NASA/TM-20220007605

Development of the Suited Injury Modes and Effects Analysis for Identification of Top Injury Risks in Lunar Missions and Training

Teresa M Reiber
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Nathaniel J Newby
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Richard Scheuring
NASA, Houston, Texas
Johnson Space Center, Houston, Texas

Marlei Walton
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Jason Norcross
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Grant Harman
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Jeffrey Somers
NASA, Houston, Texas
Johnson Space Center, Houston, Texas

June 2022

NASA STI Program Report Series

The NASA STI Program collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the “General” help request type.

NASA/TM-20220007605

Development of the Suited Injury Modes and Effects Analysis for Identification of Top Injury Risks in Lunar Missions and Training

Teresa M Reiber
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Nathaniel J Newby
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Richard Scheuring
NASA, Houston, Texas
Johnson Space Center, Houston, Texas

Marlei Walton
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Jason Norcross
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Grant Harman
KBR, Houston, Texas
Johnson Space Center, Houston, Texas

Jeffrey Somers
NASA, Houston, Texas
Johnson Space Center, Houston, Texas

National Aeronautics and
Space Administration

Johnson Space Center
Houston, TX 77058

June 2022

Table of Contents

1 Introduction

A new extravehicular (EVA) suit is being developed for National Aeronautics and Space Administration's (NASA's) upcoming lunar missions that will be designed to operate in both the lunar surface and in microgravity. This suit will allow for increased range of motion compared to the current Extravehicular Mobility Unity (EMU) and Apollo era suits and have additional features (*e.g.* ability to increase pressure in the field) that will enhance the health and safety of exploration astronaut [1].

Figure 1. One of NASA's current exploration EVA suit designs.

A current design concept of the exploration EVA suit can be seen in Figure 1 [2]. Most of the suit is comprised of soft components, with the exception of the helmet bubble, hard upper torso (HUT), and an Exploration Portable Life Support System (xPLSS). The suit also has a rear-entry hatch for suit ingress and egress. Evaluation of prior suit designs demonstrated ingress and egress to be potential sources of injury. However, the new rear entry design will have its own unique characteristics for potential injury. With the design of lunar missions and the exploration EVA suit progressing, it is important to consider possible injuries and injury mechanisms that could occur in the suit.

Addressing these concerns, the Suited Injury Modes and Effects Analysis (IMEA) was developed to outline suited injury scenarios and rank them based on risk score. After review from internal stakeholders, the IMEA was presented at the Suited Injury Summit which was held on January 5, 2022, and February 15, 2022, to vet the analysis further with internal stakeholder and external subject matter experts (SMEs). The finalized analysis will be used to identify top injury risks and drive future work as we train, prepare, and execute planning and operations for lunar missions.

2 Injury Modes and Effects Analysis

2.1 Overview

The IMEA (Appendix A) was created to document possible scenarios of injury while wearing an EVA suit. Currently planned training events to prepare for lunar missions and tasks during lunar surface EVA were considered. Each scenario is ranked with consequence and likelihood scorings based on our current understanding of suit and launch system to identify high-risk cases that will drive further work on suited injury. Injuries, mechanisms of injury, and mitigation strategies are evaluated within each scenario. The IMEA was vetted internally and with external experts at the Suited Injury Summit (Section 3).

2.2 Scoring

Using the Exploration Systems Development (ESD) Risk Score Card (Appendix B), each scenario was given a risk score based on consequence and likelihood, then ranked. Scenarios with red and yellow scores are identified as our top risks that will drive forward work. Likelihood and consequence scores were decided based on available evidence described within each scenario and SME opinion. A new consequence scoring system, the Operationally Relevant Injury Scale for Exploration (ORIS_x), detailed in Section 2.2.1, was developed to score individual injuries within each row of the IMEA, these columns of the analysis are still in work and have not been vetted.

2.2.1 Operationally Relevant Injury Scale for Exploration (ORIS$_x$)

The ORIS$_x$ was created to assess suited injuries on the lunar surface and in training. It is intended to evaluate suited injuries such as those due to lunar landing, rover activities, EVA repetitive tasks, training activities, falls on the lunar surface, etc. This injury scale scores injuries based on three components: injury severity, mission impacts, and long-term impacts (Table 1).

Injury Severity (IS) measures the seriousness of an injury and is scored based on the Abbreviated Injury Scale (AIS) [3]. Mission Operations Capability (MOC) measures the functional impacts of an injury based on the injured crewmember's capability of performing EVA tasks as well as his/her EVA downtime. Long-Term Health Consequence (LTC) addresses post-mission consequences, assessing quality of life post-mission and ability to return to duty.

Table 1. ORIS$_X$ scoring system.

Score	Injury Severity (IS)	Mission Operations Capability (MOC) *EVA capability & downtime*	Long-Term Health Consequence (LTC)
0	None*	No impact	No recovery time
1	Minor	Minor reduction of EVA task performance or short delay in return (≤ 1.5 days)	Short recovery time (<3 month)
2	Moderate	Major reduction of EVA task performance or intermediate delay in return (≤ 1 week)	Intermediate recovery time (< 1 year)
3	Serious	Unable to perform some EVA tasks, may require assistance to return to lander or long delay in return (≤ 1 month)	Long recovery time (>1 year)
4	Severe	Unable to complete EVA, requires rescue or will not return (> 1 month)	Never fully recover/DQ'd from future missions

Equation 1 below is used to combine the three components, IS, MOC, and LTC, into one overall ORIS$_x$ score. The final score is rounded up to the nearest integer, making the scale more conservative, and all scores will be discrete values from 0 to 4. Weighting factors were implemented to align the importance of the component to the overall ORIS$_x$ score.

Equation 1. ORIS$_X$ Score Calculation.

$$Score = \sqrt{0.25 * (IS)^2 + 0.5 * (MOC)^2 + 0.25 * (LTC)^2}$$

More information on the ORIS$_x$ and how it is scored can be found in NASA/TM-20220006715 [4].

3 Suited Injury Summit

3.1 Overview

A Suited Injury Summit was held on January 5, 2022, to vet the IMEA. This was an all-day virtual meeting with the suited injury team, ergonomists, suit engineers, safety engineers, Flight Operations Directorate (FOD), flight doctors, astronauts, Astronaut Strength, Conditioning, and Rehabilitation Specialists (ASCRS), and external SMEs (Section 3.2). There was also a follow-up to the initial Summit on February 15, 2022, to address remaining additional questions. The intent of these meetings was to walk through the top injury risks identified in the analysis, identify any gaps that are not captured, and discuss mitigations. Lessons learned from the Summit and the final vetted IMEA will be the driver for forward work in suited injury.

3.2 Participants

3.2.1 Internal Participants

Below are points of contact for each team that supported the Summit, all participants are not listed.

Richard Scheuring	Summit Planning Team/NASA Flight Surgeon
Nathaniel Newby	Summit Planning Team/Suited Injury Team
Teresa Reiber	Summit Planning Team/Suited Injury Team
Marlei Walton	Summit Planning Team/Suited Injury Team
Jason Norcross	Summit Planning Team/Suited Injury Team
Grant Harman	Summit Planning Team/Suited Injury Team
James Pattarini	NASA Flight Surgeon
Michael Rapley	Crew Office/Astronaut Corps
Randolph Bresnik	NASA Astronaut
Michael Barratt	NASA Astronaut
Richard Rhodes	Suit Engineers
Scott Ross	Safety Engineers
Emily Matula	FOD
Sudhakar Rajulu	Ergonomists
Jordan Lindsey	EVA Exploration
Danielle Anderson	ASCR/Exercise

3.2.2 External Subject Matter Experts

Henry Goitz	Orthopedic Surgeon, Detroit Medical Center, MI
Robert Goitz	Orthopedic Surgeon, University of Pittsburgh Medical Center, PA
Josh Harris	Orthopedic (Hip) Surgeon, Houston Methodist, TX
Mel Helgeson	Orthopedic (Spine) Surgeon, Walter Reed Military Medical Center, MD
Paul Holman	Neurosurgeon, Houston Methodist, TX
Wayne Inman	Orthopedic Surgeon, Naval Hospital Camp Pendleton, CA
Shari Liberman	Orthopedic (Hand) Surgeon, Houston Methodist, TX
Pat McCulloch	Orthopedic (Shoulder/Knee) Surgeon, Houston Methodist, TX
Francis O'Connor	Primary Sports Medicine, Fort Belvoir, VA

3.3 Lessons Learned

Lessons learned are organized by human body part followed by more general topics based on what was discussed. Discussion consisted of open dialogue and specific questions about the IMEA. All comments and recommendations are captured below. *The notes below are not necessarily all encompassing of suited injury concerns, rather only what was discussed and learned in this Summit.* All feedback and recommendations have been included in the IMEA, which should be used as the reference for all suited injury concerns (Appendix A).

3.4 General

All injuries and issues are situation and design-dependent. We see different injuries in the same suit and in the same subject based on training and mission environment. In addition, the issues may not be resolved solely with suit design; we will need to change tasks and/or tools to prevent some injuries. It was discussed that flight surgeons, ASCRS, and physical therapists need to get time in the suit to better understand the tasks and movement in the suit.

