ORIGINAL PAPER

CrossMark

Initial Adaption of the Injury Risk of the Human Leg Under High Rate Axial Loading for Use with a Hybrid III

Peter J. Mildon[1] · Douglas White[1] · Craig Girdlestone[2] · James Keirl[2] · William McGeehin[1] · Mark Dorn[1] · Andrew J. Sedman[2] · Spyros D. Masouros[3]

Abstract

Hybrid III Anthropomorphic Test Devices (ATDs) are widely used in testing of military vehicles against Under Body Blast. The relationship, however, between the axial load through the lower leg of the Hybrid III and that through the human tibia has not been quantified. This paper describes a transfer function that relates the measurement from the lower tibia load cell of a booted Hybrid III to the axial force in a post mortem human subject (PMHS). By incorporating this transfer function into an existing injury risk function, a prediction of the likelihood of fracture within the human leg can be obtained from the Hybrid III data. By changing the values of the coefficients within the transfer function to those derived using the maximum error, rather than the average, conservative predictions of probability of fracture can also be obtained. The transfer function is based on a combination of published experimental data, new experiments, and computational modelling. This imposes limitations on the applicability of this prediction process and its accuracy: the time to peak axial force must be less than 10 ms; the accuracy of the prediction depends on the veracity of the PMHS lumped-parameter model used, and the predictions are only truly applicable to the specific boot used in this study. This tentative prediction process indicates that the 10% probability of fracture for a 55 kg female under 40 years old and for an 85 kg male under 40 years old wearing a desert combat boot is related to forces measured by the lower tibial load cell of a Hybrid III wearing the same boot of 7.2 and 11.7 kN, respectively. The transfer function suggested here is the best tool to date for interpreting Hybrid III leg forces into risk of injury to the human leg.

Keywords Lower limb · Risk function · Fracture · Impact · Blast · Hybrid III · Combat boots

Introduction

Explosive attacks to vehicles epitomised recent conflicts in Iraq and Afghanistan and are likely to continue to be common in future conflicts and in post-war humanitarian efforts [1]. When a mine is detonated underneath a vehicle, high-rate axial loading is transferred to the legs of occupants causing injuries that often result in poor clinical outcomes [2, 3]. The industry standard for assessing the level of safety a vehicle offers to its occupants is through Anthropometric Test Devices (ATDs); these are mechanical representations of the human, designed to be human-like in terms of anthropometry and structural response. The current NATO description of such tests, AEP-55 Volume 2 [4], requires the use of a Hybrid-III ATD with its original leg and lower tibia load cell or replacing the original leg with the Military Lower Extremity (Denton model 585-0000). The recorded loads are then compared to pass/fail thresholds. Those thresholds are based on fracture loads obtained from studies on post mortem human subject (PMHS). The response of the Hybrid-III leg, however, has been shown to be stiffer than that of a human lower limb in

✉ Andrew J. Sedman
  ajsedman@dstl.gov.uk

[1] Frazer-Nash Consultancy Ltd, Stonebridge House, Dorking Business Park, Dorking, Surrey RH4 1HJ, UK

[2] Blast & IED and Injury Analysis & Modelling Team, Platform Systems Division, C012 Building 04, Dstl Porton Down, Salisbury, Wiltshire SP4 0JQ, UK

[3] Department of Bioengineering, Imperial College London, London SW7 2AZ, UK

simulated under-vehicle explosions [5–7]. The AEP-55 pass/fail thresholds do not account for this difference.

In addition, the relationship between axial force in the PMHS and a Hybrid III when boots are worn is unknown; yet, during vehicle testing, the ATDs are normally dressed with relevant clothing and personal protective equipment (including boots). Data available from booted PMHS tests and comparable booted Hybrid III tests are too limited to develop a risk function directly. At the same time, previous risk functions available used data from unbooted PMHS tests. Therefore, a transformation that accounts for both the use of the Hybrid III and the inclusion of boot materials within the load path is required.

Existing work that can inform the development of the transformations includes that of Barbir [8] who carried out tests on a booted Hybrid III under three loading conditions. Unbooted Hybrid III and PMHS were also tested under these conditions, with the exceptions of the Hybrid III for most severe condition and PMHS for the least severe condition. The PMHS tests (five at each loading condition) used an implanted mid-shaft tibia load cell to report tibia force. McKay [9] carried out 18 unbooted PMHS tests using the same apparatus and method as Barbir [8] addressing three additional loading conditions.

While comparative tests between unbooted Hybrid III and PMHS legs are reported by Bailey et al. [6], only two data sets that include tibial force measurements are provided. A block of polyurethane was used between the foot and floor as a 'pulse shaper', that block may have behaved in a similar way to boot material. Further insights on potential transfer functions are provided by Kuppa et al. [10]. In addition to eight PMHS tests using a pendulum rig at four loading conditions, they also carried out a Hybrid III test at each of the four loading conditions. While they used an original Hybrid III that lacks biofidelic heel pad compression characteristics, a 25.4 mm rubber layer was used between the impactor and the foot of both the PMHS and the Hybrid III. Kuppa et al. [10] also investigated the stiffness and damping of each test carried out and demonstrated that the transfer function between the force measured at the knee of the PMHS and the Hybrid III depends on the time to peak force. They found a variation in the transfer function with time to peak force greater than 10 ms.

