Modeling and Simulation Credibility Assessments of Whole-Body Finite Element Computational Models for Use in NASA Extravehicular Activity Applications

Richard A. Perkins[a], Christopher A. Gallo[b], Athena E. Ivanoff[a], Keegan M. Yates[c], Courtney M. Schkurko[b], Jeffrey T. Somers[d], Nathaniel J. Newby[c], Jerry G. Myers Jr. [b], Raj K. Prabhu[d]

[a] Universities Space Research Association, Glenn Research Center, Cleveland, Ohio 44135
[b] National Aeronautics and Space Administration, Glenn Research Center, Cleveland, Ohio 44135
[c] KBR, Inc., 2400 NASA Parkway, Houston, TX 77058
[d] National Aeronautics and Space Administration, Johnson Space Center, Houston, Texas 77058

Abstract

Computational finite element (FE) models are used in suited astronaut injury risk assessments; however, these models' verification, validation, and credibility (VV&C) procedures for simulating injuries in altered gravity environments are limited. Our study conducts VV&C assessments of THUMS and Elemance whole-body FE models for predicting suited astronaut injury biomechanics using eight credibility factors, as per NASA-STD-7009A. Credibility factor ordinal scores are assigned by reviewing existing documentation describing VV&C practices, and credibility sufficiency thresholds are assigned based on input from subject matter experts. Our results show the FE models are credible for suited astronaut injury investigation in specific ranges of kinematic and kinetic conditions correlating to highway and contact sports events. Nevertheless, these models are deficient when applied outside these ranges. Several credibility elevation strategies are prescribed to improve models' credibility for the NASA-centric application domain.

Keywords
Finite Element, Credibility Assessment, Extravehicular Activity, Whole-Body Computational Models

Computer Methods in Biomechanics and Biomedical Engineering

1.0 Introduction

Finite element (FE) models are computational tools that have been widely used for simulation-based investigations of human dynamic and traumatic injury mechanisms. The societal issues surrounding the concussion and the design of protective helmets in contact sports brought forth the effectiveness of FE models in studying human head injuries and designing helmets. In a number of these studies (Bastien et al., 2020; Bruneau & Cronin, 2021), Commercially-Off-The-Shelf (COTS) whole-body FE models, such as GHBMC or THUMS, have been used to quantify the biomechanical responses of the human head and neck due to mechanical insults. These COTS models have been developed over several years through many calibrations, and Verification and Validation (V&V) procedures to ensure they adequately simulate the real-world responses of highway and contact sport injury scenarios (Iwamoto et al., 2012; Schwartz et al., 2015; Untaroiu et al., 2013). The Modeling and Simulation (M&S) credibility assessment factors – V&V, data and input parameter pedigree, simulation result sensitivities, model results' Uncertainty Quantification (UQ), and model use history – are essential to the FE modeling and simulation development process. They are vital to ensure that an FE model is credible in the intended application domain – highway and contact sports applications in cases of the Elemance and THUMS models.

Within the NASA ecosystem, FE models are widely utilized for design and mission-based applications to predict failure mechanisms of aerospace and aeronautical structures or injury metrics for suited crew members. Here, FE models inform NASA decision-makers regarding design or process flaws, failure risks, and insight into how to prevent accidents or injuries from occurring in future missions. As NASA prepares for future missions to the Moon and Mars as part of the Artemis program, quantitative information is being collected to ensure crew safety, vehicular design, and mission planning. In preparation for these future missions, NASA has been using COTS simplified pedestrian and occupant versions of whole-body FE models – Elemance and THUMS – to study and quantify potential injury modalities suited astronauts might encounter during training or in mission. In this regard, M&S credibility assessment procedures, as mentioned above, play a critical role in evaluating the credibility of FE models for application in suited astronaut injury investigations.

Credibility standards have been previously proposed for assessing computational models such as the ASME V&V 40 standard, (ASME, 2006) the NIH's ten rules for performing M&S credibility practices (Erdemir et al., 2020), and FDA's guidance for qualification of medical device development tools (Food & Drug Administration, 2017). These credibility guidances were created to serve researchers through a standardized methodology and suggested guidelines for assessing a given model's M&S capabilities within a specific context of application. Within NASA, subsequent to the Columbia accident investigation that led to standardization of credibility assessments of computational models used in NASA-centric designs and informed decision-making, additional credibility assessment criteria (or credibility factors) for the traceability of experimental data utilized in defining model initial and boundary conditions, model use and history, model management, and people qualification were added (NASA Headquarters, 2008). The NASA-STD-7009 was then revised and updated to NASA-STD-7009A, which features a similar V&V evaluation criteria as other credibility assessment standards (NASA Headquarters, 2016). Akin to NASA-STD-7009, NASA-STD-7009A also includes credibility assessments of the inputted model parameters, understanding how any associated uncertainty or variance in model input parameter can affect M&S results, model use and history, and model management. However, people qualifications credibility factor is excluded from NASA-STD-7009A.