Generally, crew have not noticed a big difference in suit fit between microgravity and Earth gravity. In contrast, there have been reports of suit fit changes on the lunar surface. During Apollo missions, crew reported suits feeling tighter on the lunar surface compared to Earth fit checks, particularly in the arms and gloves. The reason for this is unknown, but it was postulated that it could be caused by spinal elongation and/or differences in the Apollo EVA suits. There is a 4-6 cm increase in spinal length experienced in microgravity [4, 5]. The extent to which spinal elongation will occur in lunar gravity and how this could affect suit fit or overall injury risk is not known.

Artemis crew will each have their own suit, which will come in generic sizes with adjustment capability. There will be a suit fit check in orbit before descent to the lunar surface. It was recommended that extra padding be flown to account for unknowns of suit fit. Additional adjustability could be implemented with rings, straps, etc., but none of these are currently planned. Fit may be task dependent between rover operations, standing versus sitting, ambulation, specific EVA tasks, etc. The suits should also be sized to account for spinal elongation. Ideally, there will be mechanisms for crew to adjust suit size and padding between EVAs if needed.

It was also discussed that robotics or power-assist devices could be used to mitigate injury risk during repetitive tasks. This is a technology that is still being explored, especially a robotic-assisted glove to address hand fatigue. It is unlikely that robotic assistance will be available in initial Artemis missions, though this is something that could be implemented in sustained missions in the future. However, power tools external to the suit could feasibly be designed to mitigate repetitive injury risk during early Artemis missions.

A rover will be available in early Artemis missions that will help mitigate lower limb overuse injuries associated with ambulation on the lunar surface. However, the rover dynamics do pose its own injury risks. The suit needs to be restrained to the rover, but the crewmember must also be restrained inside the suit. Rover vibration and acceleration could cause injury due to repetitive contact with rigid structures inside the suit if not properly restrained. A closed, pressurized rover could also be used as a mitigation strategy for radiation.

Parabolic flight has been used previously to replicate weightlessness and partial gravity environments [6]. Many tasks have been evaluated in this test analogue, for example suit don/doff testing. This is not a capability that we currently have in preparation for lunar missions. The inability to test in an unsupported partial g environment poses a risk to developing nominal suit operation procedures, proper don/doff hardware, and characterizing injury risk in the suit. It was a general consensus that this testing capability is critical to understanding injury risk in different gravity environments and must be pursued.

3.5 Hand/Wrist

3.5.1 Concerns

The greatest absolute number of reported injuries with the current suit have been in the hand. Although some may be considered mild, nail issues and extreme pain in the fingers following EVA and ground/Neutral Buoyancy Laboratory (NBL) training can be problematic. A majority of these cases are caused by the tips of the fingers pushing against the glove for prolonged periods of time. Hand fatigue is another concern. Suited subjects and crew have reported hand fatigue from working against the pressurized glove in repetitive gripping tasks. With the total number of EVA hours and frequency expected to dramatically increase for lunar surface operations, hand and finger injuries may become more frequent and severe.

3.5.2 Mitigations

Optimizing glove fit will help address nail and finger pain and has demonstrated benefit in the current suit. Operating at a lower suit pressure is another mitigation strategy. Baseline strength and pinch assessments in the hand can be used to assess hand strength before tasks. Electromyography (EMG) sensors can be placed on the hand to investigate what muscles are being used during certain tasks and can be used to assess effectiveness of countermeasures. Once those muscles are identified, they should be trained pre-mission in a work hardening program to mitigate excessive fatigue during those tasks. Tools for measuring hand kinematics are becoming more abundant. Incorporating hand movement and perhaps force measurements in ground training/studies could be used to correlate hand kinematics/kinetics with types of hand injuries and severity.

3.6 Elbow

3.6.1 Concerns

There have been recent concerns with bruising and rubbing of the elbow in the current EMU during NBL runs. There have been reports of 2-3 elbow injuries in the NBL due to repetitive motion.

3.6.2 Mitigations

These injuries have been shown to decrease with follow-on runs as the subject learns how to move in the suit and improves suit-human interactions. Future work is needed to understand elbow injuries that could occur on the lunar surface.

3.7 Shoulder

3.7.1 Concerns

Shoulder injuries during NBL training have been amongst the most frequent and severe suited injuries seen to date. There have been more than 10 surgical shoulder repairs arising from NBL-related training issues. Inverted training has been identified as a primary driver for these injuries. A previous summit has been held to examine these injuries and develop a detailed mitigation strategy, which is being implemented today [7]. Since adopting these approaches, shoulder injury rates have been driven to near zero.

Looking forward, the main task eliciting shoulder concern was suit doffing. The motion and forces required to egress a rear entry suit creates strain in the shoulder that could lead to injury. A Superior Labrum, Anterior to Posterior (SLAP) tear has been recorded during suit doffing after an NBL run. During on orbit doffing, there was also an injury due to a crewmember getting out of the current EMU suit too quickly.

3.7.2 Mitigations

The previously developed NBL mitigation strategy should continue to be enacted. For suit doffing, currently crew self-direct the rate they get out of the suit and may get tech support help during doffing in training environments. Crew and subjects do stretch and warm up before donning the suit; there is a pull up bar in the locker room to start stretching their shoulders. Don/doff of a rear entry suit in micro- or partial-gravity may be less injurious than on the ground. It was recommended to adapt the previously developed shoulder work hardening and mitigation strategies to incorporate the new demands with rear entry. This may include a pull up activity or lat (latissimus dorsi) pull down exercises to train for the doffing movement. Technology and creative design could also be explored to lower injury risk associated with suit don/doff.

3.8 Spine

3.8.1 Concerns

There were no major concerns for spinal injury expressed with specific suit design or tasks. The main concern was if unknown pre-existing injuries or abnormalities could lead to unanticipated chronic injuries.

Spinal elongation also must be considered. We don't have a lot of information on how spinal elongation and compression will present itself on longer lunar surface stays and how this will affect injury risk. There is a possibility of higher risk of herniation or other spinal injuries with the combination of muscle atrophy and spinal elongation especially in an uncontrolled environment.

3.8.2 Mitigations

Pre- and postflight spinal Magnetic Resonance Imaging (MRI) should be implemented to identify preexisting injuries and abnormalities. Clinicians can use this information to prescribe exercises for strengthening specific muscles to address certain conditions and weaknesses for optimizing performance before a mission. Screening will be the largest and most important mitigation strategy for spinal injuries.

3.9 Hip

3.9.1 Concerns

Chronic or overuse injuries were the main concern discussed for the hip. These could become more common with increased training frequency and long EVAs on the lunar surface. Crew could experience symptoms or pain due to abnormal morphology of the hip joint combined with certain movements or positions. It is possible that crew also have undiagnosed mild asymptomatic osteoarthritis that only becomes apparent when certain motions elicit symptoms.

Certain postures will increase risk of symptoms; hip flexion of greater than 90 degrees combined with adduction and internal rotation was specifically stated [8]. These symptoms will not occur immediately but after significant durations of long hours. It could be days or weeks before symptoms arise due to these overuse injuries.

3.9.2 Mitigations

It is recommended that screening before flight be implemented to identify any abnormal hip morphology to aid in anticipating future issues.

3.10 Knee/Ankle/Foot

3.10.1 Concerns

There are potential ankle injuries during suit doff due to increased ankle torque. EMU had a reported ankle injury ingressing the articulating portable foot restraint (APFR), which requires and ankle inversion/eversion movement.

Injuries due to increased joint mobility must also be considered. The potential scenario of the foot being stuck with 360-degree rotation in the xEMU ankle bearing was discussed; this could lead to a fall and subsequent ankle or knee injury. Notably, similar injuries have been seen in snowboarding and skiing. The most common ski injuries are currently knee injuries. Originally, skiers experienced a disproportionally high volume of ankle injuries, but that problem was solved with a rigid boot. This solution transferred rotational stresses up the leg, causing more injuries at the knee. This is important to consider when limiting joint movement. If range of motion is altered at one joint to decrease injury risk, the implication to surrounding joints must be assessed, although the mitigation discussed involved ankle joint stops to limit motion to normal physiologic ranges.

The long-distance walk back on the lunar surface was also discussed. For early missions, the walk back could be up to 2km. The exploration EVA suit will offer more hip flexion than Apollo suits, so the motion will be closer to Earth ambulation. Rolled ankles are unlikely because of the rigidity in a pressurized suit; however, overuse injuries could be a concern here. Apollo crew had no foot, ankle, or boot issues, but the additional suit mobility of the exploration EVA suit may increase risk of injury. Additionally, any ambulation not in a straight line, for example navigating diagonally down a slope, will increase the risk of injury due to rotation. The risk of blisters and abrasions on long EVAs must also be considered, as these can develop into EVA-limiting injuries. This may become more problematic when suit fit is changing dynamically on the lunar surface, as previously seen with the Apollo program.

