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Surface EVA Readiness and Performance Optimization (SERPO): An Integrated Human Performance Approach

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Acronyms

Acronym	**Definition**
ABF	Anthropometry and Biomechanics Facility
ACFT	Army Combat Fitness Test
ACR	Assisted Crew Rescue
AIB	Applied Injury Biomechanics
AOH	Astronaut Occupational Health
AOHMG	Astronaut Occupational Health Management Group
APACHE	Assessments of Physiology and Cognition in Hybrid-reality Environments (APACHE)
ARGOS	Active Response Gravity Offload System
ASCANS	Astronaut Candidates
ASCR	Astronaut Strength and Conditioning Rehabilitation
AX3S	Active Response Gravity Offload System (ARGOS) eXploration EVA Systems
AxEMU	Axiom Exploration Extravehicular Mobility Unit
BHP	Behavioral Health & Performance
CB	Center of Buoyancy
CE	Competitive Exercises
CG	Center of Gravity
CGM	Continuous Glucose Monitoring
CHAPEA	Crew Health and Performance Exploration Analog
CMJ	Countermovement Jump
CMOP	Comprehensive Model of Optimizing Performance
CO2	Carbon Dioxide
COM	Center of Mass
CONOPS	Concept of Operations
CSRM	Crew State and Risk Model
CTA	Cognitive Task Analysis
DCS	Decompression Sickness

DIDB	Disposable In-Suit Drink Bag
DOF	Degrees of Freedom
DST	Digit Span Test
DVT	Design Verification Testing
EEPL	EVA and Environmental Physiology Laboratory
EHP	EVA and Human Surface Mobility Program
EMR	Electronic Medical Record
EMU	Extravehicular Mobility Unit
EPC	Exercise Physiology and Countermeasures
ESP	Elevated Suit Pressure
EV	Extravehicular
EVA	Extravehicular Activity
FAM	Familiarization
FCE	Functional Capacity Evaluation
FFA	Functional Fitness Assessment
FOD	Flight Operations Directorate
FOOSH	Fall On an Outstretched Hand
FOV	Field of View
FY	Fiscal Year
GPE	General Preparatory Exercises
GPP	General Physical Preparation
GRU	Government Reference Unit
GVS	Galvanic Vestibular Stimulation
HERA	Human Exploration Research Analog
HHP	Human Health and Performance
HITL	Human-in-the-Loop
HLS	Human Landing System
HNW	Hydration, Nutrition, and Waste Management
HPO	Human Performance Optimization

HR	Heart rate
HS3	Hybrid SpaceSuit Simulator
HSM	Human Surface Mobility
HUT	Hard Upper Torso
IBP	Isometric Bench Press
ICR	Incapacitated Crew Rescue
IMPALA	Information Management Platform for anALysis and Aggregation
IMTP	Isometric Mid-Thigh Pull
IMU	Inertial Measurement Unit
ISS	International Space Station
IV	Intravehicular
IVA	Intravehicular Activity
JERY	JSC EHP Rock Yard
JETT	Joint EVA & HSM Test Team
JSC	Johnson Space Center
KPI	Key Performance Indicator
LCVG	Liquid Cooling and Ventilation Garment
LSAH	Lifetime Surveillance of Astronaut Health
LTA	Lower Torso Assembly
LTV	Lunar Terrain Vehicle
MAG	Maximum Absorbency Garment
MAVRIIC	Multidisciplinary Analytics, Visualization, and Reporting Interface for Integrated Countermeasures.
MCO	Mars Campaign Office
MetRate	Metabolic Rate
MK-III	Mark-III
MMC	Markerless Motion Capture
MSK	Musculoskeletal
NASA	National Aeronautics and Space Administration
NBL	Neutral Buoyancy Lab

NSL	Neuroscience Laboratory
O2	Oxygen
PersEIDS	Personalized EVA and Informatics Decision Support
PLSS	Portable Life Support System
POGO	Partial Gravity Simulator
PR	Pressurized Rover
PVT	Psychomotor Vigilance Test
RAMP	Raise, Activate, Mobilize, and Potentiate
RGA	Reduced Gravity Aircraft
RM	Repetition Maximum
ROM	Range of Motion
RPE	Rating of Perceived Exertion
SAAT	Suited Anomaly Assessment Team
SAFER	Simplified Aid for Extravehicular Rescue
SCU	Servicing and cooling umbilical
SDE	Specific Developmental Exercises
SERPO	Surface EVA Readiness and Performance Optimization
SJ	Squat Jump
SME	Subject Matter Experts
SPE	Specific Preparatory Exercises
SRD	System Requirement Document
SUITS	Suited User Incident Tracking System
TAP	Tiered Assessment Protocol
TIM	Technical Interchange Meeting
TLX	Task Load Index
UTA	Upper Torso Assembly
VO2pk	Maximal Oxygen Uptake
VR	Virtual Reality
WBH	Waist, Brief, and Hip

WFPT	Wildland Firefighter Pack Test
xEMU	eXploration EMU
xPGS	Exploration Pressure Garment System
XR	Hybrid Reality

Preface

NASA's Apollo Program marked a historic milestone in human spaceflight, yet it included fewer than 20 extravehicular activities (EVAs), with no astronaut completing more than three. In contrast, NASA's future Lunar and Mars missions are expected to involve a significantly higher number of EVAs, presenting unprecedented physical, cognitive, and operational demands. These realities underscore the need to evolve beyond the legacy designs of the Apollo era, which—while groundbreaking at the time—present limitations that are not scalable for future sustained operations.

In this context, optimizing human performance is no longer a secondary consideration: it is central to mission success. Surface EVA Readiness and Performance Optimization (SERPO) was established to address this challenge through a fully interdisciplinary approach, bridging operations, engineering, medicine, research, and other domains. SERPO aims to close the knowledge and communication gaps across traditionally siloed fields, promoting integrated EVA system development that reduces operational overhead while approaching, or exceeding, performance levels seen in shirtsleeve conditions on Earth.

This report contributes to that vision by highlighting key factors influencing human performance in the context of surface EVA training and execution. It outlines the physical and environmental challenges inherent to exploration EVA, as well as relevant testing methods, facilities, equipment, and personnel. While the primary focus is on physical performance and environmental constraints, the report also touches on behavioral and cognitive performance, acknowledging that future work must expand to include all dimensions and domains of the human system.

As we transition toward more demanding exploration-class missions, with new spacesuits, vehicles, and an increased tempo of operations, the complexity of EVA will grow. Addressing cognitive workload, physical fatigue, and overall performance in these conditions is critical. Continued interdisciplinary collaboration and systematic study will be essential to ensuring EVA systems are optimized not only for technical feasibility but also for the full spectrum of human performance.