Currently, comprehensive M&S credibility assessments – especially for NASA Extravehicular Activity (EVA)-centric astronaut injury biomechanics applications – of THUMS or Elemance computational models is limited. Such assessments are needed to convey the credibility of these models within a NASA-related context of use. Additionally, these assessments inform of the credibility of the underlying modeling abstractions and assumptions that differ from on-Earth highway and contact sport applications, for which these COTS have been verified and validated. In this study, we evaluate the M&S credibility of two existing COTS whole-body FE models – THUMS and the Elemance simplified pedestrian models.

Here, we present a methodology to quantify the credibility of these models for six of the eight factors outlined in the NASA-STD-7009A. More specifically, we focus on performing credibility assessments of THUMS and Elemance models for the Falling From Heights (FFH) EVA injury scenario. These credibility assessments are conducted for potential injury mechanisms identified within the FFH injury scenario. The injury mechanisms are based on documented clinical evidence and expert opinions from Subject Matter Experts (SMEs), internal and external to NASA. In this manuscript, the Methods section (Section 2.0) details the credibility assessment procedures. The results of our findings are described in the Results section (Section 3.0), a synthesis of assessments are given in the Discussion section (Section 4.0), and results summarized in the Conclusions section (Section 5.0). Lastly, evidence of the clinical information for the FFH injury scenario (A1.0), assessment methodology (A2.0), and documentations pertaining to the FE model's credibility assessments (A3.0) are presented in the Supplementary Material.

2.0 Materials and Methods

The credibility assessment process used in this study evaluates the M&S credibility of the aforementioned FE models in simulating injury mechanisms associated with FFH injury scenario. In this assessment, we evaluate the data and input pedigree, V&V, results uncertainty and robustness credibility factors in NASA-STD-7009A. Further, the V&V factors are subdivided by assessing code/solution verification and conceptual/referent validation credibility factors (see supplemental section A2.0 for details). A summary of the assessed credibility factors is shown in Table 1. Our implemented methodology is summarized by Figure 1. Firstly, suspected injury scenarios are defined by NASA EVA injury biomechanics SMEs based on a suited injury matrix, which is developed based on existing evidence (Reiber et al., 2022). Specifically, in this study the FE models are evaluated for a FFH injury scenario, which is classified as an EVA scenario within NASA contexts. Vertebral, lower limb, shoulder, and thorax injuries arising from this injury scenario are suspected to occur during instances of falling from the SpaceX Starship, (maximum height of 50m) or falling into a crater on the lunar surface with a worst-case slope of 20 degrees.

For each of these injury mechanisms, an initial conceptual evaluation of the model is conducted to determine if the FE model consists of sufficient anatomical inclusions to capture the biomechanical response of the injury mechanisms. Insufficient anatomical representation results in an ordinal score of 0 for data pedigree and conceptual validation credibility factors. The ordinal scores vary between 0–4 for each credibility factor, with the scoring details shown in Supplemental Table 1. Credibility sufficiency thresholds for each factor are specified by NASA EVA SMEs (Figure 1) for the FFH injury scenario. In this study, credibility sufficiency thresholds of 2 are specified for data and input pedigree, and code and solution verification while a threshold score of 3 is specified for the conceptual and referent validation, results uncertainty and robustness. Information is assimilated from the published literature, NASA reports, and model developer provided documentation for evidence of the computational models' calibration, training, V&V, credibility, model history, and management procedures. Based on evidence identified in this search, ordinal factor scores are assigned for each credibility factor within the injury mechanisms, using a weighted average approach detailed in the Supplementary Material A2.0 (Figure 1). For each of the FFH injury mechanisms, if the ordinal scores for the FE model achieves the threshold level, the FE models are considered reliable for simulating the FFH EVA injury scenario. If the resulting score is below the credibility sufficiency threshold, score elevation strategies are identified to achieve satisfactory credibility levels.