There is also a risk of injury from falls. Falls during ambulation in lunar gravity likely don't have the energetics to cause injury, though there will still be risks from falls from heights or down slopes. In addition, falling on a rock or another sharp object could lead to injury.

3.10.2 Mitigations

Stops at the ankle joints that prevent motion beyond non-injurious limits should be considered to prevent ankle injury. Also, all ambulation not in a straight line must be identified as higher risk. Mitigation must be in place to prevent falls, including ensuring adequate lighting, analyzing operational tasks, and developing fall prevention aids.

3.11 Overuse Injuries

3.11.1 Concerns

In preparation for lunar missions, there will be an increase in training frequency. Mitigation strategies need to be in place to prevent an increase in overuse or repetitive use injuries. In training and on the lunar surface, there is concern that repetitive activity over long periods of time and repeated EVA bouts will lead to injuries.

3.11.2 Mitigations

Crewmembers must train specifically to meet demands of preflight training as well as mission tasks. It was recommended that an individualized work hardening exercise program be implemented for each crew member in preparation for increased training runs. Specific functional training needs to be incorporated by replicating motions and tasks in the gym that are needed for lunar missions. Regular meetings should take place among all groups involved in training and exercise plans including flight doctors, ASCRS, FOD, and the suited injury team to close the loop on what tasks are being done in each training environment and what exercises are being done to prevent injuries.

A strategy to monitor and manage load and fatigue in training and on the lunar surface should be developed. Fatigue and load management also must be considered when developing mission and training timelines. Wearable technology to monitor subjects is one option. There are sports teams that use wearable sensors in practice and at the gym providing a general sense of how much work is expended. It is hard to predict when excessive fatigue will lead to injury, so flight surgeons need to have insight during a mission or training exercise to know when to stop a given task to protect crew from injuring themselves.

There is also an element of picking the right subjects or crewmembers for specific tasks. We can mitigate certain injuries by understanding pre-existing conditions in each crewmember and tailoring their maintenance and strength program. Analysis of in-suit kinematics/kinetics could help understand the forces and moments required by specific EVA tasks and help identify correlation to risk of overuse injuries. Crew and subject imaging along with ergonomic assessments will be essential in mitigating overuse injuries.

3.12 Correlating Conditions

3.12.1 Concerns

The concern is that certain injuries could predispose the injured crew member to develop or sustain other injuries or progress a minor injury to something more severe. Discomfort or pain often alters normal motion causing tendonitis, pain, and/or strain in other parts of the body. It is difficult to quantify and address this risk.

3.12.2 Mitigations

This likely needs to be addressed by looking at each injury individually, taking preexisting conditions into consideration. Reduced or altered range of motion from previous injuries may result in injury. Robust screening programs should be used as a tool to prepare, and not exclude, crew from tasks or missions. To manage risk on an EVA, screening results need to be understood and correlated with what tasks will be done on the EVA. This is also another reason for fatigue management; flight surgeons need to monitor this throughout training and EVA.

Current screening before EVA includes assessing sleep, nutrition, medications, and hot spots or injuries, but not physical testing. For lunar missions, a robust reliable test must be developed to see if crew are stable from a neurovestibular and musculoskeletal perspective before going out on the surface. We will also need to communicate the screening intent with crew members who historically avoid testing for concern of grounding.

4 Top Risks

Inputs received from the Suited Injury Summit were incorporated into the final IMEA. Listed below are the top 10 injury risks identified in the analysis. The complete vetted IMEA is included in Appendix A.

4.1 Neutral Buoyancy Laboratory Training

NBL training was identified as the top risk. Concerns include hand injuries, abrasions, bruising, blisters, muscle strain and ligament injury, especially in the shoulder. Glove use, poor suit fit, inverted operations, and tool use are all injury mechanisms in this training environment. Water drag, the center of gravity (CG) shift due to the suit, and mass of the suit are also contributors.

To mitigate injury, training activities in the NBL must be monitored, including performing ergonomic and simulation assessments as needed. A personalized medicine approach may be appropriate. A summit was convened to understand and develop mitigations for NBL shoulder injuries. A 17-point mitigation plan was developed and has been implemented, greatly reducing occurrences of shoulder pain/injury. It was recommended that these mitigations continue to be implemented and adjusted in an iterative process with new suit design. Future work should also focus on mitigating NBL elbow and other identified injuries. Hand injuries in the NBL are highly prevalent with almost all crew experiencing some issue during training. Several approaches and investigations have been undertaken in the past with limited success. Other than obtaining the best glove fit possible, the summit was unclear about further potential mitigation or solution. The idea of a thin inner lining in the glove could also be explored to address hand and fingernail issues. Commonly, if subjects experience bruising from repetitive motion on initial NBL runs, extra padding can be used as prevention. For lunar mission preparation, NBL training hours could possibly be minimized with the use of other analog training facilities.

4.2 Hand/Glove Injuries

Major concerns with hand/glove injuries include abrasions, hot spots, and nail injuries. This can be caused by overuse, training in humid environments like the NBL, and improper tool design. Varying environments and suit pressures will also change the risk.

A glove sub-team should be formed to look at hand injury mitigation strategies and improved glove design. Mitigation efforts would focus on glove fit and hand fatigue. Using motion capture and EMG, specific motions/tasks can be analyzed to investigate what muscles are being activated. Motion capture and EMG can also be used to correlate motion/forces with frequency and severity of hand injury. Once identified, training and exercises can be implemented to mitigate fatigue, and tasks that appear to cause the most severe issues can be redesigned, reduced, or have the duty cycle lessened. Analysis must include environmental and scenario contexts.

4.3 Poor Suit Fit

Poor suit fit is another top risk. Poor suit fit may cause issues with human-suit joint alignment, reduced range of motion, and inconsistent or injurious suit-body contact. There may also be suit fit changes between Earth and lunar gravity; Apollo crew reported suit feeling tighter on the lunar surface, especially in the arms and hands. There could also be injuries associated with padding not being sufficient, or padding moving during repetitive motions. Possible injuries include abrasions, bruising, blisters, muscle strain, ligament injury. With poor suit fit, main concerns are the hips, knees, and ankles. Hand and fingernail injuries are also caused by poor suit fit.

Mitigation needs to start with improving 1g fit for training, then understanding suit fit differences in 1/6 g. Modeling and testing to improve fit algorithms should be implemented. Collaboration with providers on customizable suits is important. We need to account for the fact that the same suit will be used in microgravity and on the lunar surface in the same mission and that we have necessary sizing adjustments available where needed. Spinal elongation must also be considered. Extra padding and capability to adjust sizing during missions including in-between EVAs should be explored.

4.4 Field Training

In field training, glove use can lead to hand injuries and potentially frostbite issues. Boots can lead to abrasions, hot spots, blisters, and frostbite. There is a risk of impact injuries from falls due to terrain, ice, and limited visibility. Strains and ligament injuries may occur due to suit fit or range of motion issues. There is also a potential for back injuries based on activities like shoveling and suit CG issues.

To mitigate field training injury, runs should be monitored and ad hoc ergonomic and simulation assessments should be performed. We must work with the Anthropometry and Biomechanics Facility (ABF) for ergonomic risk assessments of tasks. Lessons learned could also be applied to training activities from falling assessments. A personalized medicine approach may be appropriate for specific crew injury risk based on suit fit and range of motion. A boot sub-team should be formed to develop a detailed roadmap for boot design and injury mitigation. Thermal sensors should be explored that give advance warning of frostbite conditions.

4.5 Specific EVA Tasks/Design of Task

Specific EVA tasks and task design include shoveling, sample retrieval, etc. Injuries in this category include subtle findings such as blisters, low back soreness, or abrasions. They can also include more significant injuries to muscle, bone, and ligament. Injury contributors include fatigue, falls, overuse, tool design, poor suit fit, changes to the human's CG and joint range of motion limitations. The use of high-risk postures and increased task workload and/or frequency in tasks will also increase risk of injury. There is also a possibility that we could send crew with unknown pre-existing conditions or joint abnormalities that could cause symptoms with repetitive motion.

Surveillance will be conducted during training and mission operations to document type and frequency of injuries. We will complete ergonomic assessments and use these to influence inputs to task development and tool design. Ergonomic injury assessments will also be used to allow mission designers to allocate a balance of tasks and duty cycle that lessen injury risk. Ad hoc assessments will also be completed, including muscle and joint torque estimates.

Pre- and post-flight spine MRIs should be used for screening. Pre-flight hip screening will also be a valuable tool in identifying abnormal joint morphologies and asymmetry of joint motion or mild asymptomatic osteoarthritis that could cause issues during EVA. We need to understand in-suit kinematics to understand crew motions and develop specific screening measures. Individual work hardening programs should be developed to address certain conditions and weaknesses. To better inform injury risk, flight surgeons and PTs should get time in the suit to understand tasks and movements in the suit. We also need to develop a strategy to monitor load and manage fatigue, this could potentially be done with wearable sensors. An integrated effort should be implemented on a weekly basis to close the loop regarding what training tasks are being done in the suit and what exercises can be done in the gym to best prepare crews for lunar missions. Eventually in sustaining missions, repetitive tasks may need to be done robotically or with powered assistance to prevent these injuries.

