A1.0 Summary of Relevant Clinical Documentation for the Falls From Heights Injury Scenario

Our study evaluates the Falls From Heights (FFH) injury scenario, which encompasses several potential injury modalities for a suited astronaut. There is some clinical evidence relating to possible injury mechanisms associated with the FFH injury scenario, such as the documentation of falls occurring during the Apollo missions as astronauts navigated the lunar terrain during EVAs (Thuro & Stirling, 2021). It is to be noted that the uneven terrain and lunar gravity ($1/6^{th}$ G) cause gait stability issues for the astronaut while walking on the moon's surface, thereby increasing the likelihood of falls (Scheuring et al., 2008). Further evidence of known physiological changes in the soft tissues and lower back soreness in the vertebral region is of concern to astronaut clinicians (Belavy et al., 2016; Kerstman et al., 2012). The physiological changes to the lower back could increase the risk of intervertebral disc herniations when performing EVAs in reduced gravity environments (Ramachandran et al., 2018). Due to the limited clinical documentation, most suspected injury mechanisms are hypothesized by EVA biomedical Subject Matter Experts (summarized in Reiber et al., 2022). Possible injuries with the highest identified risk consist of abrasions, bruising, skeletal, muscle, and ligament injuries to an astronaut's vertebral, lower limb, shoulder, and thorax regions. Additionally, they can occur while egressing the lunar terrain using a rover, falling into a crater, or falling from the SpaceX Starship lander. Therefore, the injury mechanisms proposed for our study within the FFH injury scenarios are the vertebral, lower limb, shoulder, and thorax injury mechanisms.

A2.0 Details of Credibility Assessment Methodology

The methodology presented in our study is implemented to analyze the THUMS and Elemance FE models to quantify their credibility levels within a NASA-centric FFH injury scenario. This methodology is discussed in section 2.0 of our manuscript; however, additional details will be presented in this section.

This credibility assessment is conducted according to the credibility factors outlined in the NASA 7009A standard (NASA Headquarters, 2016). This standard outlines the credibility factors: data pedigree, input pedigree, verification, validation, results uncertainty, and results robustness, which is evaluated in our study. Our study categorizes the verification credibility factor into computational model feature unit testing (code verification factor) and model result convergence (solution verification factor) assessments. Similarly, the validation credibility factor is sub-divided into conceptual (conceptual validation factor) and referent validation (referent validation factor) assessments. The code verification process is performed to ensure the coded representations of a model feature or the model itself appropriately capture the underlying physics-based conceptions associated with the responses derived from the data used for model calibration. Code verification can be accomplished for FE models using single element simulations and comparing the outputs to the experimental biomechanical data used for model calibration. The solution verification factor ensures the model prediction is consistent and correctly resembles the real-world response as the FE mesh is refined. In other words, the solution verification procedure ascertains if the model results are independent of mesh refinement for simulating the injury scenario of interest. This factor is performed through a mesh convergence study. The conceptual validation factor is implemented to assess the capability of the FE model to capture the biomechanical modalities observed in an injury scenario. An example includes the multi-axial loading and a wide range of strain rate conditions associated with the FFH injury scenario. If the FE material model descriptions have multi-axial stress state and strain rate dependencies, subsequent verification and validation procedures would better simulate multi-axial and varied impact rate loading conditions. Finally, the referent validation factor determines the degree to which the model represents the intended real-world scenarios (RWS). This factor is defined based on evidence that simulates the RWS or appropriately analogous RWS and shows agreement between the computational model and experimental data.

Each credibility factor is assigned an ordinal score ranging from 0-4. A summary of the necessary evidence that needs to be demonstrated to achieve the factor scores for each factor is shown in Supplemental Table 1. Notably, to achieve a factor score of 4, all input data and verification/validation studies should correlate with the real-world system. Additionally, a significant understanding of any sensitives or uncertainties throughout the model should be demonstrated. For our study, the factor scores throughout the injury mechanisms did not achieve this threshold. This is caused by the difficulty in acquiring information from a lunar/reduced gravity system to assess these models. As such, this highest expected achievable score is 3. Generally, to achieve this score, input data must be traced to a sufficiently similar referent, verification analysis should assess the full model with minimal error demonstrated, and validation practices must demonstrate agreement with an analogous system.