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The successful completion of this report would not have been possible without the collaborative efforts of contributors across multiple organizations at NASA's Johnson Space Center (JSC). We extend our appreciation to all those who participated in the Technical Interchange Meetings (TIMs), biweekly team meetings, and project presentations. The insightful discussions, presentations, and ongoing engagement from presenters and attendees alike were instrumental in shaping the outcomes of this work. Funding for this effort was provided by the Mars Campaign Office (MCO) through the completion of this report

1 Introduction

1.1 Background

Training in the extravehicular mobility unit (EMU) for extravehicular activity (EVA) has historically posed a unique and elevated risk for sustaining a variety of injuries, including but not limited to musculoskeletal (MSK), onycholysis (fingernail delamination), and compressive neuropathies. During an investigation into the shoulder injuries during EVA training in the Neutral Buoyancy Lab (NBL), a Shoulder Injury Tiger Team determined that there was a link between spacesuit design, operational techniques, training culture, and environment as factors contributing to the elevated injury risk. They recommended a multi-directorate team to detect, evaluate, and respond to the medical issues associated with EVA training and to allow for appropriate resource allocation to reduce the risk of injury to crew during training (Williams & Johnson, 2003).

In 2009, the NBL Safety Team initiated a review after a crewmember sustained a training related injury to the shoulder. During this review, recommendations from the Shoulder Injury Tiger Team were evaluated, and it was concluded that two key items were not implemented: the EMU planar shoulder was not redesigned and there was limited tracking of crew physical training due to variability of training venues (Williams & Johnson, 2003). This prompted the NASA EMU Shoulder Injury Technical Interchange Meeting (TIM) in 2012, led by Dr. Rick Scheuring (NASA Johnson Space Center [JSC]) in collaboration with members from the Crew Office, Human Health and Performance (HHP) Directorate, the EVA Robotics and Crew Systems Operations Division, the Exploration Integration and Science Directorate, and external subject matter experts (SMEs).

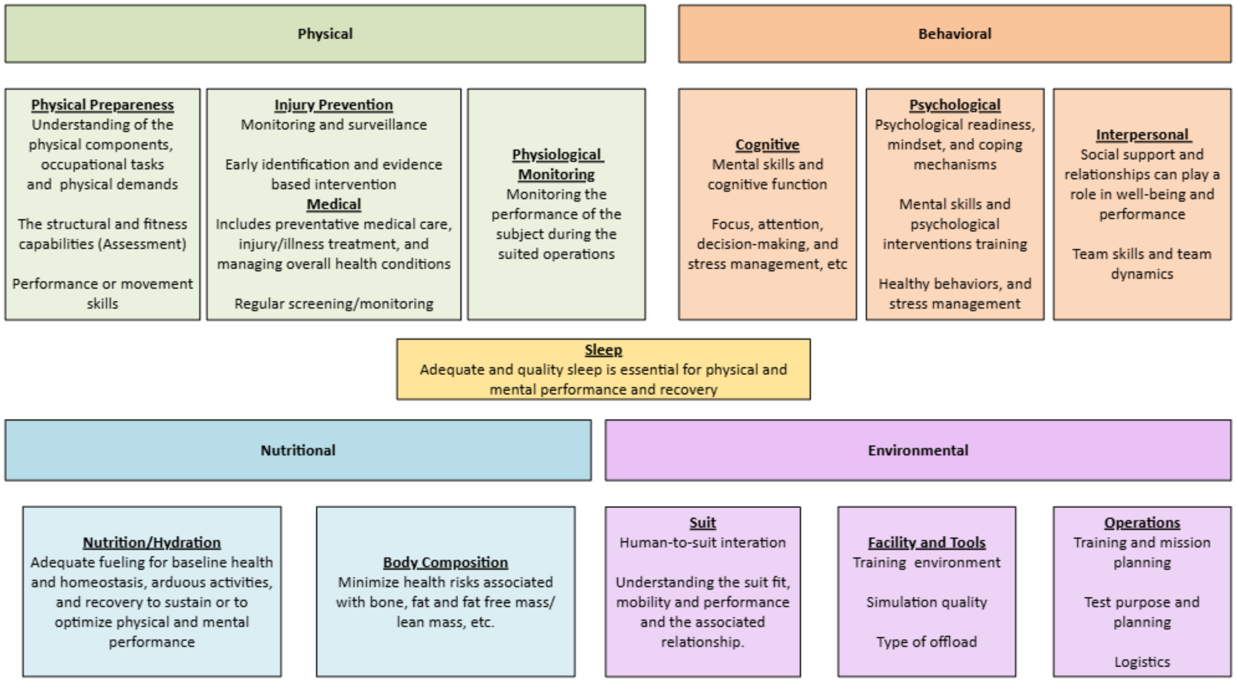
Recommendations from the EMU Shoulder Injury TIM included three primary objectives: develop an NBL Functional Capacity Evaluation (FCE), develop a supervised mandatory rotator cuff and scapular stabilizer training program to be conducted within 6 months of initial NBL runs with a pre-run fitness check, and develop a Work Hardening program, to be performed on land before NBL training and following rehabilitation from an injury or surgery (Scheuring, 2013). The program represented a thorough understanding of the injury risk, provided unique recommendations to the tasks and the training environment, guided rehabilitation, and cleared individuals to return to suited operations after sustaining an injury. Additionally, one of the program's key advancements was the ability to bridge the gap between injury recovery and mission requalification by enabling rapid access to evidenced based injury management. It reduced the time needed for astronauts to resume to full-duty status and improved outcomes for those recovering from injuries. This program has also informed broader human performance strategies across NASA, contributing to long-term health surveillance and injury prevention planning. This historical approach provided the foundation for the characterization of injury risk, development of a Work Hardening model, and implementing appropriate resources to reduce injury risks to ensure mission success. The Work Hardening model is now considered a critical component of NASA's approach to injury risk reduction and serves as a template for performance-based recovery in other high-demand environments.

The Artemis program represents NASA's return to the Moon and serves as a critical step in advancing human space exploration. Encompassing all planned Lunar missions, Artemis is a key component of the agency's broader Moon to Mars strategy. As part of this initiative, NASA will land the first woman and the next man on the Lunar Surface, where they will explore the Moon's South Pole with a focus on a sustained Lunar presence. As we shift our focus toward the future of space exploration, EVA training, and performance, there remains limited information about finalized vendor designs (e.g., suits, Lunar Terrain Vehicles [LTV]). Additionally, mission challenges, environmental conditions, and physiological demands associated with training and operational activities need further characterization and understanding. Due to the immediate need, the newly named Surface EVA Readiness and Performance Optimization (SERPO)—formally known as the Work Hardening program—is now co-led by Dr. Rachel Thompson (Leidos, NASA JSC) and Dr. Danielle Anderson (United States Air Force, NASA JSC). The project seeks to establish a proactive, integrated, and stepwise approach to optimized human performance through SERPO.