4.6 Boots/Ankle Injuries

Since the end of the Apollo era, boot and ankle injuries have not been an area of focus. However, with ambulation within the suit being required again, boot and ankle injuries present another top risk for lunar surface EVA. Possible injuries include blisters and ankle injuries and sprains. Injuries can be caused by improper boot fit, stepping wrong on the lunar surface, falls, or navigating sloped or diagonal terrain. Ankle injuries are also possible during suit don/doff.

Work is ongoing to optimize the boot design via 3D human anthropometric modeling. As the design matures, training sessions should be observed, and any injuries or soreness documented. As issues are identified, we will work with the design team to improve boot design where possible. Ankle joint stops at physiological limits should also be considered as a possible mitigation. These could be implemented as inversion/eversion blocks to ankle twisting on uneven terrain. To mitigate blisters or hotspots, a foot and ankle sock or sleeve within the boot could be considered.

4.7 Falls from Heights

Falling from a height could cause abrasions and bruising, as well as skeletal, muscle, and ligament injuries. Falls could occur while ingressing or egressing the Human Landing System (HLS) or rover on the lunar surface. We also have concerns of falling down a crater wall or onto a sharp object. Suit fit, lighting, and visibility may also be contributors to falls. Suit CG and ladder design should also be considered.

Coordination needs to be done with suit designers on assessment of falls in the xEMU during fall tests using the Active Response Gravity Offload System (ARGOS) and parabolic flight. Skeletal 3D biomechanical models should be tuned with motion capture and force data from fall studies and used to predict injury risk of falls from heights on the lunar surface. Countermeasures or aids should be developed as needed. Causes of falls need to be identified and prevented. Education and practice in fall techniques should be considered, similar to contact sports training in football.

4.8 Background Radiation (Missions > 30 days)

For sustained missions on the lunar surface (> 30 days), there is a concern for increased likelihood of bone fracture due to background radiation. Background radiation can cause structural changes to bones and weaken the immune system. To mitigate this risk, radiation protection should be implemented in the lunar habitat for sustained missions. Bone loading exercises and pharmaceutical solutions should be used as additional mitigation strategies. A closed, pressurized rover could also be used as radiation protection on the lunar surface.

4.9 Repetitive Contact

Repetitive contact in the suit has potential to cause abrasions and bruising in training and while on the lunar surface, especially with any dynamic changes in suit fit. This scenario does not include acute injury from impact with the suit. Repetitive contact with the suit over hours within a given EVA, or across multiple EVAs, may prove to be EVA-limiting. Modeling with subject-specific human models will help identify potential sources of injury for each crewmember. Enough padding and other materials need to be flown to the lunar surface so that it can be placed appropriately to lessen injury from contacts. Implementing ergonomic assessments will determine whether tasks or task performance can be altered to mitigate contact injuries. These assessments will also determine the length of time appropriate for each task to mitigate injurious events. Surveillance in training will be a crucial component in understanding mission risk and establishing mitigation strategies.

4.10 Ambulation/Long-Distance Ambulation

Potential injuries in ambulation and long-distance traverse include blisters and low back soreness, as well as lower body muscle, bone, and ligament injury. Injury mechanisms include falls, lack of visibility, suit CG, poor suit fit, changes to range of motion, uneven or sloped terrain, and balance or coordination issues caused by vestibular issues. Fitness level can also contribute to injury risk, as fatigue may lead to decreased vigilance in long-distance ambulation.

Fall assessments should be completed in the xEMU in ARGOS or suborbital or parabolic flight. Biomechanical models can be tuned with motion capture and force data and used to quantify gait and injury risk during simulated walk-back or fatigued walking tasks. If it is found that risk is elevated, work should be done with designers to develop aids or countermeasures.

5 Forward Work

The IMEA is a living document. Yearly meetings are planned to update the analysis and reevaluate top risks and mitigation. Although some columns in the analysis have yet to be finalized and vetted with the stakeholder community, these are included in the working IMEA. For now, we will start working mitigations on the top risks identified in the IMEA and reviewed by the summit stakeholders.

6 References

[1] M Smith, D Craig, N Herman, E Mahoney, J Krezel, N McIntyre, K Goodliff, "The Artemis Program: An Overview of NASA's Activites to Return Humans to the Moon," in *2020 IEEE Aerospace Conference*, 2020.

[2] "Safety and Health Magazine," 21 November 2019. [Online]. Available: https://www.safetyandhealthmagazine.com/articles/19155-nasa-introduces-spacesuits-with-enhanced-safety-features. [Accessed 11 April 2022].

[3] T Gennarelli, E Wodzin, "Abbreviated Injury Scale," Association for the Advancement of Automotive Medicine, Barrington, IL, 2008.

[4] T Reiber, N Newby, D Nusbaum, K Dolick, J Somers, "Development of the Operationally Relevant Injury Scale for Exploration (ORISx) to Identify High-Consequence Suited Injuries," NASA, Houston, 2022.

[5] K Young, S Rajulu, "The effects of microgravity on seated height," in *Human Research Program investigator's Workshop*, Houston, TX, 2011.

[6] W Thornton, T Moore, "Height Changes in Microgravity," *Results of the Life Sciences DSOs Conducted Aboard the Space Shuttle 1981-1986,* pp. 55-57, May 1987.

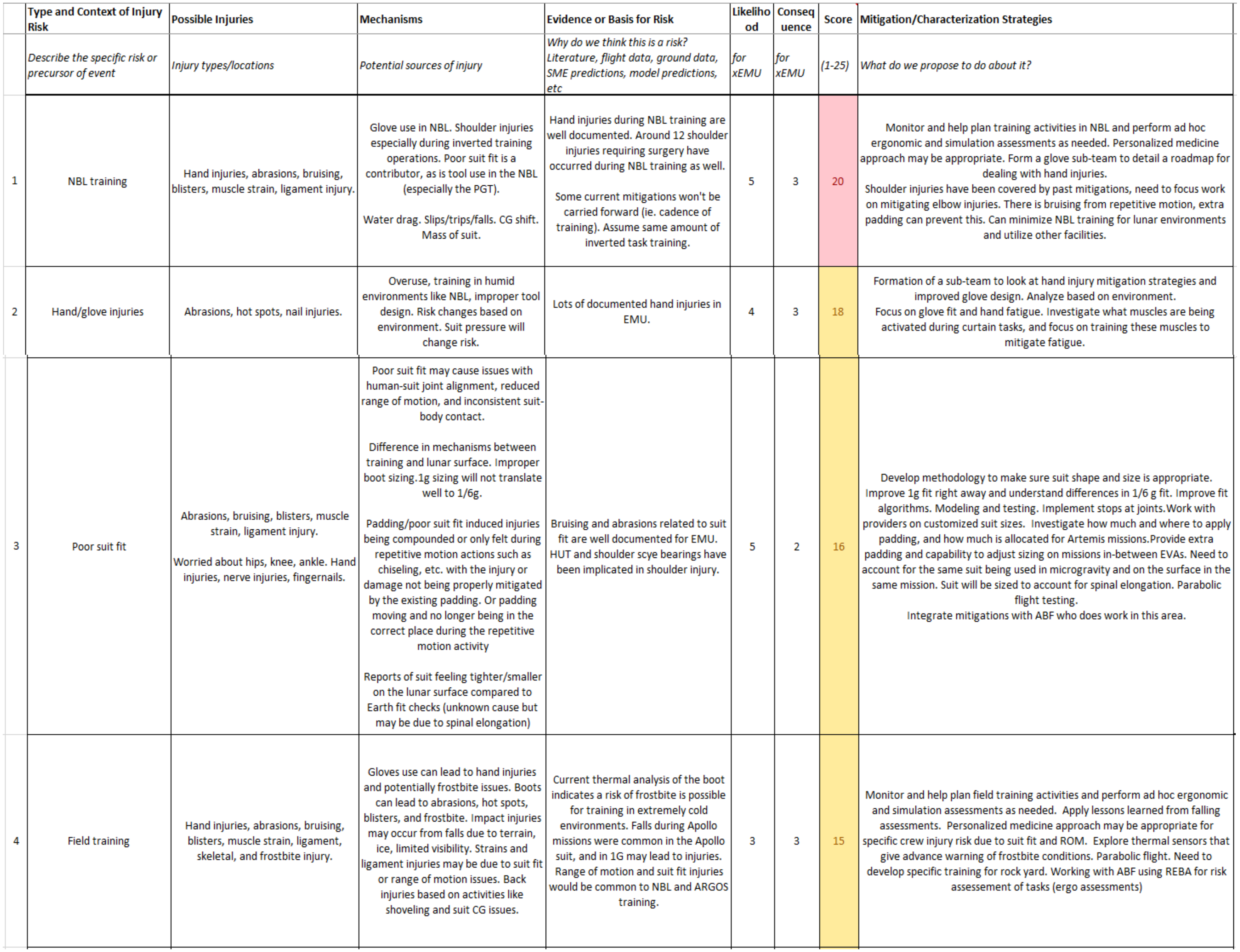
[7] "Analog Missions; Parabolic Flight," NASA, 10 October 2019. [Online]. Available: https://www.nasa.gov/analogs/parabolic-flight. [Accessed 11 April 2022].

