LTV-xEVA Applied Injury Biomechanics

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Beginning in Artemis V, Lunar Terrain Vehicles (LTV) will be utilized to enable astronauts to explore the lunar south pole and conduct science farther from the landing site than during the Apollo program. However, LTV operation has the potential to cause injury to the suited crew member during their Extravehicular Activity (EVA). Injury risk caused by LTV acceleration and jerk combined with blunt loading from rigid suit components needs to be better understood. An effort began to create requirements for, model, and address the injury risk caused by the LTV combined with Exploration EVA (xEVA) suits. Mitigation of crew injury is a shared responsibility between LTV and the suit since neither can accomplish this independently. The modeling completed in Fiscal Year 2023 (FY23) helped to verify the fidelity of the requirements and parse out vendor responsibility (LTV, xEVAS, or NASA) for Artemis V and beyond. The scope of the modeling in FY23 used the LTV System Requirements Document (SRD) as worst-case inputs and modeled female 5th-, male 50th-, and male 95th-percentile subjects in hard-mounted seated and semi-standing postures. Soft-mounted (i.e., lap belt) and testing to validate the analysis was determined out of scope for FY23 work.

Nomenclature

ATD = Anthropometric Test Devices
BDRC = Brinkley Device Response Criterion
FE = Finite Element
FY = Fiscal year
F05 = Female 5th percentile
GHBMC = Global Human Body Models Consortium
HBM = Human Body Models
HUT = Hard Upper Torso
LTV = Lunar Terrain Vehicle
M50 = Male 50th Percentile
M95 = Male 95th Percentile
NASA = National Aeronautics and Space Administration
SRD = Systems Requirement Document
xEMU = Exploration Extravehicular Mobility Unit
xEVA = Exploration Extravehicular Activity
xEVAs = Exploration Extravehicular Activity Services Contract

I. Introduction

FUTURE lunar missions may involve the use of a lunar rover. There are two conceptual categories for lunar rovers: pressurized and unpressurized. A pressurized rover is built to enable long distance travel and would incorporate an airlock or suit ports to allow extra-vehicular activities (EVAs). This rover would then be operated in shirtsleeves, so the operational environment and occupant protection requirements would be similar to standard automobiles (i.e., seat, seatbelt, and so on). An unpressurized rover, on the other hand, referred to as a lunar terrain vehicle (LTV) would

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be designed for shorter range sorties and would be operated while wearing an EVA suit. The presence of an EVA suit fundamentally changes the operational environment. EVA suits add a considerable mass to the crewmember, and the inertial effects of this mass could increase injury risk to crewmembers, even in lunar gravity. Additionally, EVA suits contain rigid elements that could increase injury risk by blunt loading.

Restraints used for an LTV occupant also cannot operate like restraints in a terrestrial vehicle or typical spacecraft. For example, a 3-point seat belt in an automobile interfaces with bony structures, such as the pelvis and shoulder, through relatively thin clothing. Similarly, spacecrafts typically use a 4- or 5-point belt system that interfaces with bony structures through soft-goods. In most spacecraft, much of the restraint is provided by the seat itself, which is usually aligned with the ideal principal direction of force (i.e., typical launch or landing loads push the crew member into the seat, not the restraints). In an unpressurized rover, restraining an occupant would require restraining the suit to the vehicle, either through soft restraints like a seat belt, through rigid coupling of a vehicle component to a component of the suit, or through a rigid restraint that does not couple to the suit such as a roller coaster lap-bar. Once the suit is restrained within the vehicle, the crewmember needs to be restrained inside the suit.

The current government reference design suit, Exploration Extravehicular Unit or xEMU, has a shoulder harness connecting the crewmember to the suit, but this harness is designed primarily to help index and support the weight of the suit on the crewmember's shoulders for optimum mobility, not to tightly index the crewmember inside of the suit. Additionally, if a harness could tightly index a crewmember in the suit, it might affect the crewmember's ability to operate within the suit. Much of the restraint of a crewmember within a suit is therefore done through contact between the crewmember's body with the rigid surfaces of the suit or the crewmember's muscle response (e.g., centering head in helmet).

The operation of a vehicle on Earth also involves a relatively light occupant driving a relatively heavy vehicle, while the operation of an LTV on the Moon involves a relatively heavy occupant driving a relatively light vehicle. For example, the Apollo Lunar Roving vehicle had a mass of 210 kg, compared to the maximum payload (including crew) of 440 kg.[1] This difference could also lead to increased injury risk through rollover or other unfavorable dynamics.

