Implications of Space Suit Injury Risk for Developing Computational Performance Models

Leia Stirling; Pedro Arezes; Allison Anderson

INTRODUCTION: Although a space suit is a technological feat sustaining human life outside the spacecraft, working in the space suit environment can lead to musculotendon and soft tissue injuries in astronauts. In this literature review, we consider the injury risk mechanisms for human-space suit interactions. We first present a review of space suit injury risk founded in empirical, statistical, and experimental studies. We then review efforts in computational modeling of a human and space suit. As the interpretation of models for injury risk has not previously been defined, a review is presented of biomechanical considerations of injury risk to the tissue and joints based on previously observed space suit injuries. A review of risk assessment in occupational health in the workplace is then presented, an adjacent area that informs relevant measures of consideration for human-space suit applications. Finally, we discuss how the work-to-date can inform continued efforts in minimizing risk of musculoskeletal injury to the human when using a space suit. From the literature, this review concludes space suits cause biomechanical alterations, inducing musculoskeletal injury. Combining occupational health kinematic constraints with computational models could enable a trade space evaluation on space suited biomechanics to reduce risk mechanisms. Future work, though, is required to enable computational models to be predictive of individual injury risk. Our findings show there are significant gaps in our current knowledge on tissue injuries that preclude biomechanical models from being used directly as an injury risk assessment model. This review identifies how risk factor monitoring and modeling will enable improved space suit design and evaluation.

KEYWORDS: extravehicular activity, musculotendon injury, soft tissue injury, work-related musculoskeletal disorders.

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There are many challenges in sending humans to Mars, with a critical requirement for success being the continued health and performance capabilities of the human.[115] The space suit provides protection during extravehicular activity (EVA) when the human leaves the vehicle or habitat to perform exploration, science, or maintenance activities. The operational profile for future lunar or Mars missions will require many more EVAs than have currently been performed[33] and current space suits and EVA concepts of operations are currently inadequate.[1] Space suit designs must consider the interaction of many diverse factors, including mass, volume, walking effort, mobility, agility, and suit fit.[2] Training is important for space suit operators (inclusive of personnel wearing the space suit that may or may not be astronauts) to learn to use a suit in ways that map the human joint degrees-of-freedom (DOFs) with the suit DOFs while minimizing required torques in an efficient manner.[57] When programmed motions are not appropriately selected by the operators, the operators may have additional increases in their joint torques as they fight against the suit. These interactions between the human and suit have led to operators developing a variety of injuries due to prolonged use, including erythema, abrasions, muscle soreness/fatigue, paresthesia, bruising, blanching, and edema.[101,112]

One challenge to the design and development of the complex space suit is that these systems must be built and evaluated experimentally or as deployed to understand the complex relationship between the space suit and human interaction. There is a need to develop computational tools that enable evaluation of space suits prior to human testing. However, the pathways for

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From the Massachusetts Institute of Technology, Cambridge, MA, USA; the University of Colorado-Boulder, Boulder, CO, USA; and the University of Minho & MIT Portugal Program, Guimarães, Portugal.

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Address correspondence to: Leia Stirling, Ph.D., Massachusetts Institute of Technology, 77 Massachusetts Ave., Bldg. 33-311, Cambridge, MA 02139, United States; leia@mit.edu.

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injury risk in a space suit have not been formally defined. Thus, it is unclear how measures obtained from novel computational modeling can be related to musculoskeletal injury risk.

In this literature review, we consider musculoskeletal injury risk mechanisms for human-space suit interactions. We first present a review of space suit injury risk founded in empirical, statistical, and experimental studies. We then review efforts in computational modeling of a human and space suit. As the interpretation of models for injury risk has not previously been defined, a review is presented of biomechanical considerations of injury risk to the tissue and joints based on previously observed space suit injuries. A review of risk assessment in occupational health in the workplace is then presented, an adjacent area that informs relevant measures of consideration for human-space suit applications. Finally, we synthesize these results to inform future areas to reduce risk of musculoskeletal injury to the human when using a space suit.

Review of Studies on Space Suit Injury Risk

With the history of accumulated time in the space suit, both in microgravity and on the ground, it is clear that the space suit environment is harsh and leads to injury, discomfort, and fatigue. The mechanisms behind space suited injuries have come into focus through compilations of historically reported empirical data on injuries, statistical assessments of causal factors, and through experimental analyses on human-space suit performance.

Empirical studies. Analysis on empirical data from recorded injury and discomfort incidences and retrospective analysis of prior missions elucidate paradigms in which EVA injuries occur. Scheuring et al.[112] evaluated all injuries reported in the U.S. spaceflight program from previously collected databases and found 0.26 injuries reported per EVA, representing a staggering increase in injury incidence compared to other phases of flight. The two most commonly reported injuries were to the hands and feet. Scheuring et al.[111] also performed a retrospective analysis on injuries in Apollo missions 7–17. Data were collected from existing records and by surveying 14 of the 22 surviving Apollo crewmembers. The primary injury mechanisms were due to the glove on the hand causing fatigue, abrasions, swelling, and pain over the joints. Additionally, astronauts reported locomotion was inhibited. Hip, thigh, hand, and skin irritation, fatigue, and injuries were identified as the most important biomedical issues to be addressed for future planetary space suit designs.

