Study of Advanced Occupant Models to Quantify Injury Risk for eVTOL Vehicles

Nathaniel Jones
Graduate Researcher
Virginia Tech
Blacksburg, VA, USA

Costin Untaroiu
Associate Professor
Virginia Tech
Blacksburg, VA, USA

Jacob Putnam
Research Aerospace Engineer
NASA Langley Research Center
Hampton, VA, USA

ABSTRACT

Urban transportation is currently evolving from traditional ground-based vehicles (cars, taxis, and buses) to include air-based electric vertical take-off and landing (eVTOL) vehicles which can be utilized for on-demand transportation, cargo transport, and emergency services. These new eVTOL vehicles are designed to be small, lightweight, and able to operate autonomously without user intervention. Safety is a big part of eventual eVTOL adoption, however gaps in the consideration of safety features exist. Anthropomorphic test devices (ATDs) are used in aerospace crashworthiness standards to quantify occupant injury risk and develop improved safety designs for emergency landing situations, but the ATDs currently used in aircraft certification requirements were developed many decades ago. Developments have occurred over the years involving ATD technology, which includes a host of newer and more biofidelic ATDs such as the Test Device for Human Occupant Restraint (THOR). Increased computing power has also allowed for detailed computational human body models (HBMs) to be created, such as the Global Human Body Model Consortium (GHBMC). This study aims to assess the capability of both HBMs and new ATD designs to identify injury mechanisms within eVTOL relevant emergency landing conditions. Finite element (FE) analysis was used to expand upon full-scale and seat level impact testing conducted by researchers at the National Aeronautics and Space Administration (NASA) to look at effects of occupant model configurations on prediction of injury. The GHBMC HBM and THOR ATD models were simulated in the seat level test conditions to characterize differences between these advanced assessment tools and traditional ATDs in the isolated seat loading environment. Results identified key differences in the responses from each of the models utilized and compared their impact response in head, neck, and spinal injury metrics. The THOR model identified potential risks for head injuries due to head impacts on the seat, however it predicted lower spinal loads than the other occupant surrogates. The GHBMC showed distinctly different biomechanical responses compared to the ATD. The GHBMC model is much more deformable than the ATDs and it exhibited higher distribution of forces and increased sensitivity to the duration of acceleration pulses. Both models incorporated into this study identified key mechanisms for injury that should be considered for passenger safety in the development of these novel aircraft. In addition, this study demonstrated the value of FE modeling for running a variety of complex human surrogates to identify potential injury mechanisms for consideration in regulation and development of new aircraft. Continued research in this field to improve validation these models will only lead to safer aircraft and more comprehensive safety measures.

INTRODUCTION

The development of electric Vertical Take-off and Landing (eVTOL) vehicles creates a big opportunity for revolution in the world of urban air travel. These vehicles are designed to change urban transportation from ground-based vehicles to autonomous eVTOL transportation. These vehicles would allow for more efficient transport for cargo, people and emergency services. These vehicles are designed to be small and lightweight to benefit mobility and efficiency. In addition, many of these vehicles are designed as combination aircraft with vertical takeoff capability which can transition to a gliding configuration during flight. These unique features create new loading conditions in emergency landing situations that may necessitate novel safety features for passengers.

Recently, the Federal Aviation Administration (FAA) added powered lift to the definitions in § 110.2 of title 14 of the Code of Federal Regulations (14 CFR)[1]. This added definition begins the regulation process that applies to eVTOLs. However, this update focuses on operation and utilization of these vehicles rather than safety in the design process. The safety regulations of standard aircraft may apply to the novel design of the emerging eVTOL market. However, in these

Presented at the Vertical Flight Society's 80th Annual Forum & Technology Display, May 7-9, 2024, Montreal, Quebec, Canada.

unique vertical loading environments more research into mechanisms of injury may be required.