All these factors give the operation of an LTV the potential for injury, and they make it difficult to predict this injury potential with typical tools. The typical tools to evaluate injury probability in a land vehicle are anthropomorphic test devices (ATDs) or ATD finite element (FE) models. ATDs are limited in their ability to predict injury in an LTV for a few reasons. First, ATDs are typically designed to predict injury in the event of a single axis crash. While a crash in an LTV is possible, what is certain is that the LTV will be operated over uneven terrain, and the accelerative loading of hitting an obstacle such as a crater during nominal operations could result in injury. Driving a vehicle over an obstacle can involve multi-axial acceleration in different phases, which is not a typical use case for ATDs. The second reason that ATDs cannot be used in this scenario is the space suit. An ATD designed for use in an automotive crash will be both unlikely to fit into an EVA suit and unlikely to measure loads in the locations most likely for injury. For example, a Hybrid III ATD has an inflexible spine, and simple ball and socket shoulder joints, which prevents it from being placed in the curved-spine, shoulders-forward posture of a suited subject, and any impact would impart loads through areas such as the shoulder bearings, bypassing instrumentation on the ATD. The potential for damage to an expensive suit also makes this an unlikely option. The FE models of the ATDs can address some of these concerns, but they still may not be compatible with the suit. The Brinkley Dynamic Response Criterion (BDRC), an injury metric common in spaceflight injury prediction, is similarly unable to predict injury effectively during LTV operation. The BDRC can only be used in accordance with the model assumptions (e.g., occupant must be seated with a 5-point restraint), which precludes its use in EVA suit injury modeling without further development.[2] Human body models (HBMs) have been developed that can overcome some of the shortcomings of ATDs and ATD FE models. An ATD like the Hybrid III series is designed primarily for automotive frontal crash, resulting in a structure that is aimed at reproducing human-like behavior in a frontal crash while being durable to multiple impacts and recording data relevant to frontal crash injury. This involves simplification of the anatomy at the expense of biofidelity to different loading regimes. For different loading regimes, different ATDs have been developed (e.g., WorldSID for side impact, WIAMan for underbody blast). In spaceflight, however, loading can come from any direction. Since human body models do not need a physical counterpart, there are no concessions necessary for durability or ease of manufacture, and they can be designed to react like a human in any loading condition. These models have all the joints that a human has, so they can be positioned inside of a model of a suit. Finally, since these models are purely digital, they can record as many forces, accelerations, or other kinetic/kinematic measures as desired.

To specify occupant protection requirements for the LTV that are suit agnostic, seat agnostic, and vehicle provider agnostic, NASA created requirements that apply at the level of the occupant.[3] These requirements allow two types of restraint: rigidly connected or belt restrained. If the occupant is standing, only a rigidly connected restraint method is allowed. Specifically, these requirements also state the maximum acceleration, jerk, and vibration limits acceptable for a crewmember in the LTV. Additionally, blunt injury due to point loading from the suit is possible. Relatively mild injury such as contusions have received little focus in terrestrial applications. In a lunar environment where a crewmember may be subject to repetitive loading on an already contused area, contusions could have significant performance effects.

At this stage, there are still many unknown variables pertaining to the design and operation of the LTV that will affect the loads that a crewmember could experience during lunar operations. The objective of this study was therefore to use human body models to evaluate the loads on a crewmember while encountering the worst possible loading conditions that meet the requirements.

II. Method

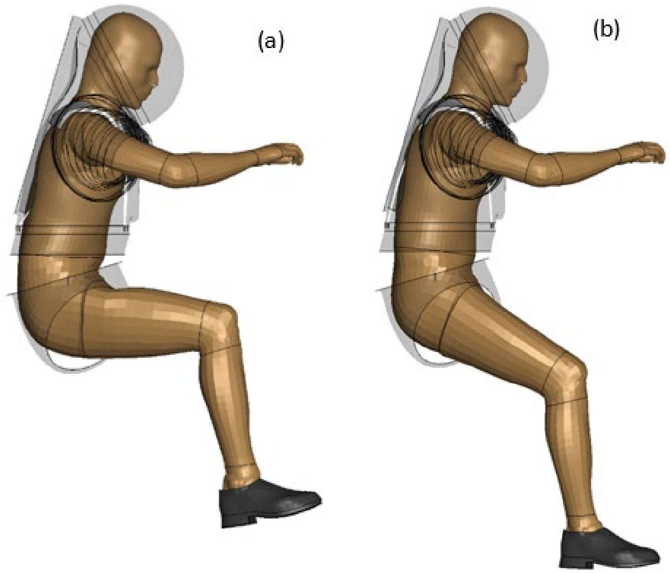

Figure 1. GHBMC M50-OS model in the seated (a) and semi-standing (leaning post) postures (b).

