ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Vertical accelerator device to apply loads simulating blast environments in the military to human surrogates

Narayan Yoganandan [a,*], Frank A. Pintar [a], Michael Schlick [a], John R. Humm [a], Liming Voo [b], Andrew Merkle [b], Michael Kleinberger [c]

[a] Department of Neurosurgery, Medical College of Wisconsin, Milwaukee, WI, United States
[b] Applied Physics Laboratory, Johns Hopkins University, Laurel, MD, United States
[c] US Army Research Laboratory, Soldier Protection Sciences Branch, Aberdeen Proving Ground, MD, United States

ARTICLE INFO

Article history:
Accepted 15 June 2015

Keywords:
Vertical loading
Military events
Under-body blasts
Impact biomechanics

ABSTRACT

The objective of the study was to develop a simple device, Vertical accelerator (Vertac), to apply vertical impact loads to Post Mortem Human Subject (PMHS) or dummy surrogates because injuries sustained in military conflicts are associated with this vector; example, under-body blasts from explosive devices/events. The two-part mechanically controlled device consisted of load-application and load-receiving sections connected by a lever arm. The former section incorporated a falling weight to impact one end of the lever arm inducing a reaction at the other/load-receiving end. The "launch-plate" on this end of the arm applied the vertical impact load/acceleration pulse under different initial conditions to biological/physical surrogates, attached to second section. It is possible to induce different acceleration pulses by using varying energy absorbing materials and controlling drop height and weight. The second section of Vertac had the flexibility to accommodate different body regions for vertical loading experiments. The device is simple and inexpensive. It has the ability to control pulses and flexibility to accommodate different sub-systems/components of human surrogates. It has the capability to incorporate preloads and military personal protective equipment (e.g., combat helmet). It can simulate vehicle roofs. The device allows for intermittent specimen evaluations (x-ray and palpation, without changing specimen alignment). The two free but interconnected sections can be used to advance safety to military personnel. Examples demonstrating feasibilities of the Vertac device to apply vertical impact accelerations using PMHS head–neck preparations with helmet and booted Hybrid III dummy lower leg preparations under in-contact and launch-type impact experiments are presented.

Published by Elsevier Ltd.

1. Introduction

It is important to simulate external load vectors to replicate field injuries, understand their mechanisms, determine human tolerances, and develop anthropomorphic test devices (ATDs) for injury prediction and improve safety. In automotive crashes, impact loading is generally horizontal, i.e., the vector lies along a clock direction: twelve, three or nine and six o'clock representing frontal, side and rear impacts (Backaitis and Mertz, 1994; Kuppa et al., 2003; Morgan et al., 1994; Yoganandan et al., 2014a; Yoganandan et al., 2015a; Yoganandan and Pintar, 2000). Devices such as acceleration and deceleration sleds have been used for over fifty years to simulate such loadings by positioning physical and biological models on their platforms to apply the intended load vector (Maltese et al., 2002; Philippens et al., 2000; Pintar et al., 1997; Yoganandan et al., 2007). The use of a pendulum is another example. Injury criteria and risk curves continue to be derived and/or updated, and ATDs are developed using such devices (Kuppa et al., 2003). This horizontal orientation is not suitable for studying all applications.

Vertical loading from improvised explosive devices is a causal factor for injury in recent military conflicts (Gangani and Vidye, 2013; Wang et al., 2001; Yoganandan et al., 2013). Sub-system and component tests are needed to investigate injury mechanisms and derive tolerance criteria under the vertical mode. Horizontal (sled) and vertical devices (drop tower and TROSS system) are used to apply vertical loading (Newell et al., 2012; Pandelani et al., 2010; Yoganandan et al., 2014b; Yoganandan et al., 2015b). The objective of this study is to present another device, Vertical accele-

* Correspondence to: Chair Biomedical Engineering Department of Neurosurgery 9200 West Wisconsin Avenue Medical College of Wisconsin Milwaukee, WI 53226, USA. Tel.: +414 384 3453; fax: +414 805 0115.
E-mail address: yoga@mcw.edu (N. Yoganandan).

http://dx.doi.org/10.1016/j.jbiomech.2015.06.008
0021-9290/Published by Elsevier Ltd.

rator (Vertac), to apply vertical loading to human surrogates. Its capabilities include the application of dynamic loading to different body regions of the human for sub-system and component experiments and the flexibility to account for preloads and accommodate the effects or use of personal protective equipment (PPE) under different initial conditions. The ability to conduct matched-pair tests with post mortem human subjects (PMHS) and ATDs is demonstrated.