Details regarding each of these credibility factors can be found in the 7009A standard documentation; however, a brief overview will be provided in this section. For the data and input pedigree factors, documentation which describes the traceability of the material properties and boundary conditions in the model is considered. Additionally, V&V studies assess if the conceptual implementation is correctly formulated for the intended real-world scenario. For the FFH injury scenario considered in this study, an impact velocity range between 0-15m/s is defined by falling from the top of SpaceX Starship lander (worst case impact velocity of 12.8m/s) or falling into a crater (worst case impact velocity of 2.06m/s), which is defined based on information reported by SMEs and derived by kinematic relationships. Based on the recommendations of computational modeling and EVA injury biomechanics SMEs, agreement between simulations and experiments within an acceptable uncertainty range (assumed to be approximately 20% difference) is used to define the credibility score for the responses. Additionally, it is recommended that impacts within 20% of the impact velocity used in the validation case correlate to this defined credibility score, with decreasing scores outside of this range. Within the referent validation credibility factor, impact velocities and loading directions are considered to define the factor scores. This is an appropriate assessment procedure based on the NASA standard for achieving an ordinal score of 3 (NASA Headquarters, 2016). Finally, the credibility factor scores for results uncertainty and robustness are specified by literature which assesses changes or variations in the solutions by input parameter uncertainty or variance, respectively.

The factor scores for the FE models are depicted by comparing the ordinal factor scores (shown in "yellow") against the sufficiency thresholds (shown in "gray"). Also, these scores are compared to the elevated factor scores (shown in" blue") in a separate figure. Finally, credibility ranges corresponding to the referent validation cases identified in literature for the FE models are shown through the histogram-type contour plots representing the credibility scores for each loading orientation (prone, supine, top, standing, lateral) and relevant impact velocities (0-15m/s).

3.0 Results

This study presents M&S credibility assessments of THUMS and Elemance FE models for simulating FFH injury mechanisms by evaluating 8 credibility factors. Scores are assigned for each of the credibility factors for injury mechanisms within the FFH scenario (Figures 2-9) and elevation strategies are summarized by Tables 1 and 2.

3.1 Vertebral Injury Mechanism

The credibility scores for the vertebral injury mechanism are shown for the FE models in Figure 3. Resultant credibility factor scores for the data pedigree, conceptual and referent validation, and results robustness factors are defined as 1 for Elemance and all other factor scores are set at 0 (Figures 2a,b). Further, credibility scores for THUMS regarding the data and input pedigree, conceptual validation, referent validation, and results robustness credibility factors are prescribed 1 (Figures 2c,d). The elevated credibility factor scores for Elemance and THUMS are shown in Figure 2b and Figure 2d, respectively. The updated factor scores for Elemance are 1 for the input pedigree, 2 for the data pedigree, code and solution verification, results uncertainty and robustness, and 3 for the referent validation credibility factors (Figure 2b, Table 1). Similarly, for THUMS, factor scores can be increased to values of 1 for the results uncertainty, 2 for the data and input pedigree, code and solution verification, and results robustness, and 3 for the conceptual and referent validation credibility factors (Figure 2d, Table 2). Figure 3 depicts a summary of the current Elemance (Figure 3a) and THUMS (Figure 3b) referent validation cases for impact conditions within the FFH injury scenario.

3.2 Lower Limb Injury Mechanism

The lower limb injury mechanism ordinal and elevated credibility scores are shown in Figure 4 for Elemance (Figure 4a,b) and THUMS (Figure 4c,d). Credibility factor scores of 1 are assigned for the data and input pedigree, and conceptual and referent validation factors for Elemance (Figure 4a). Additionally, the data and input pedigree, code verification, and conceptual validation credibility factors for THUMS are defined as 1 and the referent validation factor is set as 2 for this model (Figure 4c). The credibility factor scores for the rest of the factors are 0 in Figures 4a,c. Elevation strategies are identified to elevate all credibility scores to 2 for the Elemance model, except for the conceptual validation factor, which is elevated to 3 (Figure 4b, Table 1). Elevation strategies for THUMS result in achieving the sufficiency thresholds for all factors other than results uncertainty (elevated factor score of 2) (Figure 4d, Table 2). Figure 5a and Figure 5b present contour plots that describe the referent validation cases identified in the literature, which are corresponding to FFH impact conditions in five different landing postures using the Elemance and THUMS models, respectively.

