A standing vehicle occupant is likely to sustain a more severe injury than one who has flexed knees in an under-vehicle explosion: a cadaveric study.

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Abstract The lower limb of military vehicle occupants has been the most injured body part due to under-vehicle explosions in recent conflicts. Understanding the injury mechanism and causality of injury severity could aid in developing better protection. Therefore, we tested 4 different occupant postures (seated, brace, standing, standing with knee locked in hyper-extension) in a simulated under-vehicle explosion (solid blast) using our traumatic injury simulator in the laboratory; we hypothesised that occupant posture would affect injury severity.

No skeletal injury was observed in the specimens in seated and braced postures. Severe, impairing injuries were observed in the foot of standing and hyper-extended specimens. These results demonstrate that a vehicle occupant whose posture at the time of the attack incorporates knee flexion is more likely to be protected against severe skeletal injury to the lower leg.

Keywords Blast injury, anti-vehicle mine, biomechanics, cadaveric, impact testing

I. INTRODUCTION

Current military conflicts are characterised by the use of the Improvised Explosive Device (IED). Improvements in personal protection, medical care and evacuation logistics have resulted in increasing numbers of casualties surviving with complex musculoskeletal injuries, likely to lead to life-long disability. Most of the non-fatal injuries caused by IEDs during the conflicts in Iraq and Afghanistan have been to the lower extremities, resulting in impairment or disability [1]. Specifically for in-vehicle occupants, 91.5% of their injuries are to the lower extremity [2]. Thus, there exists an urgent requirement to investigate the mechanism of extremity injury caused by these devices in order to develop mitigation strategies. We hypothesise that the posture of a vehicle occupant affects the resulting injury to the lower limb following an IED attack to the vehicle. The aim of this study is to compare the response of four different occupant postures by testing cadaveric legs in a traumatic injury simulator.

II. METHODS

In a typical vehicle explosion, the floor of the vehicle accelerates beyond 12 m/s at 100 g, and transmits forces to the legs of the occupants that are mostly vertical and short in duration (< 10 ms) [3,4]. Our injury simulator (AnUBIS) is capable of recreating the response of a vehicle floor due to an under-vehicle explosion, by accelerating a 42 kg plate (Fig. 1). AnUBIS utilises compressed air to trigger a shearing mechanism that releases the plate. Depending on the pressure at release, the plate can accelerate up to 25 m/s within 3 ms. Braking arms that are mounted on horizontal springs are utilised to decelerate the plate back to rest. The pressure at plate

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release was recorded by a pressure gauge (Pi602, Applied Measurements, Berkshire, UK); the acceleration of the plate was measured with a uniaxial accelerometer mounted on the plate's top surface (352C04, PCB Piezotronics Depew, NY, USA; frequency response = 10 kHz); the flight of the plate was measured utilizing high speed photography (Phantom v12.1, Vision Research, Wayne, NJ, USA) at 4,000 frames/s; the velocity profile of the plate was calculated by integrating the accelerometer data and confirmed by differentiating the displacement data. Acceleration and pressure signals were recorded at 25 kHz via a PXIe data acquisition system and a custom-written LabVIEW® software program (NI instruments, Austin, TX, USA). This program was also used to control and trigger the synchronous data acquisition of PXIe system and camera. An anti-aliasing filter was used for the accelerometer, strain and pressure signals as part of the PXIe data acquisition system.

