Scaling animal to human injury response for use in improved behind armor blunt trauma injury criteria

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Abstract. Developed more than four decades ago, the current behind armor blunt trauma (BABT) evaluation standard based on plastilina clay has limited biofidelity for assessing thoracic injury from backface deformation (BFD) from high-velocity rifle threats. Further, the standard relies on complex and uncertain analogies between an animal model and human thoracic and injury response. To improve the biomechanical basis for future BABT injury assessments, we have performed representative BABT impacts on swine and human cadavers for BFD velocities representing high-velocity rifle rounds on hard armor plates. Impactor dynamics were determined using an onboard accelerometer and high-speed video, and rib fractures were assessed using post-test micro-CT imaging and necropsy. The kinetic energy of the impact was scaled according to body mass based on equal velocity scaling, widely used in injury biomechanics. This scaling was used in logistic survival analysis to determine rib fracture injury risk for cadaveric swine and humans. Scaled impact energy to produce a 50% risk of rib fracture was 113.9 Joules (J) (Confidence Interval [CI]: 90.3, 137.6) for the human cadavers and 143.9 J (CI: 103.8, 184.1) for the porcine cadavers. Confidence intervals of injury risk curves substantially overlap for the human and swine cadavers, suggesting that this scaling is appropriate for transferring risk across these species. Residual energy differences of 20 to 30% for similar injury risk between the human and swine cadavers suggest an additional bone quality scaling is desirable since the swine cadavers are generally at an earlier developmental age than the available human cadavers. This is the first comprehensive study to provide scaling to humans from a porcine model of hard armor BABT. The structural scaling relationships between the human and swine cadavers are valuable in developing transfer functions for injury risk curves from planned live swine BABT impact experiments assessing the pathophysiology.

1. INTRODUCTION

Body armor provides effective protection from penetrating trauma for military and law enforcement personnel [1,2] using a 'passive defeat' mechanism that transfers localized momentum from the incoming round into the regional momentum of the deforming body armor. This mechanism slows and often fragments or deforms the projectile, greatly reducing the potential for penetration of the armor. However, a defeated round can still cause the armor backface to deform into the thorax or other body regions and cause damage to the underlying anatomy, known as behind armor blunt trauma (BABT). This BABT to the skeletal anatomy and internal organs, such as lungs, heart, and liver, can cause severe morbidity or death [3-6].

Initially developed more than four decades ago, the current BABT evaluation standard based on a maximum of 44 millimeter (mm) deformation measured in plastilina clay has limited biofidelity for its current uses, such as assessing thoracic injury from backface deformation (BFD) resulting from high-velocity rifle threats. Further, the standard relies on complex and uncertain analogies between the animal model and human thoracic and injury response based on limited testing with goat thoraces. Goats with mass 40-50 kg (assumed equal to a human) were exposed to a handgun round impacting on a soft body armor. Roma Plastilina #1 (RP1) clay was found to deform at different (stiffer) rate, but the final deformation was similar to the final deformation in goats as well as in gelatin based on high speed video. The soft armor was then shot with a gelatin backing in a configuration that was estimated to produce a 10% lethality based on a general blunt impact model, but no actual lethality in animals was tested [5, 7-9]. The average maximum deformation in the gelatin was 44 mm which was then assumed to be equal to the clay, and representative of the human torso response [9]. No correlation between BFD and injuries was established. The original researchers and many later researchers have called for additional animal and surrogate tests to improve these initial assessments [10], with a particular focus on the potential to improve and optimize hard armor characteristics based on a systematic assessment of BABT injury biomechanics. The standard was developed to be conservative, and as such modern hard body armor provides high levels of protection, while potentially being excessively heavy. A critical target for

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optimization is reducing soldier-borne mass and bulk while maintaining effective ballistic protection. The weight, bulk, and thermal load of armor reduce the mobility of the Warfighter, which negatively impacts operational performance [11-13]. Region-based thoracoabdominal injury criteria are necessary to provide tools to avoid under-designing (i.e., increased risk of penetration or BABT injury for a given threat) or over-designing armor (i.e., carrying unnecessary mass).

