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Injury Analysis using Anthropomorphic Test Device under Vertical Shock Loads

A. Prasanna*, G.K. Kannan, N. Mohan, Shivaraj Yaranal, Kartik S. Patil, and Vikash Kumar

Defence Bioengineering and Electromedical Laboratory, Bengaluru -560 093, India
**E-mail: prasanna@debel.drdo.in*

ABSTRACT

Natural and manmade injuries due to terrorism, military weapon and accidents lead to cutting edge research for engineers and clinicians alike. The study of injury and its mechanism can help in predicting the severity of an injury which in turn shall guide the engineers to design safer structures and medical specialists in treating casualties. This article summarises the various advancements and technologies available in the field of Injury Analysis. The objective of the study is to quantify the levels of an injury which occurs when an Anthropomorphic test device is subjected to a given vertical impact load. As a baseline a half sine shock test simulating the vertical impact was carried out on Hybrid III 50th percentile male dummy and injury analysis was done based on the standards prescribed by NATO TR-HFM-090. In the present test the injury analysis predicts that the injury during the loading is well within 10 per cent probability of an AIS 2 or greater (AIS 2+).

Keywords: Injury, Shock Test; Injury Analysis; Anthropomorphic test device.

1. INTRODUCTION

Injuries associated with lethal explosive devices in the battlefield are of a major concern for the health and safety of military personnel. Due to underbody mine blasts, injuries in the lower extremities such as pelvic injuries are of a common occurrence on occupants of military vehicles[1]. To combat health risks to the crew, developing protective measures against such blast and impact loads has been one of the primary areas of research in the field of safety of military personnel. In order to develop world class mitigation systems there is a need to understand the injury mechanism and quantify the injury levels associated with a given load.

A shock pulse which is similar to arrested landing shock experienced by pilots of fixed wing aircrafts landing on aircraft carrier is simulated in the present study. The objective of the present study is to quantify the levels of injury when the anthropomorphic test device (ATD) is subjected to a given vertical impact load. Simulation of occupant responses under vertical impact has been attempted experimentally on ATD where the ATD was instrumented to record the pelvis accelerations and lumbar loads for injury assessment[2]. Vertical impact tests, using Hybrid III 50th percentile and Hybrid II 50th percentile ATDs to compare the impact responses under two different loading conditions have been reported[3]. The tolerance levels for the impact are given by the NATO TR- HFM-090[4].

1.1 Anthropomorphic Test Device

ATD are instrumented human surrogates that represent the geometry, weight, mass distribution and can imitate the kinematics and kinetics of the human body for a given loading application[5]. ATDs are used widely by the automobile industries to evaluate the levels of passenger protection offered by vehicle manufacturers during an on road accident or collision of a vehicle. ATDs are instrumented with sensors to measure the accelerations, deflections and forces on critical body parts during the impact. The measurements obtained from these sensors will be used to derive the injury severity. ATDs can be configured based on direction of impact, sitting or standing position to suit specific application and also are available in various size, age, sex and impact direction viz. Hybrid III 50th percentile male, The Hybrid III 95th percentile Male , Hybrid III 5th percentile female, Side impact dummies such as EuroSID, EuroSID-2re and Child dummies[6].

1.2 Injury Biomechanics

According to Narayan[6], *et al.* biomechanics deals with using the principles of mechanics to assess the response of biological systems. Injury biomechanics is the study of the response of mechanical loading on the human body. Physical injury can occur when a particular loading during an event causes damage to anatomical structures and/or alteration in normal function of the human body. The injury mechanism is the method in which the damage/alteration is caused.

1.3 Injury Criterion Analysis

According to Diagarajen[7], *et al.* “an injury criterion is defined as a physical parameter or a function of several physical parameters which correlates well with the injury severity of the body area under consideration for a specific loading condition.

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Parameters that can be measured may include the linear acceleration experienced by a body part, the global forces or moments acting on the body or the deflection of a structure".

