EXTRAVEHICULAR ACTIVITY ON THE LUNAR SURFACE: MAPPING MITIGATION RISK CONSEQUENCE FOR CREW NEEDING ASSISTANCE OR RESCUE

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ABSTRACT

The lunar environment offers unique challenges for human health and safety over the course of performing Extravehicular Activities (EVAs) during early Artemis missions. Driver medical conditions leading to an injured EVA crewmember needing assistance or rescue were analyzed and correlated to established, defined consequence categories. Catastrophic Drivers were identified, and three mitigation strategies were analyzed to determine if there was a potential change in consequence with their application. Risk consequence across the mitigations were compared with each other and the original risk without mitigations. Mitigations were further evaluated in a broader context with prospective preventions to understand the design and risk trade space associated with an early Artemis EVA.

1. BACKGROUND

1.1 Lunar surface extravehicular activity (EVA)

Planned upcoming EVAs at the lunar surface south pole region during early Artemis missions present unique risks to both human and hardware. It is imperative that risk associated with this highly hazardous partial gravity mission phase is sufficiently identified and characterized early in vehicle and hardware development life cycles to allow mitigations to be tested for feasibility and design changes to be implemented if needed. As in Apollo missions, early Artemis activity on the lunar surface will include traverse, geology sample collection, and scientific payload deployment, creating the potential for crew injury encompassing musculoskeletal, integumentary, environmental, and other medical events [1]. Additionally, lunar mobility assets such as rovers are not planned for these early Artemis missions, thus if a crewmember is unable to nominally ambulate back to the Human Landing System (HLS), the crew will be reliant on whatever other mitigation capabilities are feasible and provided.

1.2 Incapacitation on the lunar surface

Many medical events that may occur during a lunar surface EVA can be mapped to the Incapacitated Crew Rescue (ICR)/Acute Injury spectrum (Fig. 1). ICR spectrum classifications have been categorized based on the degree the affected astronaut requires action from the other crewmember (Rescuer): low (help), medium (assistance), and high (incapacitated) where the injured crew member respectively requires either temporary or continuous partial assistance, or continuous full assistance from the rescuer.

Figure 1. Incapacitated Crew Rescue (ICR)/Acute Injury Spectrum

With focus on the human system, 264 potential medical conditions from previous spaceflight incidents and subject matter expert (SME) concerns were identified. Of these, a subset of ~60% were identified as potential causes of incapacitation and mapped to the ICR/Acute Injury Spectrum. From this subset, a smaller subgroup of fifty-four Drivers (medical events thought most likely to occur during an early Artemis Mission) was further characterized. This included mapping to the ICR spectrum (Fig. 1) and determining associated incidence based on astronaut data (from Apollo, Skylab, Mir, Shuttle, and International Space Station missions) as well as astronaut analog, general population, and model data. [2]

1.3 Early Artemis Driver medical conditions

Many of the Artemis Driver conditions comprised those medical events that occurred during the Apollo missions, but other conditions were also included given the rougher terrain, harsher lighting conditions, and increased propensity for falls at the lunar south pole, as well as increased Artemis suit mobility and mass [2,3]. A notional early Artemis design reference mission (DRM), which included two crew members on five lunar surface EVAs, was used to calculate probability for these Drivers across the early Artemis DRM [2]. Medical resources for diagnosis and treatment of these conditions were not considered in these probability calculations nor were any preventions or hazard controls. Furthermore, all driver conditions were assumed to be completely independent with no consideration of correlating conditions or prior EVA events, likely underestimating probability for certain Drivers [4]. Driver conditions have been classified using the ICR spectrum injury scenario categories, however, to standardize risk, each condition needs to be analysed and correlated to an established, defined consequence definition. Since temporary partial reliance Drivers are not expected to result in a premature EVA return to HLS, our work concentrated on analysing continual reliance Drivers where the affected crewmember needed assistance or was incapacitated.