Furthermore, all uncertainty propagation must be assessed along with the sensitivities known for the key parameters in the model. Lower scores of 1 or 2 for the data and input pedigree are caused by limited traceability in the defined material or input properties. Similarly, for the validation factors, agreement to similar or available referents should be demonstrated for scores of 2 and 1, respectively. Also, lower scores of 1 or 2 for the results uncertainty and robustness correlate with a reduced understanding of the uncertainty or sensitivity propagation throughout the model.

The credibility assessment is conducted by identifying the injury mechanisms (Vertebral, Lower Limb, Shoulder, and Thorax) based on EVA injury assessment SME for the FFH scenario as part of the study presented in (Reiber et al., 2022). The models are initially evaluated through assessments of the anatomical implementations in the model. This initial evaluation correlates with factor scores for the data pedigree and conceptual validation credibility factors. If sufficient anatomical implementations cannot be established, a factor score of 0 is assigned for these factors. For example, the shoulder model in Elemance does not include sufficient soft tissue representations to simulate injuries to the musculature or ligaments in the shoulder during an FFH injury scenario and is assigned factor scores of 0. After this evaluation, credibility sufficiency thresholds are assigned in consultation with computational modeling and EVA injury SMEs. These thresholds are specified for each credibility factor to denote the level at which the FE models are deemed to be credible for simulating the FFH injury scenario and their resulting outputs. It should be noted that these sufficiency levels are set explicitly for the FFH injury context and may not well represent sufficiency levels for other injury scenarios. Each credibility factor is evaluated by reviewing the existing literature and scores are assigned based on the level specifications outlined in Supplemental Table 1. A weighted average scoring approach is used to specify the factor scores for each injury mechanism. The factor scores for each anatomical part are averaged across the anatomical regions to present a comprehensive factor score for the region. Additionally, a weighted average is used for regions with a higher injury risk. For instance, the lumbar vertebral region is known to be of a higher injury risk during EVA activity than the thoracic or cervical region. As such, the anatomical incorporations throughout the lumbar region are assigned a weight of 50%, while those in the cervical or thoracic region are assigned a weight of 25%. The resulting factor scores are then compared to the sufficiency thresholds. If the scores do not achieve the necessary sufficiency scores, elevation strategies are identified, and the potential elevated factor scores are specified. These strategies are determined based on the limitations associated with the model for the FFH scenario and are intended to elevate the credibility levels of the model for implementation in this scenario.

A3.0 FE Credibility Assessment Supplemental Information:

A3.1 Elemance Vertebral Injury Mechanism

The Elemance vertebral model implements different modeling incorporations throughout each of the cervical, thoracic, and lumbar regions. In the cervical region, the cortical bone is defined using deformable elements, while the trabecular bone, which shows insufficient credibility evidence, is defined as rigid. The deformable bone is traceable to data compiled from studies in the literature (Kopperdahl & Keaveny, 1998; McElhaney, 1966). The remaining vertebral bone throughout the thoracic and lumbar regions is also defined with rigid elements; thereby, indicating insufficient evidence. The intervertebral discs in the vertebrae are also defined with different incorporations for each vertebral level. The cervical region is defined with 1-D spring and damper elements. The thoracic region is defined with a 2-D shell disc representation. Finally, the lumbar regions incorporate a 2-D “ring-shaped” annulus to represent the discs. These disc definitions could not be correlated with traceable evidence. The credibility factor score for the data pedigree is defined as 1 since only some data could be formally correlated to literature evidence. The input pedigree of the vertebral region is controlled primarily through 1-D beam elements, which are supplied loading force and moment versus displacement curves and tie constraints to define the interactions through the vertebral regions of the model. These loading curves could not be correlated to literature evidence, which results in a credibility factor score of 0 for this factor.

The Elemance vertebral model is assessed conceptually for the cervical neck region for stress-states of tension, compression, posterior shear, and extension loads. Further, these loading conditions are catered for automotive applications. The conceptual assessment of the model is accomplished by comparing the simplified Elemance FE model to a more detailed Elemance vertebral model. Good correlation was found between the models in several of the tested stress-states; however, some limitations in the simplified formulation are found for shear, flexion, torsion, and bending (Gepner et al., 2020). A similar conceptual validation design is also used by considering rigid hub impacts and restrained sled loading accelerations, which are presented in (Johnson et al., 2020). Evaluations are presented by considering the response of the anterior thoracic and cervical neck region. Based on these studies, a resulting credibility validation factor score of 1 is defined. Supporting evidence for the referent validation credibility factor is found using lateral impacts to measure displacements and accelerations at the T1 vertebrae (Perez-Rapela et al., 2019). These outputs are also measured at the T1 vertebrae caused by frontal and lateral impacts (Decker et al., 2017). Finally, the model validation is presented in (Decker et al., 2019) by tracking model response displacements due to a vehicle-pedestrian impact. Evaluation of the outputs in comparison to the experimental data in these studies produces the referent validation credibility factor score of 1.