The protective shelter and vehicles used for military application is designed to withstand and safeguard the personnel against the primary and secondary blast injury. However the military crew inside the shelter or vehicle is exposed to tertiary blast loads, which are high acceleration and short duration impact or shock loads. The crew is considered to be safe if the values of injury criteria are below a value corresponding to a risk of injury explained in terms of injury scales. The most widely accepted and used injury scale worldwide is the abbreviated injury scale (AIS)[8]. The acceptable injury threshold is a 10 per cent probability of an AIS 2 or greater (AIS 2+) injury for different body regions of interest as per NATO TR HFM-090[4].

2. INJURY CRITERIA

The injury criteria of interest in the present study are discussed as follows.

2.1 Head Injury Criteria (HIC)

The head injury criteria HIC is a measure of possibility of head injury arising from a direct head impact. The HIC value is the standardised maximum integral value of the head acceleration. According to Report of NATO HFM-090[4], the HIC value is limited to 250 that refers to a 10 per cent risk of AIS 2+ injuries. The length and ΔT of the corresponding time intervals is of maximum 15 ms (HIC15). The head injury criteria can be calculated using Eqn. (1)

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

Where t_1 and t_2 are any two arbitrary times during the acceleration pulse and $a(t)$ is the resultant acceleration which is given in Eqn. (2)

$$a(t) = \sqrt{x^2+y^2+z^2} \quad (2)$$

Where x, y and z are the accelerations in x, y and z direction respectively. Eqn. (1) also indicates that HIC includes the combined effects of head acceleration and its duration. Large accelerations may be considered safe for very shorter times.

2.2 Neck Injury

Neck injuries are caused by indirect loading produced by inertial loads being transferred during head impact leading to a combination of translational and rotational motions in all the three dimensions. According to NATO, the force based injury criteria consisting of individual tolerance limits of neck compression, tension, flexion and extension moment is the better system to use during vertical impact loads. If flexion and extension bending moment peak values are below 190 Nm and 96 Nm respectively and compression load is below 1.8 kN then the risk of serious neck injuries are unlikely and corresponds to a 10 per cent risk of AIS 2+ injuries[4].

2.3 Dynamic Response Index

The spinal column is one of the vulnerable parts of the crew during vertical loading since the axial loads on the spinal region are more. Pelvic injuries may also occur due to such vertical loadings. As an indicator Dosquet[9] suggested dynamic response index (DRI), a dimensionless value related to a spine deflection, as the most important parameter for axial compression injuries. To calculate DRI, the equation of motion of a single degree of freedom spring-mass-damper system is considered and which is given by the Eqn. (3). The probability of injuries due to loading mechanisms in *X* and *Y* directions are quite low because of the predominant of axial (*Z*) loads during vertical loading[4].

$$\ddot{z}(t) = \ddot{\delta} + 2\,\xi\,\omega_n\dot{\delta} + \omega_n^2\,\delta \quad (3)$$

Where, $\ddot{z}(t)$ is the acceleration of the pelvis in the vertical direction.

δ is the relative displacement

ξ is damping coefficient with $\xi = \frac{c}{2\,m\,\omega_n}$

ω_n is the natural frequency with $\omega_n = \sqrt{\frac{K}{m}}$

DRI can be calculated by the maximum relative displacement δ_{max}, ω_n and gravity g using Eqn. (4)

$$DRI = \frac{\omega_n^2}{g}\delta_{max} \quad (4)$$

where ω_n is the natural frequency (52.9 rad/s), δ_{max} is the deflection (compression) and g is acceleration due to gravity (9.81 m/s^2). According to NATO, the maximum tolerance value for the DRI is 17.7 that refer to a 10 per cent risk of AIS 2+ injuries.

2.4 Lower Extremity Criteria

The load that acts on the lower leg portion is the axial load transferred from the floor of the structure or vehicle. The proposed tibia axial force tolerance value is 5.4 kN for Hybrid III dummy legs and is limited to 2.6 kN for Hybrid III dummy with MIL legs. The tolerance limit for the Femur is 6.9 kN. These tolerance limits of Tibia and Femur refer to a 10 per cent risk of AIS 2+ injuries4.