2. Methods

2.1. Load-application section

The Vertac device consisted of two free-standing stanchions/towers (Figs 1–3). The frame of the first section was termed as the load-application section. It was fixed to the laboratory wall and floor. An outrigger protruding from the wall carried a cart assembly with bilateral bearings. The cart was held in place at a pre-determined height using a pneumatically controlled quick-release (TR5 Sea Catch Toggle Release, McMillan Design, Inc., Gig Harbor, WA, USA; equipped with LS-07777 Pneumatic Cylinder, Nason, Walhalla, SC, USA). The design of the cart allowed different weights to be placed on its seat and upon release of the cart, the weight dropped onto a lever arm placed above the laboratory floor of the load-application section. An energy absorbing material was used on the lever arm. The thickness and type of material can be varied depending on the desired external input, i.e., loading severity such as velocity and time to peak. The stroke of the lever arm can be controlled by placing metal plates of varying thickness between the floor and the load-application end. The lever arm was supported eccentrically using an axle and pillow-block bearing. The eccentric support had the flexibility to accommodate different operating lever arm ratios. A rectangular metal plate (launch plate) was accelerated by the load-receiving end of the lever arm. The size of the launch plate conformed to the inferior end of the prepared PMHS/ATD surrogate, placed on the second independent component of the Vertac device.

2.2. Load-receiving section

The frame of the second section was termed as the load-receiving section. It consisted of a moveable stanchion, made out of a metal frame with braced vertical fixtures. A second cart assembly was attached with precision bearings such that PMHS/ATD preparation, rigidly fixed to its base, could freely translate superiorly along the vertical direction upon impact from the lever arm plate of the load-application section. The cart assembly consisted of a metal base to which PMHS/ATD preparation could be secured. It had the flexibility to accommodate additional fixtures such as a simulated vehicle roof structure for subjecting military helmeted head–neck complexes and applying vertical loading from the load-application section to inferior end of the neck of PMHS/ATD dummy surrogates. Using this design it was possible to position the roof at different initial helmet-roof clear distances. For applying loads to the foot–ankle complex of lower leg preparations, it also had the flexibility to accommodate an articulated specimen restraint complex (simulated thigh).

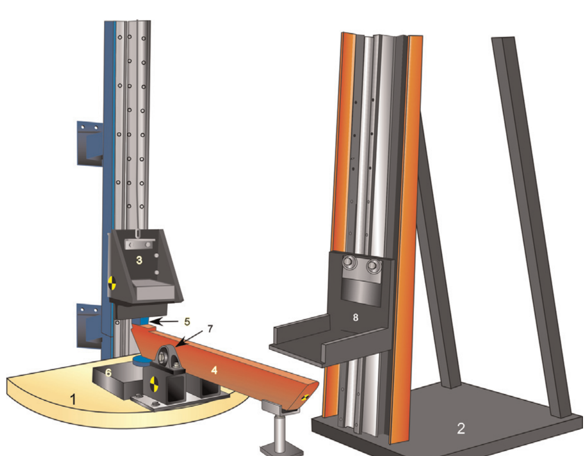

Fig. 1. Schematic of the Vertac showing the two stanchions and the lever arm. Left side of the illustration shows the load-application section and the right side shows the load-receiving Section 1: load application stanchion, 2: load receiving stanchion, 3: drop mass cart, 4: lever arm, 5: pulse shaping material, 6: stroke limiter, 7: pivot point (sets lever arm ratio), 8: specimen cart. 2:1 lever arm: 45.7 cm in length.