A NASA LTV reference vehicle model has been developed for physics simulations to predict the accelerations on various vehicle structures during simulated drives using the Trick Simulation Toolkit.[4] At the time of this study, there were two potential configurations for the seating in this vehicle; a true “seated” posture (Figure 1a), and a semi-standing “leaning post” posture (Figure 1b). The Global Human Body Models Consortium 5th percentile female model, 50th percentile male model, and 95th percentile male models (GHBMC F05-OS, M50-OS, and M95-OS) were placed into a model of the xEMU suit and positioned into the two configurations (Figure 2). This was done via the marionette method to pull the human-suit model into position with cable elements. The xEMU suit model at this stage consists solely of the rigid components of the suit that are occupant-facing. The shoulder harness, which contains a foam pad over the shoulders was also implemented into the model. Suit occupants may choose different configurations of padding within the suit for personal comfort or better fit. In this study, no additional padding was added to the model except for the F05. It was determined that a suit occupant of that size would be very unlikely to use an EVA suit without thick padding on the back hatch to index the occupant towards the front of the suit.

While wearing an EVA suit, portions of the body will be in contact with the suit, including soft tissue that will be naturally compressed, and suit joints will move to accommodate the occupant’s positioning. To replicate this behavior, the GHBMC models were positioned such that they were as close to the desired posture as possible without any contact between the suit and occupant. The beginning of the simulations then contained a preloading phase where the GHBMC models were pulled into the desired posture, and the soft tissue and suit joints were then allowed to equilibrate prior to any loading. For the M95 model, the soft tissue volume was enough that overlap with the suit was unavoidable in some areas. To position that model, the suit surfaces were expanded out away from the soft tissue. The preloading phase of the simulation for the M95 model was then done in two phases. First, the suit was contracted back to its correct geometry, compressing the soft tissue as necessary. Second, the M95 model was pulled into its final position like the other two models.