3. TEST METHODOLOGY

Pneumatic shock test machine (Model DPSTM-7575) developed by Dynamic Associates and Services, Roorkee, India was used to generate an arrested landing half sine shock pulse. The experimental setup consists of Hybrid III 50th

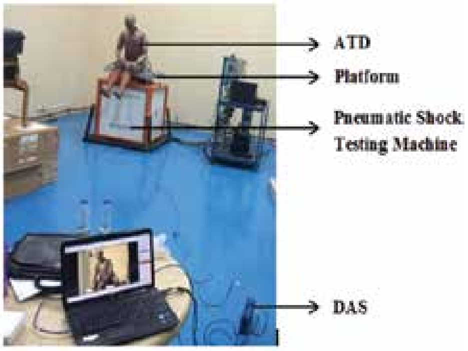

Figure 1. Experimental Setup.

Figure 2. Positioning of ATD.

percentile ATD with MIL-Lx leg, and data acquisition system (DAS) as shown in Fig. 1 and positioning of ATD is as shown in Fig. 2. The instrumented dummy was placed on the shock test platform and the sensors of the dummy were connected to DAS to record the response of the dummy for applied loading conditions. The platform is lifted to a predetermined height and accelerated downward to impact on elastomer pads to generate the required acceleration pulse. Accelerometer (charge type sensor, model 357B03, Make PCB, USA) was used to monitor the acceleration on the platform.

The standard Hybrid III dummy was chosen for scenarios where the loading is located underneath, in front or at the rear of the ATD[7]. In the present study the standard Hybrid III seated dummy with MIL-Lx Leg developed by Humanetics Inc. was used. The parameters were measured using the sensors integrated in the dummy as shown in Fig. 3. The Hybrid III 50th percentile dummy has a weight of 78 Kg and sitting height is 0.884 m. Table 1 explains details of sensors and their location in the dummy and associated injury criteria. Crash analysis tool of DIAdem software from National Instruments was used for data filtering, processing and injury assessment. Channel frequency Class (CFC) 1000 and CFC 600 were used for various signals as described in SAE J211/1[10]. The co-ordinate system adopted in the present study was as per SAE J1733[11].

4. RESULTS AND DISCUSSIONS

The experiment was carried out to capture the response of the ATD when it was subjected to the half sine shock pulse. The resultant acceleration pulse generated by the platform was 33.02 g with duration of 29.4 ms. The time plot is as shown in Fig. 4.

The ATD response data obtained were filtered as per SAE J211/1 CFC 600 and 1000. Since the impact was along the vertical direction head injury criteria (HIC), neck tension

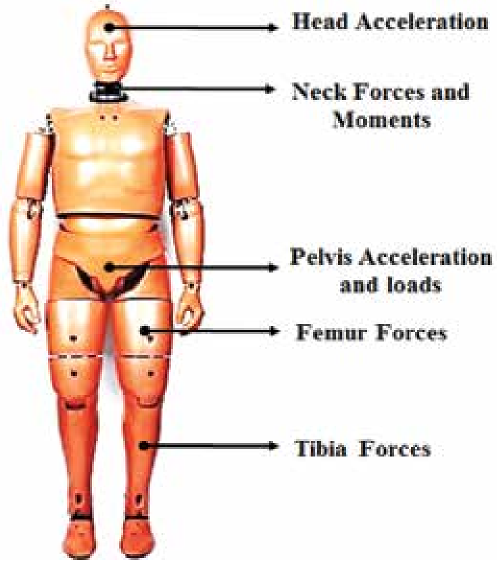

Figure 3. Hybrid III 50th percentile dummy configuration.