[8] R Scheuring, P McCulloch, M Van Baalen, R Watson, S Bowen, T Blatt, "Shoulder Injuries in US Astronauts Related to EVA Suit Design," in *Aerospace Medical Association*, Atlanta, GA, 2012.

[9] D Griffin, E Dickenson, J O'Donnel, R Agricola, T Awan, M Beck, J Clohisy, H Dijkstra, E Falvey, M Gimpel, R Hinman, P Holmich, A Kassarjian, H Martin, R Martin, R Mather, M Philippon, M Reiman, A Takla, K Thorborg, S Walker, A Weir, K Bennell, "The Warwick Agreement on femoroacetabular impingement syndrome (FAI syndrome): an international consensus statement," *British Journal of Sports Medicine,* vol. 50, pp. 1169-1176, 2016.

7 Appendix

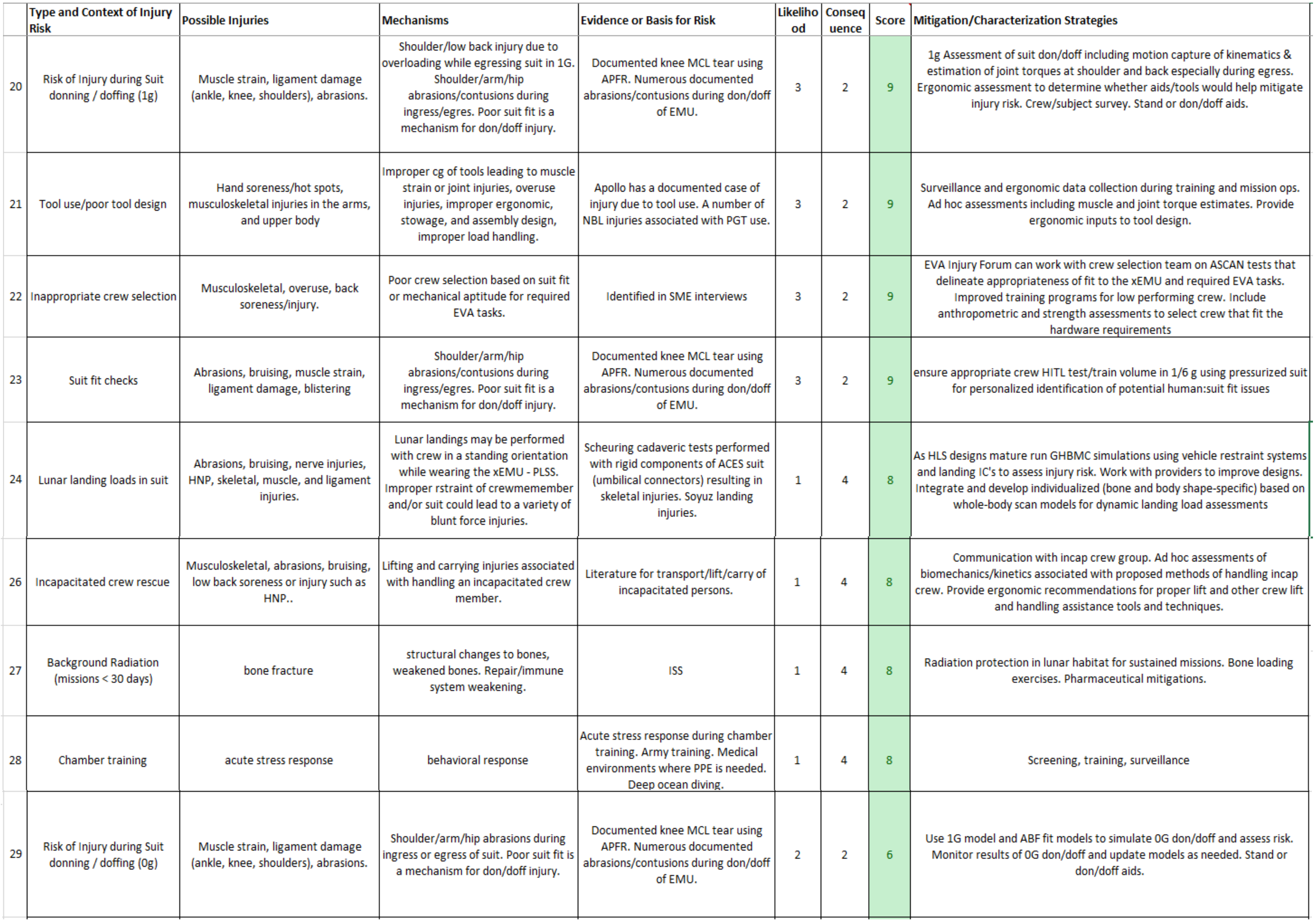
7.1 Appendix A: Suited Injury Modes and Effects Analysis



	Type and Context of Injury Risk	Possible Injuries	Mechanisms	Evidence or Basis for Risk	Likelihood	Consequence	Score	Mitigation/Characterization Strategies
	Describe the specific risk or precursor of event	*Injury types/locations*	*Potential sources of injury*	*Why do we think this is a risk? Literature, flight data, ground data, SME predictions, model predictions, etc*	*for xEMU*	*for xEMU*	*(1-25)*	*What do we propose to do about it?*
1	NBL training	Hand injuries, abrasions, bruising, blisters, muscle strain, ligament injury.	Glove use in NBL. Shoulder injuries especially during inverted training operations. Poor suit fit is a contributor, as is tool use in the NBL (especially the PGT). Water drag. Slips/trips/falls. CG shift. Mass of suit.	Hand injuries during NBL training are well documented. Around 12 shoulder injuries requiring surgery have occurred during NBL training as well. Some current mitigations won't be carried forward (ie. cadence of training). Assume same amount of inverted task training.	5	3	20	Monitor and help plan training activities in NBL and perform ad hoc ergonomic and simulation assessments as needed. Personalized medicine approach may be appropriate. Form a glove sub-team to detail a roadmap for dealing with hand injuries. Shoulder injuries have been covered by past mitigations, need to focus work on mitigating elbow injuries. There is bruising from repetitive motion, extra padding can prevent this. Can minimize NBL training for lunar environments and utilize other facilities.
2	Hand/glove injuries	Abrasions, hot spots, nail injuries.	Overuse, training in humid environments like NBL, improper tool design. Risk changes based on environment. Suit pressure will change risk.	Lots of documented hand injuries in EMU.	4	3	18	Formation of a sub-team to look at hand injury mitigation strategies and improved glove design. Analyze based on environment. Focus on glove fit and hand fatigue. Investigate what muscles are being activated during curtain tasks, and focus on training these muscles to mitigate fatigue.
3	Poor suit fit	Abrasions, bruising, blisters, muscle strain, ligament injury. Worried about hips, knee, ankle. Hand injuries, nerve injuries, fingernails.	Poor suit fit may cause issues with human-suit joint alignment, reduced range of motion, and inconsistent suit-body contact. Difference in mechanisms between training and lunar surface. Improper boot sizing.1g sizing will not translate well to 1/6g. Padding/poor suit fit induced injuries being compounded or only felt during repetitive motion actions such as chiseling, etc. with the injury or damage not being properly mitigated by the existing padding. Or padding moving and no longer being in the correct place during the repetitive motion activity Reports of suit feeling tighter/smaller on the lunar surface compared to Earth fit checks (unknown cause but may be due to spinal elongation)	Bruising and abrasions related to suit fit are well documented for EMU. HUT and shoulder scye bearings have been implicated in shoulder injury.	5	2	16	Develop methodology to make sure suit shape and size is appropriate. Improve 1g fit right away and understand differences in 1/6 g fit. Improve fit algorithms. Modeling and testing. Implement stops at joints.Work with providers on customized suit sizes. Investigate how much and where to apply padding, and how much is allocated for Artemis missions.Provide extra padding and capability to adjust sizing on missions in-between EVAs. Need to account for the same suit being used in microgravity and on the surface in the same mission. Suit will be sized to account for spinal elongation. Parabolic flight testing. Integrate mitigations with ABF who does work in this area.
4	Field training	Hand injuries, abrasions, bruising, blisters, muscle strain, ligament, skeletal, and frostbite injury.	Gloves use can lead to hand injuries and potentially frostbite issues. Boots can lead to abrasions, hot spots, blisters, and frostbite. Impact injuries may occur from falls due to terrain, ice, limited visibility. Strains and ligament injuries may be due to suit fit or range of motion issues. Back injuries based on activities like shoveling and suit CG issues.	Current thermal analysis of the boot indicates a risk of frostbite is possible for training in extremely cold environments. Falls during Apollo missions were common in the Apollo suit, and in 1G may lead to injuries. Range of motion and suit fit injuries would be common to NBL and ARGOS training.	3	3	15	Monitor and help plan field training activities and perform ad hoc ergonomic and simulation assessments as needed. Apply lessons learned from falling assessments. Personalized medicine approach may be appropriate for specific crew injury risk due to suit fit and ROM. Explore thermal sensors that give advance warning of frostbite conditions. Parabolic flight. Need to develop specific training for rock yard. Working with ABF using REBA for risk assesement of tasks (ergo assessments)

