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Original Article

Developing a custom Anthropomorphic Test Device for measuring blast effects on occupants inside armored vehicles

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Anthropomorphic test device, armored vehicles, improvised explosive device, injury criteria, vehicle blast.

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Abstract

This work represents our first step at forming the concept of a measuring system of blast effects on humans inside armored vehicles.We present our initial attempts at developing a custom anthropometric test device (ATD) for measuring blast effects on human occupants in armored vehicles. It was designed to mimic the body of a 50th percentile human male in shape, weight and size. A drop tower was specifically built to simulate dynamic loads resulting from the explosion of improvised explosive devices under vehicle structures. The custom ATD was dropped from a 10 m height and the results were used to verify its design using published data. The ATD was then used to validate the effectiveness of the design of an armored vehicle that was equipped with passive blast protection devices. Useful information was derived from test results and design improvements were suggested. Future experiments are planned to improve the design of the next version of the custom ATD.

I. INTRODUCTION

Improvised Explosive Devices (IEDs) are an effective weapon in the hands of militias against regular armed forces. They are readily available, inexpensive, and can be produced in large quantities without sophisticated technology. One optimally buried IED can be detonated at a safe distance from the opposing insurgent. This single IED can induce a catastrophic destruction to vehicles and inflict severe human casualties. In Iraq and Afghanistan, IEDs were responsible for the deaths and injuries of many coalition troops[1]. It was estimated that IEDs resulted in more than half of the US army vehicle losses from 2003 to 2009[2]. Moreover, approximately 20% of all combat troops suffered from some degree of traumatic brain injury (TBI)[3]. The approximate cost for treating such injuries was around two billion US dollars[4]. Around the world, it is estimated that there are between 40 to 50 million land mines leading to around 10,000 human casualties annually[5].

A typical IED consists of an explosive material usually, trinitrotoluene (TNT) and a detonator. When detonated, an exothermic chemical reaction starts and unleashes all its energy in microseconds. Super-heated gaseous products are released and they cause a spontaneous rise in the surrounding pressure. The pressure propagates in what is termed as 'shock wave' or 'detonation wave'. The wave travels at speeds up to 7000 m/s,with local pressure around 200,000 atm, and temperatures reaching up to 3000 K[6].

Figure 1 shows a schematic drawing of a typical IED blast under a vehicle. When an IED is detonated underneath a vehicle, the shock wave from explosion hits the underbelly of the vehicle within around 0.5 ms.The wave then reflects back and forth between the vehicle and the ground, causing a multiplication of pressure. After approximately 5 ms from the detonation, the bottom structure of the vehicle reacts and deforms under the load from the wave pressure. The shock wave travels through the vehicle structure at speeds up to 5000 m/s and causes violent vibration in all vehicle parts[7]. These vibrations along with local deformation can cause severe injuries to human occupants.

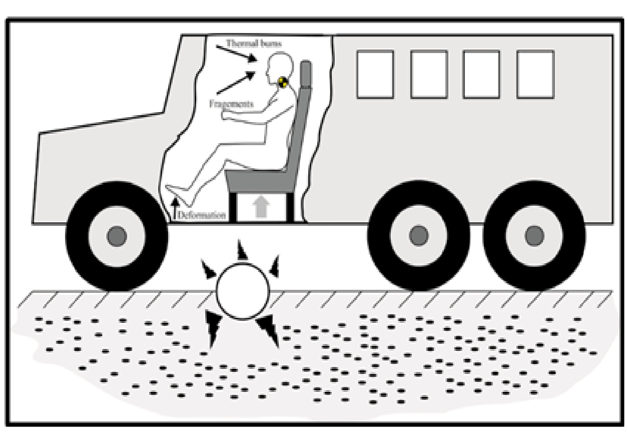


Fig. 1: Effect of mine blast on occupants of armored vehicle

Injuries inflicted on vehicle occupants are traditionally classified into four main groups[8]:

1. Primary: when the shock wave directly affects human body. In case of armored vehicles, this could occur if the vehicle structure is breached by the blast wave.