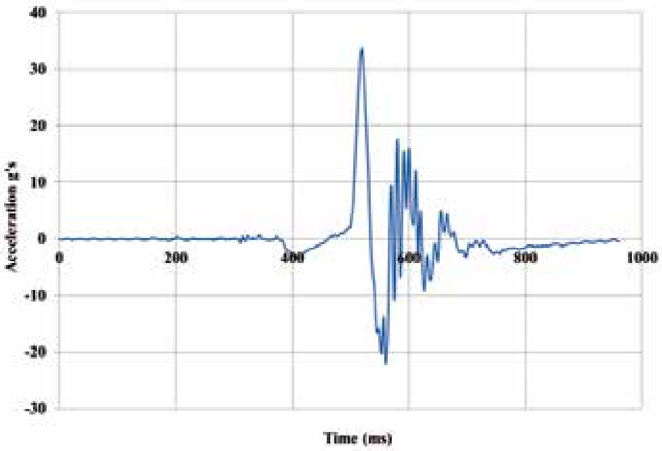

Figure 4. Platform Acceleration measured by accelerometer mounted on the platform of shock test machine.

Table 1. Location of sensors in the ATD

Body region	Location of sensor in ATD	Sensor (Symbol)	Parameter	Associated injury criterion
Head	Centre of gravity of head	Uni-axial accelerometer (A_x, A_y, A_z)	Linear accelerations	HIC15
Neck	Upper neck	Upper neck load cell (F_z , M_y)	Axial force (tension/compression)	F_z
			Bending moment (flexion and extension)	M_y
Pelvis	Centre of gravity of pelvis	Uni axial accelerometer Load cell [Lumbar-seated position] (A_z)	Linear acceleration (vertical)	DRIz
Legs	Femur	Load cell (F_z)	Axial force (compression)	F_z
	Tibia	Load cell (F_z)	Axial force (compression)	F_z

and bending moment, pelvis force, femur and tibia force were considered. The responses obtained from various sensors were recorded and injury criteria were calculated and compared with the NATO TR-HFM-090 standards[4].

4.1 Head Injury

It can be seen from the experimental test result as shown in Fig. 5, that there was less acceleration induced in the head region and the value for HIC was 2.93 which is well within the limit. HIC value was less since there was no direct impact of head on any rigid body during the experiment. According to Little[12], *et al.*values of HIC will be more when the head is in direct contact with the loading or during a direct impact. The results obtained in test were well related with Little[12], *et al.*

4.2 Neck Injury

The maximum neck load and moment observed in the test were 0.45 kN and 9.5 Nm as shown in Figs. 6 and 7, respectively. The values observed were within the limits since there was no direct impact on head. The flexion and extension moments were less and the compression load was more since the body was impacting vertically downward. The weight of the head and direction of impact accounts in the increased compressive load. However this indicated a low risk (10 per cent) of AIS 2+ injuries based on information given by Mertz[13], *et al.*

4.3 Pelvis Injury

The observed value of pelvis force in the test was 1.98 kN and acceleration was 18.75 g as shown in Figure 8 and Figure 9 respectively. The Pelvis load observed was nearer to the limit because the load applied was in direct contact with the Pelvis region. Since the ATD was placed on the platform and no cushioning was used during the test, the loads experienced by the ATD were high and closer to the limit. The DRI value calculated was 2.9. Results were in good agreement with the Dosquet[9].

4.4 Leg Injury

The observed values of the femur and tibia force were 0.61 kN and 0.55 kN, the values observed were well within the limits and were less as shown in Figs. 10 and 11, respectively. Since the legs did not make any contact with the floor or platform, the load experienced was low. Hence the values observed in the femur and tibia region were less. However, the same may not be true, as higher loads would be predicted if the legs were in direct contact with the floor or structure.

The above experiment has given fair idea about injury occurring during a vertical shock impact. The values observed

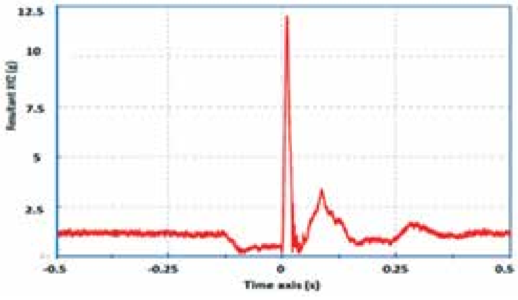

Figure 5. Head resultant acceleration.