3.3 Thoracic Injury Mechanism

The results of the credibility assessment pertaining to the thoracic injury mechanism is shown by Figure 6 for the Elemance (Figure 6a,b) and THUMS (Figure 6c,d) FE models. Factor scores of 1 are assigned for the data and input pedigree for both models and for THUMS' conceptual and referent validation factors. Additionally, factor scores of 2 are specified for Elemance's conceptual and referent validation and THUMS' results robustness factors (Figures 6a,c). For Figures 6a,c, credibility factors not mentioned above have a score of 0. Elevated factor scores of 2 are identified for Elemance pertaining to the data pedigree, code and solution verification, and results uncertainty and robustness and 3 for the conceptual and referent validation factors (Figure 6b, Table 1). For THUMS, the identified elevation strategies increase the factor scores by 2 (Figure 6d, Table 2). Finally, the identified referent validation cases pertaining to the FFH injury scenario for five different impact postures are shown for Elemance in Figure 7a and THUMS in Figure 7b.

3.4 Shoulder Injury Mechanism

The results of the credibility assessment for the shoulder injury mechanism are shown in Figures 9a,b for Elemance and in Figures 8c,d for THUMS. The credibility factor scores for Elemance are limited to the referent validation factor with a score of 1 (Figure 8a). The remaining credibility factors are assigned a score of 0. Factor scores of 1 are defined for the data pedigree, input pedigree, and referent validation credibility factors for THUMS, with all other factors assigned scores of 0 (Figure 8c). Elevation strategies of the credibility scores result in identical elevated factor scores between Elemance and THUMS with newly defined values of 2 for the data and input pedigree, code and solution verification, results uncertainty and robustness and 3 for the conceptual and referent validation factors (Figures 8b,d, Tables 1,2). The referent validation contour plots are also depicted for five different impact conditions within FFH for Elemance and THUMS by Figures 9a and 9b, respectively.

4.0 Discussion

Our study presents a credibility assessment using the NASA-STD-7009A for two COTS FE models – Elemance and THUMS whole-body FE models – for simulating astronaut injury biomechanics within the context of NASA-centric applications. V&V is an essential part of the development process for computational models; however, the results of the V&V procedures are often significantly influenced by data and input parameters used to develop these computational models. By using the NASA-STD-7009A, comprehensive credibility assessments of these models are conducted by ascertaining the M&S credibility across the input parameters, and several V&V procedures. Each model's M&S credibility is evaluated based on the evidence compiled through an extensive literature search, and scores are assigned according to reported model V&V procedural evidence for each M&S credibility factor. Details regarding the evidence for prescribing the credibility factor scores and the evaluation of the overall scores can be found in the supplemental section A3.0. To the best of the author's knowledge, this is a first-of-its-kind comprehensive assessment for performing a verification and validation credibility assessment of computational models for EVA-related suited astronaut injury modeling, specifically for injury mechanisms associated with the FFH injury scenario.

During our credibility assessment, the FE model input parameters are taken into account by establishing the traceability of the source of data (to published literature or reported experimental evidence). The input parameters herein fall under the data and input pedigree credibility factors, as per NASA-STD-7009A. As an example, the elastic-plastic material properties of the lower limb cortical bones (femur, tibia, and fibula), excluding the foot/ankle skeletal features, are traceable to experimental evidence from tensile tests for the THUMS model (Yamada et al., 1970), and are defined using experimental data across multiple loading (or stress) states for the Elemance model (Burstein et al., 1976; Keller et al., 1990; Linde & Hvid, 1989). However, the trabecular bone properties defined for the femur, tibia, and fibula is derived from experimental data using vertebral and knee samples for THUMS and Elemance, respectively. There is an inherent mismatch in the assignment of these material properties to femur, tibia, and fibula model components, where the experimental data used for deriving these material properties come from vertebral or patella specimens. It is plausible that the material properties used in these FE models for femur, tibia, fibula, vertebral, and patella trabecular bones are similar, albeit not justifiable without observed evidence as the anatomical differences could also correlate to different bone fracture and failure criteria. Furthermore, but not limited to these, the mechanical behavior parameters for the knee ligaments, shoulder bones, thoracic, and lumbar vertebrae in Elemance or the ankle, shoulder, cervical ligaments, patella, and humerus bone in THUMS are not found to have traceable evidence, which are defined by a credibility score of 0 due to the insufficient evidence. For most FFH injury scenario-related injury mechanism investigations, the use of Elemance or THUMS FE models would result in factor scores between 0 - 1 for data and input pedigree credibility factors. In essence, these scores are often limited by the lack of formal traceability to experimental data used for calculating their properties, or the applied assumptions, such as those associated with the contact and interfacial definitions lacking observed evidence.