The most comprehensive empirical study on space suit injury during training was performed by Strauss[120] for data from 2002 to 2004. The anatomical location, severity on a scale from 0 (no pain) to 5 (severe pain), and cause of injury were cataloged for Neutral Buoyancy Lab training events. During this time, 45.7% of the training events resulted in the astronaut reporting a suit-related symptom. The most common symptom was on the hands (in particular at the fingernail and fingertip) with 166 (47.2%) reported incidences, and shoulder symptoms the second most frequently reported, with 73 reports (20.7%). Shoulder symptoms were also rated the most painful. Common areas of discomfort were the feet, legs, arms, neck, trunk, groin, and head. Although most injuries were mild and limited in duration, with repeated exposure working in the suit, these incidences could lead to long-term consequences for astronaut health and mission objectives.

The most debilitating EVA-related injury is shoulder injury requiring surgical intervention. In 2003, Williams and Johnson[130] performed a retrospective survey with 44 astronauts to document shoulder injury incidences. Of those surveyed, 22 astronauts participated in EVA-related training, and 14 reported shoulder pain attributed to working in the Neutral Buoyancy Lab. The primary causes of pain and injury related to the space suit hardware were decreased mobility and altered biomechanics in the planar hard upper torso, improper suit fit and sizing, and inadequate or improper use of padding and shoulder harnesses. Factors related to the training environment contributing to shoulder injury and pain included training in the inverted position, the use of heavy tools, overexertion in training or under reliance on diver assistance, and training frequency. The study provided recommendations on injury prevention, but despite their implementation as a result of this study, additional findings from Scheuring et al.[113] from 2012 indicated the shoulder injury issues due to working in the space suit had not been resolved.

These studies focused on retrospective and Extravehicular Mobility Unit (EMU)-based injury mechanisms, but also provided a standard by which future injury mechanism research could be investigated. Findings indicate injuries reported during training have similar causal mechanisms to those on orbit, but with higher incidence rates and severity. Ongoing efforts within NASA have increased documentation and provided a standardized methodology for documenting injury incidences.[94]

Statistical studies. In addition to cataloging the number, type, and suspected causes of injury, databases also serve as a resource to perform statistical assessment of injury. Opperman et al.[101] and Charvat et al.[34] have performed statistical assessments of hand injury in U.S. space suit gloves, with conflicting findings. Opperman et al.[101] found hand metacarpophalangeal joint circumference to be statistically significant, but did not find middle finger-to-hand ratio to be significant. Charvat et al.,[34] however, found the length of the index and middle fingers to be important factors associated with hand injury. The study also related anthropometry, glove type, and training information to injury records, and found the Phase IV EMU gloves and increased training time to be indicative of injury. Anderson et al.[9] assessed shoulder injury incidences during training. Corroborating findings from Williams and Johnson,[130] this study found the percent of training incidences performed in the planar hard upper torso, as compared to the pivoted hard upper torso, was the strongest predictor of injury. Anthropometric factors related to how the person's torso fit into the space suit hard upper torso were also found to be significant. Finally, previous shoulder injuries and reduced time in between training incidences to recover contributed to shoulder injury. Little work has been published on in-flight statistical models of injury, likely due to the sparser nature of these datasets. With the previously described improvements in reporting, future work should re-evaluate the findings of all these studies to further resolve the conflicting results on hand injuries and reevaluate mechanisms that may be preventative of injury, rather than solely predictive of injury.

Experimental studies. To overcome limitations in empirical reporting of EVA injury incidences, experimental work has investigated hypothesized mechanisms of injury to inform differences across subjects and suits. A study on the feasibility of suited ambulation in planetary, advanced space suits indicated the boot area was of particular focus for injury mechanisms due to rubbing.[98,99] Hand injury mechanisms have been investigated by several researchers, particularly to determine the factors influencing onycholysis, or fingernail delamination. Jones et al.[65] found air circulation and humidity build up was a significant contributor to onycholysis. Ansari[10] developed a fingertip sensor to investigate blood perfusion, finding the glove decreased blood flow, particularly in the fingertip, with increased pressure. Anderson et al.[7,8] and Hilbert[63] investigated the repeatability of motions using standardized upper body tasks with suited subjects donning wearable pressure sensors. These studies investigated pressure profiles due to contact with the suit over the arm and shoulder and found subject placement inside the suit varied and biomechanical movement strategies were altered with time, likely due to fatigue. Reid et al.[106] investigated the influence of fit within the pivoted and planar hard upper torsos on strength and metabolic cost, and found that, in general, working in a larger than optimally sized hard upper torso was not a major decrement to performance, but did increase pressure loading on the body, which could have implications for injury with extended use.

Although not specifically investigating injury mechanisms, there have been many experimental studies on space suit biomechanics that are informative of injury mechanisms. Work to develop in-suit assessment of joint angles, which are not observable externally, has been performed at the University of Maryland,[42] the Massachusetts Institute of Technology,[19,50,90] and the University of Colorado-Boulder,[116] as well as in unpublished internal studies performed at the NASA Johnson Space Center Anthropometry and Biomechanics Facility. These efforts have focused primarily on the use of inertial measurement units and comparing with the externally measured space suit joint angles. Suited tests by Cullinane et al.[39] found significant gait parameter changes when wearing the Mark III, in particular a widening of stance parameters both in static and walking conditions. Another body of work focused on measuring strength decrements caused by the suit (e.g., Morgan and Wilmington,[92] England et al.,[45] and Amick et al.[6]). In these studies, subjects showed a decrease in strength performance due to the joint torques imposed on the subject, which may contribute to over-recruitment of muscles and increased fatigue, both of which contribute to injury.