2. Secondary: flying fragments and debris ejected from blast can cause serious wounds.

3. Tertiary: When the whole vehicle body is lifted up then slams down to the ground, the occupants are exposed to large impulsive forces. Injuries usually occur in the lumbar and cervical spine area, which can cause paralysis or even death.

4. Quaternary: If the blast wave penetrates vehicle structure, it can cause fire inside the cabin, which in turn releases toxic fumes. Injuries are in the form of burns and asphyxiation.

Armored vehicles are usually equipped with passive protection to mitigate injuries from the blast of IEDs. Anthropomorphic test devices (ATDs) are used to evaluate the efficacy of vehicle protection against blasts. Standard ATDs are exclusively used by large automotive manufacturers at selected test facilities around the world. Due to these limitations, the objective of this workwas to develop a functional ATD to test the safety performance of anti-blast systems.

II. DESIGN AND DEVELOPMENT OF THE ATD

Anthropomorphic test devices (ATDs) are human like mannequins that are designed to represent humans of different sizes, ages, and sexes. They are used to evaluate the effects of extreme impact forces and large acceleration on the human body. They are instrumented with numerous sensors for measuring the response of crash in terms of accelerations, deformations, and loads of various body parts. The measurements are then compared with human tolerance levels, or Injury Assessment Reference Values (IARVs) for each vital body part[9]. ATDs have been primarily used to evaluate the crashworthiness of vehicles in simulated traffic accidents[10]. Recently, they are being systematically used to evaluate and certify vehicles for blast protection[11] and[12].

As a part of our work to develop armored vehicles capable of protecting troops against IEDs blast, we started to develop our own ATD. We focused on measuring tertiary blast injuries starting by measuring traumatic brain and back injuries since they constitute a significant percentage of major injuries[13].

Our custom ATD represents the first step at forming the concept of a measuring system of blast effects on humans inside armored vehicles. This ATD was designed to follow the guidelines of the Hybrid III dummy as close as possible.

HYBRID III, a mid-size male dummy that was presented in 1976, mimicked the human shape, size mass and responses to impact at different body parts[14]. The design of the ATD started by gathering information on size and shape from studies made on demographic and health of Middle Eastern population[15]. Accordingly, a standing height of 172 cm and weight of 65 kg were adopted for this design. Basic lengths of each body segment of the dummy were calculated based on data from Ref. 16. Figure 2 shows the length of each body segment related to the standing height "H".

The parts of the dummy were made primarily from wood using the basic dimensions as mentioned earlier. The mass of each body segment is calculated based on its percentage to the total mass of the body as taken from Ref. 17. This is shown in Table 1.

In order to verify the dimensions and masses of our custom dummy, data for each segment is compared with corresponding one of the Hybrid III dummy for a 50th percentile male. Table 2 shows the comparison along with the percentage deviation in dimensions and masses. It is clear that they are in close agreement