Researchers at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) have looked extensively at developing tools for eVTOL testing and safety quantification. A main avenue of research in these novel eVTOL aircrafts is safety considerations in seat design. Researchers at NASA LaRC have performed extensive seat testing utilizing an anthropomorphic testing device (ATD), the Hybrid III FAA, in a 30-foot drop tower to compare a variety of potential seat designs and materials for implementation in these vehicles [2]. ATDs are valuable tools for understanding mechanisms of injury that occur in emergency landing situations. However, the Hybrid III, developed over 40 years ago by General Motors for automotive safety, has many associated limitations[3]. For example, the Hybrid III was originally designed to represent human response to impact scenarios corresponding to automotive frontal impacts with limited datasets for alternate loading scenarios. Implementation of these devices in aircraft impacts has been improved with modified models such as the Hybrid III FAA model, but due to their rigid construction for repeated testing they carry biofidelic limitations. Developments have occurred over the years involving ATD technology, which includes a host of newer and more biofidelic ATDs such as the Test Device for Human Occupant Restraint (THOR)[4, 5]. However, there is limited data in vertical loading scenarios for these ATDs.

While Postmortem Human Surrogates (PMHS) are biofidelic, it is challenging to work with PMHS and tests are costly. More efficient and cheaper alternatives to physical testing are finite element (FE) models of the human body which have been validated to PMHS tests. Recently, newer and more biofidelic FE human body models (HBM) have been developed for occupant loading [6, 7]. One of these widely used models includes the Global Human Body Models Consortium (GHBMC). This model has been extensively validated in various occupant[8] and pedestrian[9] loading scenarios and used to predict human injury risks during impacts. The selection of the GHBMC was influenced by its previous usage in a study of airplane crash scenarios. The study showed the GHBMC to be the most stable advanced human body model available with significant instrumentation and reasonable computational cost [10].

Researchers at NASA LaRC developed FE models which were representative of the vertical seat drop tests they performed. These models utilized the seat geometries and the various crash pulses implemented in the physical testing. To validate the loading conditions and seat materials to represent the physical tests, the response of Hybrid III FAA FE model was compared with corresponding test data. In this study we seek to implement alternative HBMs, such as the GHBMC and THOR FE models, to further understand the injury mechanisms and magnitude in these new impact conditions.

METHODS

Testing conditions

The GHBMC male 50th percentile occupant detailed model (v6.0)[7] and THOR occupant model (v2.1)[5] were selected to be utilized in the simulation of the vertical seat drop tests. The THOR model required no specific modifications or settings to be selected for these tests. The GHBMC utilized standard settings of the version 6.1 model with no bone failure and no muscle activation. Both models were tested in six crash scenarios, four of which were in a standard seat bucket and two were in the same standard seat bucket with additional energy absorbing (EA) crush tubes (Figure 1). The materials and geometries of both standard seat buckets, floor and seatbelts were the same in all tests. The only alteration between the two seat models was the implementation of the energy absorbing crush tubes. The standard seat was rigidly constrained to the floor of the model. In the energy absorbing seat tests, however, the floor was directly constrained to the bottom of the crush tubes and the seat was rigidly constrained to the top of the crush tube.

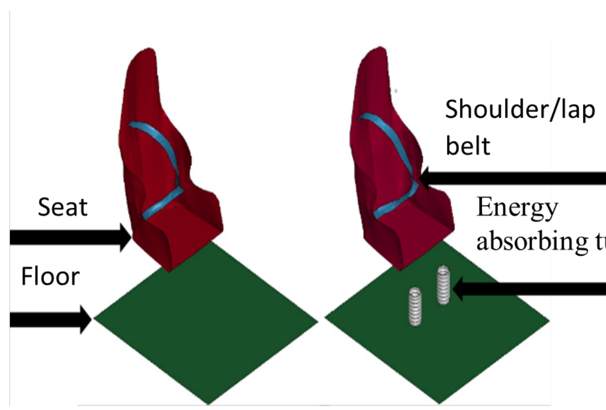

Figure 1. Seat models for the standard seat (Left) and energy absorbing (EA) seat (Right).