Together, these studies show general sources of injury include improper suit fit, shifting or improper use of protective garments, and repetitive motion working against the suit.[17,120,130] At the joints, skin surface injuries are caused by rubbing and impact, and the likelihood of injury is increased when the space suit joint is not aligned properly with the body joint.[17,120] In training, these issues are exacerbated due to shifting with gravity, leading to skin indentation and reddening.[112,120] Additional sources of impact and discomfort include the hard bearings and boot inserts while working in footholds, as well as discomfort caused by the pressure bladder wrinkles, which cause blisters, contusions, abrasions, and loss of feeling. Finally, shoulder injuries are the most debilitating and severe injuries seen in the space suit.

Research based on cataloged injuries and experimental assessments allow for engineers and doctors to determine the design elements which have demonstrated injury implications. These data can be used to direct future space suit hardware development, but these methods are limited in their ability to predict the injury likelihood for future designs.

Computational Models

Most efforts to assess injury risk mechanisms are derived from data taken with a human interacting with a real, physical space suit. Within this section, efforts in modeling the space suit are considered. Here we specifically present models that enable an understanding of musculoskeletal risk factors. We do not include models for radiation-based injuries, decompression sickness, micrometeoroid damage to the suit, thermal regulation of the suit, or mechanical failure analysis. We also exclude models of bone strength and fracture risk.

Rigid body models. Schaffner et al.[110] developed a physics-based 6-DOF rigid-body model that represented the human-suit system. The suit was integrated into the model through increases in rigid-body masses and inertias, as well as adding joint stiffness and damping parameters to model the forces required to maneuver the suit. Newman et al.[97] and Schmidt et al.[114] experimentally characterized the suit-generated loads from the EMU and developed a hysteresis model of the loads required of the human to maneuver the suit. These data were initially integrated into a 6-DOF two-dimensional sagittal plane model of the astronaut to examine the effect of the suit on specific motion profiles.[97] Stirling et al.[119] later integrated these torque profiles into a three-dimensional 37-DOF model to assess astronaut rotation maneuvers. Li et al.[77] also implemented a 37-DOF model to examine load maneuvering tasks. More recently, Valish and Eversly[122] characterized the joint torques in the Mark III space suit, which were integrated into a musculoskeletal model by Diaz and Newman.[14] This latter model used an optimization methodology to estimate active muscles during a suited knee flexion task to assess potential for injury risk through increased required peak muscle activations. In this analysis, a fixed human musculoskeletal model was implemented; however, efforts have shown that these estimated forces can depend on the underlying musculotendon parameters that are selected.[4,28] Li et al.[78] have also developed a 6-DOF upper extremity inverse dynamics model.[24] Exoskeletons provide similar modeling challenges as space suits, as they can affect natural mobility and interface with the body. Similar to these space suit models, exoskeleton models typically assume that the exoskeleton is "securely fastened" to the human.[5,48,85]

In these models, there was an estimation of a suit-imposed torque; however, the models do not consider that the suit may move with respect to the human and that interaction forces (and thus induced joint torques) may be present at different locations on the limbs. These interaction forces have been measured previously, as seen by Anderson et al.[8] for the upper extremity. Relative motions between the human and space suit have also been measured by Fineman et al.[50] in the lower extremities and Bertrand et al.[20] in the upper extremities.

To enable developing separate, but interacting models of the human and space suit, Cullinane et al.[38] created a solid model of the Mark III space suit that enables estimating the torques required to move the space suit and were able to computationally predict the hysteresis profiles observed experimentally. Similar to the multibody and musculoskeletal models, the solid models assume that the underlying bodies cannot deform. However, human tissue is compliant and will deform when a force is applied.

Deformable interaction models. Deformable models provide a methodology for improving model fidelity. There are three main classes of modeling contact interactions with deformations included. The first methodology is multibody surrogate models,[46,71,86] which provide macroscopic resolution of contact, but do not provide detailed localized deformation. A second class is Finite Element Models (FEM), which can describe highly complex human and object geometries with localized deformations.[60] The third class is particle-based methods,[121,125] which is similar to shell-based FEM and can be used to simulate contacts with thin objects. Gourret et al.[60] highlight that FEM formulations permit contact events with sliding and sticking forces that enable the appropriate shape of the human or object to be represented. While FEM formulations provide a high degree of fidelity in modeling structural and contact mechanics for arbitrary, complex geometries, and can account for deformation of both human and system contacted, they come with the drawback of a significantly higher computational expense than the other two classes that make simplifying assumptions.[68,82] Despite this computational expense, applications of FEM contact formulations have been successfully applied in capturing the effects of contact interactions between a human and flexible garment.[126] King[68] performed a trade study comparing two FEM contact formulations and found that when the material stiffness between two contacting objects are similar, it is important to model the deformations in both the objects. As one object becomes stiffer than the other, simplifications can be made to model deformation in the less stiff object, while assuming the stiffer object is nondeformable.

FEM enable representing the human-suit interaction to analyze deformations due to interaction forces, including the location and force magnitude of the interactions. Similar to musculoskeletal modeling, FE analysis does not have the ability to predict injury and still has open questions of how model outputs relate to injury mechanisms. Radford et al.[103] examined the estimated loads a seated astronaut would experience during nominal and off-nominal ascent and landing scenarios due to interactions with the suit and seat configuration. Risk was assessed by looking at head accelerations, as well as forces and moments (tension, compression, shear, flexion, extension, lateral) of the neck, lumbar, tibia, and femur. These values were compared to measures specified in the NASA Constellation Program Human-Systems Integration Requirements[95] to minimize risk of injury.