Spaceflight mitigations serve to reduce consequence severity, including loss of crew life (LOC), and may include operational, hardware, and crew capability. Spaceflight mass and volume constraints will require Driver mitigations to be optimized [5,6], and communication latency or temporary loss will necessitate that the crew can use provided mitigations and perform medical care more autonomously [7,8]. Mitigations involving planned or real time restriction of EVA operations typically involve decision input from Earth-based Mission Control and are not preferred options. We therefore chose to focus our analysis on crew capability as well as hardware mitigation options.

2. METHODS

2.1 Assessing risk consequence

A team of SMEs analyzed the continual reliance subset of previously identified Driver conditions [2] to determine a standardized risk consequence rating for each. Conditions were considered at the granularity of best case and worst case scenarios, thus a given condition could be represented as both best and worst case scenarios (i.e. two conditions) or just one scenario (i.e. best or worst case). Applicable Safety Personnel categories of the AES Risk Scorecard (Tab. 1) were primarily used in this assessment with secondary evaluation consideration given to the Performance Operations categories [9].

Safety Consequence	Personnel Definitions
1	Minor injury not requiring first aid treatment, minor discomfort
2	Injury requiring first aid treatment, moderate discomfort
3	Terrestrial injury or occupational illness requiring medical treatment
4	In-flight injury or illness that requires medical intervention from a second crewmember and/or Flight Surgeon and is not treatable by first aid alone; ground personnel occupational injury or illness requiring definitive/specialty hospital/medical treatment
5	Loss of life or permanent, disabling injury

Table 1. Advanced Exploration System Risk Scorecard: Personnel Safety Consequences [9]

Upon initial evaluation of these thirty Drivers, five of the upper body conditions were not included in subsequent analyses given that a crewmember with one of these conditions could likely walk back with minimal assistance (e.g. other crewmember carries additional load or pushes back cart if used). Each of the remaining twenty-five continual reliance Drivers were then mapped to the AES 5x5 Risk Scorecard based on previously calculated likelihood (L) threshold associated with a notional early Artemis mission (i.e. the probability across all EVAs in the mission, not the probability for an individual EVA) [2] and the newly ascertained consequence (C) rating for an LxC value corresponding to a specific cell value on the AES 5x5 Risk Scorecard (Fig. 2). This process served to distinguish which of the continual reliance Drivers were catastrophic and led to a permanent, disabling injury or LOC (i.e. consequence Level 5).

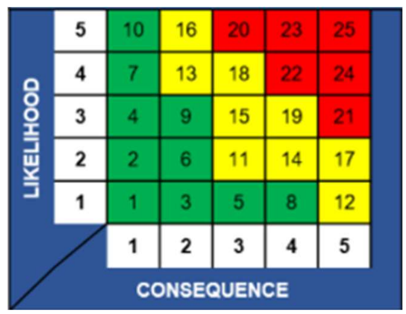

Figure 2. Advanced Exploration System Risk Scorecard: Likelihood and Consequence 5x5 [9]

2.2 Mitigation analysis

A mitigation analysis was then performed on the catastrophic Drivers to assess risk reduction associated with three different mitigation capabilities: crew assistance (rescuer crew) only (Rescuer), walking assist hardware devices (Walk Assist), and a wheeled transport device (Wheeled Transport). The worst of the worst-case scenarios were considered, and each Driver condition was analyzed as an independent event. The assumption was made that the mitigation device performs as designed or the capability works as planned for purposes of consequence scoring. It was understood *a priori* that a mitigation may not lead to a full or complete medical or mission resolution for a given event. The mitigation analysis process consisted of decomposing the original Driver risk by assessing mitigation capability correlated with 1) protecting the affected crew member and providing safe crew return to the lander (mission assurance), and 2) decreasing the likelihood for permanent disabling injury or loss of crew life (safety). This analysis process was hypothesized to recategorize the risk associated with each original catastrophic Driver into two new LxC values (Fig. 3) and was repeated for each catastrophic Driver for each of the three different mitigation capabilities listed above. Once completed, the original LxC risk