The results robustness credibility factor is supported by a sensitivity analysis presented in (Ye et al., 2020) for the lumbar vertebral region. Using a Latin Hypercube simulation design, this study assessed the sensitivities associated with spaceflight boundary conditions using a seated and restrained Elemance FE model. Therefore, a resulting credibility score of 1 is defined for this factor as material properties in the lumbar region and assessments of the cervical and thoracic region have not been evaluated based on the presented literature search. The remaining credibility factors of input pedigree, code, and solution verification, and results uncertainty are assigned a score of 0 since supporting evidence could not be found in the current literature.

The credibility eleveation strategies for the Elemance model are summarized in Table 1 pertaining ot the vertebral injury mechanism. These credibility elevation strategies consist of updating the input properties and parameters to traceable experimental evidence for the elevation of the data and input pedigree factor scores. Additionally, defining deformable elements throughout the full vertebral region for both the cortical and trabecular bone will elevate the data pedigree score. Performing verification and validation studies pertaining to the expected EVA impact conditions in an FFH injury scenario will elevate these factor scores. Finally, performing analysis to better understand the uncertainty and sensitivity propagation throughout the model, especially due to the defined material properties, will elevate the results uncertainty and robustness credibility factors to scores of 2.

A3.2 THUMS Vertebral Injury Mechanism

Each anatomical incorporation and modeling definition is defined identically throughout the cervical, thoracic, and lumbar regions of the vertebral model in THUMS. The trabecular bone is defined by tensile experiments of vertebral trabecular bone (Yamada et al., 1970), and the definitions for the cortical bone are informally traceable to (Kemper, 2005). The intervertebral discs are defined to account for the regional stiffness differences in the annulus fibrosis and the nucleus fibrosis. Stress-strain responses are defined for the annulus fibrosis at different strain rates based on data from (Kemper et al., 2013; Yamada et al., 1970), while material definitions for the nucleus pulposus could not be correlated with reported evidence. Some information regarding the material properties assigned for the cervical muscles is informally traceable to (Thelen, 2003), while the ligaments and tendons could not be correlated with traceable properties. The remaining material properties such as those assigned to the cervical dura, pia, cerebral spinal fluid (CSF), and spinal cord could not be correlated with experimental data. Based on this information a credibility factor score of 1 is assigned for the data pedigree. The input pedigree factor score of 1 is largely defined by the rigid connections between the elements of the anatomical incorporations. Additionally, it is also defined by some anatomical attachment points being traceable to (LY & Winters, 1990). The contact properties assigned to the automatic single surface algorithm could not be correlated with evidence in the literature.

Conceptual validation data is found for simulations that assess loadings in stress states of flexion, extension, shearing, torsion, and compression for the L4-L5 vertebrae (Iwamoto et al., 2015). Good agreement is demonstrated for quasi-static strain rates for these loading conditions. The referent validation studies for the model are presented by measuring accelerations at the T1 and T8 vertebrae resulting from a restrained sled loading scenario (Iwamoto et al., 2015). Additionally, the cervical neck is validated through drop tests and corresponding outputs of neck forces (Toyota Motor Corporation & Toyota Central R&D Labs, 2021). Finally, lateral impacts are implemented for validation through the evaluation of the displacement in the full vertebral column (Paas et al., 2015). Based on the agreement and loading scenarios presented for these validation studies a factor score of 1 is assigned for the referent validation.

This FE model has assessed some sensitivities for the intervertebral disc's material properties and contact implementation. This is accomplished using T12-L5 and L4-L5 vertebral units, which are stressed at dynamic stress states (Afewerki, 2016). This study resulted in a factor score of 1 for the results robustness. The credibility factors code verification, solution verification, and results uncertainty resulted in a factor score of 0 as evidence cannot be found in the literature.