Injury risk for seated astronauts in launch and entry scenarios combine using the Brinkley criteria and metrics extracted from experimental tests with anthropomorphic test devices, also referred to as crash-test dummies.[73] The Brinkley model[26] is a simplified lumped mass-spring-damper representation of the human connected to a seat. The only way to reduce risk within this model is to attenuate energy, as it is not possible to model design changes.[58] The seated injury risk FEM are typically validated by comparing to experimental anthropomorphic test device data and with injury risk assessment by comparing to the Brinkley model or the NASA Constellation Program Human-Systems Integration Requirements.[73,74] While FEM have not been developed for suited gait, they have been used to examine internal loads and deformations for the leg during gait (e.g., simulating knee replacement,[15,59] ankle replacement,[105] and deformation of the foot during barefoot gait[35]).

Biomechanical Studies on Injury Risk

The previous sections highlighted that there are many potential risk mechanisms observed and highlighted the limitations of relying solely on these kinds of studies for projecting injury mechanisms with future systems. Methods of modeling the human-space suit system were then presented. However, it is unclear how model outputs should be interpreted in the context of injury risk. In this section, we review the literature for injury mechanisms driven by the pressure and musculotendon injury mechanisms observed.

Pressure and skin surface injury. Theories of tissue breakdown involve localized ischemia, impaired interstitial fluid flow and lymphatic drainage, reperfusion injury, and sustained deformation of cells.[25] While there are methods for classifying pressure ulcerations once they occur, there is not a clear understanding of the pressure and duration of time required to induce clinical injury, nor how these values may change for different anatomical locations. Bouten et al.[25] describe two mechanisms for pressure wound formation: 1) a superficial injury that forms in the skin due to shear pressures (which is more commonly assessed experimentally); and 2) a deep tissue injury that forms near bony prominences due to sustained compression of the tissue. Although they state capillary closure pressure of 32 mmHg (4.27 kPa) is a frequently used threshold for tissue damage, this value may not be appropriate because ischemia may not be the only factor in tissue breakdown, and capillary closure depends on local pressure gradients, not just skin interface pressure. There is an inverse nonlinear relationship between the pressure applied and the duration of applied pressure in the generation of tissue damage.[64,70,80] The suggested pressures over a continuous time were observed to be variable, with clinical guidelines shown in **Fig. 1**, although it was acknowledged that variability occurs due to shear loading, collagen loss, metabolic condition, temperature, perspiration, age, edema, infection, proprioception, and psychiatric factors.[70] Further, it is difficult to compare values across laboratories as the shape of indenter can affect the pressure at the interface, although trends should be consistent.[70] Experimental measures of tissue strains usually occur at the superficial layer and not subdermal. Efforts in computational modeling are developing techniques to estimate subdermal strain and stress distributions. For example, Linder-Ganz et al.[81] develop a computational model of subdermal tissue during sitting and compared results to MRI imaging. Xing et al.[132] developed a numerical model for skin friction blistering using FEM modeling that incorporates tissue properties of the various skin layers. Carlson et al.[31] identified the peak load and number of loading cycles as the primary determinants of skin injury risk. Additional causal factors include the presence of moisture, heat, and previous exposure to injury.[31,84] For blister formation, microscopic epidermal tears coalesce to form a cleft which fills with blood or tissue transudate.[31,84] Chafing and abrasions have similar etiologies to that of blistering, but the maceration with repeated rubbing also causes skin tissue breakdown.[84] Experimental efforts in contusions have found that energy transfer to tissues could be accurately predicted and modeled, but that ultimate contusion outcome was highly variable among subjects, likely as a result of the interplay between capillary density and tissue stiffness.[40] Garcia-Fernandez et al.[56] report 83 risk factors from the literature and recommend evaluating pressure sore risk by examining the existence and intensity of four primary etiologic factors (pressure, shear, friction, and moisture), although state it is important to consider additional coadjuvant factors.

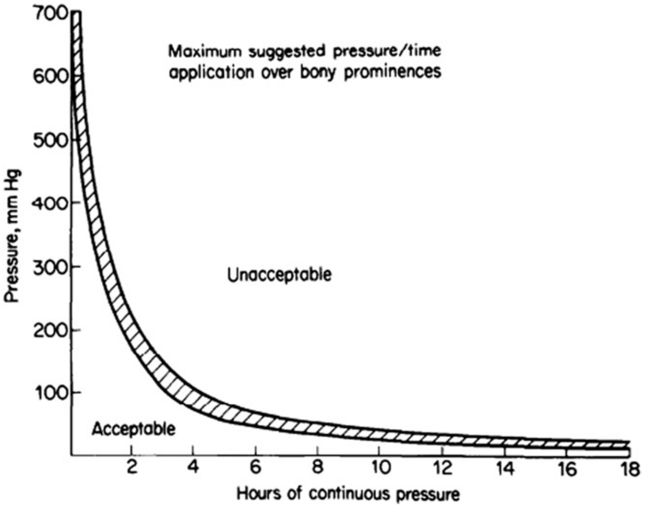

Fig. 1. Schematic relationship between pressure and time of pressure for risk of sores over bony prominences as presented by Krouskop[70] from Reswick and Rogers.[107]

