Fragment Penetrating Injury and Light-Weight Protection of the Lower Leg

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Abstract. Explosive devices (EDs) are a major threat in both contemporary battlefields and terrorist attacks. EDs are designed to energise fragments aimed at causing injuries that are life-threatening and associated with poor clinical and functional outcomes. The extremities are the most affected body regions, with the tibia having the highest rate of occurrence. Current personal protective equipment offers little protection against blast fragments to the extremities, especially the lower leg. This study quantified the risk of penetrating injury to the tibia as well as tested the potential of a light-weight hybrid liner for protecting it. A 32-mm-bore gas gun was used to launch 0.78 g cylindrical carbon-steel fragment-simulating projectiles (FSPs) over a range of impact velocities up to 600 m/s. Recovered tibia samples underwent radiography and dissection to quantify the injury outcome. Fracture-risk curves were developed for different severities of fracture based on the modified Winquist-Hansen (WH) classification. The ovine tibia was used as a surrogate for the human tibia. The cortical thickness ratio was used as the scaling factor for impact velocity from the ovine results to the human. For assessment of protection, various common ballistic materials such as silk, Twaron®, Kevlar®, and Dyneema® were tested in a single-layer configuration with 20% ballistic gelatine – a soft tissue simulant – as the backing material. At least 9 shots were conducted for each material. Based on their performance, the top three materials were combined into a 20x20 cm hybrid panel; 6 samples of this panel were tested using the same protocol. The scaled impact velocity at 50% risk (± 95% confidence intervals) for EF1+, EF2+, EF3+, and EF4+ fractures to the posterior surface of human tibia – using the modified WH classification – was 260 ± 0, 364 ± 35, 400 ± 34, and 491 ± 48 m/s, respectively. The resultant light-weight hybrid panel was shown to provide meaningful protection to the lower leg, reducing the predicted fracture severity of the tibia by at least one category in the WH classification.

1. INTRODUCTION

Explosive devices are commonly used in both modern warfare and terrorist attacks. These can cause severe damage to the human body from pressure effects such as blast lung injury, blunt and penetrating trauma, and traumatic amputation of the extremities, [1]–[3]. Of these the most common wounding mechanism is penetration of the body by blast fragments [4], [5]. Blast fragments can be glass, masonry, soil ejecta to foreign bone fragments, and objects purposely included in explosive devices such as bolts and nails [6], [7]. They are projected by the explosion with an initial speed of the order of 1000 m/s which, due to their small mass and irregular shape, quickly decelerate to 600 m/s or less as observed in survival casualties reaching surgery [8]. Extremities, especially the tibia, are the most frequently impacted body regions [9], [10], whose resulted wounds often associate with high risk of amputation, infections and slow recovery [11], [12].

The current personal protective equipment (PPE) focuses on stopping bullets to the thorax and abdomen area for essential coverage of vital organs [13]; these hard body armours provide excellent protection, but can be heavy, cumbersome and poorly fit. The UK Armed Forces also employ an elastic silk soft body armour Tier 1 shorts for the pelvic region, which has been shown to reduce ingress of debris and improve the injury outcome to this area [14], [15]. These shorts, however, only cover the pelvis and upper leg.

The aim of this work was to quantify the risk of fracture to the tibia by a small metal blast fragment. A second aim was to design and test a proof of concept with a light-weight hybrid liner against the same threat and predict the resultant improvement in ballistic protection to the lower leg based on the quantified risk of fracture to the tibia.

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2. MATERIALS AND METHOD

Impact tests were performed using a stainless-steel 32-mm-bore gas gun system (Figure 1a) as described by Nguyen *et al.* [16]. The fragment-simulating projectile (FSP) chosen for this study was a 4.5 mm wide, 0.78 g carbon-steel cylinder designed with the same ratio as recommended by the AEP-2920 NATO Standard [17]. This choice of FSP was based on the study by Breeze *et al.* [18], which found that the most common shape of small metal fragments recovered from blast penetrating injuries was cylindrical with a mean mass of 0.78 g. The test chamber of the system is compatible for studying the fracture to tibia as well as testing the performance of ballistic materials. High-speed photography was used to record the event and to estimate the impact velocity of the FSP.