A summary of the elevation strategies for the vertebral injury mechanism using THUMS is presented in Table 2 in our manuscript. Elevation strategies consist of updating the assigned material and contact properties, which could not be traced, to assignments based on traceable experimental evidence to increase the data pedigree and input pedigree factor scores. Additionally, elevation strategies consist of improved material definitions to incorporate stress-state changes prevalent in microgravity. Verification studies are needed to assess the formulations in the model; and therefore, improve the assigned factor scores for the code and solution verification factors. Presentation of additional conceptual and referent validation scenarios which evaluate loading conditions related to the multi-directional impacts associated with an FFH injury scenario is needed to improve these credibility factors. Finally, sensitivity analyses are presented for boundary conditions and material properties in the models; however, additional information is needed for these conditions for the remaining parameters not analyzed throughout the vertebral columns for credibility elevation.

A3.3 Elemance Lower Limb

The lower limb model in Elemance features deformable definitions for the bones of the leg and ankle, while the foot bones are defined as rigid. Furthermore, most of the soft tissue incorporations in the knee are defined by deformable elements, while the ankle ligaments are constructed using 1-D beam elements. The different regions throughout the femur are accounted for in this FE model, such as the femoral shaft, proximal femoral end, distal femoral end, with data traceable to literature studies (EVANS & LEBOW, 1951; Keller et al., 1990; Martens et al., 1983). Strain rate sensitivities are also captured in the model for the yielding strength and elastic modulus through untraceable stress-strain loading curves. The tibia and fibula are defined using data traceable in the literature (Burstein et al., 1976; Linde & Hvid, 1989). Finally, the calcaneus and talus bones in the ankle region are defined based on data reported in (Gomez & Nahum, 2002; Linde & Hvid, 1989). Several soft tissue representations in the model can be correlated to information in public literature, such as the ankle, foot, and patella tendon (Funk et al., 2000; Hall, 1998; Imhauser et al., 2008;

Mkandawire et al., 2001, 2005). The data pedigree is defined as a score of 1 since several features could not be traced throughout the literature, such as the material properties defined for the patella, knee ligaments, and Achilles tendon. Some information is traceable for the input pedigree with the loading joint moment loading curves specified based on information presented in (Riener & Edrich, 1999), which results in a defined factor score of 1.

Both conceptual and referent validation data for the Elemance lower limb could be identified. Conceptual validation data is presented in (Untaroiu et al., 2013) through an assessment of the femoral modeling definitions in a 3-point bending loading scenario. This study showed good agreement; however, since conceptual evaluations of the other regions could not be identified, the resulting factor score of 1 was determined. A factor scores of 1 is also determined for the referent validation factor as loading conditions assessed in the literature are constrained to a standing posture with boundary conditions set to resemble automotive loading scenarios. This validation design is presented in (Shin et al., 2012; Shin & Untaroiu, 2013) through boundary conditions of direct axial impacts to the foot, forefoot, dorsiflexion loading of the ankle joint, and muti-axial loading of the leg.

The identified elevation strategies for the credible scores pertaining to the lower limb injury mechanism using Elemance are summarized in Table 1. Updating the model definitions relating to the material properties and input data will elevate the data pedigree and input pedigree credibility factors to scores of 2 for both factors. Specifically, newly defined ligament models using deformable elements and corresponding input data representative of an analogous EVA referent will improve the score. Additionally, implementing traceable data for the knee model features and the defined contact properties will contribute to this elevation strategy. Verification of the current model is absent in the literature. It should be conducted to assess the mathematical formulations in the model definitions and ensure agreement with the real-world response. Similarly, conceptual validation of the remaining features in the lower limb should also be conducted. This procedure can be coupled with the newly defined ligament models to improve the conceptual ability of the lower limb model and improve factor scores for both data pedigree and conceptual validation. The referent validations currently presented for the model showed good agreement; however, only a standing posture has been assessed within the FFH injury scenarios. Additional validation studies are needed using impact conditions of the remaining postures within the FFH scenario for the relevant impact velocities to improve the referent validation factor score for the NASA-centric applications. Finally, uncertainty and sensitivity assessments could not be found in the available literature and are needed as part of the elevation of the model. This analysis could also be coupled with the data and input pedigree elevations strategies to capture the uncertainty in the defined material properties and ascertain their effect in the solutions predicted by the models.