Documented evidence supporting the code or solution verification factors of these FE models (THUMS and Elemance) for simulating FFH injury mechanisms, either by representing the real-world injury scenario, or a sufficiently analogous referent injury scenario, is sparse. A unit verification study is reported by Iwamoto et al. (2005) for THUMS' femur and tibia models using a single FE element model to replicate experimental compressive and tensile behaviors (Iwamoto et al., 2005), resulting in a code verification factor score of 1 (Figure 4c). However, unit verification studies for the other anatomical features of THUMS, or the solution verification (mesh convergence) study for the whole FE model is lacking in published or documented literature. Hence, almost all scores for code and solution verification credibility factors for THUMS FE injury mechanisms are 0 (Figures 2c,4c,6c,8c). Similarly, code or solution verification procedures are not reported in the literature for Elemance, and as such, the corresponding credibility scores are 0 (Figures 2a,4a,6a,8a).

Conceptual validation cases for THUMS are presented exclusively for assessments of stress-state dependent responses such as those performed for the lumbar vertebrae in compression, bending, shear, torsion, and extension (Iwamoto & Nakahira, 2015). These stress-state based assessments are also presented for Elemance through bending or compression loads (Untaroiu et al., 2013); however, additional conceptual assessments are performed by comparing the simplified Elemance model to a model with the same geometry but more detailed conceptual implementations such as the assessments presented for the vertebral region (Gepner et al., 2020). These assessments support the specified conceptual validation factor scores for these FE models of 1 - 2 for the vertebral, lower limb, and thorax injury mechanisms (Figures 2,4,6).

Both the Elemance and THUMS models have been extensively validated with over 80 combined referent validation cases, as reported in the published literature. Several of these validation cases are implemented through rigid impacts and outputs such as force-time histories (Iwamoto et al., 2005; Shin et al., 2012). (Iwamoto et al., 2012; Perez-Rapela et al., 2019). When evaluating the validation cases within the NASA application domain, mismatches between the kinematic ranges for current referent validation studies and the kinematic range of the FFH led to overall referent validation credibility scores between 1 - 2. In particular, the T1 and T8 FE vertebrae in THUMS are shown to have good agreement with experiments with a velocity range between 13.8m/s-20.7m/s. However, the validation impact test velocities are significantly higher than those relevant for the FFH scenario (Figure 3a) (Iwamoto et al., 2012). Additionally, for several cases the prone, supine, top, standing, or lateral loading directions related to the EVA injury scenario are not assessed for both THUMS and Elemance (Figures 3,5,7,9). Specifically, these loading direction-based limitations are significant in the shoulder injury mechanism as only validation cases are available for a lateral impact orientation for relevant FFH impact velocities. Contrarily, simulating the thorax injury mechanism using the Elemance model indicates credibility levels between 1 - 2 for several impact velocities within prone, supine, standing, and lateral orientations; however, these values are below the specified credibility sufficiency threshold (Figure 7a). This is primarily caused by insufficient agreement between the simulations and experimental data for validation cases that fall within the kinematic range for FFH EVA injury scenario (Figure 7a; prone, supine, lateral). This may also elucidate underlying conceptual limitations in the models for the loading conditions pertinent for these NASA scenarios, which are explored later in the credibility improvement procedures for these models.

Credibility assessments for the model's uncertainty quantification (UQ; results uncertainty credibility factor) or sensitivity analyses (results robustness credibility factor) of the model results are currently limited to a few studies (Afewerki, 2016; Hwang et al., 2020; Li et al., 2010; Ye et al., 2020). Literature on sensitivity analysis is primarily focused on vertebral and thorax regions. These studies rendered a credibility score of 1 for investigating vertebral (THUMS and Elemance) (Figures 2a,b), and 1 (Elemance) and 2 (THUMS) for thorax injury mechanisms (Figures 6a,c). Specifically, these assessments provide insights into the sensitivities in material properties in Elemance's thoracic region (Hwang et al., 2020), material and input parameters within THUMS' vertebral region (Afewerki, 2016), and some mesh specifications in the Elemance thorax model (Li et al., 2010). Further, some spaceflight-related boundary conditions have been assessed for the lumbar vertebrae in the Elemance model (Ye et al., 2020). Otherwise, there is little evidence in published literature for UQ for these FE models. Uncertainty and sensitivity assessments for these models are essential for establishing the credibility of these models as these types of analyses can be used to ascertain the FE results confidence intervals and potential variations in the model predictions for injuries relating to anthropometric variations within the broader astronaut population.