Comparison between the Hybrid III leg and PMHS were carried out by Owen et al. [11]. Three loading conditions were considered; a strike to the heel, a strike to the toe for a relaxed PMHS, and a strike to the toe of a specimen in which Achilles tendon tension was applied. This study found a similar relationship between the heel strike and the unbooted tests by Bailey et al. [12] and Barbir [8], with the Hybrid III reporting a higher load than the PMHS. The relaxed toe strike, however, reported a higher force in the PMHS than in the Hybrid III. The time to peak force for this single data point was an order of magnitude higher (at approximately 50 ms) than all the other tests reviewed. The different relationship may be explained by Kuppa et al.'s [10] rate dependent transfer function, as this data point is in the regime of strong variation in transfer function with time to peak force.

In addition to practical experiments, numerical modelling studies have also been conducted. For example Bailey et al. [12] developed a finite element (FE) model of the Hybrid III leg that was calibrated to drop tower tests on the physical Hybrid III. The response of the FE model of the Hybrid III was compared to a FE model that was developed for a 50th percentile male PMHS. Bailey et al. [12] fitted a second-order polynomial to the simulated data in order to develop a transfer function and stated that the function slightly overestimated peak tibia force when compared to published experiments on PMHSs.

The aim of this paper is to develop an improved interpretation of the loads measured by booted Hybrid III ATDs to assess the risk of leg fractures of booted vehicle occupants due to high rate axial loads, by developing a relationship between the loads measured by the ATD and the results of PMHS studies. This is done by developing a transfer function between loads measured in the Hybrid III and those measured in the PMHS, and then applying that to the fracture risk function developed by Mildon et al. [13] from a meta-analysis of PMHS data.

Methods

In order to develop a transfer function between loads measured in the Hybrid III and those measured in the PMHS with and without boots three steps were taken: (a) studies in the literature that could inform such a function were analysed, (b) additional data were produced by carrying out simple pendulum experiments, and (c) lumped parameter models of Hybrid III and PMHS legs were utilised.

Hybrid III and PMHS Comparative Data

Axial load data from the papers described in the introduction were collected for Hybrid III and PMHS. To account for variations in location of PMHS force measurement, a scale factor in accordance with the mapping found in Mildon et al. [13] between PMHS tibia and knee force was used.

Hybrid III Testing

To provide additional data for the development of a booted Hybrid III to booted PMHS transfer function, a series of simple practical tests were undertaken using a booted Hybrid III leg. The tests matched key aspects of those by Gallenberger [14] on booted PMHSs.

The instrumented Hybrid III leg was fitted with a desert combat boot (UK size 10 Lowa 'Elite Desert' boot as issued to the UK Armed Forces). To restrict lateral motion the leg was suspended using rope slings, at both the ankle and knee. The lower leg was in the neutral position, with the tibia horizontal. The foot was placed at 90° to the tibia, with the toes pointing down. The Hybrid III thigh was kept attached to the knee, providing an effective ballast of 6.47 kg. The experimental arrangement is shown in Fig. 1.

Pendulums with masses of 2.40 and 3.50 kg were used. The resting pendulum's height was adjusted so it would strike the heel of the Hybrid III, in line with the ankle and knee joints. Different release heights were used to generate a range of strike velocities. Those velocities were measured using high speed video photography (Photron Fastcam SA5 model 1000 k-M2), operating at 500 frames per second.

Force was recorded using the lower tibia load cell. The data were passed through an amplifier and anti-aliasing filter, and then sampled at 25 kHz. To support comparison to the results from Gallenberger [14], the force response was filtered using CFC1000 filter simulated in Matlab (R2014a, version 8.3, Mathworks, USA).

The ballast mass used in these tests was less than the ballast mass of 11.5 kg used by Gallenberger [14]. This issue was explored using a computational model of the Hybrid III test (described in the following section), which showed that changing the ballast mass from 6.47 to 11.5 kg would have increased the recorded axial tibia force by approximately 10%. Therefore, the test results were scaled by a factor of 1.1 for comparison with the Gallenberger [14] tests.

Lumped Parameter Model of Hybrid III

To assess the effect of the boot's stiffness and also carry out sensitivity studies of other test parameters, a lumped parameter model of the Hybrid III leg was developed in ABAQUS Explicit (version 6.13-3, Simulia, USA); a schematic is shown in Fig. 2. The Hybrid III tibia was mounted at an angle to the line between the ankle and the knee, so an axial force would generate a bending moment in the tibia. In order to capture this effect, the tibia was modelled using five linear beam elements with an outer radius of 18.33 mm and a thickness of 5 mm, allowing the tibia to deflect and rotate in all six degrees of freedom. The remainder of the model consisted of point masses used to represent the impactor, boot, foot skin, foot structure, ankle, knee, and ballast. Tables 1, 2, and 3 provide details of the characteristics of the model. The model was constrained so that the impactor, boot, foot skin, foot structure, and ballast can only move with one (axial) degree of freedom. The ankle and knee joints were given additional rotational degrees of freedom to capture the free nature of the leg in the tests, and therefore not over-constrain the bending stiffness of the tibia. The top of the tibia had all of its degrees of freedom rigidly coupled to the knee-joint mass.