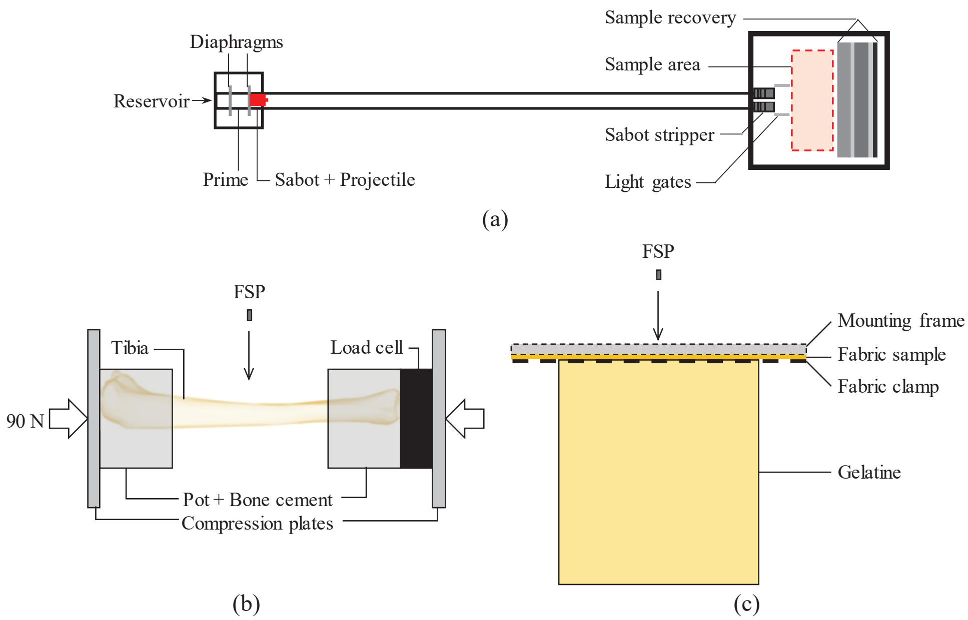

Figure 1. (a) Schematic for the set-up of the gas gun system. (b) The ovine-tibia samples were potted with bone cement and compressed by 90 N to simulate standing gait. (c) the set-up for assessment of ballistic materials; these was clamped onto a frame and put in contact with the ballistic gelatine backing.

2.1 The injury model

The animal model described by Nguyen *et al*. [19] was used to investigate the fracture pattern against impact velocity, where the tibia from skeletally mature sheep was used as a surrogate for the human tibia. The specimens were stored at -20ºC for a maximum of three months after all the soft tissue had been removed leaving only the periosteum intact. Before the impact testing, the sample was thoroughly thawed and carefully potted at the two ends in acrylic resin (Figure 1b). Prior to mounting in the test chamber, the sample was compressed with a 90 N load, which is the body weight of a 5-year-old boy, to simulate the standing posture [19]. A 6-axis load cell was used to monitor the compression. The sample was kept moist with spray water during the preparation process.

The posterior aspect of the tibia was chosen as the impacted location. According to Nguyen *et al.* [16], the effect of the soft tissue surrounding the tibia, whose average thickness is 85 mm [20]–[22] for the human posterior mid lower leg, can be considered separately, hence no soft-tissue simulant was used in this model. The prepared sample was aligned in the test chamber with the aid of a laser diode so that impact was accurately aimed at its posterior surface of the mid-diaphysis. Each tibia underwent radiographic scanning using a mini C-arm before and after each test for fracture detection and classification. For optimising the number of samples required, those with no fracture after a test were tested once more at a higher impact velocity where fracture occurred. The resulted fractures were scored by three independent orthopaedic surgeons according to the modified Winquist-Hansen (mWH) classification [23], [24]. A survival analysis using the lognormal regression model was performed to obtain the fracture risk curve of the tibia at different mWH fracture severities; the data with the fracture

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severity of interest were classified as left-censored, and those without were classified as right-censored. For samples that were re-tested, interval censoring was applied.

The fracture risk curves obtained from the ovine injury model were subsequently scaled for the human tibia, taking into account the effect of the soft tissue, using:

$$v_{impact}^{(human)} = \sqrt{\left(2.5 \times v_{impact}^{(ovine)}\right)^2 + 210^2}$$

where $v_{impact}^{(human)}$ is the scaled FSP impact velocity at the posterior surface of the lower leg for human, $v_{impact}^{(ovine)}$ is the value of the predictor variable from the survivability analysis of the ovine data, 2.5 is the human-to-ovine cortical thickness ratio and is the scaling parameter proposed and validated by Nguyen *et al*. [19], and 210 (m/s) is the FSP velocity required to penetrate the ballistic gelatine to the thickness of the soft tissue at the posterior side of the mid lower leg [25].

