SHORT COMMUNICATION
63rd STAPP CAR CRASH CONFERENCE

SC19-05

Volume and Pressure Considerations in Human Body Modeling

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ABSTRACT – The initial presence and dynamic formation of internal voids in human body models have been subjects of discussion within the human body modeling community. The relevant physics of the human body are described and the importance of capturing this physics for modeling of internal organ interactions is demonstrated. Basic modeling concepts are discussed along with a proposal of simulation setups designed to verify model behavior in terms of volume and pressure between internal organs.

INTRODUCTION

In contrast to Anthropomorphic Test Devices (ATDs) where parts are designed with emphasis on the overall response of a body region (e.g. head acceleration or chest compression), mathematical models of the human body (HBMs) typically include parts representing specific organs. The increased level of detail of the HBMs promises a more biofidelic response of body regions (e.g. overall chest compression response to blunt impact). It also promises the possibility of calculating loads experienced by the specific organs like brain, heart, spleen, liver, etc.

Apart from the detailed anatomy and mechanical properties of tissues, when calculating the stresses and strains in specific organs of an HBM it is important to consider their attachments and contacts with surrounding organs. Consider that organ-to-organ interactions are similar to interactions between various components of an ATD model. However, in contrast to ATDs, large parts of the human body form closed volumes that typically do not allow outside atmosphere to enter the space between organs. This characteristic of the human body has consequences for simulating internal organ loading and injury mechanisms.

BACKGROUND

Consider a controlled volume formed by the organs inside the abdominal cavity. Some of these organs are hollow organs of the digestive track that can be partially gas-filled and are excluded from the controlled volume. Under normal conditions, atmospheric air cannot enter this controlled volume and there are no gas-filled gaps or voids between the organs. Now consider a gap or void between organs inside this controlled volume, created by a severe blunt impact which did not compromise the hermetic integrity of the abdomen. Since the organs that form the controlled volume are practically incompressible, creation of gaps between organs means increasing the controlled volume size. Increasing the size of an enclosed volume under atmospheric pressure requires energy that can be calculated as the product of the atmospheric pressure and the increase of the volume size. If voids can freely form in an HBM abdomen without accounting for this energy, the impact energy may not be correctly absorbed by the HBM structure, allowing inaccurate internal organ interaction.

The first step to improve the interaction between internal organs of an HBM is to eliminate the initial gaps between them. These initial voids are mostly the result of imperfect representation of human anatomy by the finite element (FE) mesh. There are a number of possible methods of eliminating the initial voids, some of them are discussed by Lima et al (2019).

In the second step, means of controlling energy, volume and pressure changes of the enclosed volumes during the simulation need to be put in place so that internal voids only occur if physical conditions allow it. Let us list some of the methods.

1. Define tie-break sliding contacts (LS-Dyna, LSTC) that allow organs to slide, but prevent organ separation. This measure assumes that the energy input during a car crash is rarely high enough to cause gap formation between internal organs. Hence, one shortcoming of this method is that it would not allow gap formation even if extremely low contact pressure between organs was reached. Another shortcoming is that defining such sliding contact among a larger number of FE structures representing internal organs may be difficult. This and similar methods are used by Beillas et al (2018) and by Lima et al (2019).

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2. Define a controlled volume with atmospheric pressure acting on its boundary when its size increases from the initial size. The main shortcoming of this method is that pressure is assumed to be distributed evenly throughout the controlled volume, which may not always be correct. For example, consider a localized impact affecting only a small part of a large controlled volume.

3. Define atmospheric pressure on the outside of the controlled volume at the beginning of the simulation. The main shortcoming of this method is that initial presence of even minimal internal voids in the human body model may cause significant deformations to occur in the HBM. In theory, if there were no initial gaps between organs and if the organs were modeled using incompressible material models, there should be no deformation induced by applying the outside pressure.

Method #3 is explored in this Short Communication using two example simulations.

METHOD

The HBM used to explore this method was the detailed GHBM version 4, representing a 50th percentile male (GHBM User Manual). Example simulations A and B are shown in Figure 1. In simulation A the HBM was impacted by a horizontally-moving rigid bar aligned approximately with the iliac crest. In simulation B, the HBM was impacted from below, causing vertical acceleration of the torso. In both simulations A and B, the impactor bar had a constant velocity of 4 m/s.

After running the baseline simulations, external pressure of 20kPa was applied to the outside surface of the HBM at the beginning of each simulation re-run. Using lower than atmospheric pressure was necessary to maintain numerical stability of the FE model. It is understood that this approach is neither practical or accurate for multiple reasons. For example, due to the presence of initial voids in the HBM, the external pressure introduced non-negligible stresses, strains and internal displacements in the HBM in the beginning of the simulation. Also, proper level of air pressure inside the lungs was not modeled.

Both simulations A and B demonstrate a noticeable change in the kinematics of the heart when the outside pressure is applied. Without pressure applied to the outer surface of the HBM, the heart maintains its initial position relative to sternum, leaving gaps between itself (Figure 2, left, blue) and the liver (Figure 2, left, red) or between itself (Figure 3, left, blue) and the spine (Figure 3, left, red). These voids are believed to be unrealistic and are greatly reduced when the outside pressure is applied (Figures 2 and 3, right).