A3.4 THUMS Lower Limb

The THUMS lower limb model is defined by using deformable elements throughout the entire region. The femur, tibia, and fibula bones incorporate identical phenomenological material properties for their trabecular bone definitions, which are derived based on evidence in (Yamada et al., 1970). However, the material properties of the cortical bone in the anatomical features are defined individually based on data reported in (Yamada et al., 1970). The ankle region's cortical bone is specified based on the definitions imposed for FE models by other researchers (Beaugonin et al., 1997) while the trabecular bone is defined with the same properties as the femur, tibia, and fibula. Ligaments and tendons found in the knee representation are defined by experimental data for the lateral collateral ligament reported in (Abé et al., 1996). This information is used to set the factor score for the data pedigree as 1 for this model since other lower limb regions could not be traced in literature, such as the menisci, Achilles tendon, or ankle and foot ligaments. Musculature incorporations throughout the lower limb are also not properly defined for EVA-based analysis as interfacial properties, and muscle fiber orientations are not included, which would work in conjugation with the tendon features. The input pedigree is defined through rigid contact interactions and an automatic single surface contact algorithm with a frictionless coefficient (Kitagawa & Hasegawa, 2005). The limited traceable evidence for the definitions relating to the boundary conditions in the model results in a factor score of 1 for the input pedigree.

Some code verification data is available in the public documentation for the THUMS lower limb model as unit verification is conducted using single element simulations for the tibia and femur incorporations (Iwamoto et al., 2005). The verification results showed good agreement at the lower strain rates tested between 0.01/s-1/s, while higher strain rates indicated insufficient agreement. Furthermore, the model is also shown not to capture loadings in the transverse direction, which suggests the need for further conceptual implementations. Based on this information, a factor score of 1 is assigned for the code verification.

The conceptual validation data is presented using evaluations of the tibia and femur stress-state dependencies through three-point and four-point bending cases. Further, these assessment results indicate some agreement between the experimental and simulation results. Since assessments of the other anatomical conceptual implementations are lacking in the current literature, a factor score of 1 is assigned for the conceptual validation credibility factor. The referent validation credibility factor is supported by multiple validation cases reported in the literature. The validation cases implement direct axial impacts to the knee and ankle (Chawla et al., 2004; Toyota Motor Corporation & Toyota Central R&D Labs, 2021) and direct frontal impacts to the knee (Iwamoto et al., 2012). Error assessments are limited for the results of the lateral impacts; however, strong agreement is established in the validation results of the frontal impact to the knee as the simulation outputs are within a standard deviation of the experimental results. Finally, other validation cases implement direct axial impacts to the foot, which correlates with a standing posture in the FFH scenario, with good agreement found between experiments and the THUMS' simulations (Iwamoto et al., 2005; Schinkel-Ivy et al., 2013; Toyota Motor Corporation & Toyota Central R&D Labs, 2021). Due to the wide range of impact conditions assessed by these validation cases, a factor score of 2 can be assigned for the lower limb injury mechanism using this model. A score of 3 is not achieved as sufficient agreement was not found for all simulation cases.

The elevation strategies identified for the THUMS lower limb model, which are summarized in Table 2, consist of updating the material properties throughout the lower limb to values representing experimental evidence. Specifically, the trabecular bone and ligaments in the model should be updated to data derived from these anatomical regions. This will result in a newly defined factor score of 2 for the data pedigree. Furthermore, the inclusion of properties to represent the muscular activation throughout the lower limb along with corresponding verification and validation analysis will elevate both the data pedigree and conceptual validation factor scores for the FFH injury scenario. The contact interaction between the components throughout the lower limb should also be updated to represent their real-world behavior based on experimental evidence for score elevations to 2 for the input pedigree. Assessments for the additional referent validation cases for the impact conditions relating to the FFH injury scenario with an agreement between the simulation and experiments will elevate the referent validation factor score to the sufficiency threshold of 3. Finally, conceptual validation and assessments of the uncertainty and sensitivities through the lower limb model associated with the inputted material properties and boundary conditions are warranted for elevation in the scores defined for the conceptual validation, results uncertainty, and results robustness factors.

A3.5 Elemance Thorax

Representations are included in the thoracic region in Elemance for the ribs, costal cartilage, clavicle, sternum, and vertebrae. The vertebral region is included in the assessment of the thorax due to impacts in a supine position; however, discussion relating to the assessment of the vertebrae is presented in supplemental section A3.1. The cortical and trabecular bones specified for the ribs in Elemance are defined by considering other FE models (Kimpara et al., 2005). These values can further be traced to experimental data presented in (Kemper, 2005; Yamada et al., 1970). The cortical bone is further refined through an optimization procedure to determine the material properties based on the model's validation results (Li et al., 2010). Due to this procedure, the cortical bone material properties are likely specific to the loading conditions presented in the validation procedure, thereby warranting further evaluation before being used in NASA-centric FFH analysis. Other data in the thorax model could not be traced to experimental information, and a credibility factor score of 1 is defined for the data pedigree credibility factor. The input pedigree factor in the thoracic model is defined by the rigid connections imposed between the different anatomical regions in the model. Furthermore, contact interactions between the end of the ribs and vertebrae are also defined by loading curves, which demonstrate lacking traceability. This information results in an input pedigree factor score of 1.

