INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 18, ISSUE 01, 8531 – 8539
DOI: https://doi.org/10.15282/ijame.18.1.2021.12.0647

ORIGINAL ARTICLE

Developing a Custom Anthropometric Test Device for Experimental Evaluation of Blast Mitigation Seats

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ABSTRACT – The use of improvised explosive devices against moving vehicles has been on the rise recently. Their explosions induce devastating effects on vehicle occupants. Blast mitigation seats are used as a counter measure to reduce such harmful effects. This paper presents the scientific work for evaluating the efficacy of blast mitigation seats. The work involves designing and building a custom anthropometric test device (ATD) and a drop tower test facility that is used to simulate the drop of a vehicle from heights up to 10 m. The ATD was equipped with two accelerometers; at the neck and at the pelvis. For validation, a multibody dynamics model was developed to simulate the drop test and the results were compared with ones from experiments. An overall root mean square error of 1.28 g was achieved. The test facility was then used to measure the performance of a blast mitigation seat. The results showed that blast mitigation seats reduced peak accelerations on the pelvis and neck areas by 92% and 87% respectively and this translates into moving predicted injuries from fatal to moderate.

ARTICLE HISTORY
Received: 3rd May 2020
Revised: 28th Jan 2021
Accepted: 15th Feb 2021

KEYWORDS
Anti blast seat;
Blast mitigation;
Human test dummy;
Injury criteria;
Anthropometric test device

NOMENCLATURE

ATD	anthropometric test device
EA	energy-absorbing
IED	improvised explosive device
M	mass
C	damping coefficient
K	spring stiffness
Z	displacement
RMSE	root mean square error

INTRODUCTION

The use of improvised explosive devices (IEDs) has been on the rise by militants against regular army forces. IEDs are usually buried beneath the road's surface and are triggered either remotely or automatically to detonate under a moving vehicle. The resulting explosion causes a supersonic air pressure wave (shockwave) accompanied by soil fragments. This wave affects the vehicle in two phases. In the first phase, the vehicle's floor is affected within 0.5 ms from the initiation of the explosion [1]. The floor moves at speeds approaching 12 m/s while accelerating up to 100 g [2]. Injuries to the lower extremities of the vehicle's occupants can result, especially if their feet are rested on the vehicle's floor. In the second phase, if the amount of explosive is large enough, the pressure can lift the whole vehicle in the air; afterwards, the vehicle free falls and hits the ground. During impact, an occupant is exposed to axial compression force affecting his spinal column. If the force exceeds the tolerance level of one or more of the vertebrae, injuries occur. The severity of injuries depends on the level and duration of compression forces [3]. In extreme cases, paralysis or death may occur.

The ongoing research is to minimise the severity of such injuries. One research approach is to mount the seats to the side of the roof of the vehicle and not to the floor. In addition, blast mitigation mechanisms are placed between the seat and vehicle structure. The function of such mechanisms is to absorb impact energy as much as possible, thus reducing the transmitted energy to the occupant [4]. Experimental tests are usually conducted to evaluate the efficacy of blast mitigating seats [5, 6]. In these tests, an Anthropomorphic Test Device (ATD) [7, 8] is strapped to the seat to be tested, and both are lifted and dropped vertically in a controlled environment using a drop tower test [9]. The ATD is fitted with sensors to measure the time-varying accelerations on venerable parts of the body. Measurements are then analysed to calculate the probability of injury severity.

The objective of this paper is to present our research to developing an in-house ATD and our own local drop tower test facility to test blast mitigation seats. In addition, this paper describes the results of testing a blast mitigation seat and comparing its performance with one without any protection system. A 10 m drop tower test facility was specifically built

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to conduct the experiments. Test results showed that the blast mitigation seat successfully showed significant protection compared with a control seat that did not include any blast mitigating mechanism.