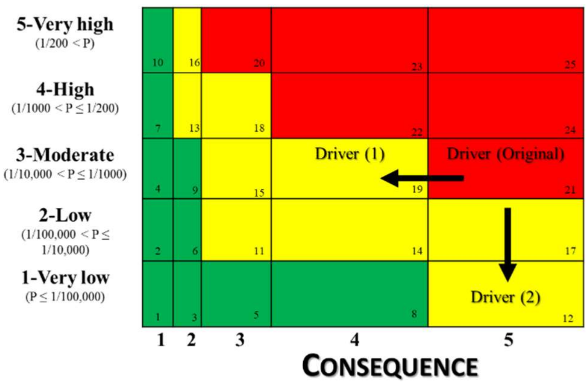

Figure 3. Mitigation Analysis: Process Overview

assignment without mitigations was compared with each of the three different mitigations evaluated: Rescuer, Walk Assist, and Wheeled Transport, to assess change in risk consequence.

3. RESULTS & DISCUSSION

3.1 Continual reliance Driver risk consequence

Severe ICR scenarios are those when the affected astronaut requires either partial or full continuous assistance from the rescuer. Safety consequences of these continual reliance subset of Driver conditions were analyzed and mapped corresponding to the likelihood and consequence of AES risk scorecard personnel safety categories as described (see Methods). Ten of the analyzed twenty-five continual reliance conditions were evaluated as "catastrophic" (Level 5, LOC or permanent disabling injury) during EVA on the lunar surface, with probabilities ranging from moderate to very low during an early Artemis mission; eight of the ten conditions are worst case scenario conditions (Fig. 4). Most of these injuries would likely not be catastrophic if they occurred terrestrially unless the environment was extreme and isolated from standard medical care [10]. The primary lunar surface risk consideration is that these injuries would preclude an astronaut from returning back to the HLS in a timely fashion without some sort of additional assistance.

3.2 Catastrophic Driver mitigation risk: consequence reduction

Fig. 5 shows the Rescuer, Walk Assist, and Wheeled Transport mitigation analyses for all ten of the identified catastrophic Drivers. During mitigation analysis (see Methods), the decomposition process revealed that some catastrophic Driver conditions had within-box changes instead of or in addition to the box-box changes hypothesized and shown in the mitigation analysis process overview (Fig. 3). Overall, Rescuer and Walk Assist mitigations show similar potential for risk reduction for all Drivers analyzed, while Wheeled Transport shows the greatest potential for risk reduction.

A key consideration for ICR during early Artemis lunar surface EVAs is that there will only be two crewmembers on the surface, making ICR more challenging by requiring single Rescuer capability. Due