The tibia was represented with thin walled tube beam elements to calculate the bending stiffness. The impactor contact spring was given a non-linear spring definition, allowing uncoupled motion of the impactor and leg for positive displacements and negative displacements up to 10 mm from the initial location of the impactor. Defining the spring in this way allowed the impactor to separate from the leg following an impact.

The Hybrid III knee and foot joint stiffnesses were calculated based on the most compliant elements in their construction. For the knee, this was the two flat plates that connect the tibia to the knee hinge. For the ankle, this was the rod between the ball joint and the bottom of the tibia.

The heel pad compliant element was defined as a nonlinear spring, following the stiffness for typical Ensolite foam over the first 50% compression, before stiffening rapidly. To calibrate the foam damping level, the lower foot impact test defined in the European Directive 96/79/EC [16] on the certification procedure for the Hybrid III lower leg and foot was used.

Fig. 1 Schematic of the impact tests on booted Hybrid III lower leg
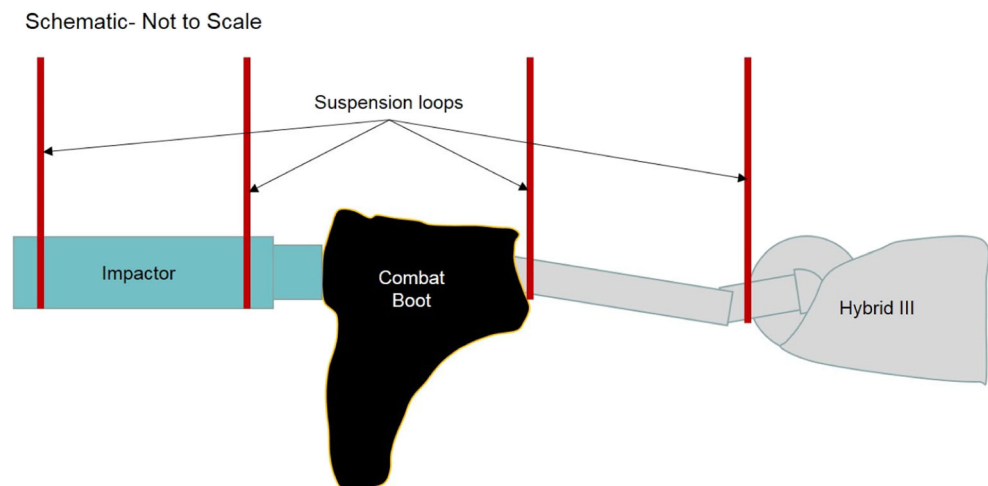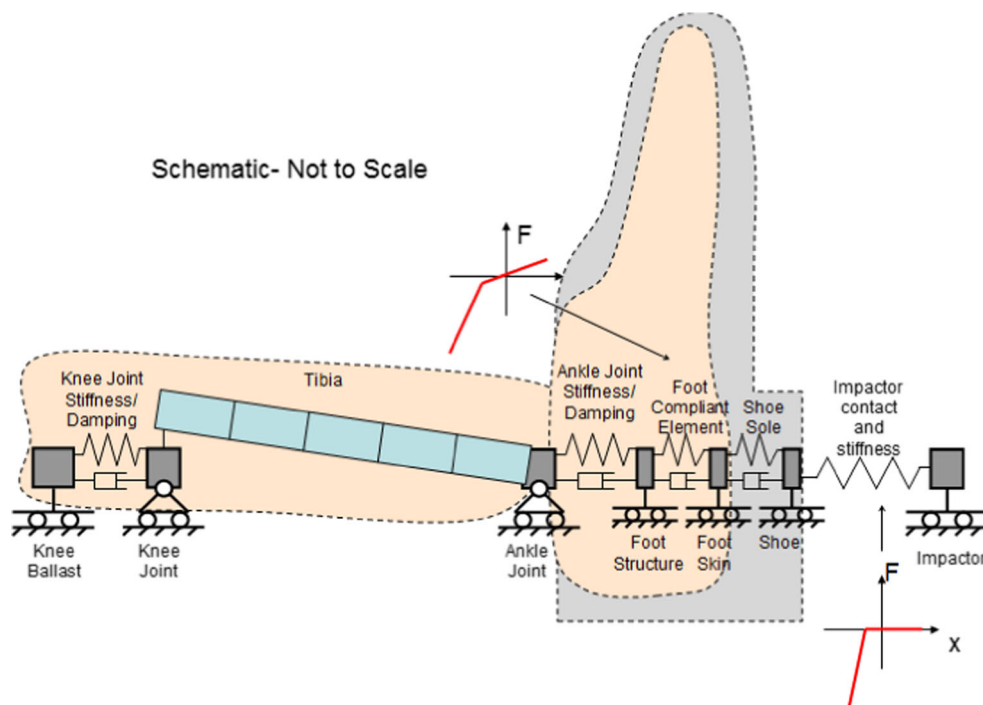