BLAST MITIGATING SEATS

Blast mitigating seats are fitted with energy-absorbing (EA) structures; they convert part of the kinetic energy into a non-recoverable form. This conversion is usually done by using a collapsing structure that is attached between the mounting of the seat and vehicle frame. The objective is to limit the transmitted force to the occupant below a limiting value, which is a function of time duration. It ranges from 4000 N at 0 ms to 1110 N at 30 ms and above [2].

The EA structures are specifically designed to deform in a controlled manner under impact load. To achieve this goal, they can be constructed in different forms, such as thin-wall crushable tubes, wires, rods, aluminium honeycomb, sandwich structures, polymeric foams [10]. There are mainly two challenges pertaining to the design of EA structures [11]:

i. There is usually little space –as shown in Figure 1– for the structure to deform in order to absorb sufficient energy. This poses a challenge for incorporating innovative designs and materials.

ii. The structure can deform only once; hence it is typically designed to deform under a predefined load, which is usually during the slam-down phase. Considering the first phase, other systems such as footrests and energy-absorbing floor mats are employed to injuries, especially lower extremities.

Figure 1. Seats inside an armoured vehicle [12].

Figure 2 shows a view of a typical blast mitigation seat. The seat is attached to the vehicle's sidewall through an energy absorbing mechanism. The mounting to the sidewall reduces the amplitude of the transferred loads to the occupant while the EA mechanism absorbs some of those transferred loads. This helps in mitigating the harmful effects of the blast on the occupants. It is then important to measure the efficacy of such EA mechanisms using Anthropomorphic Test Devices (ATD).

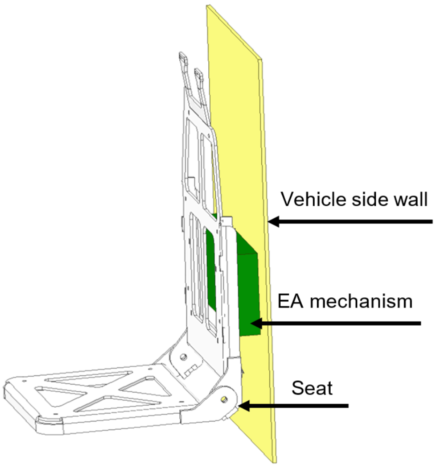


Figure 2. Typical blast mitigation seat.