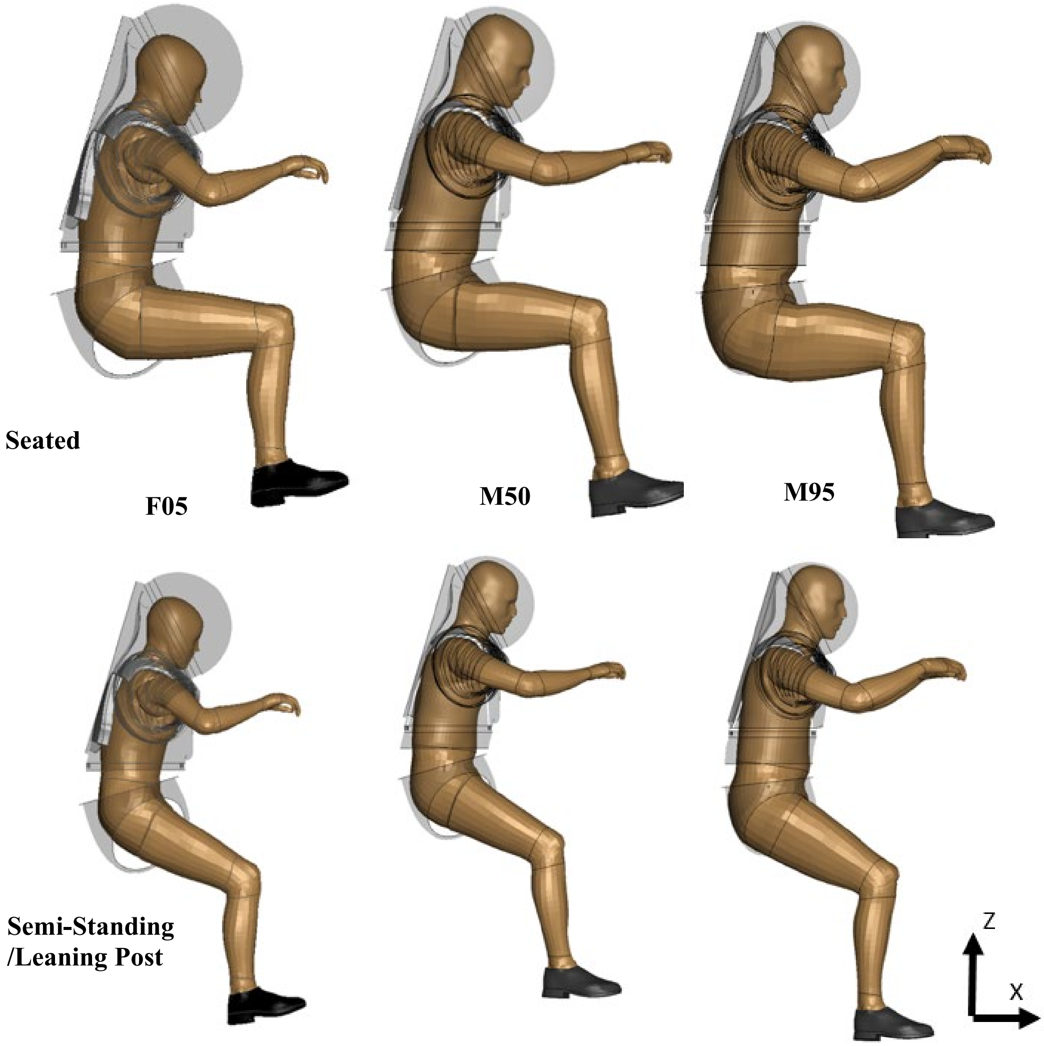

Figure 2. GHBMC models positioned in xEMU suit model in both configurations.
Note: these figures are not to scale.

There are several options to restrain the suited occupant within the seat. Soft restraints (e.g., belts) and hard restraints (e.g., a roller coaster bar) may be used for the LTV but modeling these types of restraints will: 1) be specific to the restraint design, 2) require geometrically accurate models of the seat and restraint, and 3) require accurate modeling of pressurized soft goods of the seat. Because of these limitations, the restraints in this effort were modeled as a rigid connection from the xEMU hard upper torso (HUT) of the suit and the bottoms of the feet to the LTV seat. This also simplified the simulations, as they could be driven from the HUT itself, and the LTV itself was not necessary for the simulations. This additionally provides for results that can be used without prescribing vendor seat and restraint designs.

To drive the simulations, initial conditions were created to represent the worst possible conditions that still meet the requirements for the vehicle. The requirements specify maximum linear acceleration in the ±x, y (symmetrical), and ±z directions. The requirements also state the peak onset rate of these accelerations. Therefore, for a given axis, the worst possible impact in terms of body-suit closing velocity is an impact event that starts in a steady state at one extremum, followed by a switch to the other extremum at the highest allowable onset rate. For example, in the x direction, this would take the body inside the suit from settled in the far back of the suit to the far front of the suit. This can happen in all three axes, and with symmetry about the y axis, it results in 17 total combinations (Table 1). For the purposes of running the simulations, the initial steady state was achieved by starting motionless, reaching the peak acceleration at the maximum onset rate, holding for 100 ms, then switching to the opposite extremum at the maximum onset rate. The 100 ms hold was determined through pilot simulations showing that it was sufficiently long enough for the body within the suit to reach the internal surface of the suit. This resulted in five different load curves (Figure 3), which were applied according to Table 1.

Table 1. Accelerations applied for each load case.

Case	+x	-x	y	+z	-z
1	X				
2		X			
3	X		X		
4		X	X		
5	X			X	
6	X				X
7		X		X	
8		X			X
9	X		X	X	
10	X		X		X
11		X	X	X	
12		X	X		X
13			X		
14			X	X	
15			X		X
16				X	
17					X

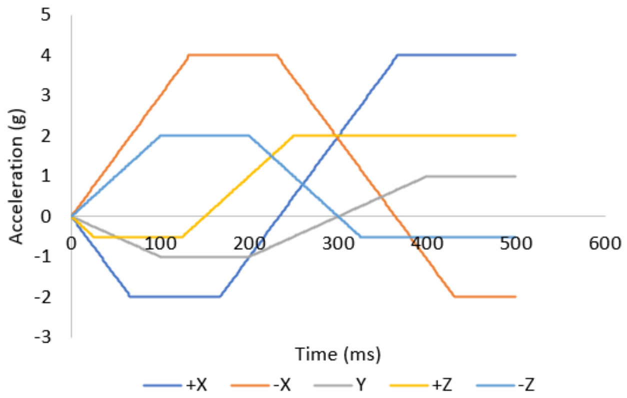

Figure 3. Load curves for each axis used in the simulation.