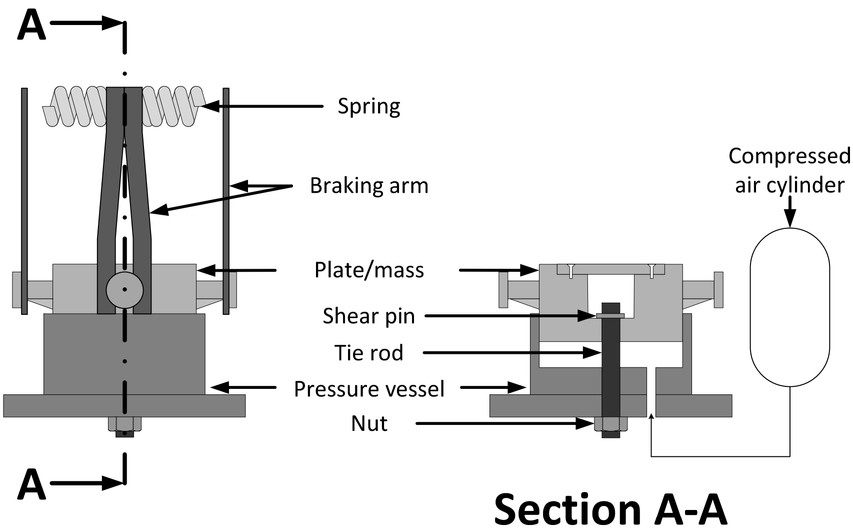

Fig. 1. Schematic of our traumatic injury simulator (AnUBIS) showing plate release and braking mechanisms.

Approval had been secured from the local Research Ethics Committee prior to testing. The cadaveric lower limbs acquired for this study were fresh frozen at -20°C. The limbs underwent computed tomography (CT) scanning (Siemens Somatom Definition AS 64; Erlangen, Germany) prior to testing in order to exclude any pre-existing lower limb orthopaedic pathology. The specimens were taken out to thaw overnight prior to testing.

The femoral head was removed and the femoral intramedullary canal was reamed in order to fit M12 studding that was subsequently inserted 150 mm into the canal. A pot with a 12 mm hole in the base was slid down the intramedullary rod such that it pressed up against the femur. The pot was secured in place with screws and bone cement (PMMA). For all specimens except for those tested in a seated position, 4 mm diameter studding was passed through the patella and cables were secured on either side (medially and laterally) in order to simulate the muscle forces required to keep the leg in the target posture whilst supporting half a body weight.

The lateral and medial facets of the calcaneus were exposed, dried with ethanol and strain gauged (CEA-06-125UW-350, Vishay, Basingstoke, UK) using cyanoacrylate as the bonding agent. The strain gauges were connected to the PXIe data acquisition system. The sole of an appropriately sized Meindl Desert Fox combat boot (Lucas Meindl GmbH and Co, Kirchanschoring, Germany) was secured onto the foot of each specimen with 3 cable ties.

The cadaveric specimens were mounted on AnUBIS in the following positions: (1) seated (90° of knee-joint flexion), (2) braced (20° of knee-joint flexion), (3) standing (~0° of knee-joint flexion), (4) hyper-extended (~-5° of knee-joint flexion) (Fig. 2). Each limb was loaded with 40 kg (typical half-body weight) through a surrogate, custom-made hip joint in order to simulate the effective mass of the rest of the body. The surrogate hip joint allowed six degree of freedom motion of the joint. Two specimens were tested at each posture at a target velocity of 9 m/s; no specimen was used more than once (Table I). Zero strain was defined as the strain when the leg was lying on a workbench, prior to placing it on the rig and applying the 40 kg mass through the hip. Zero time was taken as the time at plate acceleration equal to 30 m/s^2; we arrived at this metric after experimenting with numerous values for all sensors in AnUBIS tests with and without specimens mounted.