Four crash pulses were implemented in the physical crash tests to approximate the vertical loading during an emergency crash of an eVTOL vehicle. These pulses were a 19g, 30g, 10g, and 42g crash pulse. These four pulses correspond to approximations of emergency landing conditions defined by the Federal Aviation Administration (FAA) (14 CFR 23.562 and 27.562), and physical tests of a lightweight helicopter and a composite aircraft body dropped by researchers at NASA LaRC [11-14]. Throughout this study these pulses will be referred to as pulse 1 (19g), pulse 2 (30g), pulse 3 (10g) and pulse 4 (42g). These pulses were generated in the physical 30-foot drop tower test utilizing cardboard honeycomb stacks. Each of the four pulses were tested with the standard seat configuration while pulse 1 and pulse 2 were also tested with the EA seat. For these conditions the tests conducted with the rigid seat are designated as 1A and 2A and the tests conducted with the EA seat are designated as 1B and 2B (Figure 2).

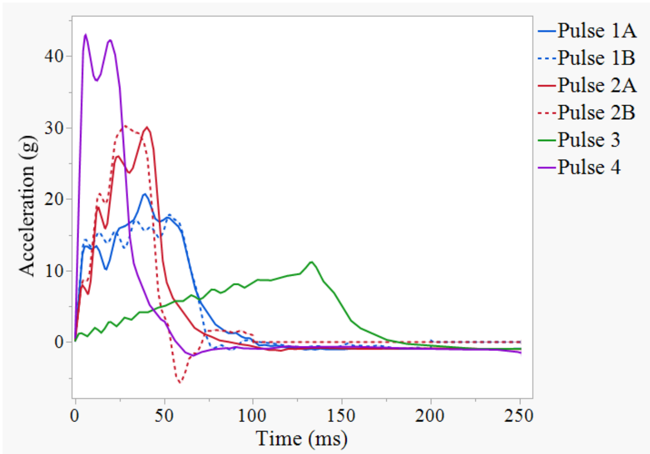

Figure 2: The acceleration pulses of the test set up.

Each tested condition was simulated with both the GHBMC and THOR model. Data was compiled from the NASA testing to compare the injury response between Hybrid III FAA physical test, Hybrid III FAA FE model test, THOR FE model test and the GHBMC model test in both the EA and standard seats.

Model Positioning

The models were positioned to represent the position of the ATD used in the testing. The position achieved was a 90° knee and 90° hip, with allow the feet in contact the floor and arms contained within the seat geometry's bounds (Figure 3). Initial positioning of the Hybrid III and THOR models were performed utilizing the model positioning tools included in LS-Dyna (Figure 3 B-C). Similarly, the ANSA Beta tool was utilized for initial positioning of the GHBMC model (Figure 3D. The final position was obtained utilizing a settling simulation that included three positioning actions. The first feature of the settling/positioning simulation was the settling utilizing the acceleration of gravity to settle the HBM into the rigid seat model. Secondly, to contain the arms of the models within the bounds of a seat a single marionette pulley was attached to each distal end of the humerus representation in each model. These pulleys resulted in slight internal rotation of the shoulder. Retraction of the seatbelt elements then finalized the upright position and created the tightened position of the seatbelt for the crash simulations (Figure 3).