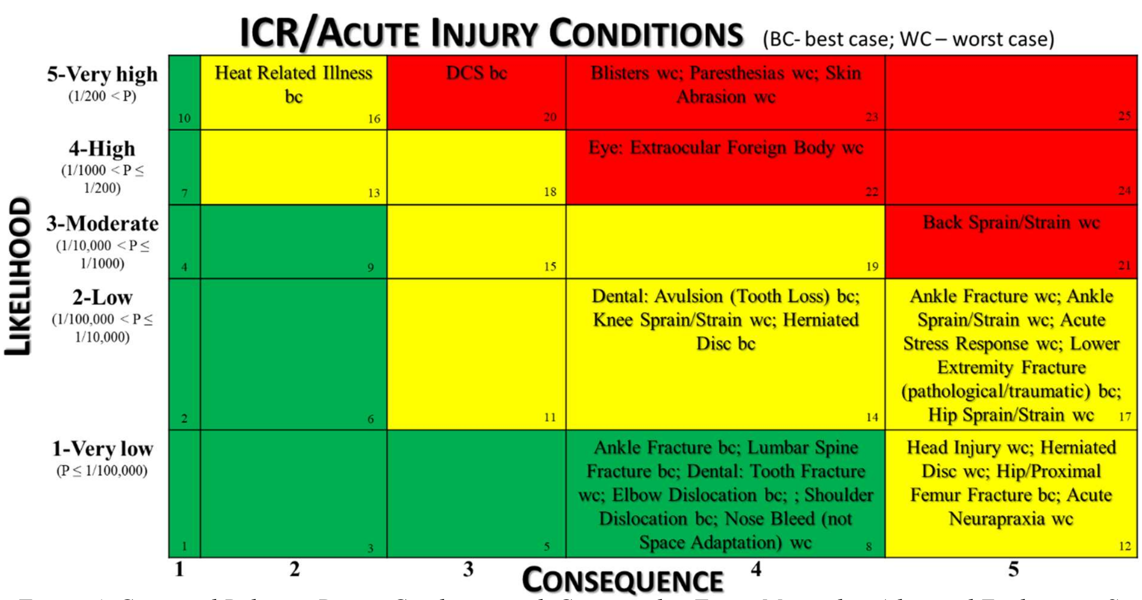

Figure 4. Continual Reliance Driver Conditions with Catastrophic Focus Mapped to Advanced Exploration System 5x5 Risk Scorecard