Currently, unavailable injury criteria for BABT include injuries to the human skeletal components under direct backface loading and injuries to underlying organ systems from stress transmitted through the wall of the thorax. Injuries may include acute damage, such as bony fracture, and injuries that require physiological processes to develop, such as lung contusion or commotio cordis [14]. Experiments using human cadaveric specimens can provide accurate kinematic and dynamic responses of the body and bony fracture tolerances; however, live animal model testing is needed to provide systemic injuries and injuries that require physiology to develop. Since there are differences between living humans, human cadavers, and live animal models, scaling principles are needed to relate dynamic responses, injury structures, and physiological results between human and swine models.

Adult swine are the most analogous animal model to humans when studying BABT due to the similarities in size and thorax anatomy [15-18]. The swine model is also widely used in automotive standards to closely represent human thoracoabdominal organs in a car crash scenario [19]. These scaling relationships will be essential for translating results from future in vivo animal research. For the current study, physiological scaling based on allometry (power law scaling relative to body mass) and the concept of physiological time (species specific time scale based on heart rate, respiratory rate, immune response, development rate) suggests that physiological scaling between adult swine and humans is unity [20]. Structural mechanical scaling is used between swine and humans of different sizes. The current study develops structural mechanical scaling for rib fractures resulting from BABT between porcine and human cadavers based on the equal velocity approach outlined by Eppinger et al. (1984) [21].

2. METHODS

2.1 Cadaveric Impactor Tests

A BABT impactor was designed to match mass and shape from BFD profiles collected from high-speed flash x-rays of human cadaveric surrogate response during hard armor defeats of a realistic battlefield threat [3, 22]. This indenter was 3D printed in polycarbonate, with a diameter of 100 mm, dome height of 25 mm, and mass of 0.22 to 0.36 kilograms (kg). A tri-axial linear accelerometer (Endevco 7284A-60k) was mounted on the back surface of the indenter. The impactor was launched at a range of velocities (13 to 52 meters per second [m/s]) using pressurized helium gas to simulate BABT impacts.

Whole-body unembalmed human cadavers and recently sacrificed adult swine cadavers were exposed to impacts to the ribcage at representative BFD velocities. Impacted areas included anterior and posterior lungs, posterior kidneys, and lateral covered liver. In the current analysis, no distinction is made between specific impact sites on the ribcage. Both surrogates were tested with increasing velocities, and x-rays were obtained in some specimens between tests; however, palpations and clinical assessments were done in all specimens between tests to ensure structural integrity before additional testing in other body regions. Linear strain gages (Micro-measurements C4A-09-060SL-350-39P) and acoustic sensors (Physical Acoustics S9225) were mounted to the ribcage, and pressure transducers (Millar Mikro-Tip SPR-524) were inserted into the lungs through the trachea. Tri-axial linear accelerometers (Endevco 7270A) were mounted on the spine. Data was gathered at a sampling rate of 100 kilohertz (kHz) or more, and high-speed video cameras (Phantom V711, Vision Research) were positioned at different planes to capture the impactor and surrogate kinematics. Following the final tests, a high-resolution computed tomography studies (i.e., CT scan) and a detailed necropsy were performed focusing on assessments of skeletal and soft tissue injuries. A bony fracture was classified as an injury, whereas the absence of bony fractures was classified as a non-injury.

2.2 Data Analysis

Impactor velocity was obtained from high-speed video imaging. The impact kinetic energy was calculated using the impactor mass and velocity, and this was used as an input variable for the injury risk calculation. In total, 73 rib impacts on 18 male cadaveric human specimens and 44 rib impacts on 16 cadaveric swine specimens were included. The body mass (± SD) for these specimens was 80.1 ± 10.9 kg for the human cadavers and 44.0 ± 10.0 kg for the swine cadavers. To normalize for specimen size, the impact energy was scaled using an equal velocity approach [20] according to the body mass of the tested specimen in both swine and human cadavers with unity scaling for allometry.

$$E_{scaled} = \frac{E_{specimen}}{\lambda} \text{ with } \lambda = \left(\frac{M_{specimen}}{M_{reference}}\right)^{a} \tag{1}$$

The reference mass, $M_{reference} = 80$ kg, represents the average male Warfighter body weight. For scaling between swine and humans, the allometric scaling exponent $a = 1$. These scaled kinetic impact energy results were then used to perform a survival analysis for rib fracture injury risk. Non-injury points were considered right censored, and injury points were considered interval censored between 0 Joules (J) and the scaled impact energy. Anderson-Darling coefficients were used to determine the optimal fit among logistic, log-logistic, Gaussian, and Weibull distributions.