Conceptual validation data has been presented by assessing the ribs under bending loads and comparing to experimental data of the 2, 4, 6, and 10th ribs (Li et al., 2010; Ramachandra et al., 2019). The favorable agreement found in these results supports the credibility factor score of 2 for the conceptual validation factor. Also, this validation study may additionally be viewed as a referent validation case. Further validation studies contributing to the referent validation credibility factor consist of the same bending experimental design for the ribs; however, the occurrence and location of fracture were compared between simulations and experiments (Li et al., 2010). Also, validation studies using axial impacts to the chest (Ramachandra et al., 2019) and seated space flight-related acceleration pulses (Gaewsky et al., 2019; McNamara et al., 2017) are identified in support of the referent validation credibility factor. These validation cases result in a defined factor score of 2 for the referent validation factor.

Some assessments of the sensitivities related to the rib formulation are available in the literature. This is presented using bending experiments of the rib FE model and assessing aspects of the mesh specifications such as cortical shell nodal thicknesses and the defined mesh density. This study may also be viewed as a conceptual validation of the FE model. The resulting factor score for the results robustness is prescribed 1.

Key strategies to elevate the credibility scores of the Elemance model when simulating the thorax injury mechanism can be seen in Table 1. Elevation strategies are accomplished by adding representations of the muscle tissues through the thorax region, such as the pectoralis muscle group. Additionally, updating the material properties and input data, including the contact algorithms to data representative of experimental investigations, will elevate the data and input pedigree factor scores. Code and solution verification studies are also warranted to establish these credibility factors for the model. High scores are found for the conceptual and referent validation factors; however, additional cases are needed to assess the remaining features throughout the thorax model and for several impact velocities with an improved agreement with conditions resembling the FFH injury scenario. Finally, uncertainty and sensitivity propagation should be assessed for both the specified material properties and FFH-related boundary conditions for the features throughout the thoracic region.

A3.6 THUMS Thorax

The thoracic model in THUMS includes several hard tissues and soft tissues, such as the pectoral muscles, in its design. The vertebral region is again included in the assessment of the thorax region due to falls in a supine position; however, the details regarding the assessment for the THUMS model can be found in supplemental section A3.2. The material properties assigned for the cortical bone of the rib and sternum can be informally traced to the work of (Kemper, 2005). Furthermore, the trabecular bone defined for the ribs and sternum is taken from vertebral tensile experiments reported in (Yamada et al., 1970). Finally, the pectoralis major and intercostal muscle are defined by tension experiments of the pectoralis major muscle (Yamada et al., 1970). Based on this information and the anatomical incorporations that could not be traced, a factor score of 1 is assigned for the data pedigree. The input pedigree of the model uses rigid contact interactions between the anatomical features and appropriate landmarks. This is deemed sufficient for a credibility factor score of 1 for the input pedigree. This value is limited by the lacking experimental evidence for the assigned contact properties used in the specified contact algorithm.

While conceptual validation assessments cannot be found for the anatomical feature abstractions for most regions throughout the thorax, some information is available for the lumbar vertebral region, which supports the conceptual validation factor score of 1 for this injury mechanism. Referent validation studies have been identified for assessments of the thorax model through anterior and lateral impact conditions using restrained sled and seatbelt impact analysis (Hwang et al., 2020; Iwamoto et al., 2012). Axial impacts on the chest are also presented in (Iwamoto et al., 2012) for validation of the thorax model. The results of this validation indicate good agreement for most impact cases between the model and the experiments; however, sufficient credibility levels are constrained to a prone impact condition. Therefore, a referent validation factor score of 1 is defined for this credibility factor score.

Sensitivity assessments related to the material property perturbations throughout the rib cortical, rib trabecular, and flesh are assessed using anterior pendulum impacts to the front of the model (Hwang et al., 2020). Some boundary conditions are also assessed by considering the positioning of the model. This study produces are resulting factor score of 2 for the results robustness.