	Type and Context of Injury Risk	Possible Injuries	Mechanisms	Evidence or Basis for Risk	Likelihood	Consequence	Score	Mitigation/Characterization Strategies
5	Specific EVA tasks/design of task (shoveling, sample retrieval, etc.)	Blisters, abrasions, lower & upper body muscle, bone, and ligament, low back soreness, HNP	Fatigue, falls, overuse injuries, suit cg, tools, suit fit/range of motion, kneeling, overhead work, crawling, push, pull, carry, human capabilities not factored into design of task, task workload/frequency, insufficient rest periods, overuse of tasks w/static work postures. Abnormal morphology of hip joint could cause overuse injury (pain/symptoms) in certain motions.Without hip screenings, could be sending crew with mild asymptomatic osteoarthritis and repetitive motion could bring out symptoms.	Apollo falls observed during tool use. PGT injuries in NBL. Expansion of EVA hours for lunar missions.	3	3	15	Surveillance during training and mission ops. Ad hoc assessments including muscle and joint torque estimates. Ergonomic assessments. Investigate in-suit kinematics to understand motions and develop specific screening measures.Inputs to tool design. Provide ergonomic injury assessment results for mission designers to allocate a mix of tasks and duty cycle that lessen injury risk. Work with ASCRs on work hardening. Implement pre- and postflight spine MRIs for screening. Screening will largely mitigate risk for spine injuries. Work hardening program to address certain conditions/weaknesses. Need to consider spinal elongation. Hip screening before flight. Flight surgeons/PTs should get time in suit to understand the tasks and movement. Replicate motions/tasks in the gym. Develop strategy to montior load and fatigue management (explore new wearable sensors). Initiate integrated effort to close the loop on a weekly basis on what tasks are being done in training and what exercises can be done in the gym to prepare (flight docs, ASCRs, CX3). Imaging along with ergo assessments to mitigate overuse injuries. Eventually make repetitive tasks done robotically (sustaining missions).
6	Boots / Ankle Injuries	Blisters, ankle injuries/sprains	Improper boot fit, sliding of foot within boot. Stepping wrong on lunar surface.Falls. Sloped terrain. Walking horizontally/switchbacks likely to cause twisting injuries. Potential ankle injuries during suit don/doff. Motions not in a straight line (ie. navigating diagonally down a slope) will increase risk of injury due to rotation.	Foot blisters are common among military troops during marches in boots. Apollo astronauts thought the boot was great, but they had limited EVA hours in them compared with future missions.	3	3	15	Work is continuing to optimize the boot design via 3d human anthropometric modeling. As boot design matures, observe training sessions and stay plugged into any injury/soreness issues likely also through the EVA Injury Forum. Work with design team to improve boot wherever possible. Form a boot sub-team to detail a roadmap for boot design and injury mitigation. Consider making stops at ankle joint a requirement.
7	Falls from heights	Abrasions, bruising, skeletal, muscle, and ligament injuries.	Falling while ingressing/egressing HLS/Rover onto the lunar surface. Falls into a crater. Falls onto a rock or sharp object. Suit fit, lighting, and visibilty may also be contributors to falls. Lack of visibility, not knowing where edges handholds are. Suit port don/doff pressurized suit. Suit CG. Ladder design.	Falls during Apollo missions were common in the Apollo suit.	2	4	14	Coordinate with EC POC on assessment of falls in the xEMU using ARGOS. Collect motion capture and force data to tune suit-integrated, skeletal 3D biomechanical models. Use landing IC's as inputs to GHMBC model. Use tuned models to predict injury risk of falls from height on the lunar surface. if risk is elevated work with designers to develop aids or countermeasures. Identify and prevent causes of falls(ops, lighting issues, etc.). Fall studies. Assess injury risk of falls due to rotational inertia tied to waist and lower body bearings.
8	Background Radiation (missions > 30 days)	bone fracture	structural changes to bones, weakened bones. Repair/immune system weakening.	ISS	2	4	14	Radiation protection in lunar habitat for sustained missions. Bone loading exercises. Pharmaceutical mitigations.Closed, pressurized rover could be used as radiation mitigation.
9	Repetitive Contact	Abrasions, bruising.	Contact injuries with the suit that are repetitive in nature rather than acute.	Many EMU-related contact injuries have been documented.	4	2	13	ABF group has been addressing this issue for EMU and will continue to do so for xEMU. Some modeling work could be done on a personalized/morphed model to identify potential sources of injury. Work with FOD on padding and other materials to lessen injuries from contacts. Ergonomic assessments to determine whether tasks can be performed with motions that lessen contact injuries. Surveillance.
10	Ambulation	Blisters, lower body muscle, bone, and ligament, low back soreness	Falls, lack of visibility, suit CG, poor suit fit/range of motion, terrain nav, up and down slope issues, and fall recovery injuries. Balance and coordination issues due to vestibular/proprioception/SA issues.	Falling during ambulation were present in Apollo missions. Ground giving way falls occurred as well.	4	2	13	Coordinate with EC POC for assessment of falls in the xEMU using ARGOS. Collect motion capture and force data to tune suit-integrated, skeletal 3D biomechanical models. Use landing IC's as inputs to GHMBC model. If risk is elevated work with designers to develop aids or countermeasures.

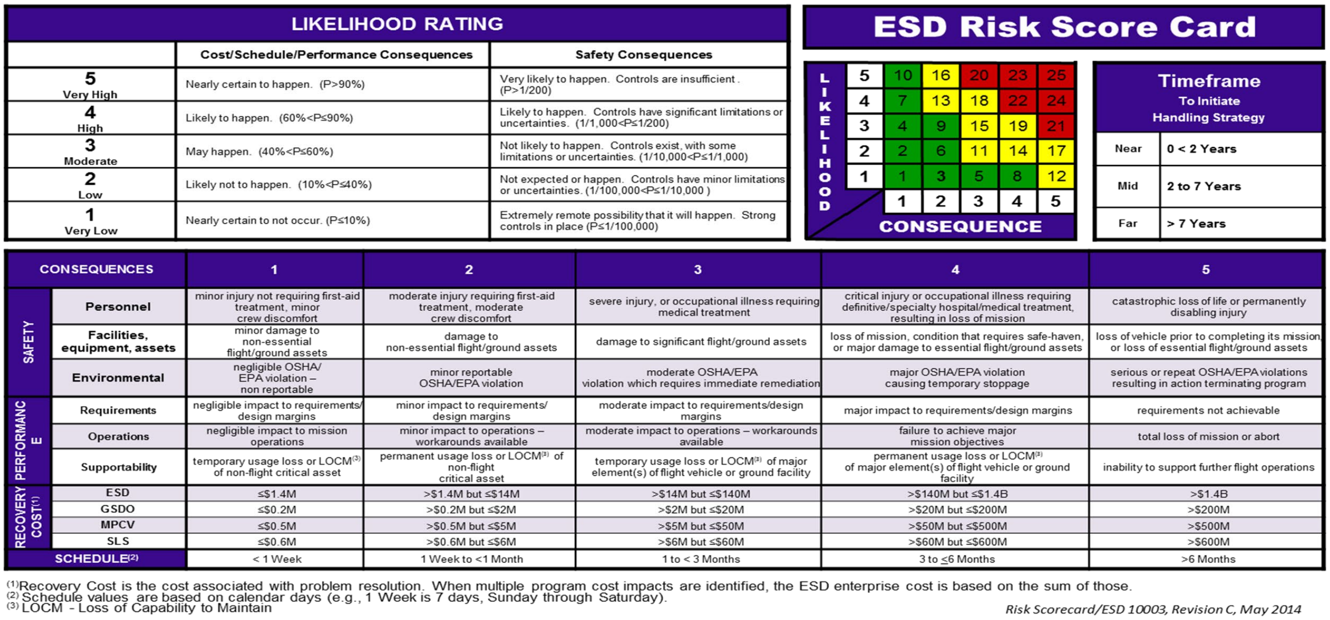
	Type and Context of Injury Risk	Possible Injuries	Mechanisms	Evidence or Basis for Risk	Likelihood	Consequence	Score	Mitigation/Characterization Strategies
11	Long-distance ambulation (Walk back)	Blisters, abrasions, lower body muscle, bone, and ligament, low back soreness, skeletal injury	Falls, lack of visibility, suit CG, poor suit fit/range of motion, terrain nav, up and down slope issues, and fall recovery injuries. Balance and coordination issues due to vestibular/proprioception/SA issues. Fitness issues to complete task. Fatigue may lead to decreased vigilance during walk back.	Falling during ambulation were present in Apollo missions. Ground giving way falls occurred as well.	4	2	13	Coordinate with EC POC during assessment of falls in the xEMU using ARGOS. Collect motion capture and force data to tune biomechanical models. Quantify gait and injury risk changes during simulated walkback or fatigued walking tasks. Test the suit to understand blister risk and prevention.
12	Mobility system failure	Musculoskeletal, abrasions, bruising, loss of life due to running out of PLSS consumables.	Lunar dust in mobility bearings, and other bearing failure mechanisms. Suit failures like primary restraint failure, secondary will change suit size	?	1	5	12	Work with EC and develop cycle stress models and perform verifcation testing to ensure that the risk of mobility failure is low. ConOps for bearing lock/ more severe bearing drag.
13	Acute Radiation	radiation sickness, death, long term health consequences, fatigue, weakness	solar particle events, galactic cosmic radiation	3 major solar particle events high enough to cause acute clinical symptoms (1954-2007).	1	5	12	con ops for solar particle events during lunar surface EVA
14	Permanently shadowed region (PSR) EVA	Frostbite, slips, trips, falls.	Extreme cold environment beyond suit capabilities. Traversing in low light conditions. Poor visibility.	Identified in SME interviews	2	3	11	Regular EIS briefings, EVA Injury Forum, track during field training, work with suit designers.
15	Extrinsic Visibility	Musculoskeletal, abrasions, bruising.	Poor visibility can lead to falls, and improper use of tools. Poor lighting.	?	2	3	11	Use of virtual reality to simulate visual field conditions for crew training. Use 3d suited human model and visual simulations to assess suit design for sufficient lighting and field of view to mitigate injury risks.
16	Risk due to poor communication	Missed or poor communication can lead to many different injuries	Poor comm between crew on the moon.	?	2	3	11	Work with suit designers to ensure comm systems are clear and cover the necessary range. Train for non-verbal/auditory comm between crew.
17	Correlating conditions	Musculoskeletal, sprains/strains, blisters, abrasions	Falls, Exhaustion, Overexertion, Over-use injuries, altered motion due to injury Discomfort/pain could alter motion causing tendonitis/pain/strain in other parts of the body. May have more issues with increased mobility in certain joints.	SME feedback	2	3	11	establish data cascade event structure for correlating conditions/events (e.g. ExMC susceptibility inference network); look at condition worst case scenario for correlation data; identify key events leading to increasing risk (e.g. falls, SPEs, lighting, etc.) Assess by individual injury. Fatigue management. Consider preexisting conditions - reduced/altered range of motion from previous injuries could result in injury. Screening before mission. Understand screening and what tasks will be done on EVA to manage risk.
18	Mockup Suit Training	Abrasions, bruising, muscle strain, ligament damage	Blunt impact injuries possible. Other mechanisms are dependent on the task being trained. Injury risk due to interactions between suit and ARGOS gimbal system are not well characterized.	Falling injuries have occurred with ARGOS. Many NBL training issues have high likelihood of occurring in ARGOS. Falls during Apollo missions were common in the Apollo suit, and in 1G may lead to injuries. Range of motion and suit fit injuries would be common to NBL and ARGOS training.	2	3	11	access to full suite of suits and suit sim options and analogs for assessing full range of population sizing
19	ARGOS training	Abrasions, bruising, blisters, muscle strain, ligament injury, skeletal injury.	Blunt impact injuries possible. Other mechanisms are dependent on the task being trained in ARGOS. Injury risk due to interactions between xEMU and ARGOS gimbal system are not well characterized.	Falling injuries have occurred with ARGOS. Many NBL training issues have high likelihood of occurring in ARGOS.	2	3	9	Monitor and help plan training activities in ARGOS and perform ad hoc ergonomic and simulation assessments as needed. Personalized medicine approach may be appropriate.