1.2 Defining Human Performance Optimization

Optimizing human performance on the Lunar Surface is a complex challenge, particularly as we prepare for the demands of both the training environment and the future of space exploration (Lunar and Mars surfaces) with all new commercially developed hardware (e.g., spacesuit, LTV) and new operational demands, like the increased EVA tempo. It is essential to enhance interdisciplinary collaboration and deepen our understanding of how various domains interact and influence the human system, including their potential contributions to optimization of human performance. Human performance optimization (HPO) is "the process of applying knowledge, skills and emerging technologies to improve and preserve the capabilities of 'individuals' and organizations to execute essential [mission] tasks" (Nindl et al., 2015). HPO is a strategic, evidence-based approach aimed at enhancing and sustaining the capabilities of individuals and organizations. It involves the deliberate application of knowledge (from research, experience, and data), skills, and emerging technologies to improve performance outcomes. This process encompasses systematic analysis, targeted interventions, and continuous evaluation to address performance gaps and foster sustained excellence.

The first step in the development of a high functioning human performance program is to understand and fully define the need around the individual in the context of the environment they face. To tackle the complex challenges related to human performance in a holistic and collaborative way, an interdisciplinary alliance and active engagement of stakeholders allows for diverse expertise to be shared across various disciplines to create innovative, evidenced-based solutions for individual domains of human performance. These domains (Figure 1-1) often intersect and vary in emphasis depending on context. For instance, the interplay between nutrition, exercise, and bone health, or fatigue management with decision making, and many more.


Physical

Physical Prepareness
Understanding of the physical components, occupational tasks and physical demands

The structural and fitness capabilities (Assessment)

Performance or movement skills

Injury Prevention
Monitoring and surveillance

Early identification and evidence based intervention

Medical
Includes preventative medical care, injury/illness treatment, and managing overall health conditions

Regular screening/monitoring

Physiological Monitoring
Monitoring the performance of the subject during the suited operations

Behavioral

Cognitive
Mental skills and cognitive function

Focus, attention, decision-making, and stress management, etc

Psychological
Psychological readiness, mindset, and coping mechanisms

Mental skills and psychological interventions training

Healthy behaviors, and stress management

Interpersonal
Social support and relationships can play a role in well-being and performance

Team skills and team dynamics

Sleep
Adequate and quality sleep is essential for physical and mental performance and recovery

Nutritional

Nutrition/Hydration
Adequate fueling for baseline health and homeostasis, arduous activities, and recovery to sustain or to optimize physical and mental performance

Body Composition
Minimize health risks associated with bone, fat and fat free mass/ lean mass, etc.

Environmental

Suit
Human-to-suit interation

Understanding the suit fit, mobility and performance and the associated relationship.

Facility and Tools
Training environment

Simulation quality

Type of offload

Operations
Training and mission planning

Test purpose and planning

Logistics

Figure 1-1. Individual domains

SERPO was established as an interdisciplinary platform to bridge the gaps between operations, engineering, medical, research, and more by adopting a comprehensive approach that actively integrates all pertinent stakeholders in attempts to break down the silos of information. This report is primarily focused on the physical, environmental, and cognitive considerations for exploration EVA training and performance. Surface exploration EVAs are likely to have increased acceptable risk levels, cognitive workload, fatigue, and demands on performance compared to microgravity EVA currently conducted from the International Space Station (ISS). High cognitive workload and fatigue present significant risks to crew safety during exploration EVAs. As a result, it is important to understand which EVA scenarios and environments impact subjective and objective measures of cognitive workload, fatigue, and EVA performance. Further research and collaboration are needed to address all domains and close existing knowledge gaps.

1.3 SERPO Objectives

The ***objectives*** of SERPO are as follows:

1. ***Build*** a platform for each individual discipline (human performance, advanced suit team, behavioral health and performance, etc.), continuously providing current or developmental information to better optimize human performance and inform discipline specific objectives.
2. ***Integrate*** key stakeholders through multiple organizations and divisions to capture an interdisciplinary team with a diverse background of knowledge related to all mission phases for exploration EVA training and performance (e.g., CA, EA, SA).
3. ***Establish*** a systematic approach for identifying potential tasks and physical and cognitive demands for pre-flight and in-flight EVA performance that may put the crewmember at risk for injury but which could be reduced through the SERPO team.
4. ***Understand*** the logistic considerations that would be required to implement a robust SERPO plan and provide recommendations to overcome these potential limitations.
5. Secure funding, logistic support, and ongoing sustainment of SERPO support throughout various suited testing environments for ongoing monitoring, characterization, identification, and intervention for MSK injuries.

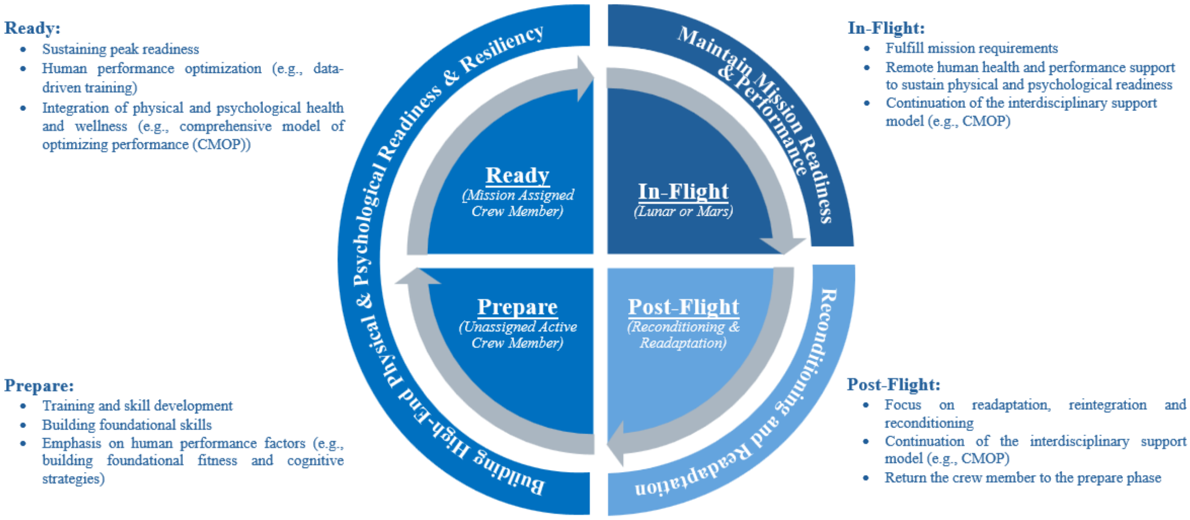
1.4 SERPO Goals

The ***goals*** of SERPO are as follows:

1. Enhance ***preparedness and performance*** in the planetary suits during training and during future exploration EVAs (on the Lunar Surface and onto Mars) with an interdisciplinary and comprehensive approach to HPO.