A summary of the credibility score elevation strategies when simulating the thorax injury mechanism using THUMS can be found in Table 2. Elevation strategies for this model consist of newly defined material properties corresponding to traceable data, which are representative of their anatomical abstractions, for score elevation to a value of 2. Similarly, the contact properties defining the interactions throughout the thorax should be updated to represent real-world experimental evidence for a factor score increase to a value of 2 for the input pedigree. Verification practices are absent in the results of the current literature search and should be conducted for the features implemented throughout the FE thorax model. Additional validation studies are needed for several of the loading conditions not currently assessed, using EVA-related boundary conditions and indicating agreement with a sufficiently analogous EVA referent. This will induce factor score increases to values of 3 for both the conceptual and referent validation factors. Finally, assessments of the uncertainty throughout the defined material properties could not be identified and warrant future analysis for the model's existing and newly defined input parameters.

A3.7 Elemance Shoulder Model

Anatomical representations throughout the shoulder model in Elemance are limited to the scapula, clavicle, humerus, and surrounding flesh. Both cortical and trabecular regions are defined for the clavicle and humerus, while only cortical elements are supplied for the scapula. The material properties assigned to these regions could not be traced; therefore, a factor score of 0 is assigned. Spherical joint and joint stiffness definitions are defined for the shoulder joint; however, these definitions are specified identically to the definitions imposed for the knee joint (Riener & Edrich, 1999). Furthermore, rigid constraints are used for the remaining contact inclusions throughout the shoulder region. Based on this information, a credibility score of 0 is assigned as the model indicates insufficient evidence for the input pedigree credibility factor.

Referent validation cases are presented in the literature to assess the response of the shoulder. Lateral impacts are presented in (Perez-Rapela et al., 2019; Zhao et al., 2020), with some agreement found in the assessments of the shoulder between the simulation and experimental data. Additionally, an agreement is found in (Gaewsky et al., 2019) through the resulting seatbelt shoulder forces. Based on these studies, a referent validation factor score of 1 can be assigned.

Several elevation strategies have been identified for simulating the shoulder injury mechnanism using Elemance, as can be seen in Table 1. The credibility elevations for the shoulder model consist of updating the material properties with traceable experimental evidence. Also, including the incorporation of soft tissues such as the rotator cuff muscles with corresponding traceable evidence will improve the data pedigree factor score to 2. The input pedigree also needs to be updated with traceable evidence representative of the contact interactions associated with the shoulder joint for elevation to a factor score of 2 for the input pedigree. Verification data of the anatomical incorporations is absent in the current literature and should be conducted to ensure the correct representation of the model. This is expected to elevate these scores to 2 for both the code and solution verification credibility factors. Elevation of the conceptual validation of the model is accomplished by incorporating the soft tissue representations along with additional validation cases for a newly defined score of 3. Furthermore, performing validation cases resembling the impact conditions relevant for the FFH scenario with a good experimental agreement is expected to increase the referent validation factor score to a value of 3. Finally, assessments of uncertainty and sensitivity propagation associated with the material properties and boundary conditions relevant for the EVA injury scenario are needed for credibility elevations. These initial assessments are expected to produce a score increase to a value of 2 for the results uncertainty and robustness credibility factors.

A3.8 THUMS Shoulder Model

The THUMS shoulder model features implementations of both hard tissues (Humerus, Clavicle, Scapula) and some soft tissues throughout this region (subscapularis muscle, subclavius muscle, articular capsule, coracohumeral ligament). Some material properties can be traced in this model. For instance, the material properties defined for the cortical scapula and clavicle are defined with identical properties as those specified for the ribs (Kemper, 2005). Further, experimental data using vertebral samples defines the trabecular bone throughout the shoulder region (Yamada et al., 1970). The subscapular, infraspinatus, and subclavius rotator cuff muscles are included in the model with their material properties traceable to experiments using the pectoralis major muscle (Yamada et al., 1970). The resulting score for the data pedigree is defined as 1 since the material properties of the humerus cortical bone, coracohumeral ligament, sternoclavicular ligament, and articular capsule cannot be traced to experimental data. The input pedigree is defined by rigid constraints between the anatomical regions, which is deemed sufficient to achieve the factor score of 1.