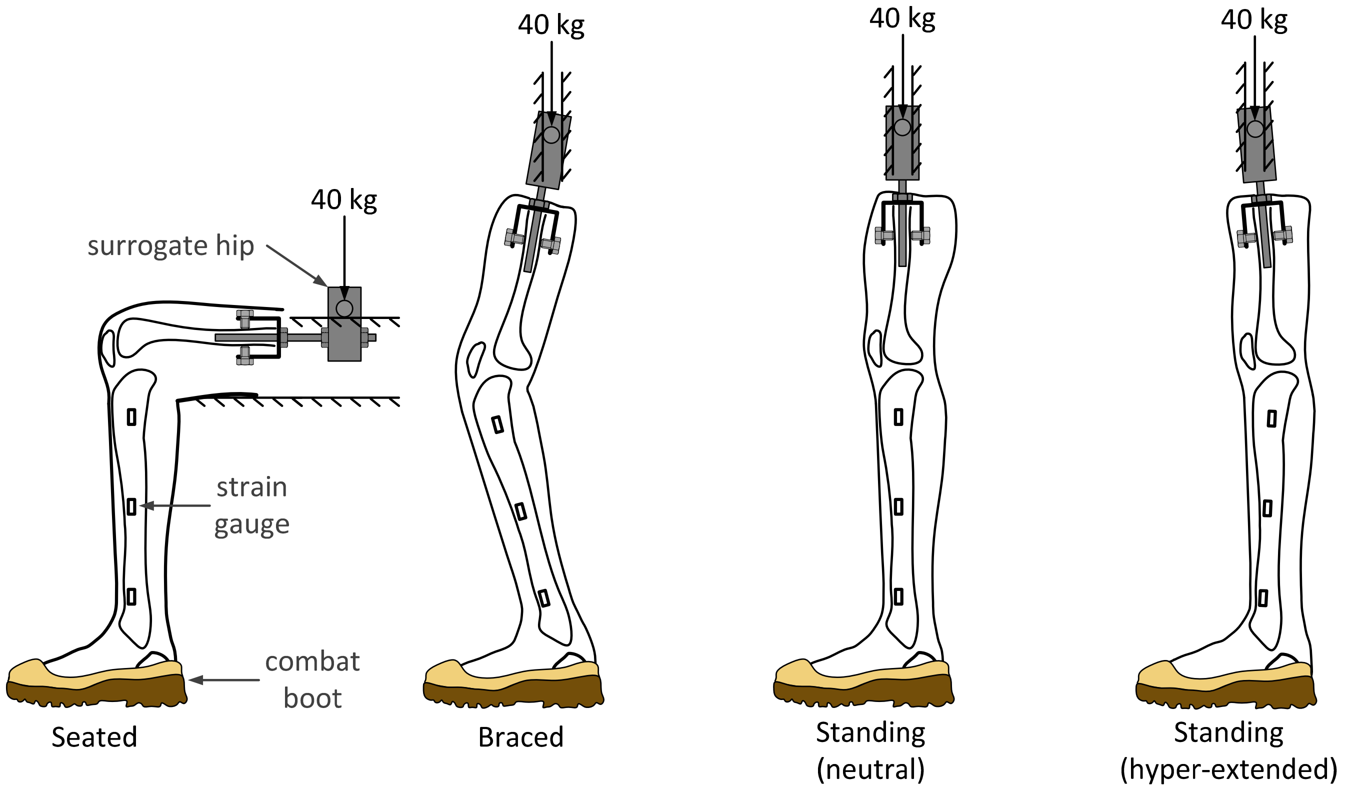

Fig. 2. Schematic of the setup of the limbs on AnUBIS at the various occupant postures.

III. RESULTS

Pressure at release was 9.2 ± 0.2 bar (n = 8; mean ± 1 SD). Maximum plate speed calculated for each group (n = 2) was 8.8 ± 0.2, 9.5 ± 0.0, 8.6 ± 0.2, and 8.1 ± 0.3 m/s for seated, brace, standing neutral and standing hyper-extended, respectively. Time at maximum plate speed calculated for each group (n = 2) was 10.9 ± 0.5, 10.7 ± 0.1, 9.7 ± 0.8, and 10.0 ± 0.8 ms for seated, brace, standing neutral and standing hyper-extended, respectively. CT scans of the cadaveric legs prior to testing were assessed by a consultant radiologist (ATHW); no skeletal injury was observed. The legs were recovered and examined clinically by two trauma surgeons (TJB and AR) immediately after the test. No skeletal injury was observed in the specimens in seated and brace postures. Severe, impairing injuries were observed in the foot of standing and hyper-extended specimens. The strain-gauge signal form the lateral facet of the calcaneus for one specimen per group is presented in Fig. 3 and the maximum values and time at which they occurred are presented in Table I. Maximum strain at the calcaneus was taken as the maximum strain before the first instance whereby a reduction in strain was observed; the calcaneal wall was considered failed at that point.