2.2 The hybrid panel

Seven commercially available ballistic fabrics were examined to choose the materials for the light-weight hybrid panel. These materials (Figure 2) are Twaron® plain woven aramids (synthetic aromatic polyamides) of two different areal densities, Kevlar® plain woven aramid, Kevlar® knitted aramid, Kevlar® felt aramid, Dyneema® knitted HPPE (high-performance polyethylene), and Kevlar® plain woven aramid laminated with a highly strain-rate sensitive polymer with a range of functional geometries. The two knitted materials were carefully clamped at all sides, in a neutral stretch state, to a 100 × 100 mm test area. The other materials were cut into 400 × 400 mm squares with all sides rolled up into a 100 × 100 mm taut test area.

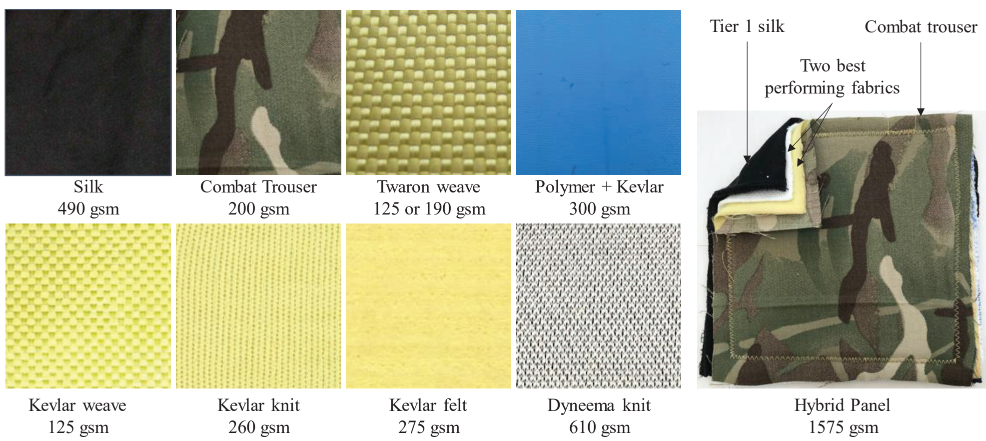

Figure 2. Ballistic materials investigated in the study

For all impact tests, a soft-tissue simulant was placed against the inner most surface of the sample to create a biofidelic boundary condition. The tissue simulant was made from type A 300-bloom ballistic gelatine of 20% by weight [16], [26]. After each impact, the fabric material was checked for deformation and the resulted depth of penetration (DoP) in the gelatine tissue simulant was measured.

A survival analysis using the Weibull regression model was performed with the FSP impact velocity as the predictor variable. Produced velocities with 50% risk (V_{50}) of (a) material perforation, (b) any penetration in the ballistic gelatine, and (c) more-than-25-mm-deep penetration in the ballistic gelatine were used to assess the ballistic performance of the seven commercial fabrics and the hybrid panel.

The light-weight hybrid panel proposed here was constructed from the two best performing materials (out of the seven tested) with the silk material from the Tier 1 shorts at the inner most surface and the fabric from standard combat trousers at the outer most surface (Figure 2). Materials from the Tier 1 shorts and combat trousers were included as the panel is expected to be used as an additional liner in the current combat clothing. The panel was tested in a 200 × 200 mm test area – a practical size for a trouser liner – where all layers were attached together along the edges. As a comparison, additional tests were performed, in the same set-up, on panels with silk and combat trousers, and on panels of combat

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trousers only in order to gauge the protection offered by the current PPE for the upper leg, and the lower leg respectively.

3. RESULTS & DISCUSSION

3.1 Risk of fracture to the tibial posterior mid-diaphysis

Thirty-five impact tests on the posterior cortex of the ovine tibia were performed and resulted in six cases with no bony fracture (F0 of mWH classification), nine fractures with less than 25% comminution (EF1 of mWH classification), three fractures with between 25% to 50% comminution (EF2 of mWH classification), seven fractures with between 50% to 75% comminution (EF2 of mWH classification), and ten fractures with more than 75% comminution (EF4 of mWH classification). The obtained fracture-risk curves for the ovine model (Figure 3) show that the V_{50} for EF1+ (EF1 or more severe fracture), EF2+ (EF2 or more severe fracture), EF3+ (EF3 or more severe fracture), and EF4 is respectively 86, 159, 186, and 238 m/s. After scaling and accounting for the kinetic energy absorbed by the soft tissue, the V_{50} risk of fracture to an adult lower leg for the fracture groups mentioned above is 300, 449, 509, and 632 m/s respectively.