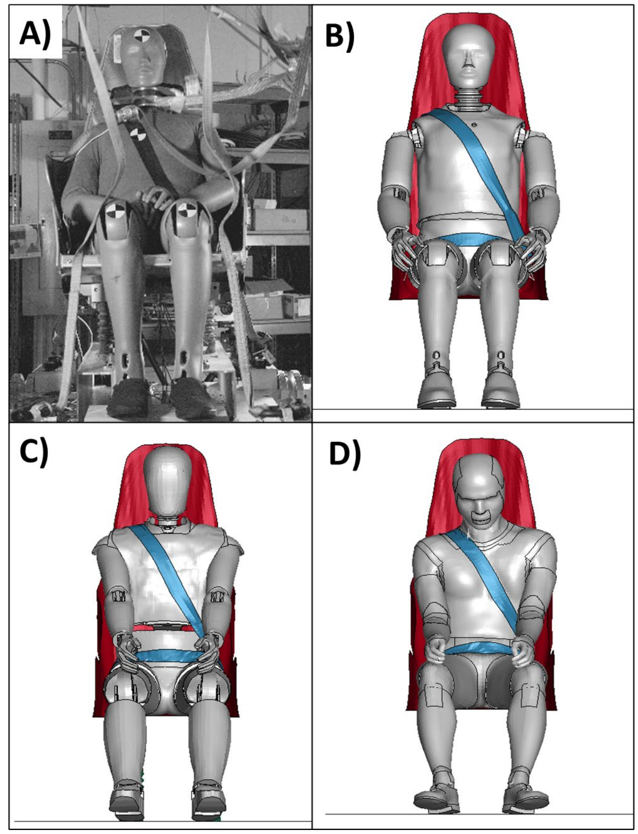

Figure 3: Tested ATD initial position (A) and model positions for Hybrid III (B) THOR (C) and GHBMC (D).

Injury Calculations

The calculations for head injuries utilized the acceleration measured at the center of gravity (CG) of the head for each occupant surrogate configuration. The instrumentation available for the neck and lumbar vertebra are somewhat different between the Hybrid III, THOR, and GHBMC. The instrumentation of the GHBMC utilized a cross sectional force/strain measurement at the C2 and L5 vertebrae. The strain of the THOR model utilizes outputs from a beam strain measurement at the occipital condyle (OC) joint and lumbar loadcell location on the THOR model. The hybrid III model utilizes a beam strain output at the OC joint and lumbar loadcell location.

The injury risk metric calculated as part of this study included the head injury criteria (HIC15) and neck injury criteria (Nij) metrics. HIC15 is the standard head injury criterion for motor vehicle safety calculated utilizing the head acceleration at its Center of Gravity [15]. Calculations for HIC15 are performed as the integral of acceleration over a 15ms time interval as:

$$HIC_{15} = 15\left(\frac{1}{15}\int_{t1}^{t2} a(t)dt\right)^{2.5} \quad (1)$$

Nij is used to characterize injury risk within the cervical spine. The injury metric was developed using piglet test data which was scaled to the human anthropometry [16]. The calculation utilizes critical intercepts to normalize force and moments measured at the OC and then linearly sums the two measures as:

$$N_{ij} = \frac{F_z}{F_{int}} + \frac{M_y}{M_{int}} \quad (2)$$

In order to evaluate relative spinal loading risk predicted by each occupant surrogate, the axial force at the lumbar L5 joint was extracted and compared for all models.

RESULTS AND DISCUSSION

The comparison between the physical data and the modeled Hybrid III data was made by Putnam et al. [2]. The seat environment model was validated against prediction of lumbar force compared to the physical test data. The injury metrics extracted for this research showed slight variation in the head and neck response. However, in all cases both sets of Hybrid III data showed similar trends when comparing across the test conditions.

Head Injury

Biomechanical response differences were observed between the surrogate models which led to variations in predicted HIC metric values across the evaluated impact environments. A much higher HIC value was reported in the THOR model for test 1B compared to the other occupant surrogates (Figure 4). This high HIC value in THOR was caused by a rebound impact of the head to the rigid seat back which did not occur in the other occupants. Outside of this one point HIC responses trended with test pulse acceleration magnitude in each model. The highest head injury reported when outside of the THOR 1B response is seen in test 4. This was expected because it is the highest acceleration pulse with the smallest peak duration of under 50 ms. The lowest reported injury, recorded in test 3, is also expected due to the lowest magnitude of acceleration pulse even with the longest duration of acceleration.

