A Human Mannequin Head-and-Neck Multibody Model for the Simulation of High-Speed Impacts

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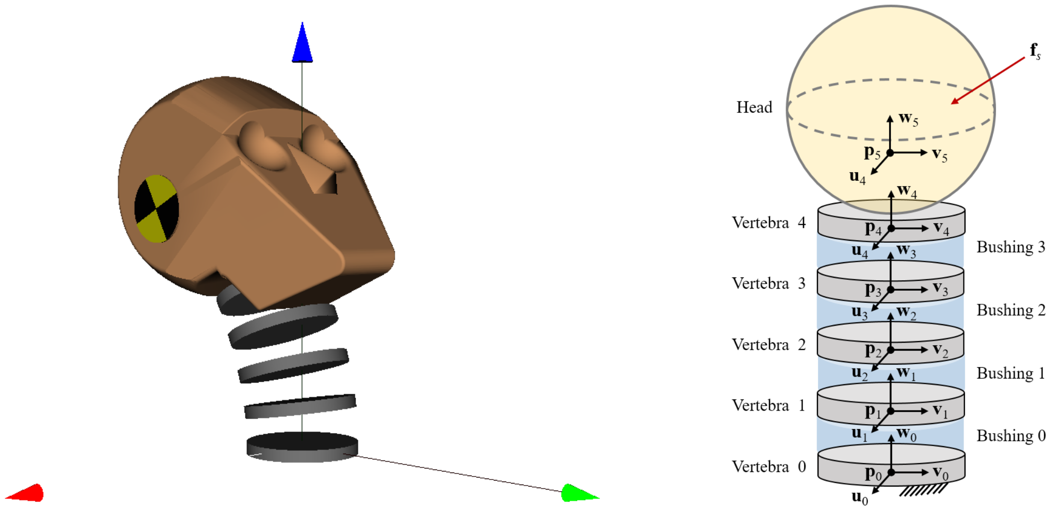
Abstract

Helmets and body armours are often employed to decrease the occurrence of head- and torso-perforating injuries caused by ballistic projectiles, shrapnel, and other objects propelled by blast. However, even when these devices successfully defeat projectiles the user may still undergo Behind Armour Blunt Trauma (BABT) [1]. The effects of BABT on the human body are currently the subject of a number of research studies [2]; typical injuries range from skin laceration to bone fractures and contusions to internal organs. As a consequence, BABT need be considered during the development of personal protective armour components [3, 4].

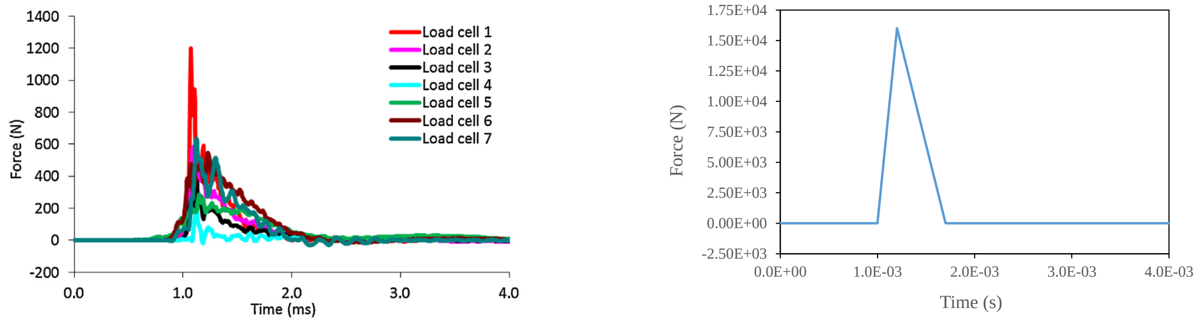


(a) Graphic representation (b) Multibody model

Figure 1: Computational model of the Hybrid III Dummy.

In this work we studied the effects of bullet impacts on subjects that wear protection helmets in order to predict their likelihood to suffer BABT. It was assumed that the helmet was able to defeat the bullet in all cases, so the head would not suffer any perforating injuries. However, the impact energy would still be transmitted to the subject, introducing significant accelerations in the system and giving rise to reaction efforts in the neck; these must be evaluated to determine up to what extent they may result in BABT. A computational multibody model of the head and neck of a Hybrid-III Dummy, shown in Fig. 1, was developed to this end. The model was formulated using natural coordinates; one point and three unit vectors were used to describe the motion of each body in the system. The vertebrae were connected by nonlinear bushings that allowed for relative three-dimensional motion between them. Each bushing was modelled as a six degree-of-freedom, linear elastic beam with bending-shear coupling and variable stiffness and damping properties. The head was pinned to the last vertebra via a revolute joint and a torsional spring. Bullet impacts were modelled with a set of time-varying forces $\mathbf{f}_s$. The number, location, and time history of these forces were adjusted to represent different impact scenarios that involved various types of ammunition and protective equipment. These forces can reach a peak value of up to 20 kN and typically have a rise period in the order of a tenth of a millisecond, while the total bullet energy is transmitted to the system in less than 3 ms [3]. Such force properties resulted in the need to use integration schemes with step-sizes in the order of 10^{-6} s.

The forward-dynamics simulation of the bullet impacts and the subsequent dummy motion was carried out with several multibody formulations. Augmented Lagrangian and Hamiltonian algorithms were selected, as they have been proven to be efficient and robust and able to deal with impact forces and system discontinuities [5]. Their performance was tested in combination with explicit and implicit numerical integrators, namely the symplectic



(a) Experimental sample reported in [3]

(b) Force profile used in simulation

Figure 2: Time history of the forces transmitted from the helmet to the head during a bullet impact.

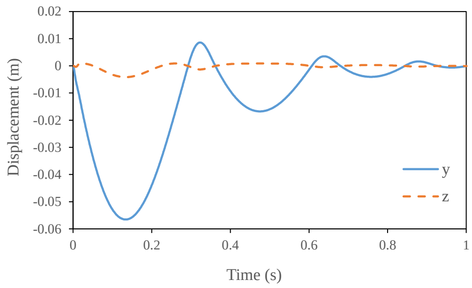


Figure 3: Displacement of the head COM during simulation.

Euler formula and the Newmark method. In the case of the implicit integrator, both fixed-point and Newton-Raphson iterative schemes were evaluated. These methods were implemented and compared in terms of efficiency, accuracy, and robustness using mbsLab, a C++ multibody system dynamics library developed at LIM [6].

In a preliminary set of numerical experiments, the impact force was modelled following the profile shown in Fig. 2b, which featured the same peak value, rising time, and impulse as experimental values reported in the literature. The asymmetric behaviour of the neck during flexion and extension was represented using a different bushing stiffness for each of these motions. The physical parameters of the bushings, including their stiffness and damping, will be adjusted in the near future with experimental data. All the tested methods delivered similar system motions, Fig. 3, successfully carrying out the integration with step-sizes larger than $h = 4 \cdot 10^{-6}$ s.

Acknowledgments

The authors acknowledge the financial support of the Ministry of Economy and Competitiveness of Spain and the ERDF (FEDER) program under Project RTC-2015-3887-8 and the post-doctoral research program Juan de la Cierva, contract No. JCI-2012-12376.

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