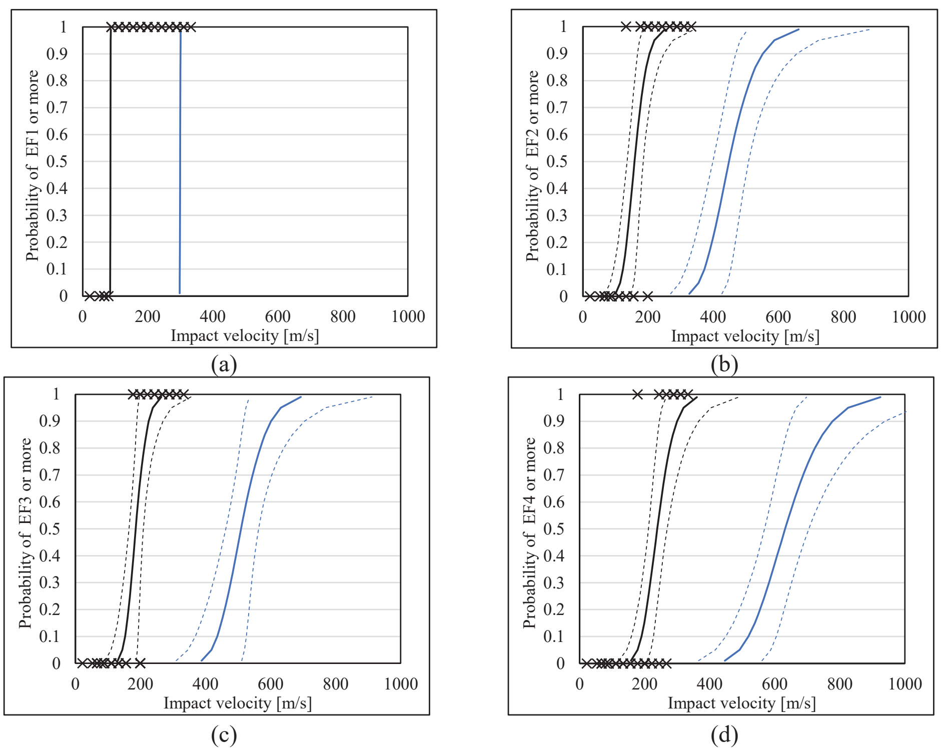

Figure 3. Fracture-risk curves for (a) EF1+, (b) EF2+, (c) EF3+, and (d) EF4 modified Winquist-Hansen fracture types of the experimental ovine model (black) and scaled human model (blue). The dashed lines indicate 95% confidence intervals.

The values of V_{50} for the posterior surface of the lower leg reported here are smaller than those for the anterior surface reported by Nguyen *et al.* [19]. This suggests that the posterior cortex of the tibia is more susceptible to injury by the FSP despite having a thicker soft-tissue layer. Since the anterior cortex is thicker than the posterior cortex, it implies that the cortical thickness is the most important factor in the risk of fracture of the tibia specifically, and by extrapolation likely of all long bones. It needs to be noted that the scaling parameter used here of 2.5 was obtained in a previous study for the anterior cortex whose cortical thickness is different. The cortical thickness ratio between human and ovine should be obtained specifically for the posterior cortex for a more accurate scaling.

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3.2 Performance of the light-weight hybrid panel

Table 1 summarises the V_{50} values for fabric perforation, any gelatine penetration and more-than-25-mm-deep gelatine penetration of the seven commercial materials tested in single-layer construction. Across these three categories, Dyneema® gave the best performance, likely due to its high areal density (610 gsm). On the other hand, despite having the second highest areal density (300 gsm), the strain-rate sensitive polymer laminated Kevlar® plain weave showed the least protection, worse than the thinner and lighter original Kevlar® plain weave (125 gsm). This is likely because the lamination fixes the woven architecture in place and limits the movement of the primary strands, thus reducing the inter-yarn friction and the energy dissipation.