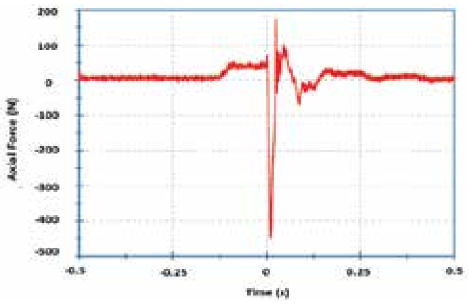

Figure 6. Neck load.

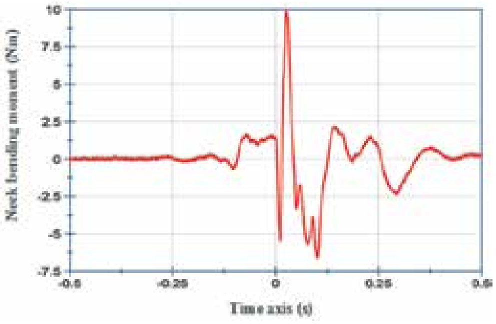

Figure 7. Neck bending moment.

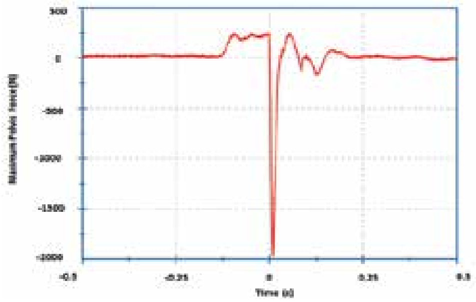

Figure 8. Pelvis force.

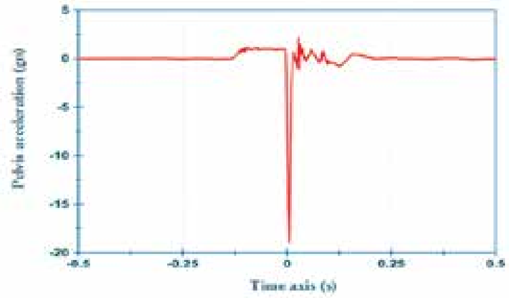

Figure 9. Pelvis acceleration.

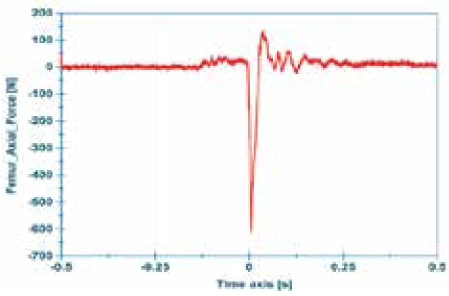

Figure 10. Femur force.

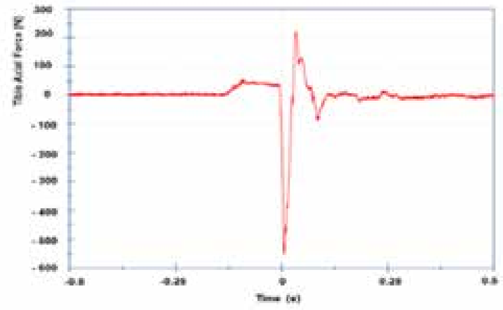

Figure 11. Tibia force.

in the tests were well within the limits prescribed in NATO TR-HFM-090[4]. Since the ATD's pelvis region was in direct contact with the platform the load experienced was high and was very closer to the limit. This was observed to be closer to the limits but well within 10 per cent probability of an AIS 2 or greater (AIS 2+) injury.

All the observed injury values of the dummy are tabulated in Table 2. The injury levels observed during the test are as shown in Table 2 as per analysis carried out using crash analysis tool of DIAdem software.