Musculotendon injury. It is well-accepted that eccentric contractions (when the muscle contracts while lengthening) can create muscle injury. Many people believe that strains are a dominant factor leading to injury.[79,109] Subcellular damage may begin as muscle pain and weakness; if fiber necrosis progresses it can become inflammation and impairment.[30,44] Activation timing and muscle length before stretch may also influence muscle injury by significantly increasing fiber strain magnitude.[30] Muscle damage creates a reduction in force generation and increase in muscle stiffness.[37] There is no literature that articulates direct values of strain for assessing muscle injury risk for human muscle. In the literature there have been a range of strains examined; however, Butterfield and Herzog[30] find signifiers of injury risk even at physiological ranges of motion (5% muscle-tendon unit strain) across stretch-shortening cycles. The values used in that study were consistent with Fukunaga et al.,[55] who measured the gastrocnemius medialis muscle in vivo during slow walking and found strains of 5–9%. Histological analysis also supports signatures of muscle injury during eccentric, but not isometric contractions for 10% strains.[89]

Butler et al.[29] note that tendon failure has been measured for a maximum stress of 60–100 MPa and strains of 13–22% when measured between grips, although the failure occurs at a lower strain and higher stress if measured optically (1400 to 1700 MPa and 5–8%, respectively). They further note that in vivo, tendons do not typically fail in this manner and chronic injuries typically occur after repetitive instances of subfailure. After an injury has occurred, failure forces are lower, and thus repeated injury can occur at lower stresses. Archambault et al.[11] review tendon overuse injury, highlighting the response of the tendon at the cellular and matrix level. They state that it is unclear how the load history directly relates to overuse injury development and what threshold should be defined below which the tendon's remodeling process is sufficient to maintain integrity.

Prospective studies permit evaluating the effect of intrinsic factors (e.g., strength, range of motion, joint stability) on injury and could provide guidelines to lower risk. However, results of injury risk factors are mixed. Morrison et al.[93] reviewed foot characteristics associated with inversion ankle injury and found inconsistent results across prospective studies. Mahieu et al.[83] found that subjects with Achilles tendon injury had lower plantar strength than those who did not get injured. Beynnon et al.[21] found underlying anthropometric and range of motion differences between those with and without ankle ligament injury, but no differences in strength. Similar mixed results have been observed for other muscuolotendon injury locations as well.

While muscle injury appears strain induced, tendon injury appears load induced. However, based on a review of the literature, more effort is needed to understand the strains that lead to pain and injury. Pain is a relevant measure because it is both a precursor to injury and a measure of the degree of injury. There is a large degree of individual variability in the perception of pain,[36] including over different areas of the body.[36,51,69] Large individual differences may contribute to conflicting threshold results from some studies.[36] It is not clear how pain directly translates to injury, nor what statistically significant differences between injured and uninjured groups are operationally relevant for the injury generation. To minimize risk of pain and injury, Chaffin et al.[32] recommend 5% maximum voluntary contraction (MVC) for continued static work by the upper extremity and 15% MVC for low-back extensor muscles, although state that variation in muscle endurance times is large and depends on the individuals, the muscles tested, and the work conditions. While we can use these subjective pain studies to suggest limits on %MVC required by the muscles for a particular task to lower risk of musculotendon injury, more research is required to better understand the relationship between intrinsic variability, neuromotor control (which leads to motor strategy selection), and mechanisms for injury.

Review of Risk Assessment Methods for Work-Related Injuries

The previous section considered the underlying biomechanical studies on injury risk and highlighted that there are no distinct thresholds for injury occurrence. However, limits need to be assessed in some manner to prevent musculoskeletal injuries. The domain of occupational health considers risk assessment for Earth work-related musculoskeletal disorders (WRMSD). The recommendations developed to minimize WRMSD can also provide guidelines for lowering the risk of space suit-induced injuries. WRMSD have a multifactorial origin,[123] involving mainly physical (e.g., work postures and movements, repetitiveness and pace of work, force of movements, vibration, temperature, etc.) and psychosocial risk factors (e.g., lack of influence or control over one's job, increased pressure for more production, lack of or poor communication, etc.), as well as individual risk factors (e.g., age, gender, body size and shape, personality type, previous symptomatology, etc.).[13,23,41] In this section, the risk assessment methods used for occupational health are presented and postural recommendations are summarized that can be considered when evaluating space-suited task performance.

Risk assessment methods. The majority of published methods for occupational health risk assessment were developed for ease of professional application in the field, and not as a tool focused on accurate measurements of the workers' exposure to the WRMSD risk factors, or the need to provide epidemiological data for a specific exposure. Most published methods or techniques developed for assessing exposure to risk factors for WRMSDs are based on posture analysis and in the upper regions of the body (back, neck, shoulder, arms, and hands).[76,123] These areas of the body are also the most frequently used in the workplace, as opposed to the lower body.

When developing methods for exposure assessment, it has been proposed[131] that mechanical exposure during physical work can be described by three parameters, namely: 1) the intensity (or level) of the force; 2) the repetitiveness, or the frequency, of the force; and 3) the duration (i.e., the time during which there is physical activity). Additional exposure factors are also considered [e.g., the postural variation, the work pace, organizational factors, and individual characteristics of the operator(s)].