2.3 Hard Armor Rifle Round Equivalence

To compare the impacts performed by the impactor to BFD of hard body armor, impacts were performed with the impactor onto RP1 clay contained in an aluminum sided box (56 cm x 56 cm x 14 cm) with plywood base according to the NIJ 0101.06 Ballistic Resistance of Body Armor Standard. These impacts were compared to impacts from a 7.62-by-51 mm-class threat round on hard polyethylene body armor on the same clay standard. Volume of deformed clay was found to have the best correlation to kinetic energy for the impactor as well as for the 7.62 round. To estimate a rifle round equivalence to the blunt impactor, the body armor was assumed to dissipate a certain amount of energy from the incoming round, with the remaining energy fraction (EF) being translated into kinetic energy of the armor backface. This percentage of energy not dissipated by the body armor was calculated by calculating the least squares fit for a residual kinetic energy to volume of displaced clay regression. This energy fraction was found to be $EF = 0.087$, meaning 92.3% of the kinetic energy of the bullet was dissipated by the armor. The impactor velocities can then be related to equivalent rifle round velocities as follows:

$$\frac{1}{2} m_{impactor}\, v_{impactor}^2 = EF * \frac{1}{2} m_{round}\, v_{round}^2 \tag{2}$$

$$v_{impactor} = \left(EF * \frac{m_{round}}{m_{impactor}}\right)^{1/2} v_{round} \tag{3}$$

The velocities of the impactor in the current study simulate BFD into hard personal protective armor from a 7.62-by-51 mm-class threat round at 206 to 890 m/s.

3. RESULTS

Of the 73 impacts (impact energy 100.4 ± 64.0 J) on the human cadavers, 58% (n = 42) had no skeletal injuries, and 42% (n = 31) had rib fractures. Of the 44 swine impacts (impact energy 89.0 ± 80.1 J), 52% (n = 23) had no injury, and 48% (n = 21) had rib fractures. The energy of the impacts by injury type before and after scaling is shown for the human and swine cadavers in Figure 1. Additional data from individual tests is available in Appendix 1 and 2. A separate survival analysis risk function was calculated for the scaled human cadavers and scaled porcine models. The resulting injury risk curves with 95% confidence intervals are shown in Figure 2. A parametric logistic distribution was the best fit among the distributions tested. While not identical, confidence intervals of injury risk curves substantially overlap for the human and swine cadavers, suggesting that this scaling may be appropriate for comparing risk across species. A 50% risk of rib fracture is obtained at a scaled impact energy of 113.9 J (CI: 90.3, 137.6) for the human cadavers and at 143.9 J (CI: 103.8, 184.1) for the porcine cadavers. Depending on the risk level, a porcine specimen required, on average, a 20 to 30% higher scaled energy to achieve the same injury risk. For example, at 20% risk the porcine energy is 21% higher, at 50% risk it is 26% higher, and at 80% risk it is 28% higher. Residual energy differences of 20 to 30% for similar injury risk between the human and swine cadavers suggest an additional bone quality scaling is desirable since the swine cadavers are generally at an earlier developmental age than the available human cadavers.