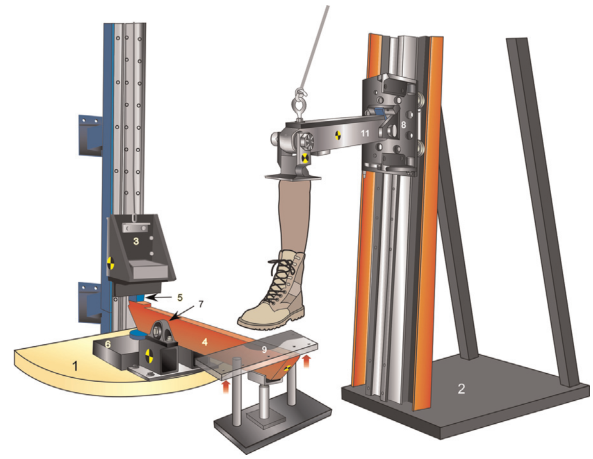

Fig. 2. Schematic of the load-application section of the Vertac showing the lower leg preparation with military boot on the Hybrid III ATD. Vertical arrows indicate the initial separating distance from the booted lower leg preparation to receive the launch-type impact.. 1: load application stanchion, 2: load receiving stanchion, 3: drop mass cart, 4: lever arm, 5: pulse shaping material, 6: stroke limiter, 7: pivot point (sets lever arm ratio), 8: specimen cart. 9: launch plate. The rectangular metal plate, (launch plate): 15.24 × 2.54 × 45.72 mm. The two pillars below the launch plate: 25.4 mm in diameter and 20.3 mm tall, separated by a center to center distance of 25.4 mm.

2.3. Vertical loading process

The launch plate was used to apply the vertical loading input. It was possible to obtain two types of inputs: the first, launch impact (Fig. 2), was accomplished by placing the plate such that upon the impact of the drop weight on to the load-application end of the lever arm, the launch plate traveled freely and vertically to contact the inferior end of PMHS or dummy preparation attached to the load-receiving stanchion. It should be noted that PMHS or ATD preparation was positioned at a pre-determined distance from the launch plate for this loading scenario. The impact of the launch plate with the preparation created the desired vertical loading input pulse. The second, in contact impact, was associated with PMHS/ATD preparations to be in contact with the plate (Fig. 3) before dropping the weight from the first stanchion. Using this design, depending on the desired input pulse, it was possible to interface energy absorbing materials, termed pulse-shapers, between the launch plate and inferior end of PMHS/ATD preparations.

2.4. Instrumentation

Accelerometers, strain gages, acoustic emission sensors, photo targets and load cells can be attached to different components of the preparation depending on its type, without any interference from the Vertac device. For PMHS lower leg preparations, accelerometers, strain gages, acoustic emission sensors and photo targets can be mounted to the calcaneus and tibia bones. Load cells can be mounted to the proximal end. For head–neck complexes, sensors can be mounted to vertebrae and load cells can be attached on top of the simulated roof fixture and to inferior end of the neck by fixing the thoracic spine in poly-methyl-methacrylate. In addition, kinematics of the preparation can be recorded in different perspectives using videos. Examples incorporating PMHS/ATD preparations from two body regions and two initial conditions are presented to demonstrate the use of the Vertac device.

Fig. 2 shows the setup for vertically loading the Hybrid-III ATD preparation using a launch impact type test. The dummy leg was disassembled at the knee and a simulated thigh was attached orthogonal to the proximal end. The preparation was maintained in the neutral posture (the foot–ankle region was perpendicular to the 'shin,' which in turn was orthogonal to the simulated thigh). The launch-type impact loading was chosen for this setup by varying the mass of the launch plate. An initial gap existed between the 'plantar surface' of the foot and launch plate. A uniaxial accelerometer was attached to the launch plate to record the applied vertical acceleration pulse. The plate was launched free at its center of gravity and high-speed videos obtained at 5000 frames per second showed no discernable rotation upon leaving the lever arm, through contacting the base of the specimen to the ensuing loading process (Fig. 3). The travel of the launch plate was uniaxial.

Fig. 4 shows the experimental setup for vertically loading the PMHS for an in contact impact test. The head–neck was isolated at the base of the neck and an Army combat helmet was attached with chin straps. The helmet size was based on the circumference of the head. In-contact type of loading was chosen for this setup by attaching the distal end of the biological preparation to the launch plate, i.e., no initial gap. In addition, tests were conducted with and without a simulated roof to