Schematic- Not to Scale

Fig. 2 Schematic of the lumped parameter model of the hybrid III lower leg

The European Directive 96/79/EC test fixes the Hybrid III at the knee, supports the ankle on a low friction table, and strikes the ankle with a pendulum. The model was updated to provide a fixed boundary condition to the knee ballast node in order to represent this configuration. As the test is defined for an unbooted Hybrid III, the axial degrees of freedom of the foot skin node and boot node were coupled. The impactor mass was set to 1.25 kg, and the stiffness was set to 211.8 kN/mm based on a calculation of the stiffness of the impactor as defined by the EU directive [16]. The impactor was given an initial velocity of -4.40 m/s (moving towards the ankle).

The model sampling rate was set to 20 kHz. The test specification defined that all data acquisition systems be filtered using a simulated CFC 600 filter (as specified by the EU directive [16]). A second-order Butterworth filter was therefore built in Matlab specifying the sampling rate of 20 kHz, and a 3 dB limit frequency of 1 kHz, as defined by SAE J211–1 [17] for a CFC 600 filter. The filter was run in both a forward and backward direction to achieve a zero phase shift, 4th-order filter. The heel pad damping was then adjusted to ensure the model matched the test requirements. The peak acceleration of

3.32 km/s^2 is within 1% of the required acceleration of 340 g $\pm 50 = 3.33$ km/s^2 specified by the EU directive [16].

Lumped Parameter Model of PMHS

A lumped parameter model based on Perry et al.'s [18] revised version of Henderson et al.'s [19] model of a 50th percentile male leg was produced. To this was added a representation of the boot, constructed in a similar manner to that within the model of the Hybrid III leg, Fig. 2. The values provided by Perry et al. [18] are reproduced in Table 4, and the values for the shoe are the same as those in Table 2. That lumped parameter model of the PMHS leg was used to generate a factor by which the unbooted Gallenberger [14] data could be mapped to booted PMHS data and therefore used in the development of a booted Hybrid III to booted PMHS transfer function.

Transfer Function

A simple transfer function between a booted Hybrid III and a booted PMHS was derived by mapping comparable results from the test data, (scaled by 1.1 to account for the differing

Table 1   Masses used in lumped parameter model of Hybrid III

Body	Impactor	Shoe	Foot skin	Foot structure	Ankle joint	Knee joint	Ballast mass
Mass (kg)	2.40[a] or 3.50[a]	0.946[a]	0.05[b]	1.11 [15]	1.585 [15]	1.585 [15]	6.47[a] or 11.5 [14]

[a] Values measured during Hybird III testing

[b] Best estimate prediction

Table 2 Stiffness and damping coefficients used in lumped parameter model of Hybrid III

Location	Impactor contact	Shoe sole	Foot compliant element	Ankle joint	Knee joint
Stiffness (N/mm)	− 235,600[a]	300	See Table 3	930,000	19,860,000
Damping coefficient (Ns/mm)	N/A	1.2	1.48	2.46	4.2

[a] Value is only applicable for less than − 10 mm of relative separation between the shoe and impactor otherwise the stiffness is zero

ballast mass) to the PMHS data from Gallenberger [14] together with a scaling factor for the effect of a boot (derived from the lumped parameter modelling). Recently, Mildon et al. [13], using published data from unbooted PMHS, provided a new risk function for fractures of the human leg under high rate axial loads that relate the probability of fracture to axial load, body mass, age, and sex. The derived transfer function between booted Hybrid III and booted PMHS was utilised to develop transformations for Mildon et al.'s [13] risk function.

Results

Hybrid III and PMHS Comparative Data

Data from the six papers described in the introduction are presented in Fig. 3 along with the transfer function presented by Bailey et al. [12]. PMHS tibia force data from Barbir [8] and McKay [9] have been increased by 16.7% in accordance with the mapping found in Mildon et al. [13] between PMHS tibia and knee force.

In Fig. 3, points that compare unbooted PMHSs to unbooted Hybrid IIIs (displayed as square or diamond points) are on a steeper trend than tests where both PMHS and Hybrid III impacts have been attenuated by either a rubber sheet (displayed as circular points) or a pulse shaper (displayed as a line). Points that represent a booted Hybrid III and an unbooted PMHS (displayed as crosses) fall on a shallower

Table 3 Foot compliant element non-linear stiffness against shoe and impactor separation used in lumped parameter model of Hybrid III

Relative separation between the shoe and impactor (mm)	Foot compliant element stiffness (N/mm)
− 35	− 500,000
− 30	− 90,000
− 11.25	− 2000
− 7.5	− 40.8
− 3.75	− 18
0	0
10	50

imagined trend line. Fracture data points are indicated in the legend by 'Censored'. It should be noted that an unfractured force value would have been to the right of the recorded value, should fracture not have occurred.