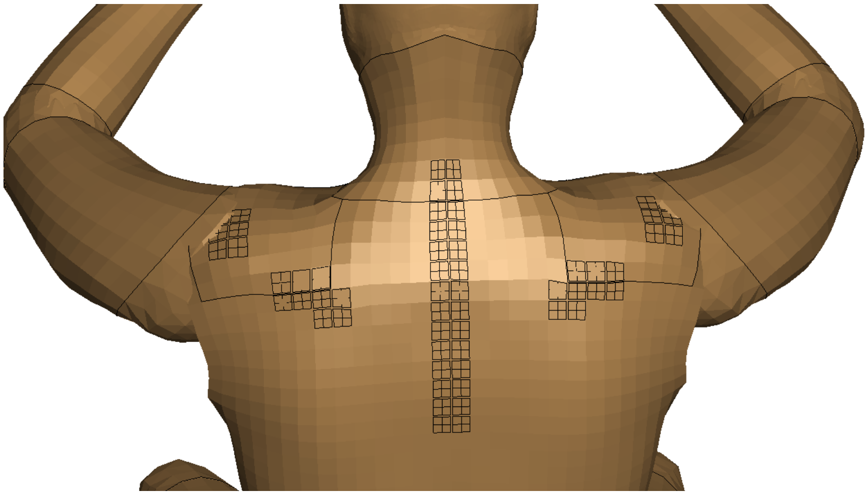

Figure 4. Contact segment patches used to extract contact forces on bony landmarks. This figure shows the acromion, scapular spine, and four vertebral landmark patches.

The GHBMC simplified models output many of the same signals that would be captured during an ATD or cadaver test, such as accelerations, forces, and bending moments at various points of the body. These outputs and the associated injury metrics are commonly used to predict injury in off-nominal automotive or aerospace loading scenarios (e.g., automotive crash, pilot ejection). In these scenarios, the greatest concern is serious, life-threatening injury, and this is reflected in how these model outputs are used to predict injury. In operating an LTV nominally, injury risk may not be life threatening, but minor injuries could make the crewmembers unable to achieve mission objectives. These include blunt loading injuries from the suit. There are not well-established methods for predicting these types of milder injury. The LTV requirements specify 80 N as a limit for blunt force to specific bony landmarks of concern based on half the force to break a cadavers clavicle, which is considered the weakest bone in the area of concern. It is important to note this study did not evaluate cumulative or chronic injuries as those are also very difficult to quantify via analysis. Future work will be required to understand if subjects can comfortably use the LTV in consecutive EVAs.

To evaluate these loads with the GHBMC models, the contact forces between the suit (or harness) and the skin above the bony landmarks were recorded with a segment-based contact algorithm (Figure 4). All simulation data were filtered according to the filter classes in SAE J211.

III. Results

Qualitative differences were seen between the different models in different loading conditions. As seen in Figure 2, the M95 occupant model fills much of the available space inside the suit. During an impact event, this leads to less movement within the suit, and lower closing velocities with the suit. On the other hand, the F05 occupant had more space to move within the suit and attain higher closing velocities with the suit. This seemed to be partially mitigated, in the anterior-posterior direction, by the use of the back hatch pad. In some cases, however, the M50 and M95 occupants experienced head impacts with the interior of the helmet, while the F05 occupant did not due to the greater clearance. It should be noted the F05 head position was placed for optimal fit, and may not reflect suit realities as the model is floating above the brief of the suit as seen in Figure 2. This suggests in suit padding or suit sizing changes may be required to achieve better head placement. The F05 model had the least contact force exceedances (Table 2). This may be attributed to both the lower mass of the F05 model, and the presence of the back hatch pad. The differences between the two postures were somewhat minimal. The sharper torso-thigh angle in the seated models provided a degree of restraint to headward motion that was not as present in the semi-standing posture. The posture appeared to have an effect on the phase of the loading in the model, but the peak loads did not favor one posture over the other.

