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Improvements in Simulations of Aortic Loading by Filling in Voids of the Global Human Body Model

Anderson de Lima* and Jiri Kral
General Motors Company

ABSTRACT – Internal organ injuries of the chest are one of the leading causes of deaths in motor vehicle crashes. The issue of initial presence and dynamic formation of voids around the heart and aorta is addressed to improve kinematics, force interaction and injury risk assessment of these organs of the Global Human Body Model. Steps to fill the voids are presented.

INTRODUCTION

Thoracic aortic injury from blunt trauma is a leading cause of death with up to 90% fatality rate on the scene (Sznol et al. 2016, Arthurs et al, 2009 and Fabian et al. 1997). Finite Element Models (FEM) of the human body are being used to understand the injury mechanisms of thoracic injuries (Kermani et al., 2016).

Kral et al., (2019) described some of the physical phenomena that play important roles in mathematical modeling of the internal organ interactions. They proposed a number of modeling techniques to capture these phenomena along with two simulation setups to test for proper internal organ interaction. That study is extended here by:

- filling the initial internal voids in the thoracic region of the Global Human Body Model (GHBM) Full Body Model of the 50th percentile male with FE mesh and defining tied contact interfaces
- adding a test simulation loadcase
- analyzing the response of the thoracic aorta with the filler and tied contact in the test simulations

The heart, aorta, lungs, spine, diaphragm and liver occupy most of the thoracic cavity. Humans have adipose tissue in the spaces between the organs. In Figure 1, the white spaces between the organs are gaps (or voids) in the GHBM that are not anatomically accurate.

Figure 2 shows the aortic arch with its main branches (brachiocephalic artery, left common carotid artery and left subclavian artery) as modeled in the GHBM. However, the left and right common carotid arteries are represented by only short stubs, the subclavian arteries are attached to the clavicles, and the ligamentum arteriosum is not modeled.

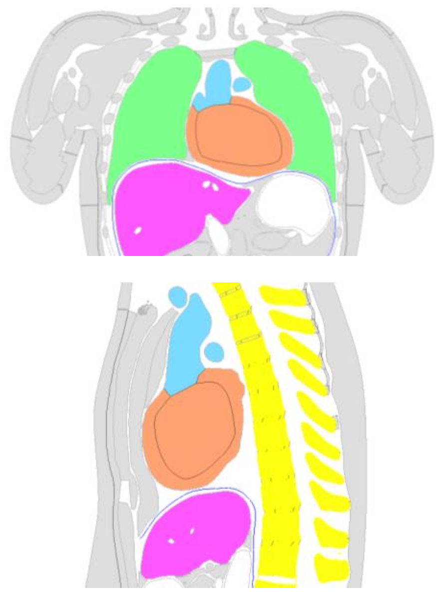

Figure 1: GHBM chest model frontal section (top) and sagittal section (bottom). The lungs are shown in green, heart in orange, aorta in blue, liver in pink, vertebral column in yellow.

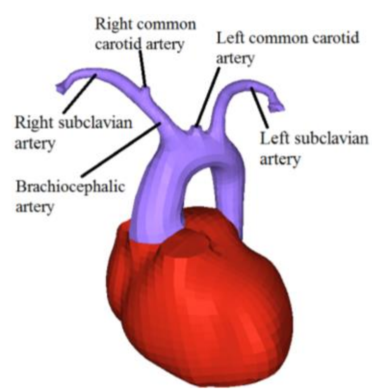

Figure 2: GHBM model of the aorta and heart.

E-mail: andersonkaipers.lima@gm.com

This paper demonstrates a methodology to fill the existing voids in the thoracic cavity and prevent voids from forming during impact simulations. The effects of this model change on the GHBM heart and aorta kinematics and loading are also shown.

METHODOLOGY

The internal empty spaces of the thoracic region of the GHBM (v5 beta – 11/30/2018) were filled by following these steps:

1. the aorta, vena cava and heart were isolated along with the surrounding organs: lungs, diaphragm, anterior thoracic fat layer and the thoracic spine;
2. a solid volume was created to fill the gaps between these isolated organs;
3. the newly created volume was meshed using tetrahedron elements;
4. external pressure was applied to move the surface nodes of the filler a short distance (a fraction of a millimeter) away from the other GHBM organs to avoid initial penetrations.

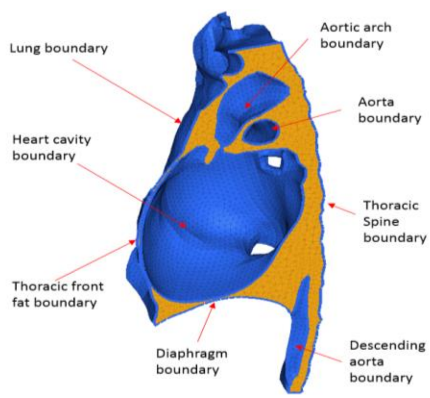

Figure 3: Filler component created in the thoracic region.

The filler component and its boundaries are shown in Figure 3. The material property for the filler component was chosen to be similar to the GHBM abdominal and thoracic fat. The existing tiebreak sliding contact between the thoracic organs was replaced by a simple tied contact between the internal thoracic organs and the filler.

To test the model behavior with and without the filler in place, three simulation load cases shown in Figure 4 were performed using the GHBM:

A. horizontal linear pelvic impact by a rigid bar,
B. vertical linear pelvic impact by a rigid bar,
C. lateral linear impact to the GHBM thorax by a rigid cylindrical impactor.