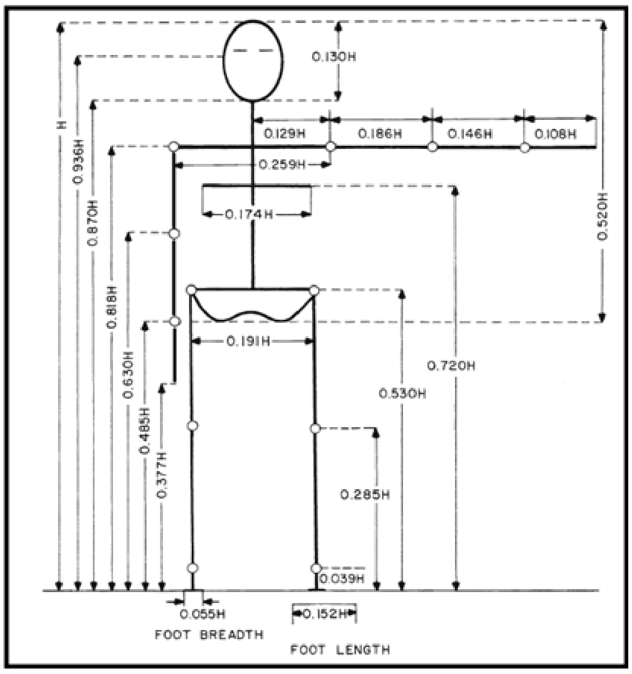


Fig. 2: Dimensions of body segments relative to height[16].

Table 1: Mass and mass densities of dummy's segments

Segment	Segment mass ratio	Segment mass density gm/cm³
Trunk	0.497	1.03
Head and neck	0.081	1.11
Upper leg	0.1	1.05
Lower leg	0.0465	1.09
Total leg	0.161	1.06
Upper arm	0.028	1.07
Lower arm	0.016	1.13
Total arm	0.05	1.11
Foot	0.0145	1.10

Table 2: Comparison between dimensions and masses of custom ATD and Hybrid III 50 male dummy[18].

	Dimensions (cm)		% Deviation	Masses (kg)		% Deviation
	Custom ATD	Hybrid III 50th male		Custom ATD	Hybrid III 50th male	
Head and neck	31.5	30.1	4.7	5.86	6.08	3.6
Trunk	49.2	44.2	11.3	38.5	40.23	4.3
Upper leg	49.5	54.4	9.0	8.79	8.53	3.0
Lower leg	44.8	46.4	3.5	20.95	23.36	10.3
Total	175	175.1	0.05	74.1	78.2	5.2

In order to mimic the relative motion of the parts of the custom ATD, the different parts were joined with mechanical connections. In addition, motion was limited to imitate the degrees of freedom as governed by the anatomy of the human body[19]. Figure 3 shows the connection between the upper and lower arms and Figure 4 shows the connection between upper and lower legs.

Fig. 3: Upper and lower arm connection

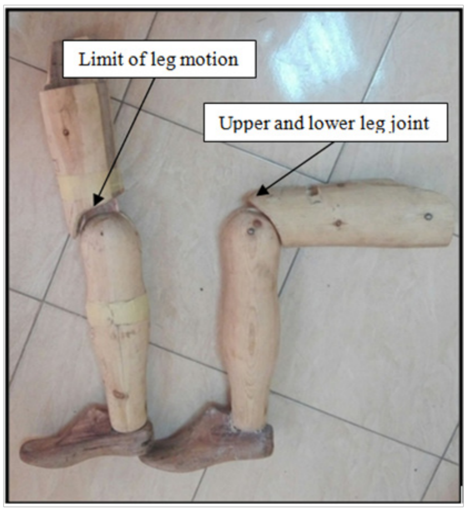


Fig. 4: Upper and lower leg connection

Instrumentation

Under blast loading, the whole vehicle can move upwards and then falls freely to the ground. The human body is then subjected to extreme loads affecting different body parts. The effect starts from feet, where the calcaneus is mostly affected, especially if it is in direct contact with vehicle floor. Then, the following parts are affected in order: tibia, femur bone, pelvis, lumbar spine, neck and finally the brain[20]. If the loads affecting one body part are high enough and exceed its biological tolerance level, injuries with varying severity levels occur. The dummy is equipped with various types of sensors to measure the different physical quantities that are then used to calculate the probabilities that a certain body part will sustain a certain level of injury.

Considering the custom ATD, we opted to install accelerometers at the following body parts:
(1) Inside the ankle of the foot.
(2) Inside the pelvis.
(3) As close as possible to the center of gravity of the head.
The reason for choosing these locations was to focus on the parts, which are most likely to be affected by blast using the limited number of sensors we had at that time.