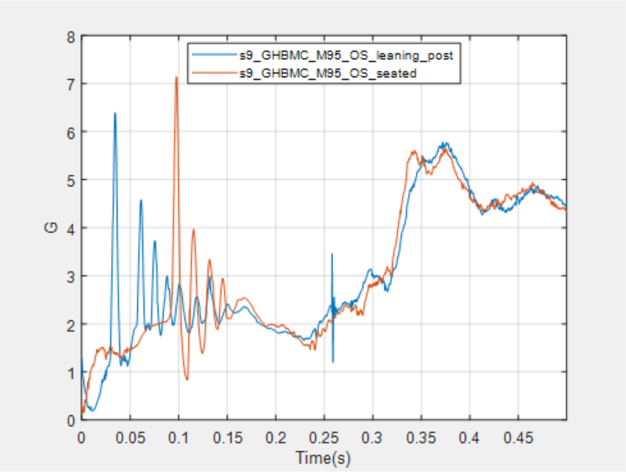

Figure 5. Resultant head acceleration for the M95 model in the seated and leaning post configurations.

Figure 5 shows a comparison of head acceleration in a simulation with the M95 model in the two postures. The loads in the lower extremities were affected more by the posture, but the loads were well below any known injury thresholds.

Table 2. Number of contact force exceedances for each simulation category.

Model, Position	Number of contact forces exceeding each simulation category
F05 Seated	1
F05 Leaning Post	6
M50 Seated	13
M50 Leaning Post	23
M95 Seated	12
M95 Leaning Post	14

Head acceleration in these simulations was typically fairly low, but there were short duration spikes when the head struck the inside of the suit. This can be seen in figure 5. The resulting head injury criterion (HIC) values (Table 3), essentially an integral of head acceleration, were well below the NASA threshold of 300 for use with ATDs.[2] Head rotational acceleration, another metric used to predict head injury, did occasionally pass the NASA threshold of 4800 rad/s/s used in human volunteer tests, though it was during very short duration spikes, so it is unclear if those spikes could be responsible for injury.

Table 3. Maximum head injury metrics for each simulation category.

	Head Injury Criterion	Head Rotational Acceleration (rad/s/s)	Resultant Head Contact Force (N)
F05 Seated	31	2180	1264
F05 Leaning Post	55	6999	1562
M50 Seated	30	5907	1570
M50 Leaning Post	59	5323	2101
M95 Seated	25	5124	1318
M95 Leaning Post	20	4692	1280

Loads throughout the rest of the body (neck, lumbar spine, femur, and tibia forces, chest deflection) were well below any known injury thresholds. The contact forces in the simulation passed the requirement threshold of 80 N (Table 3) 69 times. The majority of these exceedances (64/69) were on the scapular spines, acromions, and clavicles (31, 15, and 16, respectively), with the remainder on the manubrium (2) and the lateral aspect of the rib cage (3).

IV. Discussion

The postures used in this study, seated and semi-standing, are not the only postures that could be used for an LTV seat. However, factors like the angle of the seat back would not affect the results of this study. The coordinate system used is human based, so reclining the seat back would simply rotate the reference frame used to apply the vehicle acceleration limits. Similarly, an xEMU-type suit constrains the body to fit in a certain shape within the suit. In this study, the torso, neck, and head of the GHBMC models all conformed to roughly the same positioning within the suit prior to the presimulation. Additionally, the nature of these "worst-case" simulations was such that the initial accelerations would settle the occupant model into one side of the suit prior to accelerating the occupant into the other side of the suit, when it would experience the peak closing velocities. The initial positioning inside the suit could affect the phasing of the loads on the occupant, but there were not large differences in magnitude. The positioning of the extremities was affected by the posture, but these simulations did not pose significant risk of injury to the extremities. The upper extremities were free to move, but they did not have any rigid suit elements or vehicle structural elements to collide with. Similarly, the lower extremities did not have any rigid suit elements to collide with, and since the feet and suit were constrained to the same motion, the only loading on the lower extremities was through inertial loading of the body mass.