2. Integrate all human performance domains (e.g., physical, cognitive, psychological, and operational) to ensure cohesive strategies that support crew effectiveness in both the training and exploration environments.

3. ***Reduce the risk and severity*** of training-related injuries through proper medical support, early reporting, and evidence-based treatment; reduce injury rates through ***mitigation*** strategies/barriers during training.



Ready:
- Sustaining peak readiness
- Human performance optimization (e.g., data-driven training)
- Integration of physical and psychological health and wellness (e.g., comprehensive model of optimizing performance (CMOP))

In-Flight:
- Fulfill mission requirements
- Remote human health and performance support to sustain physical and psychological readiness
- Continuation of the interdisciplinary support model (e.g., CMOP)

Prepare:
- Training and skill development
- Building foundational skills
- Emphasis on human performance factors (e.g., building foundational fitness and cognitive strategies)

Post-Flight:
- Focus on readaptation, reintegration and reconditioning
- Continuation of the interdisciplinary support model (e.g., CMOP)
- Return the crew member to the prepare phase

Figure 1-2. Mission modelModified from the Air Force AFFORGEN cycle
https://www.af.mil/News/Article-Display/Article/3440970/airmen-to-see-changes-in-deployment-cycles-with-afforgen/

1.5 SERPO Approach

An illustration of the stages of a crewmember's mission and demonstration of how human performance support can be integrated across all phases of a mission, as shown in Figure 1-2. The framework applies to every domain of HPO (e.g., nutrition, physical, and psychological), each of which should follow this process to develop evidence-based training programs and mission support strategies. Through SERPO, guidance is provided on environmental conditions and mission-specific domains across all mission phases, while simultaneously informing each discipline. These insights span the entire mission timeline, ensuring that all human performance domains are grounded in relevant data. Input from SERPO also fosters ongoing collaboration among disciplines, promoting alignment and integration of strategies across all mission phases.

This approach ties back to the goals of SERPO to build and be a platform for each individual discipline, to continually provide up to date or developmental information to better optimize human performance, and to inform discipline specific objectives for the various stages of the mission. To achieve this, we must continually develop and refine our current baseline understanding of mission demands, integrate and expand across domains, and continually monitor performance to ensure adaptability over time (SERPO approach). Ultimately, this integrated approach enables safer operations, enhances crew resilience, and maximizes mission effectiveness.

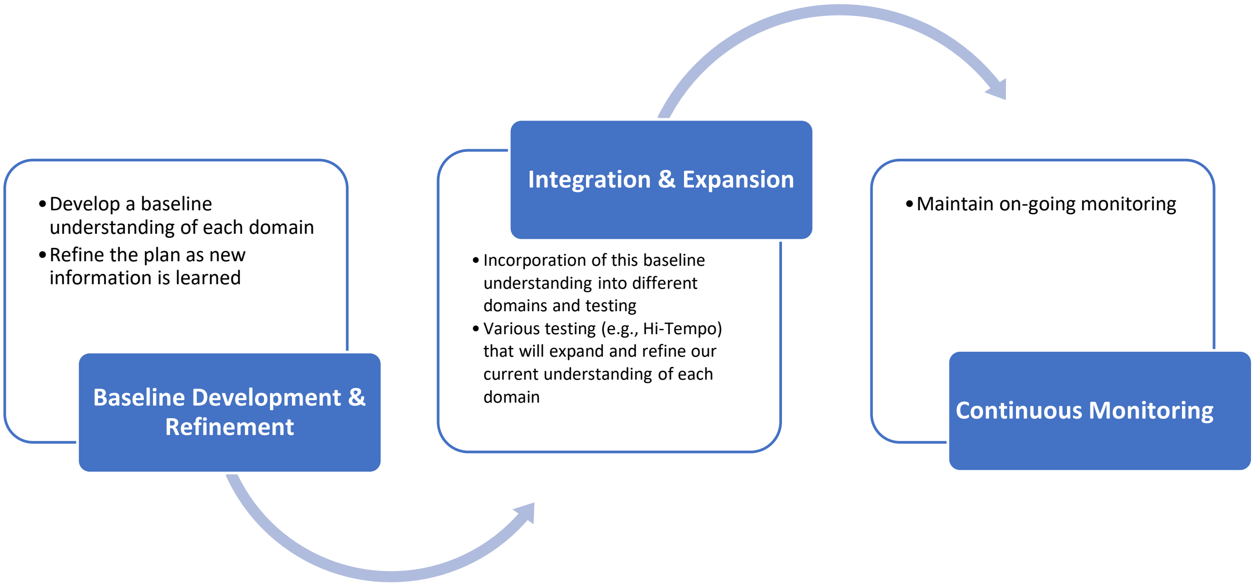


Figure 1-3. SERPO approach. Continuous development, integration, and monitoring of mission demands across all human performance domains to ensure adaptability and optimize crew performance over time.

1.6 Purpose of Technical Report

The purpose of this document is to summarize the findings from the fiscal year (FY) 2024 and 2025 TIMs and bi-monthly SERPO meetings, which were targeted to assess the environmental, physiological, and behavioral domains of exploration EVA training and performance.

Additionally, this report describes a systematic approach for developing and implementing a comprehensive physical training plan and provides recommendations to optimize human performance and reduce training related injuries based on the current understanding of the environmental and physical demands. This requirement supports the crew health and safety mission, which is designed to provide a comprehensive astronaut occupational health (AOH) program to provide the full continuum of healthcare needed to ensure astronaut health and optimize performance. Additionally, this document and the SERPO team serve as a platform for each individual discipline, to continually provide up to date or developmental information to better optimize human performance, and to inform discipline specific objectives. The contents of this document will remain a living process and be continually updated when additional data is available.