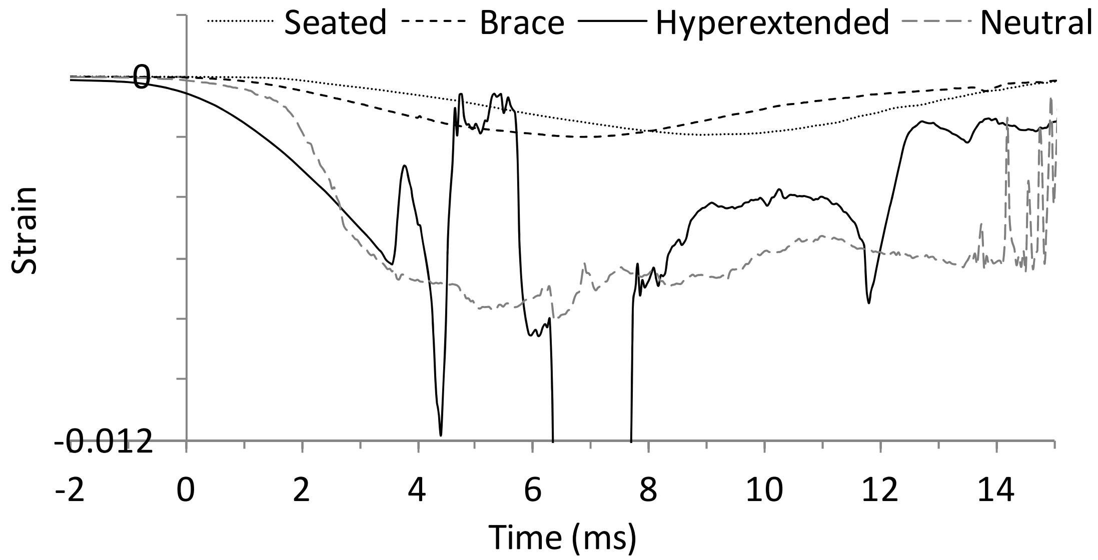

Fig. 3. Response of strain gauges bonded to the lateral facet of the calcaneus. Traces are presented for one specimen per group. The calcaneus experiences significantly higher peak strains in the standing positions than the seated or brace position. No fracture is seen in either the seated or brace position as shown by the smooth curve. Fracture is seen in both standing neutral and standing hyper-extended positions.

IV. DISCUSSION

This study investigated the effect of occupant posture on injury due to a simulated solid blast in the laboratory. Tested under the same threat level (pressure at release of the plate), leg postures with the knee joint initially flexed sustained a minor injury or did not sustain an injury at all; conversely, leg postures with the knee joint anatomically constrained sustained severe hind foot injuries. Analysis of contemporary battlefield data would suggest that the vast majority of injuries with FASS ≤ 2 are likely to make a full functional recovery after injury [5]. In contrast, FASS 5 injuries are associated with a high probability of requiring amputation.

The main limitation of this study is the small sample size; however, the consistency of the results within the groups gives confidence that the trends observed here are real. In addition, recent battlefield data suggests that severe hind foot injuries are a characteristic of solid blast [1] (i.e. loading resulting from the dynamic characteristics of a structure being directly exposed to blast; similar to *tertiary blast*); this also adds confidence to the relevance of the results in this study.

With the understanding that the sample size is small, the results show a potential correlation between maximum compressive strain and injury severity. In addtion, interestingly, strain at failure of the lateral facet of the calcaneus is in the region of 0.6-0.8%. The available literature for comparison is limited and inconclusive; nevertherless, strain at failure for human femoral cortical bone at strain rates between 1 and 17 /s have been reported within the range of 0.8-2.5% [9]. The difference in value might be reflecting the difference in microstructure between lateral calcaneal wall and femoral cortical shell.

The 40 kg of mass added through the hip in each of the tests is a typical half-body weight. Understandably, the body mass of the individuals whose lower limb was tested varied; in this study from 58-94 kg. We were not expecting that this difference in mass will be enough to mask differences in risk of injury for the various postures. Indeed, there is no indication of correlation between body weight and maximum strain; for example, in the seated samples tested here, the 66 kg male sustained maximum strain of 0.0019 whereas the 88 kg male 0.0016.