The initial positioning of the occupant models in this study was based on the ideal fit of a standing occupant within the suit. Suited human-in-the-loop tests demonstrated that while seated in an EVA suit in Earth gravity, occupants tend to sink down in the suit, with their heads fitting lower in the helmet than is ideal. It is unclear to what extent this would still occur in Lunar gravity. In future work, simulations could be conducted to investigate the effects of this altered positioning on occupant loads. The occupant models used in this study represented three sizes of potential crewmembers by overall size and stature. While size and stature certainly influence the kinematics of an occupant, they are not the only factors that affect the risk of injury to an occupant. Extremes of specific anthropometric measures, or combinations of extremes could result in higher injury risk, and future work will have to identify some of these conditions.

The conditions used in this study were meant to capture some of the worst-case conditions that are technically still within the requirements to act as an envelope for occupant loading. This has some strengths and weaknesses. One main strength is that it is agnostic to the vehicle suspension design. As mentioned previously, it also minimizes some of the effects of positioning within the suit. One of the main weaknesses for this approach is that the conditions may not be realistic or necessarily even possible for an LTV operating on the Lunar surface. Additionally, the exact conditions used in this study phased the accelerations in the three axes to start simultaneously, but these accelerations could have an alternate phasing that may be worse for the occupant. For example, an LTV driving event could result in a maximal anterior-posterior (X) acceleration followed by a maximal lateral (Y) acceleration rather than having these accelerations simultaneous. Some alternate phasing can be investigated in future work. Additionally, the LTV requirements do not specify any limits on rotational motion. Rotational motion could alter the motion of the occupant within the suit during impacts.

This study used two different sets of injury metrics. There are traditional metrics used to predict injury for high energy, single event impacts such as automotive crash, or in an aerospace context, Earth return landings. These include metrics based on acceleration of the head, and forces and moments in areas such as the spine. Injury thresholds with these types of metrics are well established and widely used in ATDs to predict injuries that are serious and/or life threatening. While there are not official injury thresholds for the use of the human body models at NASA, the ATD limits provide a useful comparison. In this study, these metrics predicted a low likelihood of injury. As all the load cases used in this study were designed to be within requirements for nominal operation, one would expect these metrics to be low. Driving or riding in an LTV has some unique injury risks that are not covered by these traditional metrics, however. An EVA suit places rigid surfaces in close proximity to the body in a way that does not occur in any common terrestrial analogs. This has the potential to cause injury to areas such as the clavicle where there is little soft tissue to provide padding. Additionally, this could simply cause discomfort at higher vehicle speeds, necessitating a lower travel speed than initially planned, which could cause a loss of mission objectives even without an injury. Unfortunately, there are not widely used thresholds for injury and discomfort due to this type of loading. In lieu of widely used thresholds, the limit for blunt loading by the suit during LTV operation was set to half of the force required to break the weakest clavicle in a set of cadaver tests. The same limit was given to several other bony landmarks of concern. This was implemented in the models by developing segment-based patches on the skin above each landmark and recording the contact forces with the suit. The segments were selected to provide complete coverage of the landmarks, so the resulting contact forces would overpredict the force applied to the landmark itself. Additionally, the forces were recorded between these patches and the shoulder harness padding. Since this padding would distribute the loading across the landmarks, it may not be necessary to use these forces to evaluate the system. The requirements also do not specify a minimum duration for exceedances of the contact force, so any force that passed the threshold was considered a failure.

While not covered in the requirements, contact loading to the head was also evaluated. For some conditions, the head-helmet contact forces had spikes exceeding a kilonewton, however, the duration of these spikes was very low, and the resulting HIC was below the injury thresholds. Dividing the maximum contact force by a rough estimate of the mass of the head (~5 Kg) is roughly equivalent to the acceleration of the head, indicating that the spikes in contact force are not just artifacts of the contact algorithm, but represent a real force transferred to the head. Both the suit, and the skull of these GHBMC models were modeled as a rigid material, so the impact may be under-damped. It is therefore unclear if these spikes represent a real risk of focal injuries to the head. Walilko and colleagues[5] investigated the biomechanics of Olympic boxer punches to the face, and calculated punch force as the sum of the neck shear force with the mass times acceleration of the head. That study found an average force of ~3.4 KN with a duration of ~11 ms, and a resulting HIC of 71. The highest HIC in this study was 59, with a corresponding force and duration of 2.1 KN and 3.6 ms, respectively. These numbers alone may not predict a high likelihood of injury, but that force delivered as a concentrated load to an area such as the jaw or forehead by a rigid suit element certainly has the potential for injury.