	Type and Context of Injury Risk	Possible Injuries	Mechanisms	Evidence or Basis for Risk	Likelihood	Consequence	Score	Mitigation/Characterization Strategies
20	Risk of Injury during Suit donning / doffing (1g)	Muscle strain, ligament damage (ankle, knee, shoulders), abrasions.	Shoulder/low back injury due to overloading while egressing suit in 1G. Shoulder/arm/hip abrasions/contusions during ingress/egres. Poor suit fit is a mechanism for don/doff injury.	Documented knee MCL tear using APFR. Numerous documented abrasions/contusions during don/doff of EMU.	3	2	9	1g Assessment of suit don/doff including motion capture of kinematics & estimation of joint torques at shoulder and back especially during egress. Ergonomic assessment to determine whether aids/tools would help mitigate injury risk. Crew/subject survey. Stand or don/doff aids.
21	Tool use/poor tool design	Hand soreness/hot spots, musculoskeletal injuries in the arms, and upper body	Improper cg of tools leading to muscle strain or joint injuries, overuse injuries, improper ergonomic, stowage, and assembly design, improper load handling.	Apollo has a documented case of injury due to tool use. A number of NBL injuries associated with PGT use.	3	2	9	Surveillance and ergonomic data collection during training and mission ops. Ad hoc assessments including muscle and joint torque estimates. Provide ergonomic inputs to tool design.
22	Inappropriate crew selection	Musculoskeletal, overuse, back soreness/injury.	Poor crew selection based on suit fit or mechanical aptitude for required EVA tasks.	Identified in SME interviews	3	2	9	EVA Injury Forum can work with crew selection team on ASCAN tests that delineate appropriateness of fit to the xEMU and required EVA tasks. Improved training programs for low performing crew. Include anthropometric and strength assessments to select crew that fit the hardware requirements
23	Suit fit checks	Abrasions, bruising, muscle strain, ligament damage, blistering	Shoulder/arm/hip abrasions/contusions during ingress/egres. Poor suit fit is a mechanism for don/doff injury.	Documented knee MCL tear using APFR. Numerous documented abrasions/contusions during don/doff of EMU.	3	2	9	ensure appropriate crew HITL test/train volume in 1/6 g using pressurized suit for personalized identification of potential human:suit fit issues
24	Lunar landing loads in suit	Abrasions, bruising, nerve injuries, HNP, skeletal, muscle, and ligament injuries.	Lunar landings may be performed with crew in a standing orientation while wearing the xEMU - PLSS. Improper rstraint of crewmemember and/or suit could lead to a variety of blunt force injuries.	Scheuring cadaveric tests performed with rigid components of ACES suit (umbilical connectors) resulting in skeletal injuries. Soyuz landing injuries.	1	4	8	As HLS designs mature run GHBMC simulations using vehicle restraint systems and landing IC's to assess injury risk. Work with providers to improve designs. Integrate and develop individualized (bone and body shape-specific) based on whole-body scan models for dynamic landing load assessments
26	Incapacitated crew rescue	Musculoskeletal, abrasions, bruising, low back soreness or injury such as HNP..	Lifting and carrying injuries associated with handling an incapacitated crew member.	Literature for transport/lift/carry of incapacitated persons.	1	4	8	Communication with incap crew group. Ad hoc assessments of biomechanics/kinetics associated with proposed methods of handling incap crew. Provide ergonomic recommendations for proper lift and other crew lift and handling assistance tools and techniques.
27	Background Radiation (missions < 30 days)	bone fracture	structural changes to bones, weakened bones. Repair/immune system weakening.	ISS	1	4	8	Radiation protection in lunar habitat for sustained missions. Bone loading exercises. Pharmaceutical mitigations.
28	Chamber training	acute stress response	behavioral response	Acute stress response during chamber training. Army training. Medical environments where PPE is needed. Deep ocean diving.	1	4	8	Screening, training, surveillance
29	Risk of Injury during Suit donning / doffing (0g)	Muscle strain, ligament damage (ankle, knee, shoulders), abrasions.	Shoulder/arm/hip abrasions during ingress or egress of suit. Poor suit fit is a mechanism for don/doff injury.	Documented knee MCL tear using APFR. Numerous documented abrasions/contusions during don/doff of EMU.	2	2	6	Use 1G model and ABF fit models to simulate 0G don/doff and assess risk. Monitor results of 0G don/doff and update models as needed. Stand or don/doff aids.