Conceptual validation cases throughout the literature are presented using three-point bending and compressive boundary conditions for testing of the humerus bone (Toyota Motor Corporation & Toyota Central R&D Labs, 2021). However, the simulation data showed limited agreement with the experiments. This resulted in a factor score of 0 for the conceptual validation, as other conceptual validation data for the shoulder regions cannot be found in the literature. There are some referent validation cases within a lateral impact orientation. An impact velocity of 4.33m/s (Lanner et al., 2010) indicates good agreement in measured kinematic outputs with those presented in the experiments. Additionally, another study (Paas et al., 2015) also used lateral impacts to compare the response of THUMS to both relaxed volunteers and PMHS. The results of the validation cases indicate good agreement with the relaxed volunteers; however, a reduced agreement was found when compared to PMHS. These studies result in a defined credibility factor score of 1 as impact velocities beyond approximately 5m/s in a lateral impact orientation and from 0m/s-15m/s in supine, tope, and prone impact orientations have not been assessed in the current literature. Finally, no studies can be found in the literature supporting the results uncertainty and robustness credibility factors; therefore, factor scores of 0 are assigned accordingly.

Several strategies have been identified to improve THUMS's credibility factor scores for the shoulder region as can be seen in Table 2 in our manuscript. Firstly, material properties and contact properties need to be updated with traceable data derived from experiments using the corresponding anatomy from the shoulder region. Additionally, the shoulder joint response should be further evaluated to ensure the correct representations of the FFH scenario, such as falling in a braced condition, can be captured. This may also be accomplished by implementing muscular activation features. These improvements will result in newly defined factor scores of 2 for the data and input pedigree. Verification studies need to be conducted to ensure correct solutions are produced by the finite element model of the shoulder region. Furthermore, a conceptual validation is needed for several of the features throughout the shoulder model to assess stress states relevant for FFH in addition to joint movement. This is especially warranted as EVAs will be conducted with an xEMU suit, and this interaction should be correctly captured between the model and the suit. Referent validation cases are also needed for impact velocities beyond 5m/s in a lateral orientation and for prone, supine, and top impact alignments with good agreement with experiments. Implementing these strategies will result in the elevation of the conceptual and referent factors to credibility factor scores of 3. Finally, uncertainty quantification and sensitivity analysis should be conducted to elevate the results uncertainty and robustness factor scores to 2.

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Supplemental Table 1: Credibilty factors presented in NASA-STD-7009A (NASA Headquarters, 2016) and the correlating factor score definitions.

Level	Data Pedigree	Input Pedigree	Verification (Code and Solution)	Validation (Conceptual and Referent)	Results Uncertainty	Results Robustness
FE Data	*Data supplying the conceptual implementation.*	*Data supplying the boundary/ initial conditions.*	*Evidence the concept is implemented correctly*	*Evidence the concept resembles the real-world system of interest*	*Propagation of variations throughout the FE model for the input conditions and properties specified*	*Changes in the outputs of the simulation due to variations in the input and design of the FE model*
4	All data known and traceable to RWS with acceptable accuracy, precision, and uncertainty.	All input data known and traceable to RWS with acceptable accuracy, precision, and uncertainty.	Reliable practices applied to verify the end-to-end model; all model errors satisfy requirements.	All M&S outputs agree with data from the RWS over the full range of operation in its real operating environment.	Statistical analysis of the output uncertainty after propagation of all known sources of uncertainty.	Sensitivities known for most parameters; most key sensitivities identified.
3	All data known and traced to sufficient referent. Significant data has acceptable accuracy, precision, and uncertainty.	All input data known & traced to sufficient referent with significant input data having acceptable accuracy, precision, & uncertainty.	Formal practices applied to verify the end-to-end model; all important errors satisfy requirements.	All key M&S outputs agree with data from the RWS operating in a representative environment.	Uncertainty of results are presented quantitatively through propagation of all known uncertainty.	Sensitivities known for many parameters including many of the key sensitivities.
2	Some data known and formally traceable with estimated uncertainties	Some input data known & formally traceable with estimated uncertainties.	Documented practices applied to verify all model features; most important errors satisfy requirements.	Key M&S outputs agree with data from a sufficiently similar referent system.	Most sources of uncertainty identified, expressed quantitatively, and correctly classified. Propagation of the uncertainties is assessed.	Sensitivities known for a few parameters. Few or no key sensitivities identified.
1	Some data known and informally traceable.	Some input data known and informally traceable.	Informal practices applied to verify some features of the	Conceptual model addresses problem statement and	Sources of uncertainty identified and qualitatively assessed.	Qualitative estimates only for sensitivities in M&S.

			model and assess errors.	agrees with available referents.		
0	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.	Insufficient evidence.