Hybrid III Testing

The pendulum masses used in this study (2.40 and 3.50 kg) bound the lower two masses used by Gallenberger [14] (3.30, 3.36, 5.70, 5.76, and 12.32 kg). As such, a linear interpolation of the gradients of the trend lines found in Fig. 4 was considered as a reasonable approach to scale the results for impactors of the 3.30 and 3.36 kg mass, permitting the axial force in a Hybrid III lower leg to be inferred for velocities used by Gallenberger [14] with the 3.30 and 3.36 kg impactors. Extending this approach to estimate velocity-force relationships for Gallenberger's [14] data produced using the 5.70, 5.76, and 12.32 kg impactors was considered inappropriate. These approaches were confirmed by further computational studies using the model described in 2.3.

The test results, for which the impact velocities range between 0.8 and 3.8 m/s, are shown in Fig. 4. Based on the logic that no force should be measured at zero strike velocity, the trend lines, one for each pendulum mass, were made to pass though the origin. This reduced the R^2 value by less than 1% for the 3.50 kg impactor, and less than 2% for the 2.40 kg impactor.

Lumped Parameter Model of Hybrid III

Having tuned the model to align with the certification procedure [16], its boundary conditions and output filters were reconfigured to match the tests presented in this paper. To allow the correct ratio of damping to stiffness of the boot to be assessed, impact velocities of three tests (1.0, 1.5, and 2.6 m/s) with the 2.4 kg impactor were simulated. Values of boot damping and stiffness were adjusted until results had

Table 4 Lumped parameter model values provided in Perry et al. [18]

Body	Tibia		Foot	
Mass (kg)	m_2	2.66	m_1	0.946
Stiffness (N/mm)	k_2	1198	k_1	300
Damping coefficient (Ns/mm)	c_2	0.499	c_1	1.2

Fig. 3 Data from comparative tests between PMHSs and the Hybrid III from the six studies
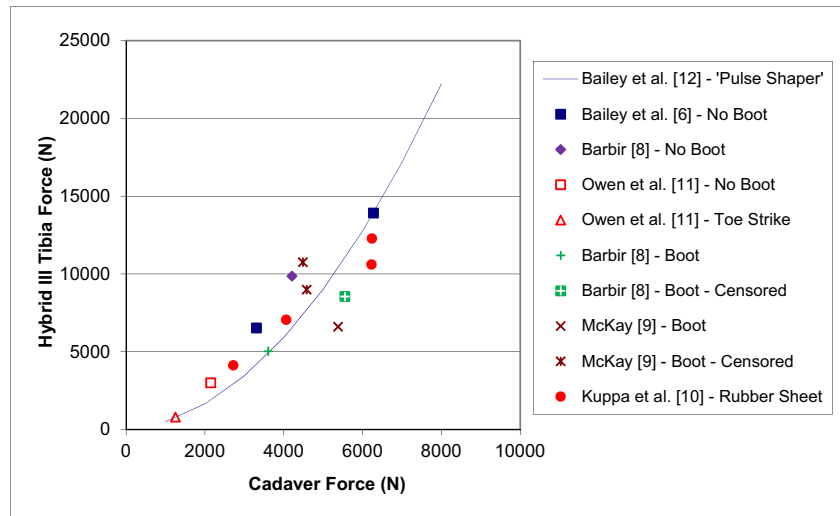
converted to the expected forces based on the trend lines fitted to the experimental data (Fig. 4). The impactor mass was then increased to 3.5 kg, and impacts at three further velocities (0.9, 1.4, and 2.4 m/s) were simulated to validate the results. The properties determined for the boot based on these results were a stiffness of 300 N/mm and a damping coefficient of 1.2 Ns/mm.

Lumped Parameter Model of PMHS

The model was run with a 2.4 kg impactor at three velocities (1.0, 2.0, and 3.0 m/s), both with and without a boot. Results from the analysis of all three velocities found that the boot

reduced the peak force by factor of 0.54 ± 0.007. A scaling of 0.54 was therefore used to generate a transfer function between a booted Hybrid III and a booted PMHS.

Transfer Function

The derived relationship between PMHS and Hybrid III axial tibia force at the knee is plotted in Fig. 5. The PMHS vertical error bars include both the natural variation in the human samples and also experimental error. The maximum percentage difference between any PMHS test result and the mean value of the group of results from which it is drawn was found