Several literature reviews[75,123,131] have classified methods for exposure assessment into three categories:

1. Self-report methods. Survey or interview-based measures directly reported from the workers. In general, these methods are considered less accurate and susceptible to reporting bias, but offer the advantage of being less invasive and easy to administer.
2. Visual methods. Methods relying on photo, video, or direct observation of the worker in their environment. Generally, these techniques result in an aggregated score of exposure risk, which can then be compared to established acceptable limits. Some primary limitations are the need for expert analysis, the limited number of workers able to be observed by the expert, intra- and interobserver variability, changes in behavior when the worker is aware of observation, and often a dependence on the task being repetitive or cyclical in nature.
3. Direct measurements. Sensor-based measures collecting quantitative data. Sensors may be attached to the subject (for example, to measure body posture) or directly embedded in their work environment (for example, to measure forces exerted). The primary advantage of these methods is their increased accuracy over self-reported and visual methods. The primary limitations of these methods are that they are more invasive for the workers, have a high cost, and are less well-suited to perform assessments in the field.

By far the most common methods used in occupational health are the visual methods, which are discussed in more detail in the following section, along with additional details on direct measurements.

Characteristics of the visual methods and direct measurements. The tables in this paper present examples of methods that are the most representative and cited in previous reviews. **Table I** lists examples of basic visual methods and their main characteristics. For these methods, the risk of a given task or activity is classified or scored according to its observation, which can be made in the workplace or through later image analysis (e.g., photography or video recording). These methods are based on the workers' posture in the context of the task-specific forces (with loads estimated or directly weighed), with frequency and task duration considered. Some methods analyze the physical factors of the work setting or workplace (such as the adopted postures, force exerted, movements' frequency and duration), as well as the psychological factors.

More advanced visual methods are developed for the assessment of postural variation for more dynamic activities (**Table II**). These methods record data either on video or by computer that are subsequently analyzed objectively using specific software. Corresponding analyses may also include the use of biomechanics models. These models can have different complexity, ranging from two-dimensional static models to three-dimensional dynamic models.

Table I. Examples of Basic Observational Methods That Require No Additional Technology.

METHOD (REFERENCE)	APPROACH	BODY AREA	RISK OUTPUT TYPE
OWAS[49,66]	Posture recording and classification with sampling for postures and force	Whole body	Postures are classified into four categories according to the expected effect on health
RULA[88]	Categorization of body postures and force	Upper body limbs	Four action levels according the urgency of implementing measures.
NIOSH Equation[127]	Identification of main parameters related to biomechanical load for manual handling	Generalized*	Estimation of a threshold called recommended weight limits (RWL)
OCRA[100]	Computation of an index of exposure to repetitive movements of the upper limbs	Upper limbs	Definition of three exposure index scores defining the urgency of implementing measures
ACGIH TLVs[3]	Threshold limit values for hand activity and lifting work	Whole body	Risk is identified by comparing the actual load and the threshold value.
LUBA[67]	Classification based on joint angular deviation from neutral and perceived discomfort	Upper body and limbs	Assessment of postural loading on one task and its relation to the corresponding maximum holding time (MHT).
MAC[62]	Flow charts to assess main risk factors and define prioritization of intervention	Generalized*	For each analyzed task, it defines three different classes of risk.
KIM[118]	It identifies workload items and evaluate the degree of probability of physical overload.	Whole body	A risk score is defined within the range of four risk categories with priorities for implementation.
Guide MMH[91]	It identifies the risk for manual handling tasks	Generalized*	A risk index based on the ratio between the expected pace for a specific task and the real pace.
HAL[72]	Based on experts' rating of hand activity level. Use of the concept of representative jobs.	Hand	Rates of the risk are expressed in a 10-point scale.

Extending these methods for space-suited observations would require additional use of wearable sensors on the person to quantify the human posture within the suit.
OWAS: Ovako Working Posture Analyzing System; RULA: rapid upper limb assessment; NIOSH Equation: National Institute for Occupational Safety and Health manual lifting equation; OCRA: Occupational Repetitive Actions; ACGIH TLVs: American Conference of Governmental Industrial Hygienists threshold limit values; LUBA: postural loading on the upper body assessment; MAC: Manual handling Assessment Chart; KIM: Key Indicator Methods; Guide MMH: Guide to Manual Materials Handling; HAL: hand activity level.
* Note that the term 'generalized' refers to methods that do not consider a specific body region but consider general risk factors.

Many direct methods have been developed that rely on sensors attached directly to the subject to measure exposure variables at work. Examples of these methods are shown in **Table III**. These methods range from simple, hand-held devices for the measurement of the range of joint motion to electronic goniometers that provide continuous recordings of the movement across joints during the performance of a task.

Across almost all the methods, posture is analyzed as a deviation from an assumed neutral posture. Deviations are usually analyzed and classified for flexion and extension, rotation (or twist), and lateral bending of the considered body segments. Even considering the differences between methods, it is possible to synthesize the literature and establish the most frequent angles used to classify high-risk movements or postures when exposure is repeated. It should be noted that in addition to the angle ranges, some methods define the related risk by complementing the deviation information with more detailed information about the frequency and duration of the analyzed movements and postures. Considering an average of the revised methods from Table I, the postures assumed to represent a situation of high risk when exposure is repeated, from a musculoskeletal perspective, are the following:

- For back/trunk, a flexion > 60°, an extension > 20°, and any clear lateral bending or rotation;
- For neck/head, a flexion > 20°, any extension, and a rotation > 45°;
- For upper arms, a flexion > 90° and an extension > 20°;
- For lower arms, a flexion > 100°;
- For elbows, pronation > 70° and supination > 90°;
- For wrist, a flexion > 15° and a radio/ulnar deviation > 15°; and
- For leg/knee, a knee flexion > 90°.