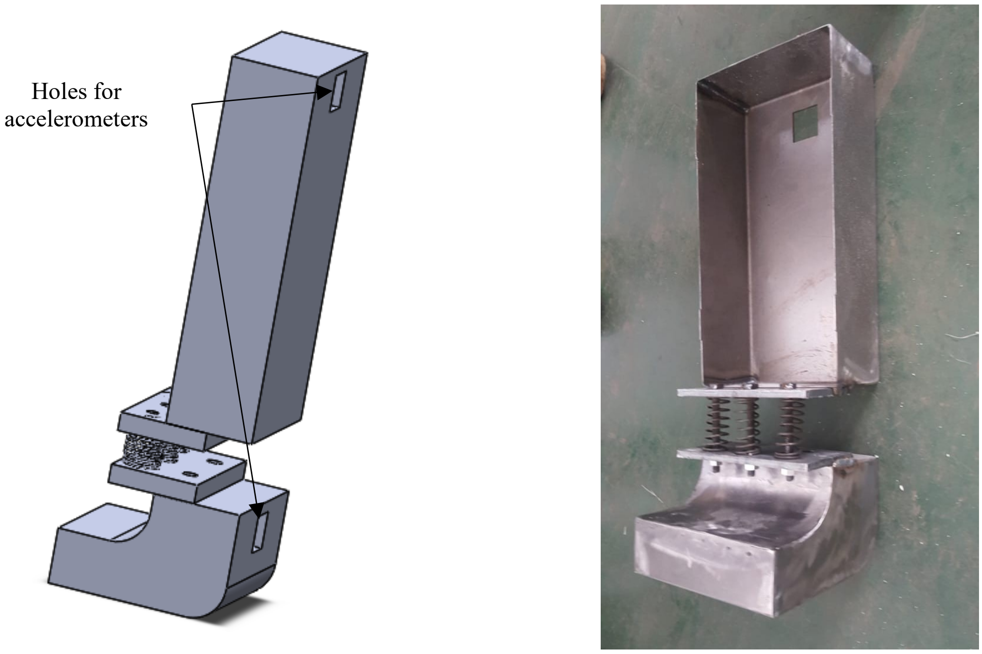
ANTHROPOMORPHIC TEST DEVICES

ATDs are human-like mannequins used to evaluate the effect of high impact loads as in blast and vehicle crashes. ATDs are designed to mimic the human body physical characteristics such as shape, size, weight, weight distribution, material stiffness, energy absorption and joint movement. They are equipped with various sensors at important locations. During a test, the sensors measure the response of each part, data is recorded, and then it is analysed. The analysis includes calculating the injury risk criterion for each vital part of the human body. This criterion predicts the probability of the severity of injury on this particular part. Accordingly, an assessment of the level of injury can be made based on the comparison with human tolerance limits. Up to date, there has been no specific ATD developed to assess vehicle blast protection. However, an ATD was made through the modification of the Hybrid III dummy, which was designed for vehicle forward crash testing.

DEVELOPING A CUSTOM ATD

Acquiring an ATD for measuring blast protection applications was not possible and it was decided that we should build our own. The ATD was primarily built for testing full vehicles in field tests where TNT charges were detonated beneath test vehicles according to NATO 4569 standards [2]. In order to ensure the validity of the readings obtained from the ATD in these field tests, a drop tower was designed and built for facilitating a controlled test. This test was conducted by strapping the ATD to a seat and dropping it from a known height. Measurements of the input impact signal to the base of the seat and the response on the ATD via accelerometers are recorded. Then, input data are fed to a mathematical multi-body dynamic model, and the results from the model are compared with ones from experiments for validating the design of the ATD.

After validation, the ATD was used to test the effectiveness of blast mitigating seat mechanisms. The focus was on predicting the severity of injuries on the pelvis and neck as critical areas. Therefore, a design was made to mimic the trunk area of an average male who is 172 cm tall [13]. The trunk dimensions and weight was calculated based on the proportions taken from Ref. [14]. The outer shape of the trunk was represented using an aluminium skeleton, as shown in Figure 3 that shows the CAD and the finished product. The skeleton was made of aluminium 6061 alloy that is commercially available, and it was manufactured by laser cutting. The upper part represents the lumbar spine of 45 cm in height and weighs 5 kg. The lower part represents the pelvis with 15 cm in height and weighs 3 kg. Both parts are 20 cm wide and are connected through three coil springs. The stiffness of each one is 25 KN/m. The three springs and the upper part constitute the total linear stiffness of the lumbar spine, which is approximately 125 kN/m derived from calculations of measurements of the compressive individual vertebral strength, refer to [2, 15] for more details. Two holes were drilled to allow for the wires of the two accelerometers to pass through; one accelerometer was fitted in the head area and one in the pelvis area.



(a) (b)

Figure 3. (a) View of the CAD for the skeleton. (b) Photo of the skeleton after production.

An aluminium skeleton was placed inside a fibreglass mould of a human mannequin trunk as shown in Figure 4. The mannequin was commercially available that was originally used for displaying men's garments. It was used as a mould for the human trunk with the head and neck. Rubber silicon was poured inside the mould after being mixed with a hardener. The weight of poured silicon was calculated as 35 kg to achieve the exact weight of the trunk according to the 172 cm height of an average Egyptian male. In addition, the selection of the mannequin and the calculation of the amount of rubber silicon was carefully made so that the final custom ATD would be as close as possible to the trunk of the 50th percentile male hybrid III test dummy. The final weight and sitting height of the custom ATD were 45.31 kg and 86 cm compared to 46 kg and 90 cm of the hybrid III ATD.