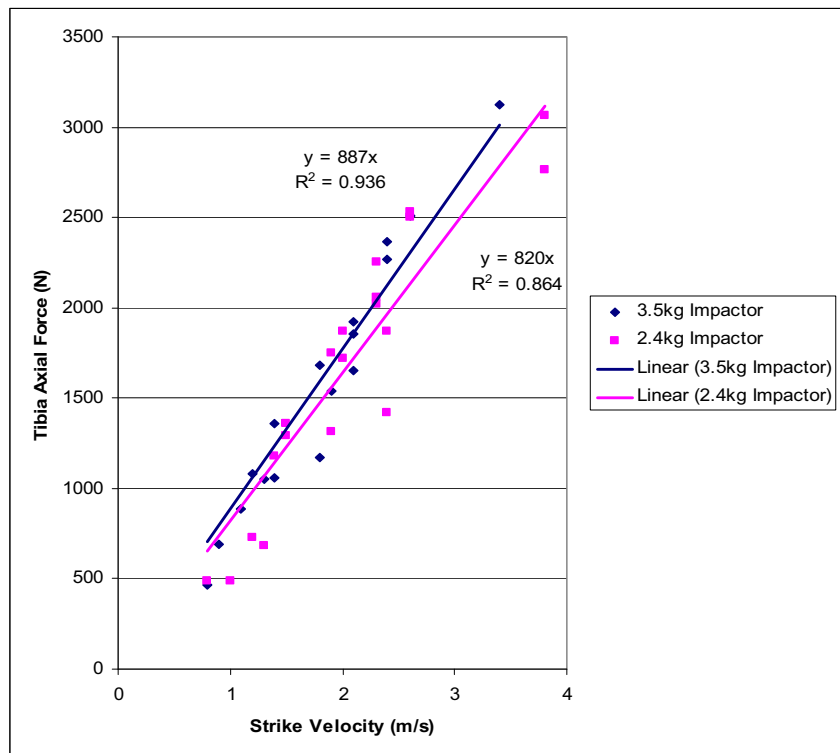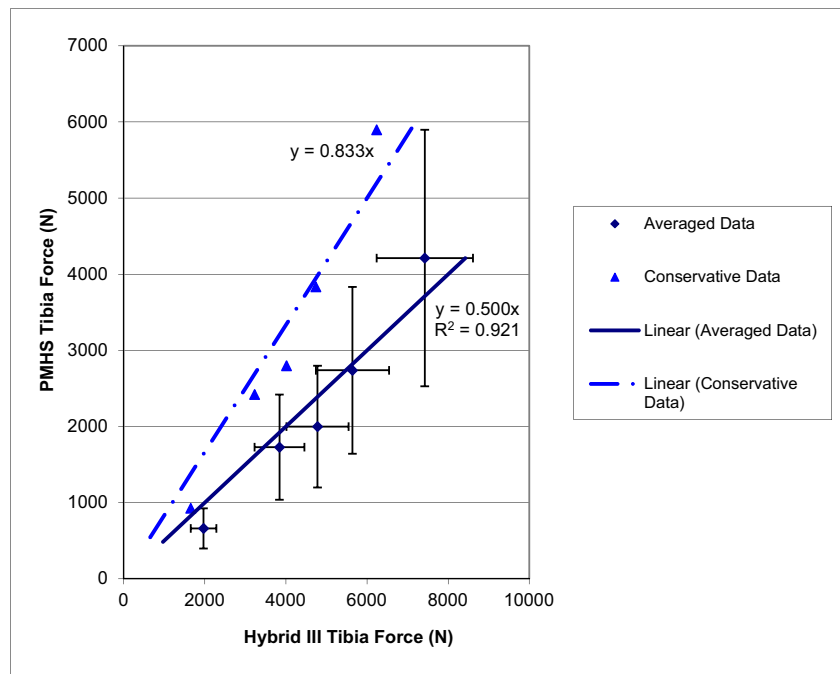**Fig. 4** Booted Hybrid III test data using two impactor masses

Fig. 5 Relationship between Hybrid III tibia force and PMHS tibia force as measured at the knee for high rate axial loading. Vertical error bars are at 40% to represent maximum possible variation in PMHS data

to be 40%. To produce a conservative representation of the variation within the available data, this 40% error has been applied to every data point, and is expressed by the PMHS error bars shown in Fig. 5. The Hybrid III error shown is the expected error, based on the mean percentage difference seen between any test data point in Fig. 4, and the trend lines fitted. This was found to be 16%.

A trend line was fitted though the averaged data points. To ensure that physically meaningful PMHS loads are predicted from small Hybrid III loads, the trend line was forced to pass though the origin (reducing the R^2 value from 0.974 to 0.921). The resulting transfer function is the best linear estimate of the true relationship for the available data.

To provide a conservative transfer function, a second trend line has been fitted to the maximum error on the two axes, so bounding the variation seen in PMHS and the errors from the Hybrid III testing.

$$F_{BC} = 0.500 \, F_{BHIII} \tag{1}$$

Best estimate transfer function, where

F_{BC} Booted PMHS Force
F_{BHIII} Booted Hybrid III Force

$$F_{BC} = 0.833 \, F_{BHIII} \tag{2}$$

Conservative transfer function.