	Type and Context of Injury Risk	Possible Injuries	Mechanisms	Evidence or Basis for Risk	Likelihood	Consequence	Score	Mitigation/Characterization Strategies
30	Risk of Injury during Suit donning / doffing (1/6 g)	Muscle strain, ligament damage (ankle, knee, shoulders), abrasions.	Shoulder/arm abrasions/contusions during ingress/egress in 1, 0, or 1/6G. Shoulder/lowback injury during self don/doff in confined HLS space. Poor suit fit is a mechanism for don/doff injury.	Documented knee MCL tear using APFR. Numerous documented abrasions/contusions during don/doff of EMU.	2	2	6	Use models to simulate lunar don/doff. Mock-up don/doff environment in HLS and perform modeling/ergonomic assessment. Stand or don/doff aids. Work hardening (pull up activity or lap pull down exercises) to train for doffing.Technology and creative design can also make this a lot easier.Parabolic flight testing.
31	Suit pressure - elevated pressure operations	Musculoskeletal, ligament, overexertion/over-use injuries. Concern for hand injuries.	poor suit fit, changes to range of motion and force required to move the suit. Increased fatigue.	SME feedback	2	2	6	explore assisted motion options (e.g. exoskeleton)- could be nominal or situationally deployable
32	Heat related injury	Heat exhaustion, dehydration, heat stroke, fatigue.	Working past heat elimination of the suit especially in emergent situations. Crew member may overheat or become too cold if the crewmember doesn't maintain TCV. Typically associated with PB protocol or unplanned DCS mitigation.	10K walk back assessments	1	3	5	Sensors for monitoring and feeding back MET rates, and suit temp. Adjusting activities as needed.
33	Overexertion	Heat stress, exhaustion, musculoskeletal injuries.	Poor decision making/loss of focus leading to injury. Overuse injuries. Musculoskeletal injuries due to change in motion form/strength due to exhaustion especially in emergent situations. Cognitive workload.	?	1	3	5	Work with EVA task planners to ensure tasks and duty cycle do not overexert the crew by providing ergonomic work assessments. Work with ASCRs for pre-mission work hardening training. Develop aids or other contingencies so that emergent situations do not require overexeretion.
34	Inadequate training/Pre-flight fitness	Musculoskeletal, abrasions, bruising, back injuries, exhaustion-related injuries.	Inadequate fitness to perform EVA tasks can lead to both acute and chronic injuries, and injuries due to lack of aerobic fitness for tasks.	Literature showing injuries arising from inadequate fitness for task perfomance demands.	1	3	5	Assess the demands that EVA tasks (MET rates, biomechanics, strength, etc.) require and communicate that information to ASCRs such that adequate training can be completed. Also communicate with mission planners on proper duty cycle and allocation of tasks. Consider crew complements.
35	Intrinsic vision issues	Blurry/damaged vision, injuries tied to poor visibility.	Sublimation of visor anti-fog material. Dust/Foreign Body in eye. Scratches on glass. Vision issues due to SANS	EMU-related injury.	1	3	5	New anti-fog process designed into xEMU to mitigate this risk. Monitor/surveill new system performance during training, and communicate issues through EVA Injury Forum.
36	Inadequate Hydration/Nutrition	Musculoskeletal, heat-related injuries, injuries tied to inattention/loss of focus.	Inadequate hydration/nutrition available to meet EVA demands.Hydration system issues.	Sports literature.	1	3	5	Assess the demands that EVA tasks (MET rates, biomechanics, strength, etc.) and ensure proper hydration/nutrition is available, or tailor tasks to reduce demands.
37	Decompression Sickness	Dizziness, headache, numbness in the limbs, physical fatigue	Inadequate decompression and denitrogenation following exposure to increased pressurization in the suit	NASA documentation	1	3	5	Assess several DCS-preventive procedures and prebreathe protocols
38	Parabolic/suborbital flight	Fracture, ligament injuries, abrasions, foreign object in eye, hypoxia	Collisions, Falls	Broken rib from parabolic flight.	1	3	5	Training, Dual purposing hardware (walking aids, fall recovery), TRRs (hazard analysis)

7.2 Appendix B: Exploration Systems Development (ESD) Risk Score Card



LIKELIHOOD RATING

	Cost/Schedule/Performance Consequences	Safety Consequences
5 Very High	Nearly certain to happen. (P>90%)	Very likely to happen. Controls are insufficient . (P>1/200)
4 High	Likely to happen. (60%<P≤90%)	Likely to happen. Controls have significant limitations or uncertainties. (1/1,000<P≤1/200)
3 Moderate	May happen. (40%<P≤60%)	Not likely to happen. Controls exist, with some limitations or uncertainties. (1/10,000<P≤1/1,000)
2 Low	Likely not to happen. (10%<P≤40%)	Not expected or happen. Controls have minor limitations or uncertainties. (1/100,000<P≤1/10,000)
1 Very Low	Nearly certain to not occur. (P≤10%)	Extremely remote possibility that it will happen. Strong controls in place (P≤1/100,000)

ESD Risk Score Card

LIKELIHOOD					
5	10	16	20	23	25
4	7	13	18	22	24
3	4	9	15	19	21
2	2	6	11	14	17
1	1	3	5	8	12
	1	2	3	4	5
	CONSEQUENCE				

Timeframe
To Initiate
Handling Strategy

Near	0 < 2 Years
Mid	2 to 7 Years
Far	> 7 Years

CONSEQUENCES		1	2	3	4	5
SAFETY	**Personnel**	minor injury not requiring first-aid treatment, minor crew discomfort	moderate injury requiring first-aid treatment, moderate crew discomfort	severe injury, or occupational illness requiring medical treatment	critical injury or occupational illness requiring definitive/specialty hospital/medical treatment, resulting in loss of mission	catastrophic loss of life or permanently disabling injury
	Facilities, equipment, assets	minor damage to non-essential flight/ground assets	damage to non-essential flight/ground assets	damage to significant flight/ground assets	loss of mission, condition that requires safe-haven, or major damage to essential flight/ground assets	loss of vehicle prior to completing its mission, or loss of essential flight/ground assets
	Environmental	negligible OSHA/ EPA violation – non reportable	minor reportable OSHA/EPA violation	moderate OSHA/EPA violation which requires immediate remediation	major OSHA/EPA violation causing temporary stoppage	serious or repeat OSHA/EPA violations resulting in action terminating program
PERFORMANCE	**Requirements**	negligible impact to requirements/ design margins	minor impact to requirements/ design margins	moderate impact to requirements/design margins	major impact to requirements/design margins	requirements not achievable
	Operations	negligible impact to mission operations	minor impact to operations – workarounds available	moderate impact to operations – workarounds available	failure to achieve major mission objectives	total loss of mission or abort
	Supportability	temporary usage loss or LOCM(3) of non-flight critical asset	permanent usage loss or LOCM(3) of non-flight critical asset	temporary usage loss or LOCM(3) of major element(s) of flight vehicle or ground facility	permanent usage loss or LOCM(3) of major element(s) of flight vehicle or ground facility	inability to support further flight operations
RECOVERY COST(1)	**ESD**	≤$1.4M	>$1.4M but ≤$14M	>$14M but ≤$140M	>$140M but ≤$1.4B	>$1.4B
	GSDO	≤$0.2M	>$0.2M but ≤$2M	>$2M but ≤$20M	>$20M but ≤$200M	>$200M
	MPCV	≤$0.5M	>$0.5M but ≤$5M	>$5M but ≤$50M	>$50M but ≤$500M	>$500M
	SLS	≤$0.6M	>$0.6M but ≤$6M	>$6M but ≤$60M	>$60M but ≤$600M	>$600M
SCHEDULE(2)		< 1 Week	1 Week to <1 Month	1 to < 3 Months	3 to ≤6 Months	>6 Months

(1) Recovery Cost is the cost associated with problem resolution. When multiple program cost impacts are identified, the ESD enterprise cost is based on the sum of those.
(2) Schedule values are based on calendar days (e.g., 1 Week is 7 days, Sunday through Saturday).
(3) LOCM - Loss of Capability to Maintain

Risk Scorecard/ESD 10003, Revision C, May 2014

7.3 Appendix C: Acronyms

ABF	Anthropometry and Biomechanics Facility
ACES	Advanced Crew Escape Suit
APFR	Articulating Portable Foot Restraint
ARGOS	Active Response Gravity Offload System
ASCAN	Astronaut Candidate
ASCRS	Astronaut Strength, Conditioning, and Rehabilitation Specialist
ATD	Anthropomorphic Test Device
CG	Center of Gravity
DCS	Decompression Sickness
EIS	(EVA Suit) Exposure Incidence (Tracking) System
EMG	Electromyography
EMU	Extravehicular Mobility Unit
ESD	Exploration Systems Development
EVA	Extravehicular Activity
ExMC	Exploration Medical Capabilities
FE	Finite Element
FOD	Flight Operations Directorate
GHBMC	Global Human Body Models Consortium
HITL	Human In The Loop
HLS	Human Landing System
HNP	Herniated Nucleus Pulposus (Herniated Disc)
HUT	Hard Upper Torso

IC	Initial Condition
IMEA	Injury Modes and Effects Analysis
IS	Injury Severity
ISS	International Space Station
LTC	Long Term Health Consequence
MCL	Medial Collateral Ligament
MET	Metabolic
MOC	Mission Operations Capability
MRI	Magnetic Resonance Imaging
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Laboratory
ORIS$_x$	Operationally Relevant Injury Scale for Exploration
PB	Pre-Breathe
PGT	Pistol Grip Tool
PLSS	Portable Life Support System
POC	Point Of Contact
PPE	Personal Protective Equipment
PSR	Permanently Shadowed Region
PT	Physical Therapist
REBA	Rapid Entire Body Assessment
ROM	Range Of Motion
SA	Sensorimotor Adaptability
SANS	Spaceflight Associated Neuro-Ocular Syndrome
SLAP	Superior Labrum Anterior Posterior (tear)
SME	Subject Matter Expert
SPE	Solar Particle Event
TCV	Temperature Control Valve
TRR	Test Readiness Review
xEMU	Exploration Extravehicular Mobility Unit
xPLSS	Exploration Portable Life Support System