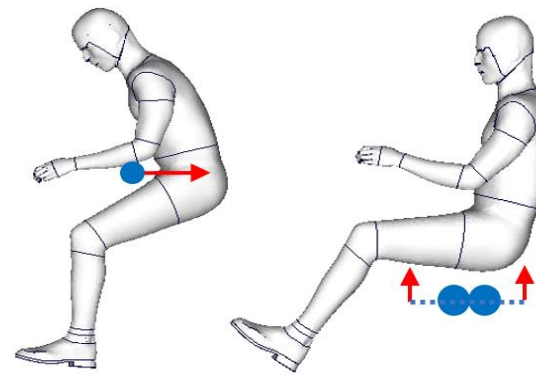

Figure 1: Example simulations A (left) and B (right).

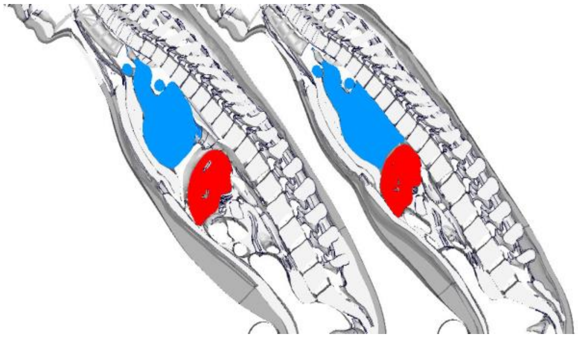

Figure 2: Example simulations A without (left) and with (right) outside pressure. Heart and aorta are shown in blue, liver in red.

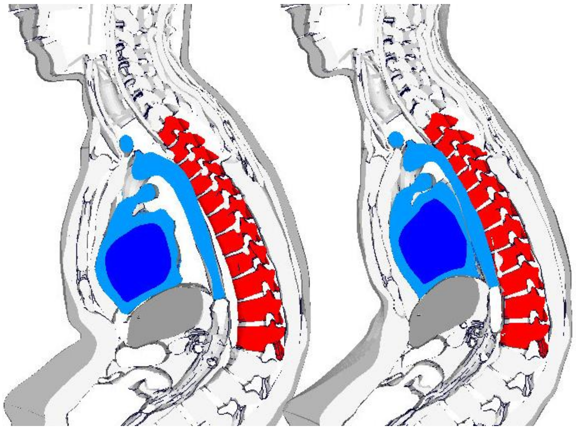

Figure 3: Example simulations B without (left) and with (right) outside pressure. Heart and aorta are shown in blue, adjacent spine vertebrae in red.

Figure 2 also shows a significant increase of heart's downward motion in simulation A when the outside pressure is applied. Due to the suspension of the aortic arch by the branching arteries and by the ligamentum arteriosum, an increase of the downward motion of the heart could increase strains in the aortic arch, where aortic rupture occurs in severe car crashes or high fall accidents (Benjamin et al, 2012).

DISCUSSION

Arregui-Dalmases et al. (2011) wrote that "rupture of the aorta is a leading cause of sudden death following motor vehicle crashes, the specific mechanism that causes this injury is not currently well understood." When discussing aortic injury mechanisms in severe crashes, most publications, consider the inertia of the heart and aorta along with the chest compression as possible contributors to aortic arch injury. Although only conceptual and in need of many improvements, example simulation A suggests that the kinematics of the abdominal organs moving away from the heart may have a significant effect on heart's downward motion and, consequently, on aortic loading. The simulation also demonstrates that modeling the closed volumes of the human body plays a key role in capturing internal organ interaction.

Human body models intended for specific internal organ injury assessment should be tested for proper behavior in terms of voids occurrence using tests A and B shown in the Method section. More tests may be suggested to verify proper model behavior in load conditions relevant to specific types of car crashes, e.g. side impact (Lima et al, 2019).

While the example simulations focused on the abdomen and chest, proper volume and pressure economy is believed to be important in many other parts of a human body model. For example, brain cavitation caused by a severe head impact can only be studied when atmospheric pressure effects and closed volumes of the human head, spinal canal and other relevant areas are correctly captured. Muscle and skin interaction with neighboring organs (bones, other muscles, fat tissue, etc.) should not create voids, unless the impact is severe enough.

In the example simulations the environment pressure was only applied on the outside surfaces of the human body model. If modeled properly, the same pressure should be applied inside the lungs, mouth, trachea, parts of the ear, etc. Such level of detail goes beyond the scope of this paper. However, for sake of mathematical modeling, these inner surfaces of the human body should be considered as surfaces directly exposed to the atmospheric pressure. The exchange of air between the volumes formed by these inner surfaces and outside atmosphere may be constricted by dynamic loading. The complexity of properly modeling the pressure inside lungs should not be too discouraging though: For example, the forces acting on the heart are affected by the pressure inside the lungs that surround it. Therefore, modeling pressure inside the lungs may be necessary to accurately simulate loading conditions of the heart and aorta.

CONCLUSION

In contrast to ATDs, a human body forms closed volumes that do not allow air to enter the spaces between organs. Modeling the physics of these closed volumes is necessary for accurately capturing internal organ interaction in HBM simulations. If an HBM is intended for assessment of internal organ injuries, the ability of the model to capture the closed volume physics should be verified using test simulations. Some of these test simulations have been proposed in this paper.

It is recommended that current and future HBM modeling strategies reflect (1) the need to reduce and eventually eliminate initial voids between internal organs and (2) the need to control dynamic formation of voids between organs.

ACKNOWLEDGMENTS

The authors thank Chin-Hsu Lin for kindly sharing his expertise in using the GHBM.

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