Transformed Risk Function for Use with Hybrid III Load Data

Mildon et al. [13] provided a new fracture risk function applicable to high rate axial loading of the human leg. That risk function was developed to provide a prediction of the risk of lower limb injuries for a younger population, that is more representative of military personnel (of both sexes), rather than the more elderly PMHS population for which the raw data was drawn. To enable that risk function to be used with Hybrid III load data, the simple transfer function (Eqs. 1 or 2 as appropriate) can be integrated into it, the revised risk function is presented in Eq. 3. The resulting value can be used to estimate the probability of fracture within the PMHS leg via Eq. 4 [13].

$$R_{amg} = \begin{cases} \dfrac{T}{17.6} F_{BHIII} \left(\dfrac{7650}{m + 350} \right), & |\text{Male and } A \leq 40 \\[2mm] \dfrac{T}{17.6} F_{BHIII} \left(\dfrac{A^2 - 80A + 9250}{m + 350} \right), & |\text{Male and } A > 40 \\[2mm] \dfrac{T}{66} F_{BHIII} \left(\dfrac{6750}{m + 8} \right), & |\text{Female and } A \leq 40 \\[2mm] \dfrac{T}{66} F_{BHIII} \left(\dfrac{A^2 - 80A + 8350}{m + 8} \right), & |\text{Female and } A > 40 \end{cases} \tag{3}$$

Optimised age, body mass, and sex dependent risk function, where

T Transfer function, 0.500 for the best estimate transfer function, 0.833 for the conservative transfer function.
R_{amg} Risk function linking force, age, body mass, and sex to the risk of fracture due to axial loading applied at the foot.

F_{BHIII}	Axial tibia force measured in the Hybrid III lower tibia load cell (kN)
A	Age (years)
m	Body mass (kg).

$$P_f\left(R_{amg}\right) = 1 - e^{-\left(\frac{R_{amg}}{9.8617}\right)^{4.277}} \qquad (4)$$

Probability of fracture.

Using the risk function and transfer function in this way indicates that the 10% probability of fracture in a human wearing a desert combat boot subjected to a low velocity impact equates to a peak force measured in a similarly booted Hybrid III of 7.2 kN for a 55 kg female under 40, and to 11.7 kN for an 85 kg male under 40.

Discussion

A simple transfer function has been developed so that a fracture risk function for unbooted PMHS data can be used with the loads measured in a booted Hybrid III. Many factors influence the accuracy of the predictions; some relate to the data on which the risk function was constructed and how they were interpreted by Mildon et al. [13]. Others relate to the transfer function developed in this work.

To increase the amount of data available to develop the transfer function, a range of approaches including physical testing and numerical modelling were used. While these approaches address limitations in the available data, they are only a substitute for a full experimental study focused on this area. As further such evidence becomes available, the robustness of this substitution can, and should, be tested.

The transfer function was developed through analysis of impacts with a time to peak force of about 3 ms, and is judged to be applicable to loads with a time to peak force of up to 10 ms. For greater times to peak force, it is expected that the relationship between the PMHS and Hybrid III response will change as indicated by Kuppa et al. [10]. This transfer function was developed using pendulum tests. The loading rates in a blast event are expected to be higher. While extrapolation of Kuppa et al.'s [10] loading rate investigation to higher rates suggests that this may not affect the transfer function between PMHSs and the Hybrid III, the different constitutive materials, associated rate dependencies, or initial effects are not factored into such a simple transfer function.

The transfer function's accuracy depends on the veracity of the computational model of the Hybrid III lower leg, the PMHS lumped-parameter model derived by Perry [18] and used in this work, and the data analysis methods. In particular, it has been assumed that the linear relationships shown in Figs. 3 and 4 should pass through the origin. While that

appears logical, it is built on the premise that the relationship is still linear close to the origin. Further, while such an assumption appears to be correct, having a function that is a more accurate predictor within the injurious loading regime but gives erroneous load results within the non-injurious regime may be preferable. These important issues should be investigated further when sufficient data is available, for if this transfer function is to be of use, it has to be sufficiently robust within the loading regime of interest. For example, the loads predicted in relation to a 10% probability of fracture are above those of the underpinning experimental data, and so currently those predictions have restrictions.

The transfer function is only applicable to the specific boot tested in this study as the results are likely to vary for other boots. This aspect could be investigated using a detailed finite element model of the booted Hybrid III with a more complex material model of the boot similar to Newell et al.'s [20] model of the MIL-Lx.

While the simplicity and accuracy of the transfer function result from the paucity of data available to build it, the work described in this paper takes a step towards providing improved assessments of injury risk from data collected by Hybrid III ATDs deployed in full scale experiments of vehicles subjected to under belly blast. As more data becomes available further improvements will be possible.

This paper addresses the prediction of only one form of injury within a particular test scenario. While the intent is to use this information to understand the risk of, and reduce the occurrence of, such injuries, the exploration of the relationship between such experimental assessments and operational scenarios is outside the scope of this paper.

Conclusions

A simple linear transfer function was developed to map the axial force reported by the lower tibia load cell of a booted Hybrid III ATD to the force experienced at the knee of a booted PMHS. A conservative transfer function was also developed by considering the experimental errors in the Hybrid III testing, and the combination of experimental errors and natural variation in the PMHS testing.