2 Environmental Domain

Because there is no equivalent terrestrial environment, analog environments have been used for EVA and spaceflight training since the beginning of the space program. Analogs simulate environmental aspects (e.g., partial gravity), working in suits or suit simulators, and EVA tasks from the operational environment with varying levels of fidelity and rely on the operators to fuse these experiences while increasing accessibility to the test subject or crewmember and reducing mission risk. An analog may include a spacesuit, a vehicle (e.g., LTV or Pressurized Rover [PR]), and/or a location representing the environmental domain for the purposed of training or testing. All have a goal of preparing the astronaut and the team for a spaceflight mission. This section discusses the training or testing environments, spacesuit analogs, and will astronaut/crewmember training activities.

Any EVA simulation environment will have its own strengths and weaknesses and the obvious environmental limitations. This section primarily focuses on gravity simulations, but other environmental factors, such as vacuum, dust, and the thermal environment, may be prioritized depending on specific test objectives.. Misaligned objectives in these environments can lead to suboptimal hardware designs, poor data quality, or inaccurate results. Tailoring test objectives in each location maximizes the strengths of the available environments. Simulation quality must be taken into consideration and is characterized as how well the test environment represents the real operations or gravitational environment (e.g., Lunar Surface), as well as whether the event meets its intended objectives. Simulation quality directly affects

- the validity of objectives across different simulation environments;
- subjects' real-time understanding and performance of the task they are attempting;
- the team's ability to accurately interpret subjects' experiences, actions, and feedback; and confidence in the resulting data and conclusions.

2.1 Analog Training Environments

2.1.1 NBL

The Neutral Buoyancy Laboratory (NBL) is one of the world's largest indoor pools and can support multiple large-scale operations simultaneously, utilizing both underwater and topside assets (Figure 2-1). A gravity offload of 1/6 (Lunar analog) can be simulated in the NBL by leveraging the natural buoyancy of the suit attached with specific weights and foam to achieve the desired offload. The NBL is used for mission planning, procedure development, hardware verification, astronaut training, and the refinement of time-critical operations essential for ensuring mission success during spacewalks and related activities. This analog serves many purposes: end-to-end EVA training, in-mission risk fidelity, full-scale mockups, 1/6-g mock-ups, two-crew EVA operations (Figure 2-2), and various grades of terrain. The current suits are used in the NBL are the EMU, the government reference unit (GRU) of the exploration EMU (xEMU), the spacesuit vendor (Axiom) xEMU (AxEMU), Z-2.5, and Z-2. The AxEMU, Z-2.5, and Z-2 will not be discussed in this report.

The NBL offers numerous benefits for astronaut training and mission simulation. Crewmembers' arms and legs can be realistically offloaded, enhancing fidelity of mission operations and enabling comparable communication between two crewmembers and the ground team. For example, the NBL is currently the only facility capable of performing the supine recovery, although the realism of this motion has yet to be fully assessed. The facility also includes a realistic testing area with environmental features such as rocks, mockups, lighting, and simulated regolith. Finally, the NBL allows crewmembers to operate in six degrees of freedom (DOF) without physical restraints, except the umbilical, which provides oxygen, removes carbon dioxide, regulates temperature, and supplies electricity for communications.

The NBL does have several limitations. Water drag introduces unrealistic resistance to movement, increases the difficulty of task completion, and the weigh-out process to 1/6-g is time-consuming and adds bulk to the suit. Additionally, diving constraints and scheduling conflicts between Exploration and International Space Station (ISS) training can limit availability. Despite these challenges, the NBL remains the only analog for two-crewmember training and operations in a pressurized, off-loaded environment (Figure 2-2), until the Active Response Gravity Offload System (ARGOS) eXploration EVA Systems (AX3S) becomes operational.

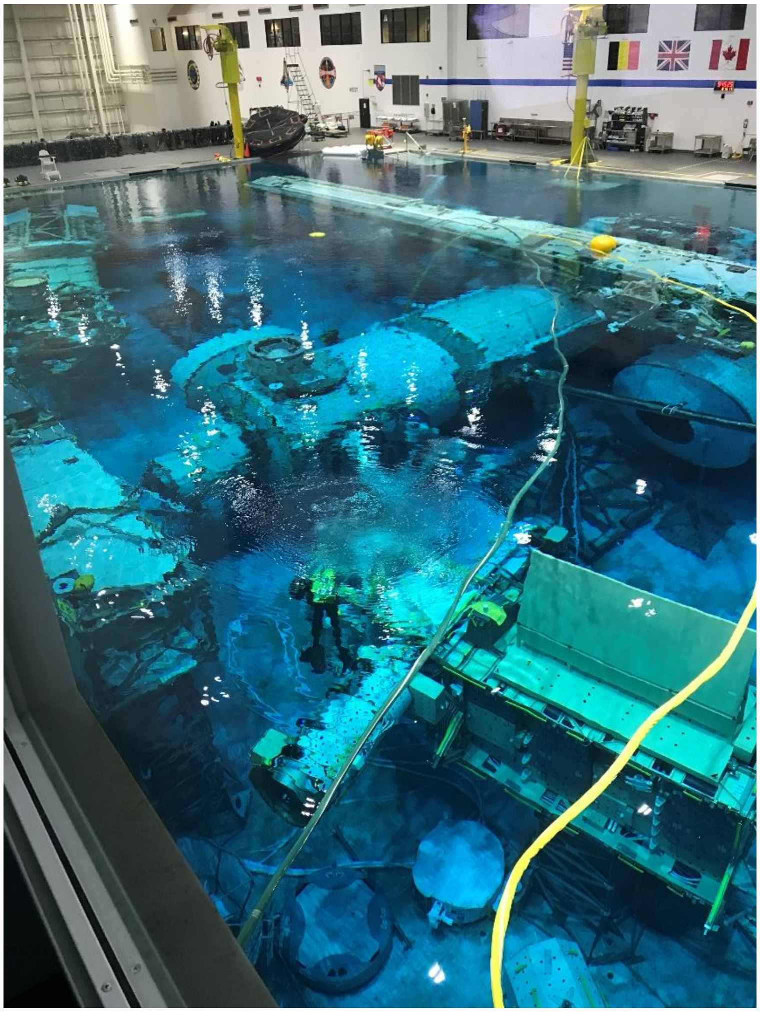


Figure 2-1. Neutral Buoyancy Laboratory
https://joshnphoto.com/joshsblog/2017/8/15/nasas-neutral-buoyancy-lab

Achieving true neutral buoyancy in NASA's NBL is essential for effective training, as it helps simulate the environment of space. A central challenge is aligning the astronaut's center of gravity (CG) with their center of buoyancy (CB) within the suit and water. Systemic CG represents the point in the human-suit system where the total weight (mass under Earth's gravity) is considered to act, essentially the average location of the system's mass distribution. The CG is influenced by the subject's body and suit components (e.g., helmet, life support system, weights), and it varies depending on suit weighting, mass distribution, and equipment arrangement.