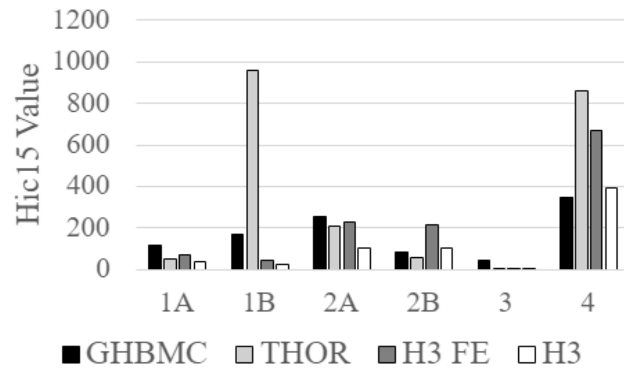

Figure 4: HIC value for each test condition.

Overall, the reported HIC values of under 300 in most of the simulated test cases would not raise concern for occupant safety. However, the high HIC value recorded by the THOR model in test 1B alludes that there is a potential for head injury resulting from a rebound head impact that can potentially be reduced by adding head padding to the seat.

The implementation of the energy absorbing tubes shows a very slight decrease in injury risk in the 1B condition, outside of the THOR response, compared to the rigid seat. In the 2B condition, which has a higher input acceleration pulse, a more significant decrease in head injury risk results from the implementation of the EA tubes. This decrease is observed similarly in all three occupant models, indicating the EA mechanisms effectiveness for reducing injury risk is consistent across all occupant surrogates for this condition.

Although the GHBMC model exhibited similar trending of increased HIC values with increased acceleration pulse the relative sensitivity to these changes was lower compared to the other models. This is particularly the case in pulse 4 in which the GHBMC exhibited the lowest HIC value compared to the other occupants. This decreased sensitivity to changes in acceleration pulse may be to the increased compliance within the biomechanical structure of the GHBMC. This increased compliance of the GHBMC structure would contribute to dampening of the short duration acceleration events in inertial based head loading, resulting in the relatively lower HIC value observed the pulse 4 condition.

Neck Injury

Nij results generally remained consistent for all the tested conditions (Figure 5). The graphical data does not show too many distinct differences between the models except during test 3 and 4 where the GHBMC model reported much higher Nij value for test 3 and THOR reported higher for test 4. This shows a higher sensitivity of the GHBMC to the duration of acceleration pulse as compared to the other models. This is caused by the higher flexibility of the GHBMC neck (Figure 8a).

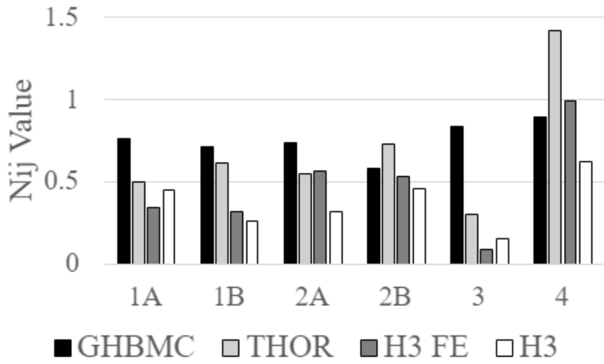

Figure 5: Nij value for each test condition.

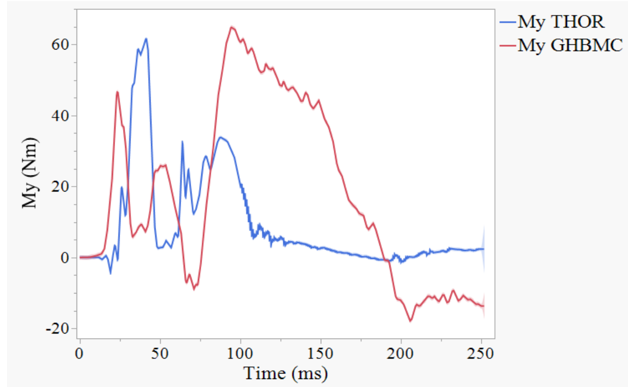

Figure 7: Sagittal moment for GHBMC and THOR in test 4.