Figure 4. Final ATD.

DROP TOWER TEST

A drop tower is used to generate controlled impact loads to simulate the effect of vehicle drop after the blast of underbody IED. Drop tower tests are typically used by the US Army to study the effectiveness of blast mitigation seats [16, 17]. In this work, a drop tower was specifically built to test blast mitigation seats. Its height could be adjusted up to 10 m height according to the required impact speed. The tower was fixed to the ground, as shown in Figure 5. The part of the vehicle cabin was represented by a 200 kg steel carriage. The carriage could be lifted using a steel wire from the top. An electric motor was used to lift the cabin to the required height. The tested seat was mounted to the cabin. The falling cabin was guided with four wires passing through its corners. Rubber plates were placed on the floor of the tower to act as dampers during impact [18]. A release system was used to free the assembly to fall after reaching the required height. This drop tower test was first used to conduct an experiment to validate the design of the custom ATD and then to test a blast mitigation seat and compare its response with one without any EA mechanism.

Figure 5. Different views of the drop tower test.

MATHEMATICAL MODEL OF THE ATD

A mathematical model was developed to represent the human test trunk. The data of this model were taken based on anthropomorphic studies from references [14, 19–21]. Figure 6 shows the lumped mass model that represents the trunk of the custom ATD. This model consists of two masses: M_1 of the upper torso and M_2 of the lower torso. $k_1$represents the stiffness of the coil springs that represents the stiffness between pelvis and torso. C_1 is the damping coefficient of the silicon between the upper and lower part. k_2 and C_2 represent the stiffness and damping coefficient of the silicon part at the bottom of the trunk. The values of the variables of the model are shown in Table 1. For simplification, the following assumptions were made:

i. The human trunk acts as two lumped masses which represent the upper and lower Torso.
ii. The upper and lower parts are two rigid bodies with uniform density and simple geometric shape.
iii. The upper and lower parts are connected with each other by springs and dampers.
iv. The motion is assumed to be in the vertical direction only.

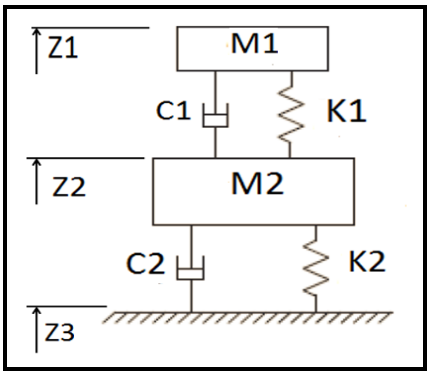


Figure 6. Representation of the lumped mass system of the custom ATD.

Equations of motion are formulated as follows:

$$\mathrm{M_1 z''_1 + c_1 z'_1 + k_1 z_1 = c_1 z'_2 + k_1 z_2} \tag{1}$$

$$\mathrm{M_2 z''_2 + c_2 z'_2 + k_2 z_2 + c_1 z'_2 + k_1 z_2 = c_1 z'_1 + k_1 z_1 + c_2 z'_3 + k_2 z_3} \tag{2}$$

The equations can then be transformed as follows. This model was used to validate the custom ATD using experimental test results.

$$\mathrm{M_1 z''_1 + c_1(z'_1 - z'_2) + k_1(z_1 - z_2) = 0} \tag{3}$$

$$\mathrm{M_2 z''_2 + c_1(z'_2 - z'_1) + k_1(z_2 - z_1) + c_2(z'_2 - z'_3) + k_2(z_2 - z_3) = 0} \tag{4}$$

Table 1. Data of the mathematical model of human test trunk.