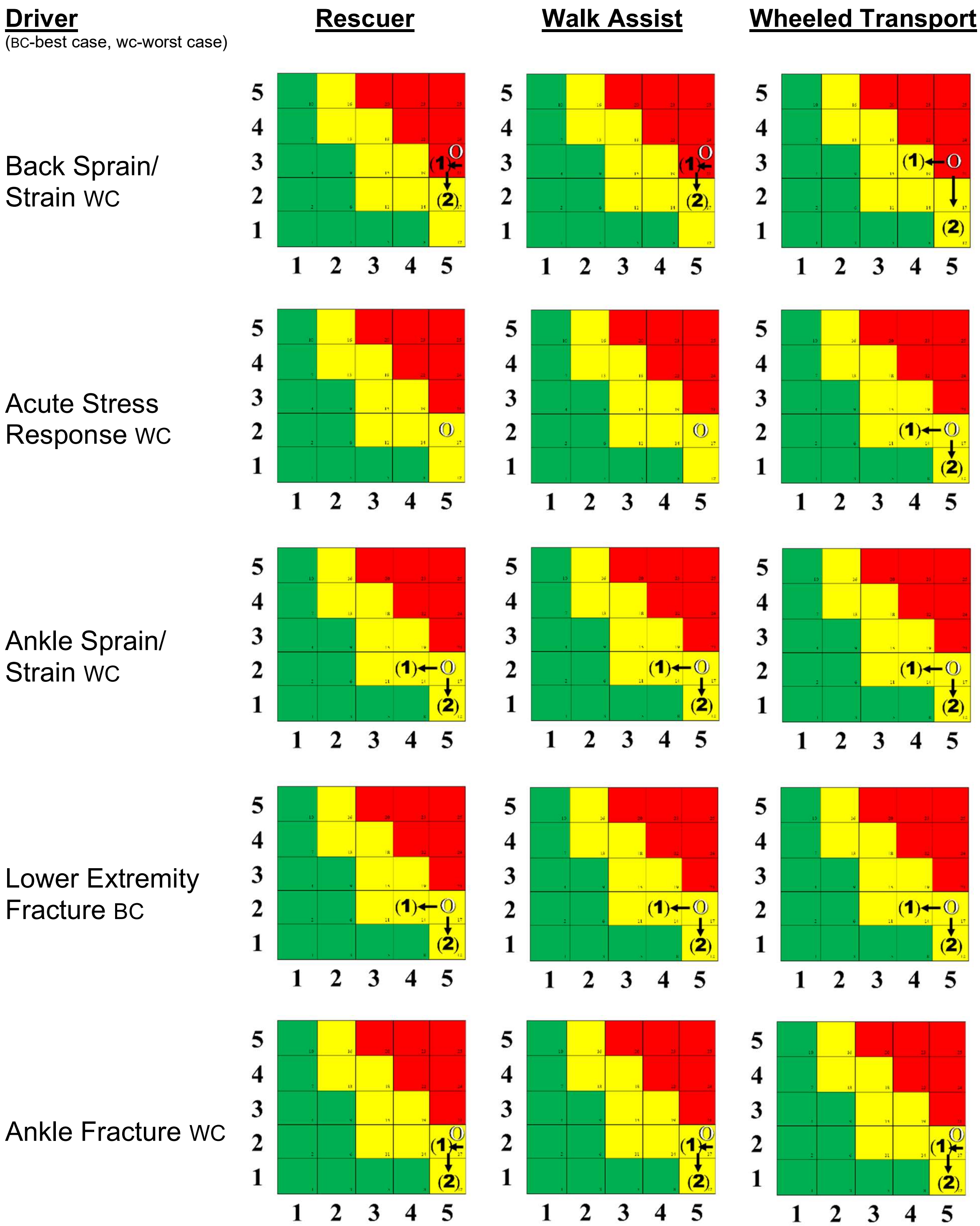

Figure 5. Catastrophic Continual Reliance Drivers with Rescuer, Walk Assist, and Wheeled Transport Mitigation Risk Analyses (O-original risk without mitigation; After mitigation: 1- Mission assurance risk, 2- Safety risk)