Further evaluation of the test 4 responses showed that both GHBMC and THOR models had very similar morphological response of force in the vertical (Z) direction (Figure 6). However, the peak magnitude of the reported force was almost double for the THOR model. This is likely due to the stiffer neck structure of the THOR ATD compared to the neck of the GHBMC. When comparing the sagittal (Y) moments of the GHBMC and the THOR models the graphs look vastly different (Figure 7). While both models have similar maximum moments of about 60 Nm, they occur at vastly differing times. In the GHBMC model the high neck moments occur later in the simulation due to the high deformations of the neck. Because the high moment occurs separately from the high axial loading, the Nij metric value reported by the GHBMC model is lower.

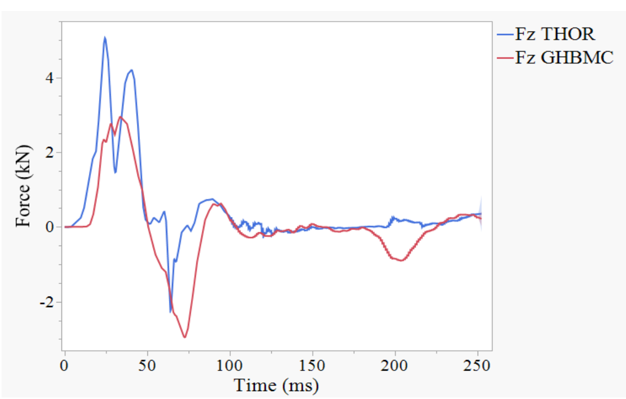

Figure 6: Vertical force for GHBMC and THOR in test 4.

The high Nij response of the GHBMC model in test 3 further supports the pulse duration sensitivity of the GHBMC model observed in the HIC response. Although test 3 had the lowest peak acceleration, the pulse duration was much larger in this test compared to the others. The ATDs appear to be somewhat insensitive to the pulse duration, while the GHBMC appears to be less sensitive to peak acceleration but exhibits higher relative loading in the long duration pulse conditions and lower relative loading in the short duration pulses. The compliance in the GHBMC structure results in much more flexion of the neck in the tested conditions compared to the ATDs. Thus, less input acceleration is required to induce neck motion and the forces and moment within the neck are able to build up over a longer pulse duration, compared to the more rigid ATD designs. This higher deformability causing higher neck injury risk in extended loading cases is an important injury mechanism that the other stiffer human surrogates may under report in their testing.

Due to the higher deformability of the GHBMC neck and torso, much higher lateral excursion of the head was observed in all tests. A comparison of kinematics between GHBMC and THOR at peak deformation in Test 3 is shown in Figure 8. This increased lateral deformation of the upper torso and neck of the GHBMC increased Nij metric values recorded by this occupant surrogate.

The recorded Nij results show an avenue for potential impact of increased safety features for eVTOL development. Due to the rigid nature of the ATD models there is little to no lateral deformation in the neck. However, there is substantially more lateral deformation in the GHBMC model. A potential safety feature to reduce this lateral deformation is a four-point harness-type seatbelt which may decrease the lateral movement of the upper torso and neck. This potentially mechanism for injury risk would not have been identified using traditional ATD evaluation and thus highlights the value HBMs to better characterize and improve occupant safety.

a)

b)

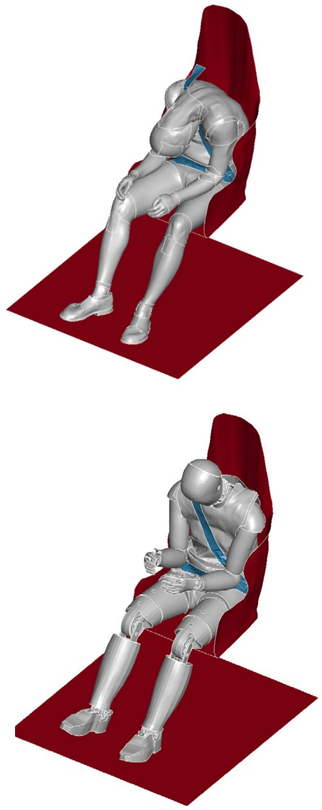

Figure 8: Test 3 occupant deformation at 200 ms: GHBMC (a) and THOR (b).