Verification

A drop tower was specifically for simulating the global blast effects on armored vehicles and evaluating the efficacy of blast attenuating seat mechanisms. In addition, it was used for verifying the custom ATD. A test was conducted where the carriage was dropped from the maximum 10 m height. This specific height was selected to enable reaching drop velocities up to and exceeding 8 m/s, which is usually used in testing energy attenuation seats[21]. As shown in Figure 5, the custom ATD is placed seated inside a carriage. The carriage represents the cabin of an armored vehicle. It is lifted by a steel wire that is hooked to the top of the carriage. Upon reaching the drop height, a release mechanism unlocks the hook and the carriage drops freely to the ground. On the drop location, rubber plates are placed to tune the resulting impulsive acceleration acting on the carriage as a result from the drop.

Fig. 5: Drop tower test facility for testing the custom ATD

An accelerometer was placed beneath the custom ATD to record the input acceleration. For verification, test data were compared with ones from Ref. 22. Figure 6 shows the experimentally recorded input carriage acceleration and a typical carriage acceleration signal from Ref. 22. Figure 7 shows a comparison between experimentally recorded pelvis acceleration and one from Ref. 22. They show a reasonable agreement in their trend. The difference in maximum acceleration values can be attributed to the fact that the input acceleration signal is lower in case of experimental test than the one from Ref. 22. Moreover, data from Ref. 22 are calculated from a mathematical model.

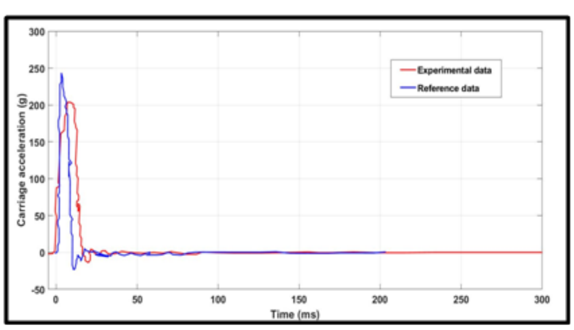


Fig. 6: Comparison between carriage acceleration in z direction and one from Ref. 22.

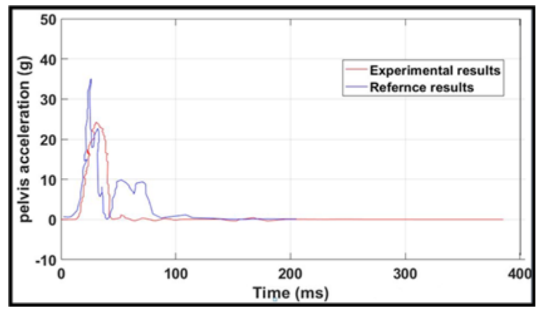


Fig. 7: Comparison between pelvis acceleration of custom ATD and one from Ref. 22.

Based on the aforementioned results, it can be concluded that the custom ATD can be used to evaluate the protection system of an armored vehicle against mine blast.

III. VEHICLE BLAST TEST

This section describes a real field test of an armored vehicle. For confidentiality reasons, some of the actual data was removed. The experimental setup was arranged as shown in Figure 8. The test was prepared in accordance with the regulations in Ref. 23. The vehicle was located at approximately 100 m distance from the control and measurement stations. The stations were located underground and were protected from the effect of blast wave by a barrier of sand bags. The test was conducted in accordance with the guidelines of the NATO standard 4569[24]. The control station managed the triggering of the TNT charge through an electric current to the charge. It also controlled the cameras, which were located around and inside the vehicle. The measurement station controlled recording the data from sensors. The recording started and ended at sufficient time before and after the blast. This was to ensure that no data were lost.

Figure 9 shows the arrangement of the measurement system. Three accelerometers were connected to the data acquisition DAQ system located in the control station. The wires were isolated inside a heat resistant shield and were buried in the ground up to the control station. This was done to protect the wires from any damage from the effect of the blast wave. The DAQ was connected to a laptop running a LabVIEW software program. The program was developed to calibrate, filter, and record the data from the sensors. Specifications of the measurement system are provided in Table 3.

