Torso Mass Effects on Hybrid III Lumbar Spine Response to Underbody Blast Loading

Narayan Yoganandan, Jason Moore, Tim Westerhof, Nico Flierman

I. INTRODUCTION

Prediction of injuries with any physical device, such as the Hybrid III dummy, is dependent on the use of injury and non-injury data from companion or matched-pair tests with biological surrogates. In the automotive world, the human cadaver model is the gold standard. This is because post-mortem human subjects (PMHS) and *in vivo* humans have the same anatomy. The short duration of the acceleration pulse is fundamentally applicable to fractures that tend to be less physiology based than internal organs, such as the brain, liver, lung and heart. Fracture mitigation is a major goal for automotive applications and it is also applicable to the military field for certain scenarios. For example, underbody blast loading from improvised explosive devices induces short-duration blunt accelerative forces on the Soldier seated in the military vehicle. The acceleration pulse is transmitted vertically from the vehicle seat to the pelvis to the lumbar spinal column. International studies have reported lumbar spine fractures from underbody blast loading [1-3]. Injuries reported in combat have been reproduced in laboratory settings using PMHS lumbar spinal columns and custom vertical accelerator equipment without resorting to the use of actual explosives, full-scale military vehicles and whole/intact PMHS [4-5]. This approach is the basis for the development of generalised human injury lumbar spine risk curves [4-5].

Although the original intent of the Hybrid III dummy was for automotive applications, it is used in military and other fields. Matched-pair tests with this device are needed to ensure that the dummy lumbar spine is capable of measuring loads under the vertical load vector and does not saturate at higher velocities. Tests are also needed to demonstrate its feasibility to record loads at the ends of the spine and to develop injury assessment risk curves (IARCs) for a range of impact conditions/scenarios. The objective of the present short communication is to present initial results on the role of effective torso mass on the upper and lower spine loads in the Hybrid III dummy lumbar spinal column from simulated vertical impact loading applied at its base.

II. METHODS

A custom vertical accelerator device designed to conduct PMHS lumbar spinal column experiments was used to test the mid-size male Hybrid III lumbar spine [6]. Briefly, the device has load-applying and load-receiving sections (Fig. 1). The stanchion of the load application section was fixed to the wall and to a cart assembly. The cart projecting from the wall was attached to a fixture to accommodate different weights for dropping onto a lever arm. The lever arm was attached to the laboratory floor. The movable stanchion of the load-receiving section was used to position the experimental model (PMHS lumbar spine or physical device, such as the Hybrid III lumbar spine). The stanchion had two vertical fixtures and a cart assembly to which the lower end of the experimental model could be attached. The cart translated vertically after impact from the lever arm. Upon releasing the drop weight from a predetermined height, the mass impacted the lever arm and accelerated the experimental model from the inferior end, applying vertical loading to the lumbar spinal column.

The standard mid-size male Hybrid III lumbar spine was used in this study. It was mounted upright between the torso mass (described later) and upper and lower load cells (Model M3944, Sunrise Instruments, Shanghai, China) that were orthogonal to the accelerator device. An effective torso mass of 12 kg (low mass) was placed above the dummy spine to mimic matched-pair isolated PMHS spinal column tests. In another series of tests, an additional 4 kg mass (high mass) was used. It was based on an analysis of unpublished data that showed changes in the mass with varying impact levels. While the geometry of the tested specimens was close to that of the mid-size male occupant, local variations such as lordosis was present due to the nature of the biological surrogate. Load cell data were gathered using a digital data acquisition system (DTS Inc., Seal Beach, CA) at a sampling rate of 100 kHz and filtered at 1 kHz. Recorded forces at both ends were transformed to the location at the midpoint of the interface between the metal and rubber representing the Hybrid III dummy spine. High-speed video images were

N. Yoganandan (e-mail: yoga@mcw.edu) is a Professor and J. Moore is a Research Engineer at the Medical College of Wisconsin, Milwaukee, USA. T. Westerhof and N. A. Flierman are Engineers at TNO, Netherlands, NE.

used to analyse the kinematics of spinal column in the lateral plane. High-speed video images were used to analysze the kinematics of spinal column in the lateral plane. Peak axial forces, shear forces and resultant forces at the upper and lower spine were used to determine the role of low and high effective torso mass and response of the Hybrid III spine to vertical impacts.