Trends between acceleration pulse magnitude and Nij values were not consistent across the different occupant surrogates. Both the Hybrid III and THOR produced higher Nij values with higher magnitude of impact acceleration. However, the GHBMC was less sensitive to pulse magnitude. The GHBMC head impacted its torso in all test conditions. The head striking the torso limited total neck excursion in the tested conditions and may have contributed to the occupant models insensitivity to pulse magnitude as additional energy was unable to produce additional neck motion.

When looking at the standard and EA seat tests both GHBMC and H3 FE models showed reduced Nij values when in the seat with the energy absorbing tubes. The THOR model and the Hybrid III physical test both had one case where there was an increase in neck injury associated with EA seat. The THOR model reported a slightly higher neck injury risk in test 1. Whereas the physical Hybrid III showed an increase in neck injury risk during test 2.

Spine Injury

The highest lumbar injury risk for all four datasets was associated with the highest acceleration pulse. Lumbar forces showed similar trends between the occupant models and the physical Hybrid III test data (Figure 9). The magnitude of force was consistent with the magnitude of acceleration pulse for all occupant conditions.

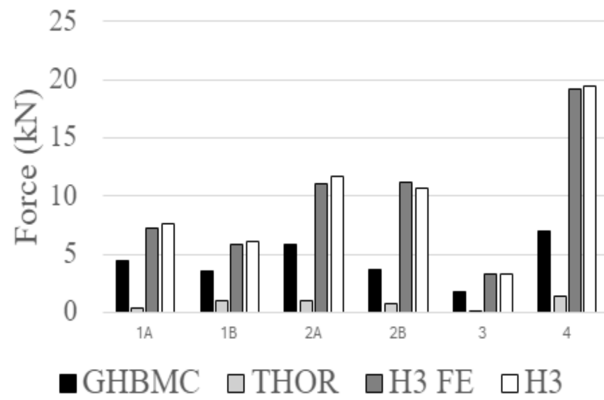

Figure 9: Lumbar force for each test condition.

The GHBMC lumbar forces follow the same trends as seen in the Hybrid III testing. Both occupant surrogates show a reduction in force in the energy absorbing seat. Both occupant surrogates also show the highest loading in the test 4 condition. However, a clear difference in the magnitude of force measured from each of the occupant surrogates can be observed. In the case of GHBMC the higher deformability appears to increase the distribution of forces away from the spine creating lower spinal loading. The deformability of the abdomen in the GHBMC model allows for the forces to be distributed into the fat, muscle and organs within the model (Figure 10).

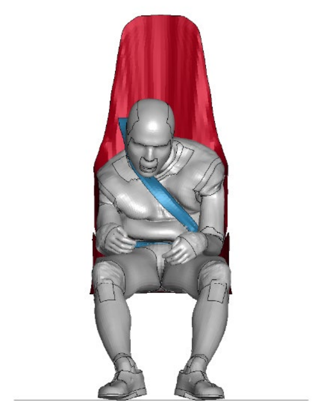

Figure 10: Abdominal compression of GHBMC model in test 4 test condition.

The vertical compression is unique to the GHBMC model due to the large number of deformable abdominal muscles and parts included in the model. Comparatively, compression of the thorax is more limited in the ATDs.