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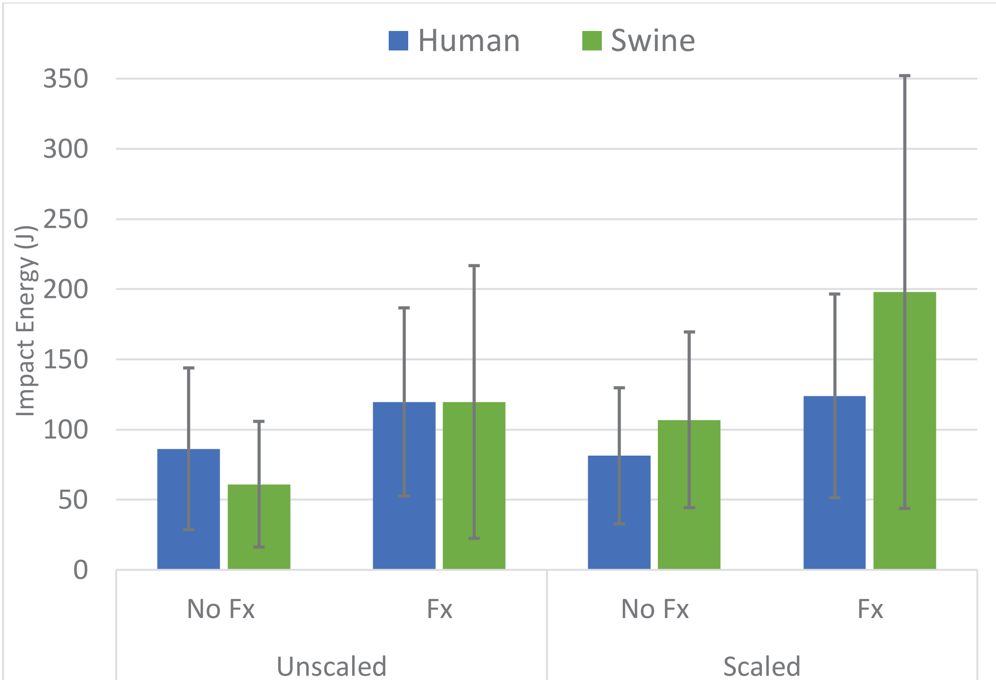

Figure 1. Kinetic energy of the impacts for which rib fractures (Fx) or no rib fractures (No Fx) occurred, for both human and swine cadavers, before and after body mass scaling. The bars indicate standard deviations. Scaling takes into account the body mass of the specimens, resulting primarily in higher scaled impact energy for the porcine cadavers.

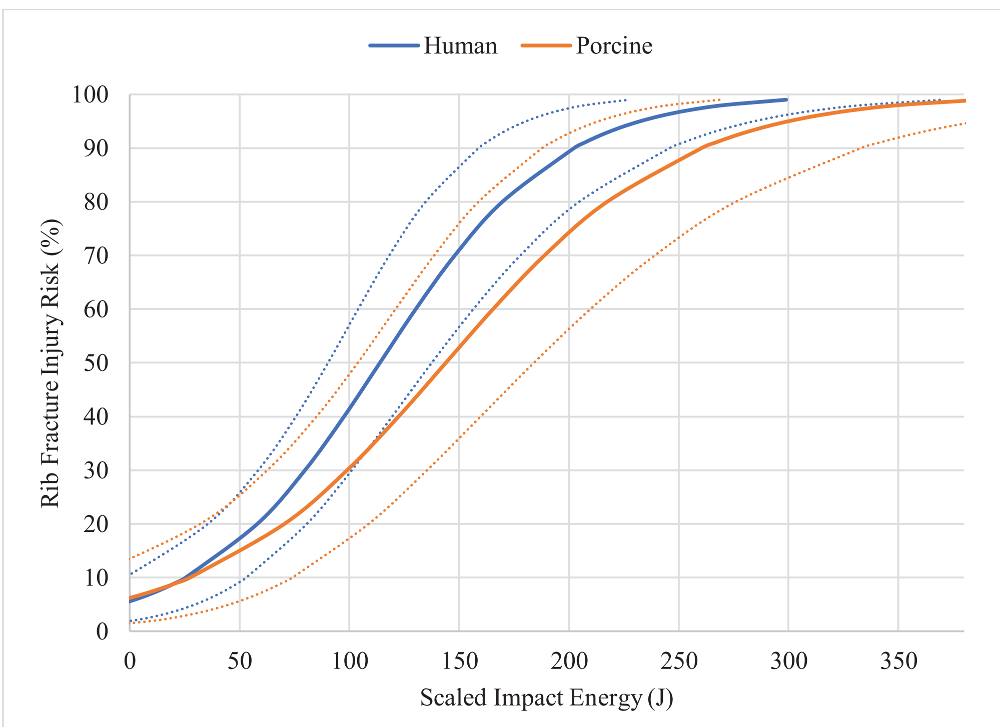

Figure 2. Rib fracture injury risk curve for BABT impacts to the ribcage in human and porcine cadavers. The dotted lines indicate the 95% confidence interval for the injury risk curves of the corresponding model.