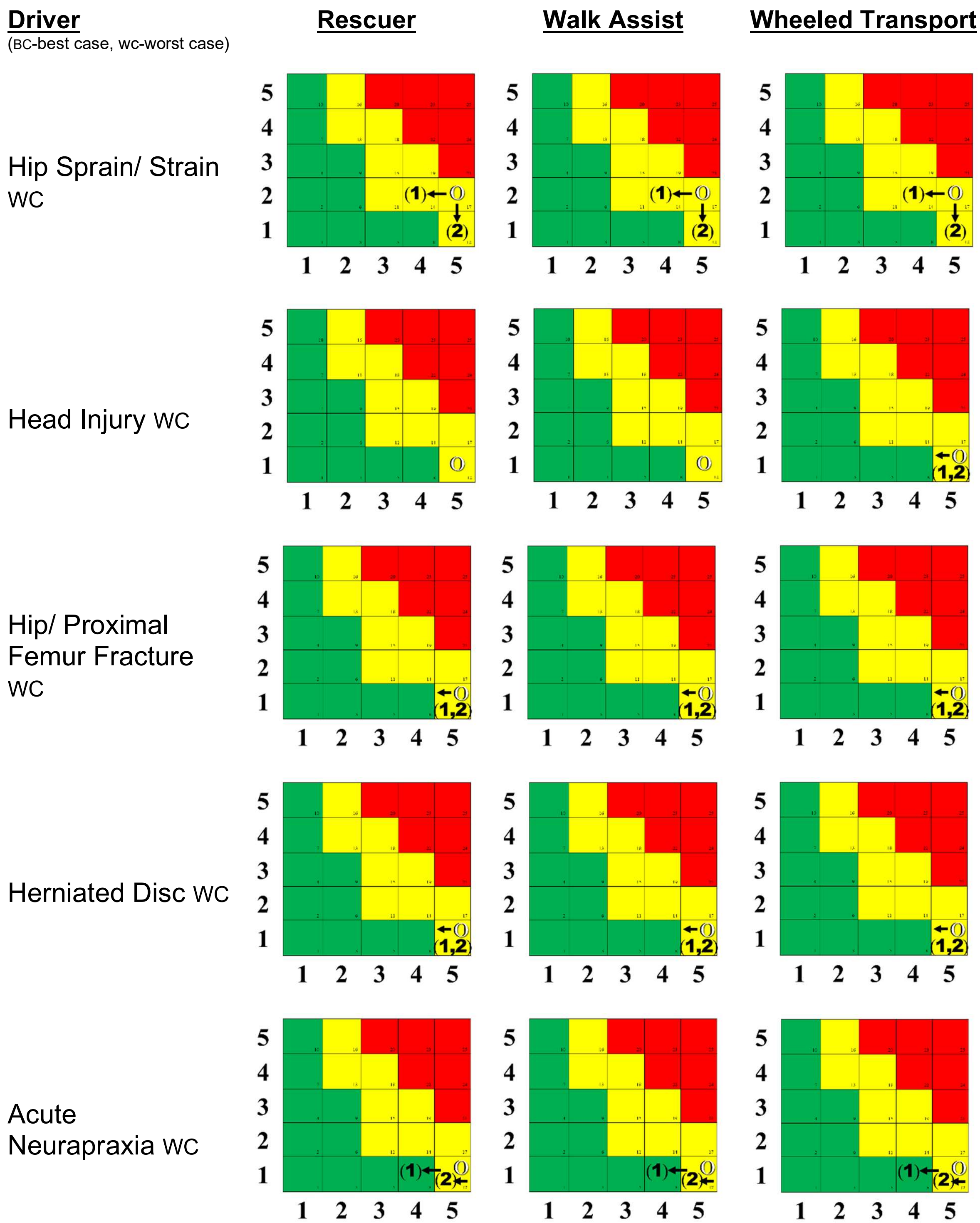

Figure 5. Catastrophic Continual Reliance Drivers with Rescuer, Walk Assist, and Wheeled Transport Mitigation Risk Analyses (O-original risk without mitigation; After mitigation: 1- Mission assurance risk, 2- Safety risk)

to pressurized suit geometry and configuration, traditional single person carry methods will either not be possible or will need to be modified to be feasible on the lunar surface [11]. Additionally, crew fitness levels will need to support the increased workload of performing Rescuer activities as even the activity of loading an incapacitated crewmember in 1/6 g can elicit a moderate metabolic rate from a Rescuer in a pressurized suit [12]. Likewise, the suit will need to accommodate likely increased metabolic rates for both Rescuer and injured crewmember [13,14], particularly in the scenario where the Rescuer is smaller than the affected crewmember. Assuming the Rescuer can provide adequate stability and return timing during assisted walk back, there is no longer a risk of LOC for worst case ankle sprain/strain, ankle fracture, hip sprain/strain, acute neurapraxia, and best case lower extremity fracture (pathological/traumatic) (Fig. 5). Additionally, a decrease in the progression of the injury is possible with Rescuer mitigation for those Drivers, although worst case ankle fracture remains a Level 5 due to the high likelihood of permanent disabling injury. Although not a box-box risk decrease resulting in a consequence level change, there are expected in-box changes in LOC risk reduction for worst case back sprain/strain, herniated disc, and best case hip/proximal femur fracture (Fig. 5), however pain from a worst case back sprain/strain may be debilitating and render the affected crewmember fully reliant on the Rescuer. Rescuer mitigation was assessed to be ineffectual for worst case acute stress response and head injury, and crew safety risk remains in all other assessed Drivers as well (Fig. 5). A generic HLS was assumed as part of these analyses, however it should be noted that HLS ingress difficulty and provider capability will contribute to the risk and success of Rescuer mitigation and other ICR scenarios [15].

In analyzing Walk Assist mitigation, no specific hardware solution was assumed, thus final capability could include dual purposed tools, a pushcart, a staff, walking stick(s), or other devices for stability and support. Additionally, various Walk Assist scenarios were considered during the evaluation that included potential use of the mitigation by the Rescuer as well as the injured crewmember. Risk analysis results for the Walk Assist mitigation are virtually identical for the Rescuer mitigation, showing a similar potential for risk reduction with four of the ten Drivers decreasing to a consequence Level 4 for mission assurance yet still carrying a safety risk even after mitigation (Fig. 5). A notable exception for Walk Assist versus Rescuer mitigation, however, is in the arena of potential prevention in that use of a walk assist device could decrease the likelihood of falls during a lunar EVA [16].

Studies evaluating use of a wheeled transport device for carrying loads equivalent to an incapacitated suited crewmember are not new [17] and encompass many of the aspects needed to make ICR achievable by a single Rescuer from anywhere the crew is allowed to go [18]. The Wheeled Transport mitigation gave the best prognosis for successful decreases in LOC risk and injury progression in the injured crew member for all ten catastrophic Drivers; mission assurance risk reduction is shown in six of the ten conditions with a decrease in consequence to Level 4, but permanent disabling injury is still possible for most of the Drivers (Fig. 5). An additional new benefit to the Wheeled Transport mitigation may be a decrease in Rescuer exertion during return to the HLS versus Rescuer alone or Walk Assist mitigations. An Apollo analog study evaluating metabolic cost of a suited subject pulling a wheeled cart showed that pulling the cart did not increase metabolic cost over locomotion alone, however this study was performed on a level surface [17], which is not flight-like with respect to an early Artemis mission and serves as a reminder that all human-in-the-loop (HITL) analogs have limitations that will be important to understand when interpreting collected data [19,20]. Integration of suit:mitigation interfaces will also need to be carefully planned for all phases of the ICR [20]. Depending on wheeled transport design, this mitigation could also serve as a walk assist device for one of the crewmembers (e.g. a dual purposed tool cart capable of also carrying an incapacitated crewmember), however the design for ICR mitigation could also be more specialized (e.g. a handcart or "Astro-dolly" wheeled transport system).