Although Kral et al. (2019) proposed a constant impactor velocity of 4 m/s, a constant velocity of 3.2 m/s was used in all three load cases.

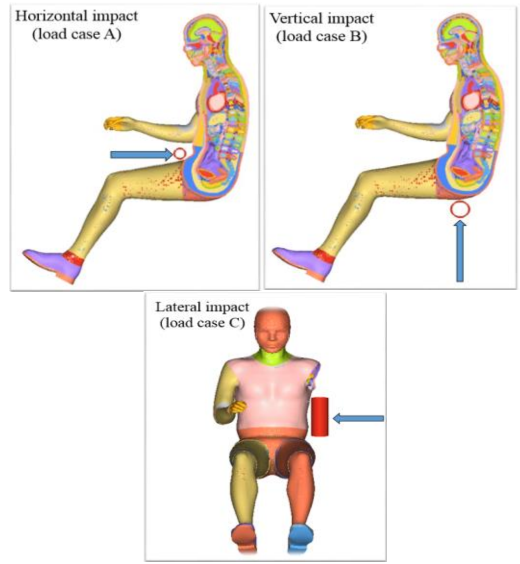

Figure 4: Simulation load cases used to test the thoracic filler.

RESULTS

Differences were observed in the kinematics of the heart and the aorta between the runs without and with the thoracic void filler. Figure 5 shows the GHBM chest internal kinematics for load case B, the vertical impact. In the sagittal cross section of the GHBM thorax without the void filler the gap between the heart and the spinal column increased (Figure 5, left). With void filler, the heart and aorta stayed closer to the spine, with no voids being created in the area (Figure 5, right). The thick dark line compares the organ section contours.

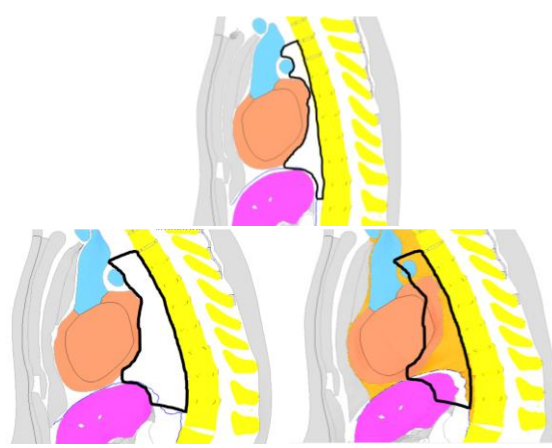

Figure 5: The top picture shows the original position of GHBM, unloaded organs. The bottom pictures

compare the heart and aorta positions at 40 ms for load case B where vertical load is applied to the GHBMs without (left) and with (right) the void filler.

Figure 6 shows the maximum first principal stress of the aorta for load case C, the lateral impact. Maximum stresses occur in the aortic arch without void filler. With the void filler maximum stresses occur near the distal end of the thoracic aorta.

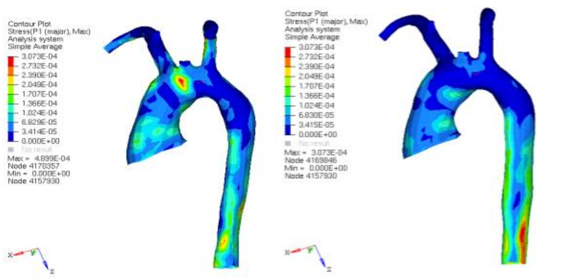

Figure 6: Maximum first principal stress contours for GHBM without (left) and with (right) the solid volume in simulation of load case C – lateral impact to thorax.

Section forces in four different regions along the aorta and the branching arteries were captured during the simulations. Figure 7 shows the magnitudes of the peak resultant section forces. The aorta experienced higher loads when the filler was in place.

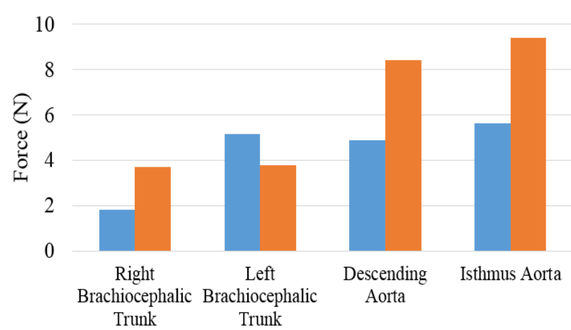

Figure 7: GHBM section forces in the branching arteries and the aorta in load case C, without (blue bars) and with (orange bars) the filler.

DISCUSSION

To further improve the accuracy of the heart and aorta modeling in the GHBM, these steps are also proposed:

- addition of ligamentum arteriosum
- extension of the left and right common carotid arteries
- modeling the correct anatomy of the subclavian arteries ends
- modeling of the blood using methods suitable for fluid-like behavior
- modeling of the lungs as expandable volumes connected to the atmosphere outside the GHBM

Additional impact scenarios, such as direct frontal impact in the thoracic region, are proposed to better understand how the void filler affects the thoracic organ kinematics and loading.

CONCLUSION

Void filler with properties similar to thoracic and abdominal fat was added around the aorta and heart of the GHBM 50th percentile male. The modification was evaluated in frontal, vertical and lateral impact load cases. The void filler significantly reduced free motion inside the thoracic cavity and significantly influenced their loading.

ACKNOWLEDGMENTS

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