Our analysis of these FE models also identified several strategies to elevate their credibility factor scores and are discussed in this section relating to THUMS and Elemance FE model-based in silico studies of vertebral, lower limb, thoracic, and shoulder injury mechanisms in the context of FFH injury scenario. The results of our study indicate these models warrant additional anatomical, and conceptual feature implementations to increase their credibility levels before employing in FFH assessments. For all injury mechanisms, sufficient traceability in the relevant material and input parameters is not achieved (Figures 2,4,6,8). Therefore, updates in several of these material and input properties are needed to establish traceability of defined parameters. The credibility elevation recommendations for specific model anatomy abstractions, and the associated elevated scores are given in Tables 1,2. These recommendations would not only improve the traceability of the data used in model calibration procedures but also provide experimental evidence for developing conceptual implementations necessary for the contextual simulation of FFH injury scenario (Table 1,2).

Verification and validation procedures are essential aspects of credibility analysis to ensure the model's credibility within the intended application domain. Additional verification and validation procedures are needed to ensure model features and conceptual formulations appropriately represent their real-world cases for improving code/solution verification and conceptual validation factor scores (Tables 1,2). It is well understood that performing verification and validation procedures for lunar conditions is difficult; however, a sufficiently analogous referent for lunar conditions would be appropriate for improving the credibility scores for V&V credibility factors. The loading condition (stress-state) dependencies at impact velocity ranges relevant for the FFH injury scenario, which have not been addressed in the current literature, need to be implemented as novel conceptual stress-state dependency formulations to increase the reliability of the models in multi-axial loading conditions (Figures 3,5,7,9). Additionally, model validation results should indicate good agreement with the experimental data to improve these validation factor scores (Tables 1,2). The goodness of the model results, in comparison to the experimental data, should be assessed through model-experimental data CORA (Gehre et al., 2009), ISO (Barbat et al., 2013), correlation coefficient (R^2) scores or similar approaches. Further, sensitivity analysis and uncertainty quantification should be conducted for key features in the model (such as femur, fibula, and tibia modulus and yield strength in Figures 4b,d) and FFH relevant boundary conditions for elevation of the results uncertainty and robustness credibility factor scores (Tables 1,2).

Lastly, when considering the credibility elevation strategies for the models in the specific application domain, it is noteworthy that several of the previously mentioned elevation strategies need to be implemented together with input data updates, conceptual formulation implementation, and associated V&V methods. For instance, when implementing conceptual formulations to better capture tissue material property stress state and loading velocity (or strain rate) dependencies in the THUMS lower limb, the use of the additional data needed to capture these stress-state and strain-rate dependencies could elevate the data pedigree credibility factor score to a value of 2 (Figure 4d, Table 2). The conceptual formulation would have to be unit tested through code verification procedures and then validated using experimental data, all of which led to score elevations for verification and validation credibility factors (Figure 4d, Table 2). Subsequently, ascertaining uncertainty propagations and model result sensitivities of the newly defined input data may be used in UQ and sensitivity analysis, which would elevate the results uncertainty and robustness factor scores (Figure 4d, Table 2). These credibility elevation strategies would in essence assist in increasing the M&S credibility of THUMS and Elemance FE models for application in NASA's FFH injury scenario and associated injury modalities. Through these elevation strategies, finite element analysis (FEA) can be conducted using these FE models for injury risk assessments relevant to future Artemis missions. However, several underlying challenges are inherently associated with the development and design of any FE simulations. For instance, when investigating NASA-relevant mission designs, the development of the FE simulation must capture the boundary conditions imposed by the spacesuit used in missions (such as the Axiom Extravehicular Mobility Unit) and the environmental loading conditions during intravehicular (IVA) or extravehicular (EVA) activity injury scenarios. These implementations warrant future work and VV&C assessments to ensure the reliability of the simulation results. Additionally, other subject-specific factors, such as differing individual geometric conditions that are associated with a crewmember's musculoskeletal system or underlying material properties, are difficult to capture and should be accounted for in the uncertainties of the simulations. Finally, FE simulations often require a large computational cost, so the necessary resources should be accounted for when designing and performing these studies. Despite these challenges, FEA possesses tremendous capabilities in performing these injury risk assessments as it offers the ability to test numerous scenarios that may result in crew member injuries using various mission parameters without the underlying risks that would be associated with experimental methods. Additionally, several mitigation strategies can be assessed using FE simulations to provide stakeholders with vital information regarding protective factors during mission preparation.