3.3 Considerations for risk reduction: mitigations and preventions

Additional mitigations are potentially available for applying alone or in conjunction with the analyzed Rescuer, Walk Assist, and Wheeled Transport mitigations. As well as the mitigation imposing real time restriction of EVA operations mentioned above, there may be suit design mitigation options such as integrated hand holds for the Rescuer or the ability to take medications in suit for the affected crewmember. Fig. 6 not only shows these possible mitigation options to reduce consequence risk for the ten catastrophic Drivers and enable crew survival, but also indicates some prospective preventions that could be employed singly or together to reduce the likelihood of these catastrophic events, thereby reducing overall LxC risk and risk posture (Fig. 2).

Methods of prevention for early Artemis missions were described for walk assist devices above but could also include other listed mitigations such as 1) suit design with features like a) less mass for the suit and carried tools, b) more stable location for its center of gravity, c) hard stops on certain joints to limit rotation, and d) optimal crew fit, and 2) restricted EVA operations including aspects such as a) limiting crew distance from the HLS, b) reducing task density, and c) crater and other dangerous terrain avoidance (Fig. 6). Reducing likelihood and or severity of injury due to physical stresses and cognitive load can be incorporated into design aspects of EVA tools. This risk reduction can also be achieved by decreasing the number and time of EVAs, ensuring appropriate crew training and crew prescreening for existing conditions as a part of EVA concept of operations (ConOps), and safeguarding crew time for targeted work hardening training encompassing physical, behavioral, and cognitive programs (Fig. 6). The mitigations and preventions listed in Fig. 6 are not intended to represent an inclusive list of all possible

Catastrophic Event \ Preventions/ Mitigations	Transport Device	Walking Assist Devices	Crew Assistance Only	Suit Design Options	EVA Tool Design*	Reduced EVAs/Hours	Restrict EVA Operations	EVA Con Ops	Work hardening
Back Sprain/Strain (WC)	x								
Acute Stress Response (WC)	x								
Ankle Sprain/Strain (WC)	x	x	x						
Lower Extremity Fracture (BC)	x	x	x						
Ankle Fracture (WC)									
Hip Sprain/Strain (WC)	x	x	x						
Head Injury (WC)									
Hip/Proximal Femur Fracture (BC)									
Herniated Disc (WC)									
Acute Neurapraxia (WC)	x	x	x						

Figure 6. Potential Mitigations and Preventions for Catastrophic Drivers (Blue- potential change in likelihood; Pink- potential change in consequence; ***x*** *indicates box-box change; blank signifies no expected change)*

mitigations and preventions for an early Artemis lunar surface EVA. Additionally, long-standing cross-cutting dependencies will need to be considered including lighting, navigation, and communication [21].

In conclusion, given the catastrophic consequence of several identified continual reliance Driver conditions, in the near term, integrated HITL assessments should be performed to determine the feasibility of mitigation and prevention capabilities. It is currently unknown whether a rescuer astronaut could effectively provide continuous assistance to enable both crewmembers to return safely to the HLS from the standpoint of both suit geometry and human performance. Although resulting in an increase in resources, our analyses demonstrated that providing a wheeled transport provides the highest risk reduction potential though walking assist devices may have prevention as well as mitigation benefits. This type of analyses should also be instigated for later Artemis missions to understand how risk posture changes with alterations in Artemis architecture and ConOps.

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