The lower leg fracture risk function by Mildon et al. [13] has been updated to include this transfer function, thereby providing a new route to link the axial force measured in the lower tibial load cell of a Hybrid III ATD during test of vehicles attacked by mines to the probability of leg fracture for a human under similar circumstances, which accounts for age, body mass, and sex.

The transfer functions are based on the available data, none of which is for loads above 8 kN. Using these relationships with higher loads should be appropriately caveated, until they can be validated or improved.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

References

1. Ramasamy A, Hill AM, Hepper AE, Bull AMJ, Clasper JC (2009) Blast mines: physics, injury mechanisms and vehicle protection. J R Army Med Corps 155:258–264

2. Ramasamy A, Hill AM, Masouros SD, Gibb I, Phillip R, Bull AMJ, Clasper JC (2012) Outcomes from foot and ankle blast injuries. J Bone Jt Surg 95(e25):1–7

3. Ramasamy A, Hill AM, Phillip R, Gibb I, Bull AMJ, Clasper JC (2011) The modern "deck-slap" injury - calcaneal blast fractures from vehicle explosions. J Trauma 71:1694–1698. https://doi.org/10.1097/TA.0b013e318227a999

4. NATO (2014) STANAG 4569. AEP-55 Volume 2, Procedures for evaluating the protection level of logistic and light armoured vehicles for mine threat Edition C Version 1

5. Pandelani T, Reinecke D, Beetge F (2010) In pursuit of vehicle landmine occupant protection: evaluating the dynamic response characteristic of the military lower extremity leg (MiL-Lx) compared to the Hybrid III (HIII) lower leg. CSIR 3rd Biennial Conference

6. Bailey AM, Christopher JJ, Henderson K, Brozoski F, Salzar RS (2013) Comparison of Hybrid-III and PMHS response to simulated underbody blast loading conditions. IRCOBI Conference 2013, IRC-13-25

7. Newell N, Masouros SD, Ramasamy A, Bonner TJ, Hill AM, Clasper JC, Bull AMJ (2012) Use of cadavers and anthropometric test devices (ATDs) for assessing lower limb injury outcome from under-vehicle explosions. IRCOBI Conference 2012, IRC-12-38

8. Barbir A (2005) Validation of lower limb surrogates as injury assessment tools in floor impacts due to anti-vehicular landmine explosions. Dissertation, Wayne State University, Detroit. Michigan, USA

9. McKay BJ (2010) Development of lower extremity injury criteria and biomechanical surrogate to evaluate military vehicle occupant injury during an explosive blast event. Dissertation, Wayne State University, Detroit. Michigan, USA

10. Kuppa SM, Klopp GS, Crandall JR, Hall G, Yoganandan N, Pintar FA, Eppinger RH, Sun E, Khaewpong N, Kleinberger M (1998) Axial impact characteristics of dummy and cadaver lower limbs, National Highway Traffic Safety Administration, US, Paper Number 98-S7-O-10

11. Owen C, Lowne R, McMaster J (2001) Requirements for the evaluation of the risk of injury to the ankle in car impact tests. In 17th International Technical Conference on the Enhanced Safety of Vehicles

12. Bailey AM, Panzer MP, Salzar RS (2014) Development of a transfer function for interpreting Hybrid-III lower leg data from axial loading, IRCOBI Conference 2014, IRC-14-28

13. Mildon PJ, White D, Sedman AJ, Dorn M, Masouros SD (2017) Injury risk of human leg under high rate axial loading. Submitted for publication to Hum Factors Mech Eng Def Saf. https://doi.org/10.1007/s41314-018-0009-x

14. Gallenberger K (2013) Foot and ankle injuries in variable energy impacts. Dissertation, Marquette University, Milwaukee, Wisconsin, USA

15. Humanetics, Hybrid III 50th Male Dummy, Technical Specification, Assembly Weights. http://www.humaneticsatd.com/crash-test-dummies/frontal-impact/hybrid-iii-50th. Accessed 27 Oct 2014

16. European Parliament and of the Council (1996) Directive 96/79/EC, on the protection of occupants of motor vehicles in the event of a frontal impact and amending Directive 70/156/EEC. Appendix 7: Certification Procedure for the Dummy Lower leg and Foot, 16 December 1996

17. Safety Test Instrumentation Standards Committee (1995) Instrumentation for Impact Test- Part 1- Electronic Instrumentation, SAE J211–1 Rev.Mar95, SAE International, March 1995

18. Perry BJ, Gabler L, Bailey A, Henderson K, Brozoski F, Salzar RS (2014) Lower extremity characterisation and injury mitigation, IRCOBI Conference, IRC-14-26

19. Henderson KA, Bailey AM, Christopher JJ, Brozoski F, Salzar RS (2013) Biomechanical response of the lower leg under high rate loading, IRCOBI Conference 2013, IRC-13-24

20. Newell N, Salzar R, Bull AMJ, Masouros SD (2016) A validated numerical model of a lower limb surrogate to investigate injuries caused by under-vehicle explosions. J Biomech 49(5):710–717