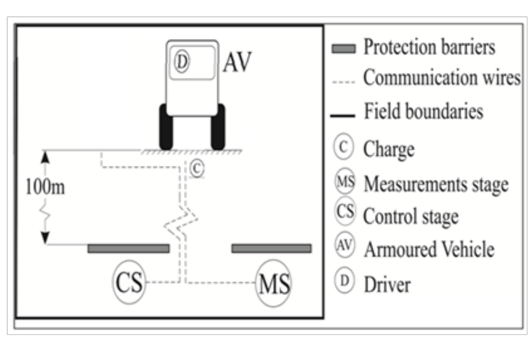


Fig. 8: A schematic drawing of test arrangement

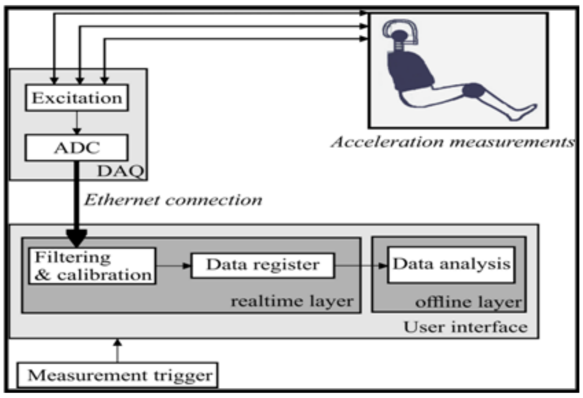


Fig. 9: A schematic of the measurement system connections

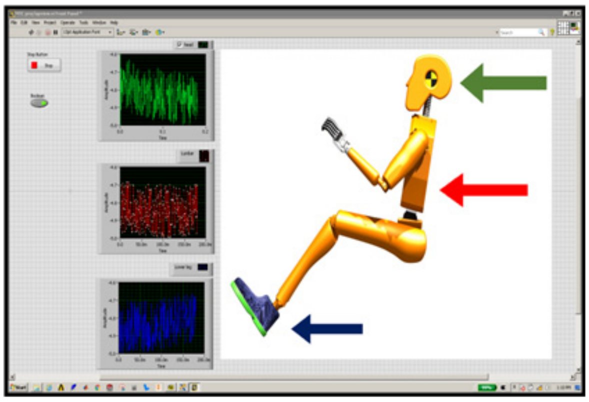


Fig. 10: Screenshot front panel of lab view program

Table 3: Specifications of measurement system

Data acquisition system	
Model	cDAQ-9178 + NI-9234
Configuration	IEPE, DC coupling
Number of channels	4
Maximum input voltage	5V
Sampling rate	51.2 kS/s/ch
Noise at max. sampling rate	50 µV/ms
Operating temperature	-40°C to 70°C
ADC resolution	24 bits
IEPE excitation power	2.1 mA, 19V
Sensors	
Model	2 PCB-353C03 and 1 PCB-353B03
Sensitivity	±10 mV/g
Measurement Range	±500 g pk
Frequency Range (±3 dB)	0.35 to 20000 Hz
Non-Linearity	1 %
Temperature Range	-65 to +250 °F
Excitation Voltage	18 to 30º VDC
Constant Current Excitation	2 to 20 mA
Spectral Noise (1 kHz)	64 µg /√Hz

A calibration process was performed before recording data. This ensured that interference from the high temperature open environment did not affect our measurements. A self-calibration step was done by applying an internal voltage reference to all channels and then comparing the measured values to expected ones. Calibration factors were then calculated and saved. They were used to count for any drift in the electronic circuitry. This compensated for any temperature effect.

Filtering was done by applying a low-pass Butterworth data filter to count for uncontrolled external noises from the open test environment[25]. Calibration and filtering were executed before the test by a sufficient initial runtime.