III. INITIAL FINDINGS

A total of 24 tests were conducted in the study. The kinematics of the impacts were such that the Hybrid III dummy lumbar spine travelled along the axial direction with no failure of the lumbar spine at all velocities and for both effective torso mass magnitudes. Axial forces were consistently greater than shear forces for both effective mass magnitudes at all velocities. Shear forces accounted for a mean of 11 ± 6% and 12 ± 4% of axial forces across all tests at the lower and upper spines for the low torso mass tests, and they accounted for a mean of 11 ± 8% and 9 ± 3% of axial forces for the high torso mass tests. Tests with the high torso mass produced greater responses than tests with low torso mass. Wit the acknowledgment of the tested sample size, a linear relationship between velocity and axial force was apparent for both mass magnitudes and at both spines (Fig. 1).

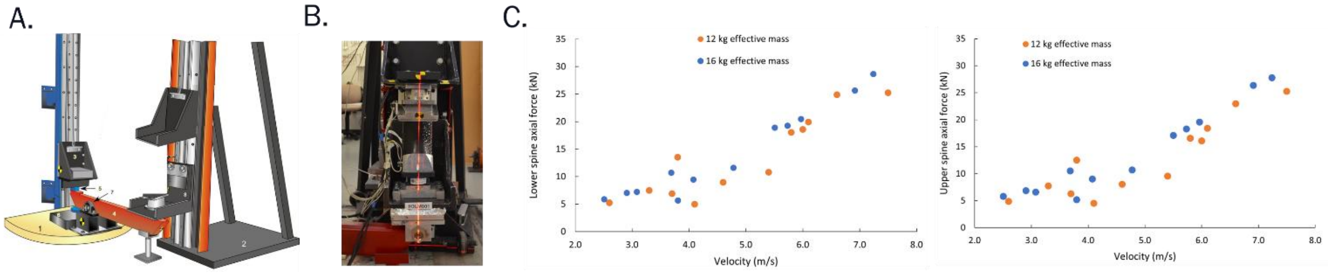

Fig. 1. A: Shows the custom vertical accelerator device [6]. B: Shows the Hybrid III lumbar spine aligned in the device. C: Shows the plot of the relationship between the lower spine axial force and velocity for both effective mass magnitudes, and the plot on the right shows a similar relationship for the upper spine axial force.

IV. DISCUSSION

The present series of tests was done using a matched-pair approach. Upper and lower spine force data from PMHS lumbar spinal column experiments under the same initial conditions with the use of the low effective torso mass were reported [5]. In the PMHS model, compression-related injuries were replicated paralleling field data from combat scenarios, and the mechanism of injury was attributed to axial loading [7]. The predominance of the axial force (low shear force contribution), infrangibility of the spine, and increasing force response with increasing velocity (demonstrating the lack of any plateauing or saturation effects) suggest that the Hybrid III lumbar spine is an acceptable and feasible device for underbody body blast scenarios. To use this dummy spine for Warfighter safety, however, IARCs are needed. It is possible to develop them for tests with low torso mass as matched-pair tests are available [4-5]. Increase in forces with the high effective torso mass (greater slopes for the force-velocity regression lines (Fig. 1) is attributed to the added stiffness stemming from the additional preload effect on the spine. In the absence of matched-pair PMHS spine tests with high torso mass, it is possible to develop IARCs using scaling relationships and low effective torso mass data. However, additional matched-pair PMHS tests will be needed to develop accurate IARCs for the high torso mass case. This is a future study topic for the international community to pursue as the Hybrid III dummy continues to be a testing device for military safety. The present results have laid a foundation for such efforts.

V. ACKNOWLEDGEMENTS

The study was supported in part by the Office of the Assistant Secretary of the US Department of Defense, Grant number W81XWH16-1-0010. Dr Narayan Yoganandan is an employee of the Zablocki Veterans Affairs Medical Center, Milwaukee, WI, USA. Opinions, interpretations, conclusions and recommendations are those of the authors and are not necessarily endorsed by the US Department of Defense.

VI. REFERENCES

[1] Vasquez, K. B., *et al.*, *Mil Med*, 2018. [2] Schoenfeld, A. J., *et al.*, *Injury*, 2013. [3] Ramasamy, *et al.*, *J Trauma*, 2008. [4] Yoganandan, N., *et al.*, *J Mech Behav Biomed Mater*, 2020. [5] Yoganandan, N., *et al.*, *J Biomech*, 2018. [6] Yoganandan, N., *et al.*, *J Biomech*, 2015. [7] Danelson, *et al.*, 2015.