One caveat of this work is that the models used did not have an active muscle response during the loading event. Bracing prior to an impact, or even muscle response during an impact can have a large effect on the kinematics of an occupant.[6] Occupants of an LTV may or may not see an obstacle prior to impact, so they may or may not brace. In lieu of bracing, they would likely still have a muscle response. There are two strategies for active muscle response in human body models: closed-loop and open-loop. A closed-loop strategy is typically implemented as a PID controller to maintain joint angles, and it requires parameters such as the strength of the given muscles and the activation time. These parameters may be affected by spaceflight deconditioning. Maintenance of joint angles is also not necessarily the strategy that a crewmember would naturally implement during an event. For example, they may attempt to maintain head position within the helmet, not head position with respect to the torso. Open-loop strategies rely on prior knowledge of how humans respond to a certain loading regime, and these data only exist for specific events. Implementation of an open-loop strategy would require extensive human volunteer testing as well as effective ways to account for deconditioning. With no muscle response, the occupant is free to move within the suit, representing a conservative, likely worst-case condition for these load cases.

In this study, the restraints were modeled as a rigid connection of the HUT to the vehicle seat. This is a possible design for the LTV, but it is not the only possible design. Non-rigid attachment restraints, such as belts or roller-coaster style bars can be implemented, but simulation with those styles of restraints would require more mature models of the soft goods of the EVA suit. For a single impact event, a rigid connection of the suit to the seat may represent a worst-case scenario, as loads are immediately transferred from the seat to the suit. Non-rigid restraints may dampen loading during single impact events. On the other hand, for biphasic or repeated events, such as driving over a series of rocks or craters, non-rigid restraints could amplify the loading delivered to the suit, and therefore the occupant by allowing increased closing velocities between the suit and seat. For example, an event that pushes an occupant away from the seat followed by an event pushing them into the seat. In this study, the feet and the suit were coupled to move in unison. This kept the loads to the lower extremities minimized. A non-rigid restraint does not couple the feet to the suit, and it allows for inertial loading of the lower extremities. This represents injury risk not covered by this study.

In this study, the only elements modeled between the suit and the occupant were the pads on the shoulder harness, and for the F05 model, the pad on the back hatch. In real-world suit operation, there are many more elements occupying this space. Inside the helmet, there could be a heads-up display, a Valsalva device, a drink bag, and communications hardware. Throughout the body, there could be a liquid cooling and ventilation garment (LCVG) and various padding. These elements could reduce the potential for injury by reducing space within the suit, and therefore reducing the closing velocity for a given impact. These elements could also pad a surface that would otherwise be rigid. These elements could also increase the potential for injury by concentrating loads on a smaller area.

V. Conclusion

Protection of an occupant in an unpressurized rover is an important task not just for the safety of the crewmembers, but also to ensure that mission objectives can be achieved. There are few analogs to this environment, and many of the standard tools used to predict and prevent injury due to dynamic loading cannot be used. Occupant protection in this environment is a joint responsibility of the suit and the rover working together. This study showed that with the existing requirements placed on the rover, the standard injury metrics predicted a low likelihood of injury, while focal injuries or discomfort remain possibilities that will have to be investigated further. The results of this study are also dependent on the suit, human body, and restraint models used in this study, so they may not be applicable to other designs or occupant sizes and shapes.

VI. References

[1] LRV Systems Engineering, *Lunar Roving Vehicle Operations Handbook,* The Boeing Company, Huntsville, AL, 1971.

[2] Somers, J., D. Gohmert, and J. Brinkley, *Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Events*. 2017, National Aeronautics and Space Administration: Houston, TX.

[3] Dolick, K., N. Newby, T. Raiber, and J.T. Somers. *Lunar Transport Vehicle Occupant Protection Requirements*, NASA, Washington, DC, 2022.

[4] Paddock, E., A. Lin, K. Vetter, and E. Crues, "Trick-A Simulation Development Toolkit," in AIAA Modeling and Simulation Technologies Conference and Exhibit, Austin, TX, 2003.

[5] Walilko, T., D. Viano, and C. Bir, Biomechanics of the Head for Olympic Boxer Punches to the Face, *British Journal of Sports Medicine*, 2005. 39.

[6] Osth, J., et al., "Muscle Activation Strategies in Human Body Models for the Development of Integrated Safety, " in *Proceedings of the 24th International Technical conference on the Enhanced Safety of Vehicles,* Gothenburg, Sweden, 2015.