Symbol	Name	Value
M1	Mass of upper torso	25 kg
M2	Mass of lower torso	20 kg
C1	Damping coefficient of upper torso	3.8 kN.s/m
C2	Damping coefficient of lower torso	2.8 kN.s/m
K1	Stiffness of upper torso	75 kN/m
K2	Stiffness of lower torso	53 kN/m
Z1, Z2 and Z3	Displacements	

EXPERIMENTAL TEST

Validation

This section describes the experimental test that was conducted to validate the design of the custom ATD. In this test, the custom ATD was seated to a conventional seat without an EA mechanism. It was dropped from 3 m to gain a maximum drop speed of 7.66 m/s in accordance with the NATO AEP-55 vol.3 [22]. The carriage was lifted until it reached the release system, at which it dropped, and the assembly decelerated to the floor of the tower. Figure 7 shows the experimental custom ATD inside the cabin before the drop.

The sensors were calibrated before performing the test. They were connected to the data acquisition system DAQ. A program was developed to filter and record data from the accelerometers. The sampling frequency was set to be 20 kHz [2]. Table 2 shows the specifications of the measurement system. The measured data from the acceleration at the pelvis was given as an input to the mathematical model. The model was then solved.

Figure 8 shows a comparison between the acceleration of the neck calculated from the mathematical model and one recorded by an accelerometer on the dummy. The root mean square error (RMSE) was calculated as $RMSE = \sum_{i=1}^{n}\left(x_{s_i} - x_{p_i}\right)^2$, where x_{s_i} and x_{p_i} are the values of simulated and practical response at the time i. A reasonable value of the RMSE was calculated as1.28 g. This means that the custom ATD was verified and could be used in experimental tests. Compared with a maximum of approximately 42 g, this means a 3% error.

Table 2. 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	3 PCB-353C03
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

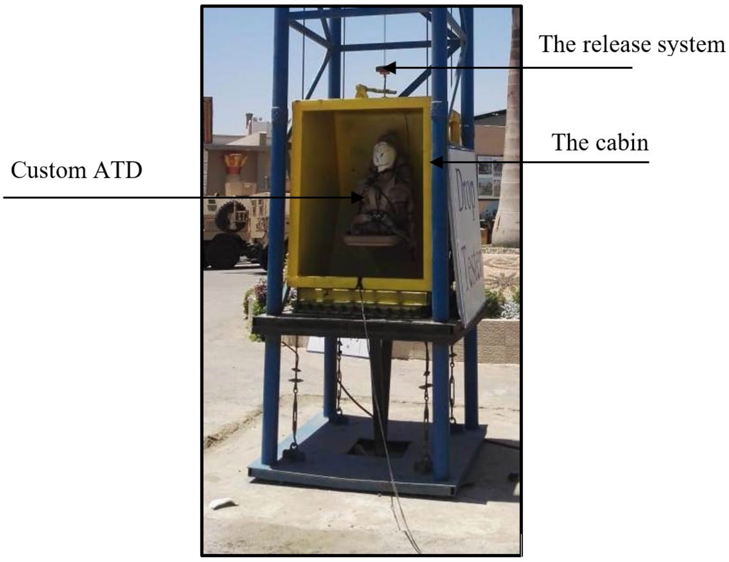


Figure 7. The custom ATD before a test.

