than on gelatine, but can only infer the BFV, whereas the gelatine-based method can directly measure the BFV. Comparing the two methods, the BFV calculated from the clay tests underestimated the peak BFV measured from the gelatine tests by 10 m/s, a difference greater than the velocity deviations allowed in armour testing. Cases where very few layers of the armour system were penetrated and the impact locations were an adequate distance from the edge showed good agreement between the two methods. Because the threat-armour interaction affected the BFV calculations, the clay-based method for estimated BFV should be implemented with care. Additional research and armour mass estimation methods, including an increased number of experiments are recommended before the clay-based method can be implemented in standard qualification testing.

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