These values can be used as guidelines for evaluating mission-specific tasks that may be selected for EVA mission operations. The methods presented in Tables I–III can also be extended for experimental space-suited evaluation, with Table III consisting of methods that are closest to current state-of-the-art for space-suited operation. Extending the methods presented in Tables I and II for space-suited observations would require additional wearable sensors on the person to quantify the human posture and motion within the suit. Sensor selection for extending any of these methods would require compatibility with the suited environment (e.g., form factor, off-gassing, power). Any method that uses video technology must be augmented with wearable sensors to obtain the human posture or motions within the space suit, which are not directly observable.

Discussion

In this review we have highlighted the mechanisms by which injuries occur during EVA that have been studied through empirical, statistical, experimental, and modeled means. We

Table II. Examples of Advanced Observational Methods That Use Video or Sensor-Based Technology.

METHOD/APPROACH	MAIN CHARACTERISTICS	TECHNOLOGY USED
Video analysis[12,47,96,117,133]	Time sampling of video films and computerized data acquisition for both body posture and force.	Analog and digital video capture (combined with electromechanic goniometer, EMG, etc.)
ROTA[108] and TRAC[124]	Computerized real time or time sampling recording and analysis of activity and posture. Assessment of dynamic and static tasks.	Video-based and software for analysis
HARBO[129]	Computerized real time recording of activity and posture. Long duration observations.	Handheld computer for register
PEO[52]	Computerized real time recording of posture and activity.	Real-time observations with portable personal or hand-held computer
PATH[27]	Computerized work sampling of posture and activity. Nonrepetitive work.	Videotape and photography
SIMI Motion[76]	Video-based analysis of 3D movement. Assessment of movement of upper body and limbs.	Video-recording system and data integration with force and EMG signals.
Biomechanical models[32,102]	Representation of the segments of the human body and estimation of forces.	Computing models (eventually assisted by motion dynamics analysis, EMG, etc.).

Extending these methods for space-suited evaluation requires sensors that are compatible with the suited environment (e.g., form factor, off-gassing, power). Video technologies must be augmented with wearable sensors to obtain the human posture or motions within the space suit, which are not directly observable.

EMG: electromyography; ROTA: Real Observation of Time and Activity; TRAC: Task Recording and Analysis on Computer; HARBO: hands relative to the body; PEO: portable ergonomic observation method; PATH: Posture, Activity, Tools and Handling.

have also presented assessment of musculoskeletal risk from a workplace perspective. A big challenge in assessing risk purely from the studies based on historically observed or experimental data is that they are specific to the design of the space suit worn by the astronaut, with additional extrinsic and intrinsic factors that are not controlled. Computational models enable extending the design space that can be examined, yet model outputs cannot currently be mapped to personalized injury assessment, although they do provide an ability to examine solutions that minimize known risk factors. Understanding the current workplace risks and biomechanical injury mechanisms provides kinematic profile bounds that can be used in computational design trade studies. These workplace injury prevention guidelines can inform astronaut mission tasks, motivate space suit neutral posture designs (i.e., postures with lower torques required to maintain a pose), as well as inform tool design for the astronaut to enable the minimization of risk-inducing postures.

Computational models have the potential to provide a broader assessment of injury risk through the ability to modify suit designs and human geometries to assess human performance at a timescale and cost that improves upon that standard experimental build and test. The computational models can output estimates of interaction force and location, muscle activation, and joint torques for a given motion profile. These estimates can map to relevant biomechanical injury mechanisms observed. For example, the interaction forces can be converted to a pressure and would be useful for assessing rubbing or impact wounds, which is an injury previously observed in space suits. However, the literature is unclear on the threshold of pressure over time on the causation of injury at different body locations. While clinical guidelines are available at bony prominences, which are assumed to have higher risk of pressure-induced injury, they are not recommended for absolute interpretation.[80,107] Barbenel[16] states that to minimize pressure injury risk, one should limit the duration for which pressure acts and reduce the peak pressures at vulnerable sites. It will not be possible within the design of the space suit to remove all interaction pressures. Reducing and redistributing interaction locations can help minimize risk. Currently, NASA is considering that astronauts may perform three 8-h planetary EVAs per week in future concepts of operations.[1] Using this estimated EVA duration, a continuous

Table III. Examples of Direct Measurement Methods.

METHOD/APPROACH	MAIN CHARACTERISTICS	TECHNOLOGY USED
LMM[87]	Exoskeleton of the spine that replicates the 3D movement of a section of the lumbar spine.	Triaxial electronic goniometers.
Electronic goniometry[22,104]	Measurement of angular movement and postures of upper limb.	Single or dual plane electronic goniometers and torsiometers to record limb angular movement.
Inclinometers[18,61]	Measurement of postures and movement of the head, back and upper limbs	Triaxial accelerometers that record movement in 2s degrees of freedom with reference to the line of gravity
Body posture scanning systems, e.g., Optical[18,76]	Measurements of displacements, velocities and accelerations of specific markers located in the body.	Optical, sonic or electromagnetic registration of markers on body segments.
EMG, e.g., Wells et al.[128]	Estimation of variation in muscle tension and force application.	Recording of myoelectrical activity from muscles
Touch Glove[54]	Measurement of wrist, hand and finger motion, as well as grip pressure	Lightweight glove with motion sensors and pressure sensors

These methods are the closest to the current state-of-the-art for space-suited applications. Extending these direct measures for space-suited evaluation requires sensors that are compatible with the suited environment (e.g., form factor, off-gassing, power).