The THOR model produced lower spinal forces in all test conditions. This model had similar biomechanical compression of the spine compared to the Hybrid III, however the recorded forces were much lower. This difference between the Hybrid III and THOR lumbar loading is in agreement with previous physical testing of the THOR and Hybrid III ATDs in which the THOR had been seen to produce lower spinal forces due to the increased thoracic stiffness when compared to the Hybrid III model [17]. The previous testing referenced was conducted to represent frontal car crash impacts and is difficult to translate to these unique vertical loading situations. In order to further explore this unexpected result physical comparison of THOR response in these environments would be necessary.

All occupant surrogates predicted a decrease in lumbar loading in the EA seat environment, except the THOR model which showed slightly higher loading in test 1B although this loading was very low overall. These results indicate the HBM and ATD occupant surrogates show similar prediction of EA effect on lumbar injury risk within the vertical loading environment.

Overall Assessment

The effect of seat type, acceleration magnitude, and acceleration duration on predicted occupant injury risk was found to be variable depending on which occupant surrogate model was used in the assessment. However, utilizing all of these datasets in combination allows for identification of potential points for intervention to increase passenger safety. The THOR model identified head injury risk due to the head striking the seatback in test 2B. This indicates the potential value for added padding to the head rest location. Neck injury risk identified by the GHBMC suggests the need for a more sufficient restraint system to prevent the large forward and lateral movement of the head and neck. Finally, the implementation of energy absorbing mechanisms within these models shows that improvement is necessary in design and function of these systems to better disperse the energy away from the occupant.

Future Studies

There are many future factors that can be considered in the continuation of this work to greatly impact the safety of these developing aircraft. The field of FE research allows for the rapid implementation and modification of such models to understand a wide range of factors which may influence occupant safety. This study can be furthered through the optimization of the energy absorption tubes along with implementation of a wider range of acceleration pulses to create statistically significant results. In addition, an evaluation of alternate occupant positioning may greatly improve our understanding of how seated posture may affect occupant injury risk. In addition muscular activation of the GHBMC model may prove a more realistic surrogate for injury responses of a human being. All of these future studies rely heavily on the continued development and validation of these models from real world data to support conclusions drawn from these studies.

CONCLUSIONS

To accurately evaluate the results developed it is important to put emphasis on potential mechanisms of injury reported by each occupant surrogate as each have been validated in their own ways. Each of the four occupant surrogates reported the highest injury risk in at least one test condition evaluated within this study.

For the ATD models the highest injury metric values were predicted with the highest acceleration pulses regardless of pulse duration. The GHBMC model was more sensitive to pulse duration than any of the other models, especially for neck injury. The THOR model had the least consistency in injury reported. The injuries reported identified three potential safety feature interventions. The first is the studied energy absorption tubes that were included in this study. The GHBMC model consistently reported benefit from the energy absorption whereas the effect on the THOR and Hybrid III models was more variable. Future studies should explore more safety features, such as a four-point seatbelt and seat headrest padding identified by high injury metric responses reported by the more biofidelic GHBMC and THOR models respectively. To develop safety features for eVTOL aircraft researchers may use each of these occupant surrogate tools, with a proper understanding of their capability and limitations, to analyze vehicle safety and identify potential avenues for injury risk interventions.

This study shows the value of FE modeling tools for evaluating a variety of human surrogates for crash injury reporting. Further studies can continue to implement more factors whether in varying occupant size, new HBMs, varying crash pulses or varying model initial positions. These all can be quickly and efficiently tested to identify factors that reduce injury risk for occupants to guide development of regulations for these new vehicles.

This area of research remains limited by the validation of these models in aerospace loading environments. Further development of aerospace specific HBMs and ATDs will provide value in developing this field of research. In addition, due to the early development stage of these novel vehicles, there is great potential to integrate new mechanisms for safety within vehicle design to prevent injury. Continued research into the safety and implementation of these novel eVTOL vehicles will need to be greatly supported by FE modeling to protect occupants in emergency situations.

Author contact: Nathaniel Jones jnate@vt.edu.

ACKNOWLEDGMENTS

We would like to thank and acknowledge NASA LaRC for funding and providing data for this study.

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