In the NBL, even when astronauts achieve neutral buoyancy (not sinking or floating), their weight still exists; it is simply counteracted by the upward buoyant force. The CB is the point through which this buoyant force acts on the human-suit system. Misalignment between CG and CB can lead to instability, unwanted body rotation, and increased reliance on safety divers. Even slight offsets can generate torque or righting moments that disrupt posture and motion control. Improper balance may also cause physical discomfort or overuse injuries, particularly if the suit is poorly weighted or fitted. CB influences how the person moves in the suit and can radically alter and effect the human-to-suit interactions. Therefore, CB management is critical for creating realistic, safe, and effective EVA training conditions that accurately mirror the dynamics of space and optimize human-suit interactions.

NASA continues to refine, develop, and expand the understanding of the NBL's CG and CB environment. Achieving realistic static postures and movements remains challenging, often resulting in unrealistic righting moments due to the difficulty of properly attaching weights and foam. Misinterpreting these righting moments at the system or component level can easily be mistaken for high joint torques, suit restrictions, or capability limitations.

The human-to-suit interaction in the NBL differs from in-flight suit interactions because the body is still subjected to 1-g, while suit buoyancy is adjusted to simulate 1/6-g. Approximately 150 to 180 lb of weight are added to the suit for buoyancy and weight adjustment, enabling training on the pool surface. However, this added mass can impact or interfere with specific movements and tasks. Additional challenges include visual distortions from the suit's curved helmet bubble, potentially contributing to motion sickness.

Unlike NBL ISS EVAs—conducted approximately 20 ft below the surface—Lunar Surface NBL runs take place at roughly twice that depth. This depth difference is not a requirement driven by physics, rather a legacy of the facility's construction. Had the NBL been built with an additional floor or customized levels, operations could just as easily be conducted at shallower depths tailored to 1/6-g simulation. This training environment requires a large support team, safety divers, and a staffed hyperbaric chamber ready to address decompression sickness (DCS), which carries higher risk than during ISS EVAs due to the increased depth, as well as substantial facility and hardware reconfiguration between runs. Additionally, risk trade-offs and operational complexities must be considered when evaluating the benefits of any training activity. It remains an open question whether the NBL provides the optimal balance for developing the skills required for partial-gravity surface EVAs.

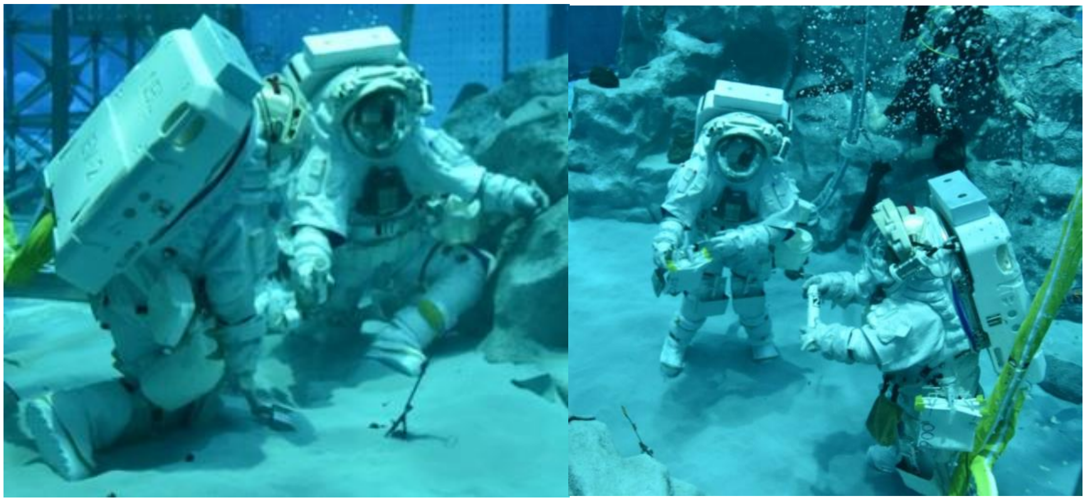


Figure 2-2. Suited testing in the NBL

2.1.2 ARGOS and POGO

The Active Response Gravity Offload System (ARGOS) and Partial Gravity Simulator (POGO) are crane-like systems that physically lift the suit and the subject (Figure 2-3). ARGOS is a robotic system simulating a reduced-gravity environment by providing active offload along three axes (X, Y, Z) using a 3-DOF robotic system. The vertical control (Z-axis) commands the motor to raise or lower the subject to maintain a constant offload force, while the horizontal controls (X and Y axes) keep the lifting mechanism centered above the subject.

In contrast, POGO uses an air-controlled piston for passive offload and can only move along the X and Z axes. Both ARGOS and POGO are typically used for hardware evaluations, suit dynamics testing, and task assessments. These analogs support a wide range of training objectives, enabling end-to-end EVA training, planetary and microgravity mockups, and mid- to long-distance ambulation. They also facilitate one-crew EVA operations. The suits currently used in ARGOS and POGO include the Mark-III (MK-III), xEMU, AxEMU, EMU, and Z-2.

Figure 2-3. ARGOS and AX3S Facilities. ARGOS: blue frame, right; AX3S: black frame, left.

ARGOS offers numerous benefits for training. It can offload any amount of system mass, including the astronaut and expected Portable Life Support System (PLSS) mass, or simulate microgravity, Lunar, or Mars operations. The system provides realistic ground reaction forces, momentum management, and the forces required to manipulate the suit. Additionally, it increases accessibility to the suit, subject, and testing area and allows for rapid adjustments to the CG.

However, ARGOS has several limitations. It only accommodates a single suited crewmember performing EVA operations and is too small for mid- to long-distance ambulation without a treadmill. The system has limited worksite and terrain variety, with no large slopes, while vertical height restrictions prevent hopping. Vertical and horizontal motions are subject to translational acceleration limits. Determining the correct CG is challenging due to the gimbal design and CG variations during different tasks, which can affect stability in specific suited postures, for example, the kneeling position. Pivot point settings are typically a compromise between realism and performance. Human-to-suit interactions differ from in-flight conditions because the suit lifts the subject within the system, and the arms, legs, and tools are not offloaded, possibly making tasks artificially more difficult and physically fatiguing.