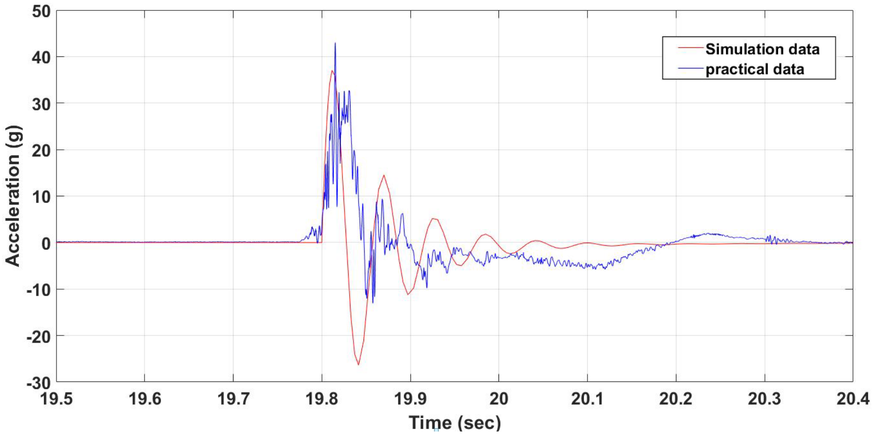


Figure 8. Comparison between acceleration from the mathematical model and measured one from the custom ATD.

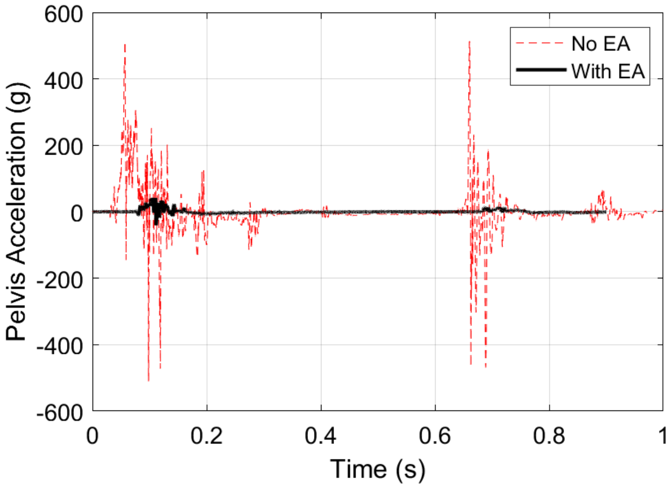
Testing a Blast Mitigation Seat

The custom ATD was used to test the efficacy of a blast mitigation seat in protecting the occupants inside a vehicle from the harmful effects of the blast of an IED. Two tests were conducted under the same conditions; a drop from a 3 m height where the custom ATD was placed once on a seat equipped with an EA mechanism and another on a seat without any protection mechanism. In the latter case, the seat was rigidly connected to the cabin's sidewall through welding in order to ensure that there was not any relative movement between each part. In each test, data from the accelerometers at the neck and pelvis was recorded, filtered and analysed.

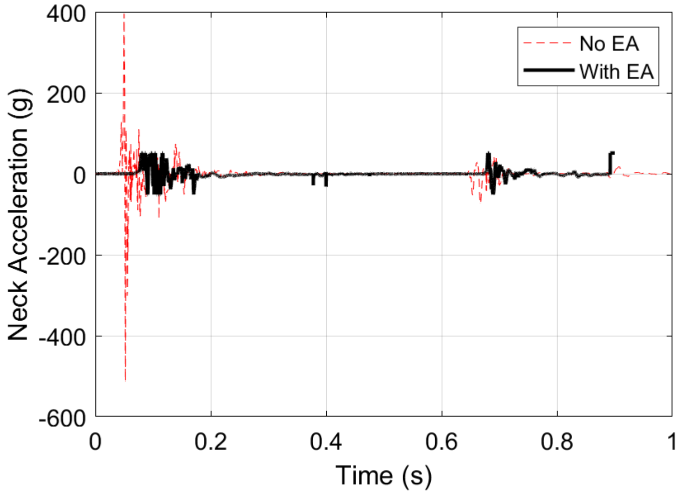
Figure 9(a) and 10(b) show the measured accelerations on the pelvis and neck areas. It is clear that the seat with the EA mechanism successfully minimised the value of acceleration on both areas compared with the seat without any EA mechanism. This means that the seat with an EA mechanism will protect the occupants in case of a blast of an IED under the vehicle.