Simulating the effect of solid blast on the human *in vitro* has been attempted elsewhere, as test-rigs have been developed that can impact cadaveric tissues and whole organs. However, these have focused primarily on simulating the impulse characteristics seen in a car crash [6-8]. The only attempt to simulate vehicle floor response due to blast is by McKay and Bir [10] who utilised a linear impactor to accelerate a 36.7 kg plate up to velocities of 12.0 m/s. They cut out a portion of the tibia in order to introduce a tibial load cell and therefore allow for a direct comparison with load cells incorporated in anthropometric test devices (ATDs) that are commonly used in vehicle tests. They reported time to peak force within 4 ms for impactor speeds of 10 m/s, which is expectedly less than the time required to reach peak strain in the seated cadaveric specimens presented here, as they impacted their specimens instead of accelerating the plate with the legs resting on it. All 6 legs that they impacted at 10 m/s sustained calcaneal fractures, and 3/6 sustained talar fractures; the FASS score was equal to 3 for 4/6 legs, and equal to 5 for the other 2 legs. All 6 legs that they impacted at 7.2 m/s had no skeletal injuries. In this study, the seated legs had the sole of a combat boot attached and were accelerated up to – not impacted at – 8.8 m/s; they did not sustain any severe skeletal injury (FASS ≤ 2). There is no data in the literature for any other occupant posture.

V. CONCLUSIONS

The results demonstrate that a vehicle occupant whose posture at the time of an under-vehicle explosion incorporates knee flexion is more likely to be protected against severe skeletal injury to the lower leg. In addition, according to current NATO standards, vehicles are considered fit for operation based on threshold load criteria measured on seated surrogate occupants (ATDs) at the shin [11]. This study demonstrates that a standing occupant has a significantly higher risk of severe injuries than a seated occupant. It is therefore recommended that threshold criteria be adjusted to account for other relevant occupant postures.

VI. ACKNOWLEDGEMENTS

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TABLE I
DEMOGRAPHIC DATA AND MAIN RESULTS FROM THE CADAVERIC EXPERIMENTS
(FASS: FOOT AND ANKLE SEVERITY SCALE [12] RANGING FROM 0-6)
(AIS: ABBREVIATED INJURY SCALE RANGING FROM 0-6)

Specimen								
Gender	Age	Weight (kg)	Left/ Right	BMI	Configuration	Max compressive strain in lateral calcaneal wall and its timepoint (ms)	Injury level (FASS/AIS)	Injury description
Male	40	66	L	21	Seated	0.0019 @ 8.9	2/1	Minimally displaced extra-articular fracture of the medial aspect of the mid-calcaneum
Male	48	88	R	24	Seated	0.0016 @ 7.8	0/0	No fracture
Female	51	58	L	23	Brace	0.0020 @ 6.8	0/0	No fracture
Male	57	60	L	19	Brace	0.0012@ 5.1	2/1	Imapacted fracture of talar neck. Schatzker type 5 fracture of tibial plateau.
Male	55	94	L	27	Standing hyper-extended	0.0039 @ 9.0	4/2	Dislocation of the subtalar and talo-navicular joints. Schatzker type 5 fracture of the tibial plateau.
Male	48	88	L	24	Standing hyper-extended	0.0061 @ 3.5	5/2	Severely comminuted intra-articular fracture of the calcaneus. Navicular fracture with dislocation of the talo-navicular joint. Minimally displaced lateral malleolar fracture.
Male	44	79	L	26	Standing neutral	0.0060 @ 7.1	5/2	Severely comminuted fracture of the calcaneum, with involvement of the anterior and posterior subtalar joints and calcaneo-cuboid joint. Lateral spread of the calcaneum
Female	51	58	R	23	Standing neutral	0.0076 @ 5.6	5/2	Comminuted fracture/dislocation of the calcaneum with a fracture of the anterior process of the calcaneum involving the calcaneo-cuboid joint. Fracture of the cuboid. Dislocation of the subtalar and talo-navicular joints. Asymmetry of the tibiotalar joint, in keeping with ligamentous instability. Minimally displaced fracture of the tip of the lateral malleolus.