LMM: lumbar motion monitor; EMG: electromyography.

pressure of 50 mmHg should not be exceeded over bony prominences. However, the restrictions over nonbony prominences or noncontinuous loads are not clear. Human-space suit interaction is dynamic and the injury risk due to cyclical loadings at specific interaction locations should be further investigated, along with an increased understanding of perceived pain due to these pressures over time.

Another potential output of the computational models is the estimated musculotendon lengths and forces. Muscle injury appears strain induced and tendon injury appears load induced. Thus, these lengths and forces would be relevant to assess these injury mechanisms. The literature supports that eccentric contractions can create muscle injury. However, similar to the review for pressure injury, it was observed that no clear thresholds exist for the development of injury. While prospective studies permit evaluating the effect of intrinsic factors (e.g., strength, range of motion, joint stability) on injury and could provide guidelines to lower risk, the literature is mixed on which risk factors are important. These differences may arise from the populations and tasks examined. As a starting point, we could use the recommendation from Chaffin[32] of limiting static work to 5–15% MVC. While these numbers were derived for static tasks, repetitive dynamic tasks would provide similar concerns regarding metabolic-induced localized muscle fatigue. To examine this recommendation for a space suit application, we can consider data from a simple knee flexion-extension task. Diaz and Newman[14] estimated muscle forces for the knee flexors and extensors for a standing knee flexion task (knee flexion from 0–100°). The peak forces for the unsuited and EMU cases ranged from 7–98%MVC in the biceps femoris long head (49% / 54%MVC for suited/unsuited), gracilis (83% / 91%), gastrocnemius medialis (4% / 12%), and Sartorius (86% / 98%) muscles. For this task, the values of Chaffin et al.[32] are exceeded, although this task also exceeds the flexion recommendations to minimize WRMSD. The use of isolated joint tasks can be misleading as functional motions may have a more limited range of motion. Future work should include modeling EVA relevant static postures and dynamic tasks with and without a space suit to obtain estimates of muscle forces and lengths required for specific mission operation tasks. Previous efforts have considered kinematic strategies to reduce knee moments and subsequent injury risk (e.g., for anterior cruciate ligament injury[43] and knee osteoarthritis[53]). Models of the EVA relevant tasks guided by kinematic constraints from the occupational safety literature would provide an understanding of current planned tasks, enabling further trade space exploration to lower potential risks.

One major consideration transitioning from workplace injury methods to space suit methods is the difference in primary drivers in these areas of study. In occupational health, visual methods are the most widely adopted. Visual methods are less popular for space suit injury assessment as the human alignment and motions within the suit are not observable. Given the relative cost to work in the space-suited environment and the smaller subject population compared to occupational health environments, quantitative sensor-based methods are of high interest. As in the occupational health world, their drawback remains the invasive nature and the operational overhead to use them. In occupational health, a large emphasis is placed on using easily implemented methods, while this requirement is relaxed in space suit assessment. Both areas are limited by the ability of people to provide detailed, accurate subjective reports. There have been recent efforts to standardize reporting methods and an increased awareness among crew on the importance of disclosing discomfort and injury.

One of the main challenges with space suit injury risk and performance assessment is the varied nature of the protocols used. The experiments conducted in this area are hypothesis driven, each with specific methodologies and requirements. The lack of consistency, though, often makes comparison across experiments difficult, if not impossible. There are ongoing efforts at NASA Johnson Space Center to develop a series of standard measures to reduce this variability, and their implementation may mitigate these issues. Although methods from workplace injury may not be directly transferrable, the methodology assessments and fundamental techniques are also relevant to consider for space suit injury risk assessment.

Conclusions

In this literature review, we considered musculoskeletal injury risk mechanisms for human-space suit interactions. We conclude space suits cause biomechanical alterations inducing musculoskeletal injury. Combining occupational health kinematic constraints with computational models enables trade space evaluations on space suited biomechanics to reduce risk mechanisms. Future work, though, is required to enable computational models to be predictive of individual injury risk. Our findings show there are significant gaps in our current knowledge on tissue injuries that preclude biomechanical models from being used directly as an injury-risk assessment model. Current models can be used to perform trade studies to lower muscle strain, tendon loads, or interaction pressures. However, these evaluations may yield overly restrictive guidelines in scenarios in which the risk level is uncertain. Additional research should examine alternate risks relevant to the human in a space suit performing mission-relevant tasks (e.g., spinal loading, fracture risk). The further development of risk factors will enable improved usage of computational models for space suit design and evaluation, as well as for other Earth applications (e.g., health monitoring, sports injury mitigation, and exoskeleton design).

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Authors and affiliations: Leia Stirling, M.S., Ph.D., Massachusetts Institute of Technology, Cambridge, MA; Allison Anderson, M.S., Ph.D., University of Colorado-Boulder, Boulder, CO; and Pedro M. F. M. Arezes, M.Sc., Ph.D., School of Engineering, University of Minho/MIT Portugal Program, Guimarães, Portugal.

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