Kevlar® felt and Kevlar® knit are respectively the second and third best performing materials. Their areal densities are similar (275 and 260 gsm) and they have similar V_{50} for gelatine penetration of > 25 mm. Being more elastic, the knitted aramid has slightly higherV_{50} for material perforation (10%), thus is less susceptible to damage by an FSP than the felt aramid, but had a lower V_{50} for any penetration in gelatine (20%), thus offering less protection for soft tissue than the felt aramid. Between the two weaves of Twaron® aramid, the one with higher areal density expectedly showed better performance.

Table 1. The assessed ballistic materials

V_{50} [m/s] / Material	Fabric perforation	Any gelatine penetration	Gelatine penetration of > 25 mm
Hybrid panel, 1575 gsm	298	290	298
Dyneema® HPPE knit, 610 gsm	245	218	249
Kevlar® felt, 275 gsm	169	150	178
Kevlar® knit, 260 gsm	188	121	174
Twaron® plain weave, 190 gsm	157	112	186
Kevlar® plain weave, 125 gsm	148	146	148
Twaron® plain weave, 125 gsm	133	124	157
Strain-rate sensitive polymer + Kevlar® plain weave laminated, 300 gsm	< 90	< 90	136

As the two best performing fabrics in single layer configuration, Dyneema® knit and Kevlar® felt were chosen to construct the hybrid panel. The different layers of the panel, from outer to inner, were light combat trousers (the default outermost layer) – Kevlar® felt – Dyneema® knit – Tier 1 silk (Figure 2). The less elastic Kevlar® felt was put outside the knitted Dyneema® HPPE to eliminate the momentum of the FSP and reduce deformation to the inner more elastic layers. The V_{50} values for fabric perforation, any gelatine penetration and more-than-25-mm-deep gelatine penetration of the hybrid panel were 298 ± 15 m/s, 290 ± 12 m/s, and 298 ± 15 m/s respectively.

Figure 4 shows the trends in DoP in gelatine and the impact velocity of the FSP for the hybrid panel (all four layers), silk and trousers fabrics only (current protection for the upper leg), trousers fabric only (current protection for the lower leg), and ballistic gelatine only (no protection). The relationship between the DoP and the FSP impact velocity for ballistic gelatine only was obtained from a previous study by Nguyen *et al.* [16]. Up to 250 m/s, the panel could stop all penetration to the soft-tissue simulant and provide a DoP reduction up to 91% compared to existing PPE. Between 250 m/s and 300 m/s, the panel started getting perforated but could still reduce the DoP by 85-90%. Between 300 m/s and 500 m/s, the protective ability dropped and the DoP reduction was between 7% and 30%. Impact tests were not performed beyond 500 m/s as this was at the protection limit of the panel.

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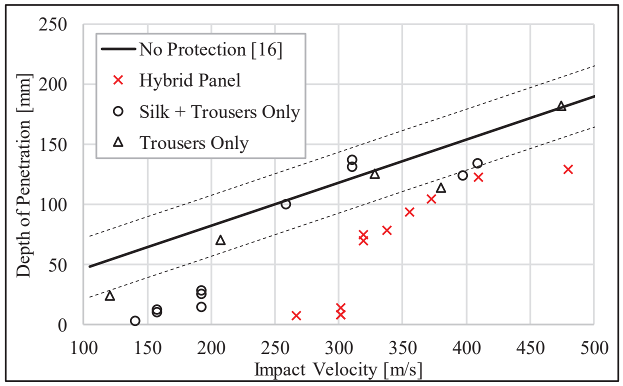

Figure 4. Comparing the depth of penetration in gelatine against FSP impact velocity between the hybrid panel (red cross), silk and trousers fabric only (black circle), trousers fabric only (black triangle), and no protection (solid line; dashed lines indicate 95% confidence intervals; obtained from Nguyen *et al.* [16]).

From Figure 4, it was estimated that below an impact velocity of 300 m/s, the hybrid panel can absorb most of the kinetic energy of the FSP as evidenced by no or almost no penetration in the gelatine; above 300 m/s and up to 480 m/s, the energy absorbed by the fabric panel has no apparent trend with impact velocity and is calculated to be 32 ± 7 J. This information was used to predict the risk of fracture to the tibia with the protection of the hybrid panel (Figure 5), assuming that the energy absorbed by the fabric panel remains constant (32 ± 7 J) above the impact velocity of 480 m/s. The equation used to predict these risk curves was:

$$v_{resultant} = \sqrt{v_{initial}^2 + 300^2}\text{ , for } v_{initial} \leq 300$$

$$v_{resultant} = \sqrt{v_{initial}^2 + \frac{2}{m_{FSP}} \times 32}\text{ , for } v_{initial} > 300.$$

The prediction shows that the light-weight hybrid panel reduces the resultant fracture by at least one injury severity classification.