4. DISCUSSION

Body mass scaling accounts for most of the differences in rib fracture injury risk in porcine cadavers compared to human cadavers, suggesting that a swine of approximately equal mass is a good skeletal surrogate for a human thorax, based on the overlapping injury risk curve confidence intervals. Since swine of equal or lesser weight than adult male humans are much younger in their developmental cycle than the human cadavers (58 ± 10.9 years old) tested, the ribcage structure contains more cartilaginous structures and is less brittle. This difference in brittleness may have contributed to the increased fracture resilience in the porcine specimens. The same is not necessarily true for internal organ injuries, as a rib fracture might dissipate more of the impact energy that is not transferred further into the thorax. Further analysis of internal organ injuries, especially for *in vivo* animal experiments, is needed.

These investigations including human and porcine cadavers, as well as *in vivo* porcine experiments, are currently underway. Thoracoabdominal regions investigated included the right and left lungs, heart, protected and unprotected liver, abdomen, kidney, and thoracic spine. The goal of these studies is to develop region-specific risk curves for BABT injuries.

In the current study, only male cadavers were included. To ensure applicability to the female Warfighter, subjecting female cadavers to an equivalent BABT regime should be a goal of future studies, especially considering the body mass scaling predicts increased risk of rib fractures for lower body mass.

One limitation of using a logistic distribution to predict injury is the asymptotic behavior near the lower end of the risk scale, combined with the interval censoring of injury data points. This results in elevated injury risk for impacts with 0 J energy, which does not represent reality. However, the logistic distribution still provided the best overall fit for the rib fracture injury risk across the range of impacts performed. Narrowing down injury censoring intervals using injury timing data from strain gauges and acoustic sensors attached to the ribs might improve these censoring intervals and the confidence intervals for the injury risk curves with further analysis.

5. CONCLUSIONS

This study is the first comprehensive approach to provide scaling for a porcine model between matched experiments simulating hard armor BABT events that incorporated BFD from the armor to whole-body human cadavers. The swine experimental model is widely used and accepted in automotive standards. The structural scaling relationships between the human and swine cadavers will be valuable in developing transfer functions from incapacitation-based injury risk curves from planned live swine BABT impact experiments exploring the physiology of BABT. Injury risk curves presented in this study may guide armor design, ensuring safety in the pursuit of lighter weight armor alternatives even when bullet penetration is prevented.

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Appendices

Appendix 1: Cadaveric Human BABT Test Data

Specimen	Test	Specimen Mass (kg)	Impactor mass (kg)	Impact Velocity (m/s)	Impact Energy (J)	Reference Scaled Energy (J)	Rib Fracture (0/1)	Scaled Rifle Velocity (m/s)
Human_01	1	81.2	0.36	21.4	82.7	81.4	0	447
Human_01	2	81.2	0.36	21.6	83.8	82.6	1	450
Human_01	3	81.2	0.36	40.9	301.4	296.9	1	853
Human_02	1	79.4	0.36	21.3	81.9	82.5	1	445
Human_02	2	79.4	0.36	20.8	77.7	78.2	1	433
Human_03	1	90.7	0.36	19.4	67.7	59.8	0	404
Human_03	2	90.7	0.36	39.6	282.4	249.1	0	826
Human_04	1	81.6	0.36	19.1	65.5	64.2	1	397
Human_04	2	81.6	0.36	18.8	63.3	62.0	1	391
Human_05	1	89.8	0.22	26.0	74.2	66.1	0	423
Human_05	2	89.8	0.22	33.3	121.7	108.4	1	542
Human_06	1	73.9	0.22	23.5	60.8	65.8	1	383
Human_06	2	73.9	0.22	20.3	45.2	48.9	1	330
Human_07	1	86.6	0.22	17.4	33.2	30.7	0	283
Human_07	2	86.6	0.22	23.3	59.7	55.1	1	379
Human_08	1	77.1	0.22	22.3	54.6	56.7	0	363
Human_08	2	77.1	0.22	21.0	48.6	50.4	0	342
Human_09	1	82.5	0.22	14.8	24.0	23.3	0	241
Human_09	2	82.5	0.22	15.4	26.2	25.4	0	251
Human_10	1	77.1	0.22	18.7	38.5	40.0	0	305
Human_10	2	77.1	0.22	18.8	38.9	40.3	0	306
Human_11	1	52.3	0.24	20.3	49.4	75.5	0	345
Human_11	2	52.3	0.24	19.4	45.1	69.0	0	330
Human_11	3	52.3	0.24	27.2	88.8	135.9	0	463
Human_11	4	52.3	0.24	28.3	96.1	147.0	1	482
Human_11	5	52.3	0.24	18.3	40.0	61.1	0	311
Human_11	6	52.3	0.24	39.6	187.9	287.4	1	673
Human_12	1	65.8	0.24	18.8	42.3	51.5	0	320
Human_12	2	65.8	0.24	42.0	211.4	257.0	1	714
Human_13	1	88.5	0.251	20.6	53.5	48.3	1	359
Human_13	2	88.5	0.251	20.4	52.3	47.2	0	355
Human_13	3	88.5	0.251	20.2	51.0	46.1	0	351
Human_13	4	88.5	0.251	29.5	109.4	98.9	1	514
Human_13	5	88.5	0.251	21.4	57.7	52.2	0	373
Human_13	6	88.5	0.251	29.5	109.5	99.0	0	514
Human_13	7	88.5	0.251	40.5	206.3	186.5	1	706
Human_13	8	88.5	0.251	29.5	109.5	99.0	0	514
Human_13	9	88.5	0.251	40.5	205.5	185.8	1	704