Table 2. Observed injury values

Injury criteria	Limit	Observed value	Probability of AIS2+ Injury (%)
HIC15	250	2.93	<10
Neck Load (kN)	1.8	0.45	<10
Neck moment (Nm)	96	9.5	<10
Pelvis Force (kN)	2.60	1.98	<10
Femur Force (kN)	6.9	0.61	<10
Tibia force (kN)	2.6	0.55	<10
DRI	17.5	2.9	<10

5. CONCLUSIONS

Comparison of the observed values with the NATO TR-HFM-090 revealed that the injury values are within the limits. It is reported that the ATD subjected to arrested landing half sine shock pulse is safe and well within 10 per cent probability of an AIS 2 or greater (AIS 2+) injury. However, the observed pelvis injury level was closer to the injury limit because the pelvis portion of the ATD was in direct contact with the load. Further it is expected that the injury levels will increase towards higher side under a higher accelerations pulse. In general a suitable seat cushions are provided in vehicles and aircrafts to spread the load uniformly over a larger area of buttocks and thighs. It also helps to modify the impact time history into a smaller peak force over a longer time reducing the pelvis injury levels. The present experimental test has given a fair account about injury criteria analysis under vertical impact loading.

6. FUTURE WORK

A strong technology base has to be developed to fully understand the dynamics and injury mechanisms of human under real tertiary blast loading conditions. Experiments involving full scale tests using ATD have remained a significant challenge due to the destructive nature and the high costs associated with setting up of full scale tests. Also, the reaction times during the event occur within a short time period and are difficult to quantify in physical testing.

With the advances in computing power, it is now possible to simulate the same physical tests in a realistic manner using virtual anthropomorphic test devices (VATD). VATDs are numerical models of the ATD and can be used with infinite possibilities of iterations with respect to intensity of loads and structure constructions using finite element simulation programs. Such programs can help in simulation of such full scale tests at laboratory level to predict the dynamics and injury mechanisms of human. These simulations shall be used to quantify a given blast load and establish critical parameters on different body parts of the VATD to derive the injury levels. It is planned to validate the present experiment using numerical simulation and use the computational models to carry out further studies.

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CONTRIBUTORS

Mr A. Prasanna has completed his BTech (Mechanical Engineering) and currently working as Scientist ‘C’ at Defence Bioengineering & Electro-medical Laboratory, Bengaluru. His areas of research interest are design and development of aeromedical life support systems and injury biomechanics under blast scenarios.
His contribution in the current study is planning the study, performing experiments, analysing results and preparing the manuscript.

Dr G.K. Kannan has completed his PhD in Environmental Science and currently working as Scientist ‘F’ at Defence Bioengineering & Electro-medical Laboratory, Bengaluru. He has been working in the area of air quality and emission monitoring, and environmental impact assessment and development of explosive vapour detection. His current research includes filter development and evaluation. His areas of research interest are injury analysis, environmental impact assessment and pollution monitoring.
His contribution in the current study is planning of experiment and critical analysis of results and guidance.

Dr N. Mohan has completed his PhD in Environmental Science and currently working as Scientist ‘E’ at Defence Bioengineering & Electro-medical Laboratory, Bengaluru. His areas of research interest are modelling and simulation of blast analysis and emissions of closed rooms, developing transducers for sensing applications.
His contribution in the current study is critical assessment of results and guidance.

Mr ShivarajYaranal has completed his MTech (Machine Design) and currently working as FEA engineer at Defence Bioengineering & Electro-medical Laboratory, Bengaluru. His areas of research interest are FEM, occupant safety simulations, dummy/ human body models, biomechanics and injury criteria, FE based simulation of blast, design and analysis of structures.
His contribution in the current study is setting up the experiment, analysing the results and preparing manuscript.

Mr Kartik S. Patilhas completed his MTech (Machine Design) and currently working as FEA engineer at Defence Bioengineering & Electro-medical Laboratory, Bengaluru. His areas of research interest are FEM, occupant safety simulations, dummy/ human body models, biomechanics and injury criteria, FE based simulation of blast, design & analysis of structures.
His contribution in the current study is setting up the experiment, analysing the results and preparing manuscript.

Mr Vikash Kumar has completed his BTech (Electronics and Communications) and currently working as Scientist ‘D’ at Defence Bioengineering & Electro-medical Laboratory, Bengaluru. His areas of research interest are instrumentation of anthropomorphic test devices (ATD), Blast injury analysis using ATD and electro-acoustic device characterisation for aviation helmets and masks.
His contribution in the current study is performing experiments using anthropomorphic test devices and analysing results.