2.1.3 ARGOS eXploration EVA Systems

ARGOS eXploration EVA Systems (AX3S) is under construction and not currently in operation. The purpose of this facility is to perform end-to-end EVA training, planetary and microgravity mockups, and to have mid-to-long-distance ambulation. This facility will provide high-fidelity testing and training capabilities. It will be the only dry training environment for two pressurized subjects during suited operations for 6–8 hr of training.

2.1.4 Field EVA Testing

Field training takes place in many different rugged environments and locations, including Flagstaff, Iceland, Nevada National Security Site, and the JSC rock yard. These analog environments serve many purposes and training objectives. Field training allows for higher fidelity geology training, longer-duration traverses, and navigation practice. Additionally, it allows for full scale mission planning/end-to-end EVA training, in-mission risk fidelity, full-scale mockups, and two-person EVA operations over a variety of slopes and terrains for traversing (e.g., walking) or for LTV and PR operations. This training is extremely valuable as it is very difficult to get the same level of geology exposure and navigational training in the other environments. The current suits used in the field include but are not limited to Backpack and Atlas EXCON, which is a simulator suit (Figure 2-4).

There are several limitations to these training environments, this testing requires a lot of travel expense and high overhead. There are environmental considerations such as summer and inclement weather limitations (heat related injury for subjects and support), terrain and foliage, and wildlife. There is a lack of technology infrastructure, access to necessary facilities (e.g., restroom, medical), and everything brought in must be carried in by the limited support. Additionally, the human-to-suit interaction is very different, offering no offloading to the test subject and not as many movement restrictions. This may provide an increase in discomfort and unrealistic significant component of fatigue from the weight of the suit.

A new JSC EVA and Human Surface Mobility (HSM) Program (EHP) Rock Yard (JERY) to will partially address some of these limitations, namely increased infrastructure, is being developed. Though limitations will persist, such as lack of environmental control, the inability for pressurized suited operations, and lack of offload.

Figure 2-4. Simulator suit testing in Atlas EXCON suit

2.1.5 Pressurized 1-g

Pressurized suit in 1-g is not designated to a specific location, rather it is a type of testing that takes place with no available offloading. When pressurized, the suit's legs form air columns that act like air springs holding the suit up. Several factors contribute to the self-supported versus carried load. The amount of the weight being carried tends to vary depending on the tasks. More mobile lower torso assemblies can re-orient and collapse, though this largely depends on the architecture. How the suit is carried, and the feeling of weight distribution, depends on suit fit and contact areas. Additionally, the shoulder harness settings change the distribution of how much is carried through the harness versus what is self-supported. Testing demonstrated shoulder harness loads ranging from 22 to 207 lb—depending on suit fit, activity, and harness tightness, for a suit with an approximate weight of 170 lb—with a range of 168 to 183 lb (Figure 2-5; Davis et al. (2024)).

2.1.6 Assessments of Physiology and Cognition in Hybrid-reality Environments

The Assessments of Physiology and Cognition in Hybrid-reality Environments (APACHE) facility is a ground-based EVA analog that seeks to create a physically and cognitively realistic exploration EVA simulation environment using a combination of virtual reality (VR), physical reality, and hybrid reality (XR). The controlled hybrid-reality lab environment enables rapid development and demonstration of EVA-related research technologies, methods, and capabilities coupled with appropriate flight-like concept of operations (CONOPS) and products. It allows for rigorous evaluation of individual and team performance and an unobtrusive capture of operationally relevant measures of EVA task performance. APACHE (Figure 2-6) boasts a 15' x 20' multiplayer testbed complete with Lunar regolith simulant, allows for optional long-distance traverse through

VR-coupled treadmill systems, and enables EVA-relevant rover/LTV simulation using a six-DOF motion platform. APACHE includes realistic exploration environmental considerations and integrates physiologic sensors, computational models, real-time informatics, and embedded performance measures. Though APACHE does not have the capability for pressurized suited testing, it can be paired with a spacesuit simulator with increasing cognitive immersion over other test environments. Additionally, the capture of unobtrusive measures (e.g., eye tracking) is an additional benefit that is more difficult to capture in other suited simulation environments.

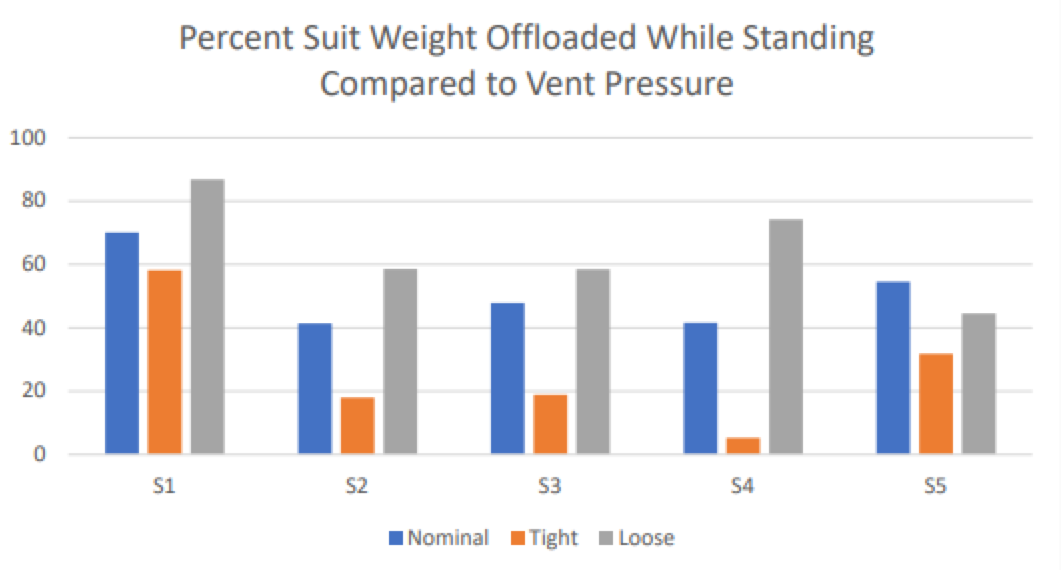


Figure 2-5. Weight distribution based on shoulder strap tightness (Davis et al.,2024)

While the pressurized suited environments provide the highest fidelity simulation, many research questions can be largely examined and evaluated in a lower fidelity simulation environment. With the use of simulation assets like APACHE and hybrid spacesuit simulator (HS3), the EVA and exploration community can evaluate hardware, develop test protocols, and establish baseline measurements that can then be applied to higher fidelity simulations or to research questions. APACHE allows for end-to-end EVA simulation content in both physical and VR. The simulation capabilities of APACHE are constantly being expanded to better promote simulation fidelity, including addition of a six-degree range of motion (ROM) platform allowing for simulated rover operations that provide physical feedback to the VR display and an omnidirectional treadmill enabling freedom of movement and navigation while navigating a virtual Lunar or Martian Surface (rather than just walking on a fixed, straight treadmill or sitting in a chair). Figure 2-7 shows an example of the ability to use the HS3 (described in section 2.2.4) on a treadmill while conducting a simulated EVA in VR. One of the greatest capabilities of the APACHE space is the ability to rapidly and seamlessly integrate sensors and informatics, proving out measures and developing preliminary iterations of physiology and performance-based models before deploying fixtures to complex suited analog environments.