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Specimen	Test	Specimen Mass (kg)	Impactor mass (kg)	Impact Velocity (m/s)	Impact Energy (J)	Reference Scaled Energy (J)	Rib Fracture (0/1)	Scaled Rifle Velocity (m/s)
Human_14	1	95.3	0.251	21.7	59.1	49.6	0	378
Human_14	2	95.3	0.251	30.2	114.5	96.1	0	526
Human_14	3	95.3	0.251	39.6	196.8	165.2	1	689
Human_14	4	95.3	0.251	20.1	50.7	42.6	0	350
Human_14	5	95.3	0.251	30.1	113.7	95.4	1	524
Human_14	6	95.3	0.251	20.5	52.7	44.3	0	357
Human_14	7	95.3	0.251	29.0	105.5	88.6	0	505
Human_14	8	95.3	0.251	38.7	188.0	157.8	0	674
Human_14	9	95.3	0.251	30.2	114.5	96.1	0	526
Human_14	10	95.3	0.251	39.1	191.9	161.1	0	680
Human_15	1	95.3	0.262	20.8	56.4	47.4	0	369
Human_15	2	95.3	0.262	30.0	118.3	99.3	0	534
Human_15	3	95.3	0.262	39.8	207.2	174.0	1	707
Human_15	4	95.3	0.262	20.0	52.2	43.8	0	355
Human_15	5	95.3	0.262	30.7	123.7	103.8	0	546
Human_15	6	95.3	0.262	39.7	206.8	173.6	1	706
Human_15	7	95.3	0.262	30.9	125.4	105.3	0	550
Human_15	8	95.3	0.262	40.1	210.8	177.0	0	713
Human_15	9	95.3	0.262	29.3	112.7	94.6	0	522
Human_15	10	95.3	0.262	40.4	214.2	179.8	0	719
Human_16	1	64.0	0.266	20.5	55.9	69.9	1	367
Human_16	2	64.0	0.266	20.2	54.3	67.8	1	362
Human_16	3	64.0	0.266	20.2	54.3	67.8	0	362
Human_16	4	64.0	0.266	30.1	120.5	150.6	1	539
Human_16	5	64.0	0.266	19.9	52.7	65.8	0	357
Human_16	6	64.0	0.266	29.8	118.1	147.6	0	534
Human_16	7	64.0	0.266	39.2	204.4	255.5	1	702
Human_17	1	74.8	0.276	26.6	97.6	104.4	1	485
Human_17	2	74.8	0.276	25.2	87.6	93.7	1	460
Human_17	3	74.8	0.276	32.8	148.5	158.8	1	599
Human_17	4	74.8	0.276	20.7	59.1	63.2	1	378
Human_18	1	85.3	0.276	19.0	49.8	46.7	0	347
Human_18	2	85.3	0.276	17.3	41.3	38.7	1	316
Human_18	3	85.3	0.276	17.2	40.8	38.3	0	314
Human_18	4	85.3	0.276	24.6	83.5	78.3	1	449