Figure 10 shows the human tolerance levels to vertical accelerations acting on a sitting human. It is known as the Eiband Tolerance Curve [23]. Amplitude and duration of acceleration govern the degree of injury severities. It is used to examine the effect of using versus not using blast mitigation mechanisms. Data from Figure 9(a) are used to calculate and plot the relevant location of the expected injuries when using a seat with an EA mechanism (green star) and one without (red star) in Figure 10.

When conducting a conservative analysis based on maximum values of accelerations and durations, an occupant sitting on a seat without EA mechanism will be exposed to severe or even fatal (>500 *g* accelerations) injuries. However, one sitting on a blast mitigation seat will experience moderate injuries. Measuring improvement in terms of reduction in maximum values of accelerations, protection of pelvis, and neck has improved by 92% and 87%, respectively.



(a)



(b)

Figure 9. Comparison between acceleration on (a) pelvis and (b) neck of custom ATD when on a seat with EA mechanism and another without any protection.

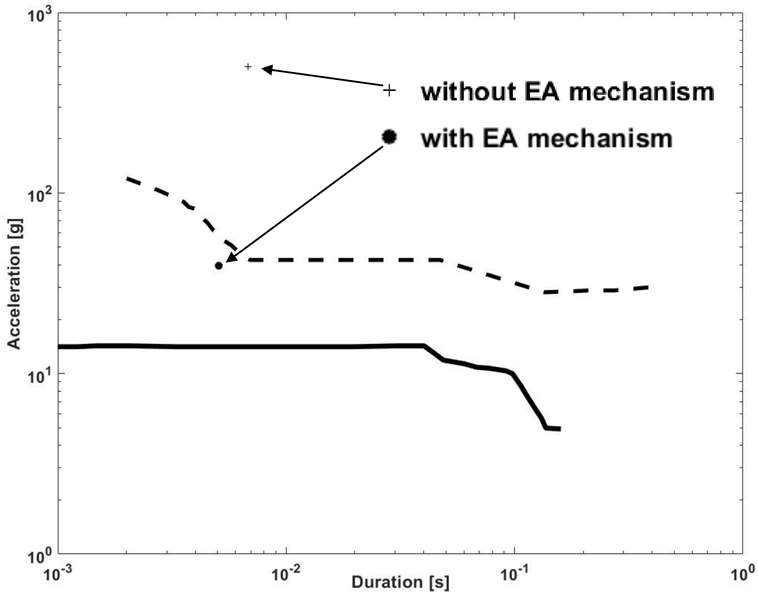


Figure 10. Eiband tolerance curve [23].

CONCLUSION

This paper presented the design and production of a custom ATD for testing blast mitigation seats. The custom ATD was designed to mimic the trunk area of an average Egyptian male in accordance with published anthropometric data. In addition, the ATD also resembled the 50th percentile male Hybrid III dummy. The design of the custom ATD was verified using a multi-body mathematical model and experimental results using a drop tower test facility. The drop tester was designed and built to allow variable drop heights up to 10 m.

The custom ATD was used to evaluate the efficacy of a blast mitigation seat and compare the results with a seat without any EA mechanism. The results showed that the blast mitigation seat succeeded in protecting the occupant by reducing the values of accelerations on the pelvis and neck areas by 92% and 87%, respectively. Based on observations during testing, it can be concluded that the efficacy of seat mitigation depends on the design of the EA mechanism, its material, shape, size, its location and the extent of space it covers. These factors are to be considered in the development of in-house blast mitigating seats.

However, it should be noted that these findings are based on results from a 3 m drop. In reality, large amounts of explosives can elevate the vehicle to higher heights, increasing the probability of more severe injuries. Therefore, these conclusions must be limited to the input of test data and care must be applied when generalising. Based on the current work, it suggested that further improvement in seat design could be achieved by making full use of the available space between the seat and vehicle structure, optimising the shape of the collapsible element and using composite and hybrid materials. This is continuous research, and further developments and improvements are planned as future work.

ACKNOWLEDGEMENT

The authors are grateful to the Egyptian Armed Forces for the facilities, equipment and tools.

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