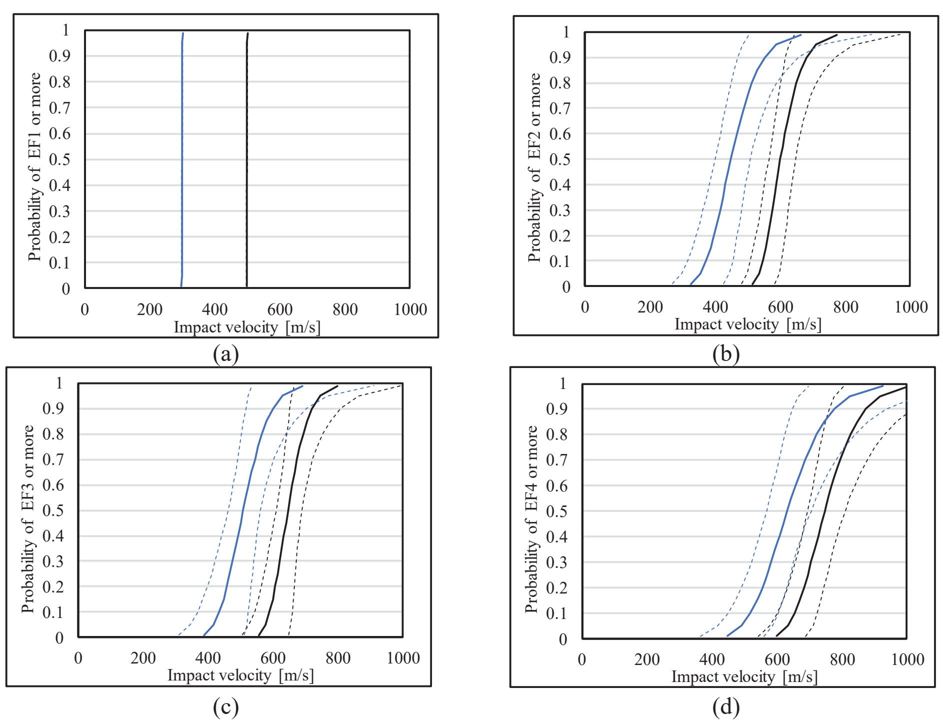

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Figure 5. Predicted fracture risk curves for (a) EF1+, (b) EF2+, (c) EF3+, and (d) EF4 modified Winquist-Hansen fracture types of the scaled human model with the hybrid panel (black) in comparison to no protection (blue). The dashed lines indicate 95% confidence intervals.

The results reported here are specific for the FSP used; a more thorough investigation needs to be carried out by repeating the experiment with other FSPs such as the traditional 1.10-g chisel-nosed cylinder and ball bearings. Due to the availability of supply, the tested ballistic fabrics had varied areal densities. Therefore, the comparison result was solely to choose between the available options to construct the hybrid panel. This result cannot be used to conclude whether one type of fabric is better than the other; further studies with fabrics of the same areal density are needed for that purpose. In addition, choosing the two best performing fabrics to include in the hybrid panel is just one combination option. More tests need to be carried out where other combinations of fabrics are considered to achieve even better protection. Finally, the protective ability of the hybrid panel, in terms of fracture risk, reported here was estimated based on the gelatine backing. The extrapolation of this prediction to a specific body part, such as the tibia, needs to be validated by conducting experiments using specimens of the specific body part. Such validation will render the method of risk prediction presented here a useful and practical assessment for the performance of ballistic fabrics.

4. CONCLUSIONS

This study reports the use of a gas gun system to quantify the risk of fracture at the posterior cortex of the tibia. An ovine model was used and scaled to the human using the ratio of the local cortical thickness and by accounting for the thickness of the outer soft tissue. The methodology presented here may be applied to quantify the risk of injury due to an FSP on a variety of biological tissues.

This study also produced and tested a proof of concept for a light-weight hybrid liner for combat clothing using one layer of commercially available ballistic fabrics. The results show a good improvement in the depth of penetration of the soft-tissue simulant suggesting a meaningful reduction in the risk of bone fracture, which would be beneficial to dismounted soldiers. Work is being carried out to investigate the performance of the hybrid panel with the tibia itself as the backing material and at the anteromedial aspect of the lower leg.

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