Appendix 2: Cadaveric Swine BABT Test Data

Specimen	Test	Specimen Mass (kg)	Impactor mass (kg)	Impact Velocity (m/s)	Impact Energy (J)	Reference Scaled Energy (J)	Rib Fracture (0/1)	Scaled Rifle Velocity (m/s)
Swine_01	1	37.6	0.22	15.3	25.7	54.8	0	249
Swine_01	2	37.6	0.22	15.6	26.8	57.0	0	254
Swine_02	1	45.4	0.22	12.7	17.7	31.2	0	207
Swine_02	2	45.4	0.22	25.1	69.4	122.2	0	409
Swine_03	1	42.6	0.22	16.8	31.0	58.3	0	274
Swine_03	2	42.6	0.22	14.8	24.0	45.1	0	241
Swine_04	1	37.2	0.22	15.5	26.6	57.1	1	253
Swine_04	2	37.2	0.22	31.5	109.1	234.6	1	513
Swine_05	1	35.8	0.22	17.6	34.0	76.1	1	287
Swine_05	2	35.8	0.22	18.0	35.6	79.6	1	293
Swine_06	1	39.5	0.22	20.1	44.6	90.3	0	328
Swine_06	2	39.5	0.22	24.1	63.9	129.5	1	393
Swine_07	1	35.38	0.22	16.6	30.3	68.6	1	271
Swine_07	2	35.38	0.22	27.2	81.1	183.3	1	442
Swine_08	1	44.45	0.22	20.9	47.9	86.1	1	340
Swine_08	2	44.45	0.22	19.9	43.6	78.6	1	325
Swine_09	1	43.5	0.22	17.7	34.5	63.4	1	288
Swine_09	2	43.5	0.22	14.4	22.9	42.2	1	235
Swine_10	1	41.3	0.22	16.8	31.2	60.4	0	274
Swine_10	2	41.3	0.22	13.4	19.7	38.1	0	218
Swine_11	1	43.3	0.29	19.9	57.4	106.1	0	372
Swine_11	2	43.3	0.29	22.2	71.1	131.4	0	414
Swine_11	3	43.3	0.36	24.6	108.5	200.4	0	512
Swine_11	4	43.3	0.36	41.8	315.1	582.2	1	872
Swine_12	1	52.1	0.348	23.8	98.8	151.7	0	488
Swine_12	2	52.1	0.348	22.2	86.0	132.0	0	456
Swine_12	3	52.1	0.348	31.5	172.3	264.6	1	645
Swine_12	4	52.1	0.348	31.5	172.3	264.6	1	645
Swine_13	1	45	0.24	21.5	55.3	98.3	0	365
Swine_13	2	45	0.24	19.6	46.1	81.9	0	333
Swine_13	3	45	0.24	40.9	200.4	356.3	1	696
Swine_13	4	45	0.24	52.3	328.2	583.5	1	890
Swine_14	1	28	0.231	19.9	45.7	130.7	1	332
Swine_14	2	28	0.231	19.5	43.9	125.5	0	326
Swine_14	3	28	0.231	19.4	43.5	124.2	0	324
Swine_14	4	28	0.231	26.0	78.1	223.1	0	434
Swine_15	1	69	0.262	33.8	149.7	173.5	1	601
Swine_15	2	69	0.262	41.6	226.7	262.8	1	740
Swine_15	3	69	0.262	19.3	48.8	56.6	0	343

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Specimen	Test	Specimen Mass (kg)	Impactor mass (kg)	Impact Velocity (m/s)	Impact Energy (J)	Reference Scaled Energy (J)	Rib Fracture (0/1)	Scaled Rifle Velocity (m/s)
Swine_15	4	69	0.262	45.5	271.2	314.4	1	809
Swine_16	1	64	0.251	19.6	48.2	60.3	0	341
Swine_16	2	64	0.251	28.3	100.5	125.6	1	493
Swine_16	3	64	0.251	43.1	233.1	291.4	0	750
Swine_16	4	64	0.251	27.4	94.2	117.8	0	477

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