The dummy was placed in driver's seat. It was instrumented with three accelerometers. The first sensor was fixed in the dummy's foot, the second was fixed at the end of the dummy's back and the last one was placed in the dummy's head. Figure 11shows the dummy in the driver's seat. All sensors are fixed to read in direction normal to the vehicle's direction. Each accelerometer was calibrated before the test.

The vehicle was loaded with sand bags to simulate its payload. All vehicle doors were tightly closed. The area around the vehicle was cleared from all personnel. First, the measurement system was started then the TNT charge was detonated. Data was recorded for offline analysis.

Fig. 11: Custom ATD seated on driver's seat inside the vehicle

IV. RESULTS AND DISCUSSION

Figure 12 shows a small crater that was formed by the TNT explosion. Some damage was inflicted on the undercarriage of the vehicle. The drive shaft, exhaust pipe and some wiring were damaged. A blast protection system was added to the underbelly of the vehicle structure; therefore, the effect of the blast was limited to the area under the vehicle. For confidentiality reasons, other areas of vehicle structure cannot be shown.

Fig. 12: Location beneath the vehicle after IED explosion

The data acquired from the sensors are shown in Figure 13. The acceleration from each accelerometer is shown in g's. The system started to record at enough time before moment of detonation. Only 0.8 seconds interval is shown –The effect of blast started to affect the dummy at the 20.25th sec. and lasted for 0.8 seconds. This specific time duration is focused and shown in Figure 14.

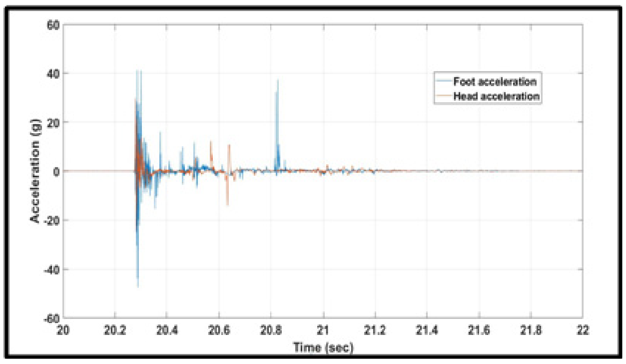


Fig. 13: Effect of blast on head and foot sensors.

Figure 14 shows the data recorded from the accelerometers for each body part separately. The event lasted for approximately 800 ms. High acceleration (41 g) affected the foot at around time point 20.28 and lasted for considerably short time. While the maximum transmitted, acceleration to the head was approximately 30 g at ~20.285 sec. The maximum acceleration that affected the head of the dummy was around 30 g.

High acceleration is short time durations can cause injuries to the human body. Injuries induced by accelerations in the vertical direction starts from difficulty in movement through loss of conscious to paralysis or death. The severity of injuries depends on amplitude of acceleration and its duration. For each vital part of the human body, an injury criterion is used to calculate the injury level.

The value of the head injury criterion was calculated using Eq.(1)[9].

$$HIC = max\left\{\left[\frac{1}{t_2-t_1}\int_{t_2}^{t_2} A_t(t)\,dt\right]^{2.5}.(t_2-t_2)\right\} \quad (1)$$

Where *t1* and *t2* are any two arbitrary times during which HIC is maximum, such that (*t2 - t1*) ≤36 ms (for HIC36) or (*t2 - t1*) ≤ 15 ms (for HIC15) and A_t is the summation of acceleration in the three coordinate directions.

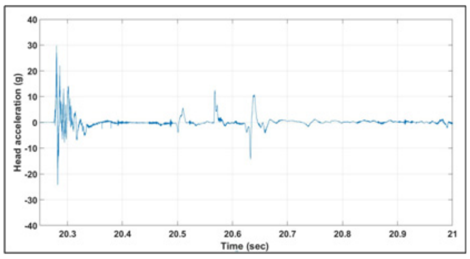
HIC36 and HIC15 were calculated using a custom build subroutine in MATLAB and the results were compared from using LSPrePost, which is a special purpose program for pre and post processing finite element models for LS-DYNA software.The values were compared with human tolerance levels. For a 50*th* percentile male, HIC15 and HIC36must not exceed 700 and 1000, respectively[13]. The values of calculated HIC36 and HIC15 were —values were removed for confidentiality— well below the human tolerance levels.