5.0 Conclusions

FE models can be used to determine significant amounts of mission related information for the future NASA missions; however, ensuring the M&S credibility of the implemented models is essential. Our study investigates the COTS FE models THUMS and Elemance through a credibility analysis relating to vertebral, lower limb, thoracic, and shoulder injury mechanisms, which can exist within an FFH injury scenario. Credibility levels are determined for these models through an extensive literature search and credibility factor scores are assigned as outlined in NASA-STD-7009A. The results of our study indicate that the credibility levels for these models are below NASA subject matter expert-informed credibility sufficiency thresholds relating to input parameter pedigrees and applied V&V practices (Figures 2,4,6,8) when simulating FFH injury mechanisms. In the context of FFH injury mechanisms, certain referent validation cases for THUMS and Elemance model can provide higher credibility scores for referent validation within a specific kinematic range (Figure 3a; lateral, Figure 5a,7a; standing, Figure 5b,7b; prone). However, additional referent validation procedures need to be conducted to cover the kinematic ranges for all potential FFH situations. Elevation of the credibility factor scores can be accomplished for these models through newly defined material properties and input parameters corresponding to experimental evidence (Tables 1,2). Further, additional V&V practices are warranted along with assessments of the uncertainty and sensitivities in the model relating to the anticipated EVA conditions (Tables 1,2). Increasing the credibility of these models will improve their reliability as they are employed in human space exploration assessments in support of the future NASA missions.

Acknowledgments

The authors would like to acknowledge the NASA Human Research Project (HRP) for supporting this work.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Afewerki, H. (2016). *Biofidelity evaluation of thoracolumbar spine model in THUMS*.

ASME. (2006). *Guide for verification and validation in computational solid mechanics*.

Barbat, S., Fu, Y., Zhan, Z., Yang, R.-J., & Gehre, C. (2013). Objective rating metric for dynamic systems. *Enhanced Safety of Vehicles, Seoul, Republic of Korea*, *2*(3).

Bastien, C., Neal-Sturgess, C., Davies, H., & Cheng, X. (2020). Computing Brain White and Grey Matter Injury Severity in a Traumatic Fall. *Mathematical and Computational Applications 2020, Vol. 25, Page 61*, *25*(3), 61. https://doi.org/10.3390/MCA25030061

Bruneau, D. A., & Cronin, D. S. (2021). Brain response of a computational head model for prescribed skull kinematics and simulated football helmet impact boundary conditions. *Journal of the Mechanical Behavior of Biomedical Materials*, *115*. https://doi.org/10.1016/J.JMBBM.2020.104299

Burstein, A. H., Reilly, D. T., & Martens, M. (1976). Aging of bone tissue: mechanical properties. *The Journal of Bone and Joint Surgery. American Volume*, *58*(1), 82–86. https://doi.org/10.2106/00004623-197658010-00015

Erdemir, A., Mulugeta, L., Ku, J. P., Drach, A., Horner, M., Morrison, T. M., Peng, G. C. Y., Vadigepalli, R., Lytton, W. W., & Myers, J. G. (2020). Credible practice of modeling and simulation in healthcare: Ten rules from a multidisciplinary perspective. *Journal of Translational Medicine*, *18*(1), 1–18. https://doi.org/10.1186/S12967-020-02540-4/FIGURES/3

Food & Drug Administration. (2017). *MDDT: Guidance for Industry*.

Gehre, C., Gades, H., & Wernicke, P. (2009). Objective rating of signals using test and simulation responses. *21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV)*, 9–407.

Gepner, B. D., Kerrigan, J. R., Moreau, D., Rawska, K., & Toczyski, J. (2020). Sensitivity of Human Body Model Response Relative to the Lumbar Spine and Pelvic Tissue Formulation. *IRCOBI Conference*.