The probability of fracture of lower leg bones can be predicted using Yoganandan's model as is expressed in Eq. (2)[26].

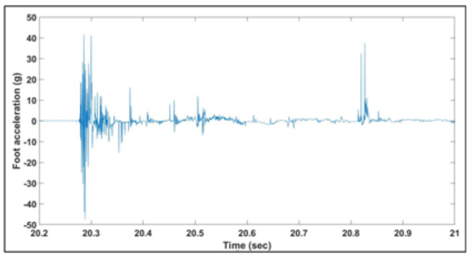
$$P = 1-\left[\exp\left(\left(\frac{-(0.0348\times age+0.415\times F)}{5.13076}\right)^{7.42582}\right)\right] \quad (2)$$

Where p is the probability of foot/ankle fracture. As shown in Eq.(2), the probability of fracture depends on occupant's age[27]. It was assumed that the occupantwas 30 years old. Figure 15shows the injury risk curve for foot/ankle bones for a 30 years old man. Using experimental data, the probability for foot/ankle injury was calculated. Based on the actual value, some design changes were suggested, such as covering the vehicle floor with energy absorbing mats.

In general, it can be safely concluded that the custom ATD helped in shedding some light on the efficacy of the vehicle protection systems. In addition, it helped in deciding on the necessary design improvements.



(a) Total acceleration on dummy's head



(b) Acceleration on dummy's foot

Fig. 14: Individual acceleration showing the effect on each body part

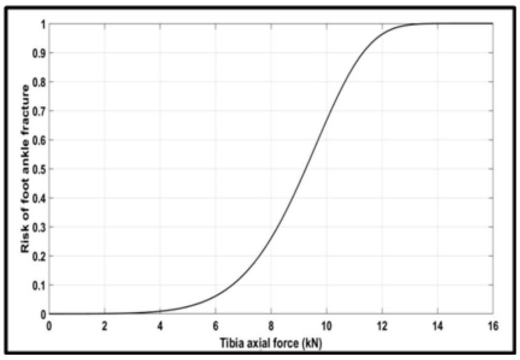


Fig. 15: Injury risk curve for foot/ankle for 30 years old man prepared from Ref. 27.

V. SUMMARY AND FUTURE WORK

This work presented our early attempts to developing a custom ATD for measuring under-vehicle blast effects on occupants. Our first custom ATD was simple and special effort was made to ensure it resembled the human body in shape, size, weight and limited motion of the limbs. It was equipped with limited number and types of sensors. It was carefully verified using data from the available published literature and experimental tests. A drop-tower test facility was specifically built for this purpose.

A field-test where a charge of TNT was ignited under the belly of an armored vehicle. The custom ATD was seated in the driver's seat to measure the blast effects. The results showed that while the blast wave had no serious effects on the custom ATD head, on the other hand, they indicated the requisite for some design modifications to minimize the effects on occupants' feet.

The authors are aware of the limitations in the current first version of the custom ATD. In light of the state of the art technology in this field, as mostexemplified in the Warrior Injury Assessment Manikin (WIAMan) that was specifically built for measuring under-vehicle blast effects[28-30], we are working to improve the design of the next version. For example, a spring system is being developed to allow for a more human-like articulated motion between the head and trunk. The lengths and masses of the different body segments will be more finely tuned to match the ones for a Hybrid-III 50th percentile male dummy. Polymers will be used to adjust material stiffness of body parts to match ones of a biological human body. The succeeding ATD version will include more and different types of sensors. This is a work in progress.

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