Hwang, E., Hu, J., & Reed, M. P. (2020). Validating diverse human body models against side impact tests with post-mortem human subjects. *Journal of Biomechanics*, *98*, 109444. https://doi.org/10.1016/J.JBIOMECH.2019.109444

Iwamoto, M., Miki, K., & Tanaka, E. (2005). Ankle Skeletal Injury Predictions Using Anisotropic Inelastic Constitutive Model of Cortical Bone Taking into Account Damage Evolution. *SAE Technical Papers*, *2005-November*(November). https://doi.org/10.4271/2005-22-0007

Iwamoto, M., & Nakahira, Y. (2015). *Development and V alidation of the Total HUman Model for Safety (THUMS) Version 5 C ontaining M ultiple 1D M uscles for E stimating O ccupant M otions with M uscle A ctivation D uring S ide I mpacts*. *59*(November), 2015.

Iwamoto, M., Nakahira, Y., Kimpara, H., Sugiyama, T., & Min, K. (2012). Development of a Human Body Finite Element Model with Multiple Muscles and their Controller for Estimating Occupant Motions and Impact Responses in Frontal Crash Situations. *Stapp Car Crash Journal*, *56*, 231–268.

Keller, T. S., Mao, Z., & Spengler, D. M. (1990). Young's modulus, bending strength, and tissue physical properties of human compact bone. *Journal of Orthopaedic Research*, *8*(4), 592–603. https://doi.org/10.1002/JOR.1100080416

Li, Z., Kindig, M. W., Kerrigan, J. R., Untaroiu, C. D., Subit, D., Crandall, J. R., & Kent, R. W. (2010). Rib fractures under anterior-posterior dynamic loads: experimental and finite-element study. *Journal of Biomechanics*, *43*(2), 228–234. https://doi.org/10.1016/J.JBIOMECH.2009.08.040

Linde, F., & Hvid, I. (1989). The effect of constraint on the mechanical behaviour of trabecular bone specimens. *Journal of Biomechanics*, *22*(5), 485–490. https://doi.org/10.1016/0021-9290(89)90209-1

NASA Headquarters. (2008). *NASA Standard for Models and Simulations, NASA-STD-7009*. NASA.

NASA Headquarters. (2016). *NASA standard for models and simulations, NASA-STD-7009A*. NASA.

Perez-Rapela, D., Markusic, C., Whitcomb, B., Pipkorn, B., Forman, J., & Crandall, J. (2019). *Comparison of the simplified GHBMC to PMHS kinematics in far-side impact*.

Reiber, T., Newby, N., Scheuring R, Walton M, Norcross J, Harman G, & Somers JT. (2022). *Development of the Suited Injury Matrix for Identification of Top Injury Risks in Lunar Missions and Training. Submitted as NASA TM.*

Schneider, S., Peipsi, A., Stokes, M., Knicker, A., & Abeln, V. (2014). Feasibility of monitoring muscle health in microgravity environments using Myoton technology. *Medical & Biological Engineering & Computing 2014 53:1*, *53*(1), 57–66. https://doi.org/10.1007/S11517-014-1211-5

Schwartz, D., Guleyupoglu, B., Koya, B., Stitzel, J. D., & Gayzik, F. S. (2015). Development of a Computationally Efficient Full Human Body Finite Element Model. *Traffic Injury Prevention*, *16*, S49–S56. https://doi.org/10.1080/15389588.2015.1021418

Shin, J., Yue, N., & Untaroiu, C. D. (2012). A finite element model of the foot and ankle for automotive impact applications. *Annals of Biomedical Engineering*, *40*(12), 2519–2531. https://doi.org/10.1007/S10439-012-0607-3

Sun, L. wen, Fan, Y. bo, Li, D. yu, Zhao, F., Xie, T., Yang, X., & Gu, Z. ting. (2009). Evaluation of the mechanical properties of rat bone under simulated microgravity using nanoindentation. *Acta Biomaterialia*, *5*(9), 3506–3511. https://doi.org/10.1016/J.ACTBIO.2009.04.042

Untaroiu, C., Yue, N., & Shin, J. (2013). A Finite Element Model of the Lower Limb for Simulating Automotive Impacts. *Annals of Biomedical Engineering*, *41*, 513–526. https://doi.org/10.1007/s10439-012-0687-0

Yamada, H., Evans, F. G., & others. (1970). *Strength of biological materials*.

Ye, X., Jones, D. A., Gaewsky, J. P., Koya, B., McNamara, K. P., Saffarzadeh, M., Putnam, J. B., Somers, J. T., Gayzik, F. S., Stitzel, J. D., & Weaver, A. A. (2020). Lumbar Spine Response of Computational Finite Element Models in Multidirectional Spaceflight Landing Conditions. *Journal of Biomechanical Engineering*, *142*(5), 51007–51008. https://doi.org/10.1115/1.4045401/1067326