Figure 2-6. APACHE environment

2.1.7 Reduced Gravity Environment

Various Reduced Gravity Aircraft (RGA) or parabolic flights have been utilized in the past. Parabolic flights simulate varying g-levels including Microgravity or Lunar and Martian gravity; however, the g-levels are only maintained for a short period of time, approximately 10 to 30 s per parabola. This environment would allow for the modeling of the flight system CG and enabling ground testing with effective and proper positioning of the CG, ideal for validating effective CGs for ARGOS and NBL, hardware/task evaluations, and training specific skills (e.g., supine recovery). Notably, Apollo mission debriefs cited parabolic flights as the most effective training analog for preparing crews to conduct surface EVAs (Scheuring et al., 2007).

2.1.8 Analog Training Environment Summary

Overall, each simulation environment is critical to further developing and advancing NASA’s space exploration capabilities. However, it is important to understand what limitations will be present when conducting a test in a specific environment. A highly simplified and generalized overview of the analogs can be found in Table 2-1. It is also important to recognize that each training analog offers both advantages and drawbacks, sometimes in direct opposition to one another. For instance, the NBL and ARGOS represent nearly opposite training environments, requiring crew to mentally calibrate their experience to something in between.

Figure 2-7. HS3 operating in APACHE space

2.2 Space Suits and Associated Physiologic Demands

Spacesuits are unique in that they effectively function as an anthropometric, personalized spacecraft. While they are designed to offer environmental protection, mobility, and life support for the astronaut during spacewalks, the spacesuit environment imposes substantial physiological stress on the human body. Due to the pressurized encapsulated nature of the environment, there are limitations on mechanical resistance and restrictions imposed on mobility. Spacesuits are simultaneously critical for an EVA during training or in-mission tasks and impose notable metabolic, MSK, thermal, cardiovascular, and cognitive demands that can degrade human performance, increase injury risk, and influence mission success.

Physiological Considerations

Astronauts expend more energy while performing suited tasks compared to unsuited movement. The spacesuit's internal pressure and architecture introduce stiffness, resistive joint torques, and locomotion inefficiencies, increasing oxygen consumption, caloric expenditure, and muscle activation. Pressurization resists natural motion, reducing joint ROM, and causing compensatory movements that heighten effort and misalignment.

Table 2-1. Analog Training Environments

	1-g	ARGOS	NBL	Field	RGA	VR
Dynamic Motion	Some significant suit weight impacts	Good ground reaction force, and good inertia management	Good ground reaction force, water dominated inertia and dynamic motions	Unpressurized and not fully mocked up	Real 1/6-g effects on entire system	Unpressurized suit simulators with artificial motion restriction, no offloading capability
Operational Factors	Minimal, can develop task specific capabilities	Limited mockups, and single offload suit	Good mockups, developed Lunar station and dual suit operations	MCC integration and dual suit	Limited duration and costly	Dual suit operations, can recreate digital/hybrid mockups
Environmental Factors	Very small workspace	Small space, and requires mockup logistics	~Size of Lunar station	Real rocks/geology and full-scale EVA	Depending on the aircraft the workspace can vary in size, some of which have a small workspace	Small space, realistic immersion in exploration landscape

Thermoregulation and Cardiovascular Stress

The spacesuit regulates internal body temperature generated by physical exertion through the Liquid Cooling and Ventilation Garment (LCVG). During high metabolic tasks or for extended durations, the core body temperature and heart rate can rise significantly. This causes stress to the cardiovascular system by increasing blood flow to support muscle activity, elevating the risk of heat injury and dehydration to the human. In planetary gravity (e.g., Moon or Mars), suit mass and terrain will further amplify cardiovascular workload and sweat loss.

Cognitive and Psychological Load

Beyond physical strain, the spacesuit also imposes cognitive demands due to limited visibility, reduced tactile feedback, and communication delays. Combined with physical fatigue, this can impact task accuracy, reaction time, and decision-making, particularly during longer EVAs or emergency scenarios. Psychological stressors include but are not limited to isolation, team dynamics, confined environments, and performance pressure. Cognitive demand is further explained in Section 4.0.

Operational Implications

While essential for spacewalks, spacesuits introduce significant physiological demands to the human system due to the pressurization, mass, and biomechanical constraints. These restrictions have an impact on metabolic rates, ROM, fatigue, and thermal and cardiovascular regulation. These have a compounding effect that will ultimately influence crew performance and the overall mission success. The increased effort required to perform even basic movements— combined with impaired dexterity and restricted visual fields—can reduce task efficiency and elevate the risk of human error during EVAs. Such limitations must be addressed in future suit designs to enhance performance, reduce injury risk, and support longer-duration missions (Scheuring et al., 2007).

The remaining sub-sections highlight specific spacesuits that are often used during EVA training at NASA JSC. Additionally, each section will briefly touch upon some of the published data on the characterization of the physiological demands (e.g., metabolic rates and mobility constraints). Future testing and results will continue to provide insight and characterization on the physiological demand from the spacesuit environment and additional considerations as we progress towards future space exploration. Future suit designs aim to mitigate these effects through improved joint mobility, lighter mass, and biomechanically aligned design.

2.2.1 Extravehicular Mobility Unit

The Extravehicular Mobility Unit (EMU) is a self-contained life support system designed to protect astronauts during EVA. Historically, the past 30 years of training has been conducted with the EMU (Figure 2-8) in preparation for microgravity operations on the ISS (JSC, 2019). The EMU design is modular, consisting of separate components that can be assembled to fit each astronaut. The upper and lower torso, arms, and gloves are available in various sizes for key hard components (e.g., hard upper torso [HUT]) and can be combined as needed for each mission to accommodate both male and female astronauts. The current suit design can accommodate individuals ranging from a 5th percentile female (5' tall, 110 lb) to a 95th percentile male (6'2" tall, 223 lb). This design is cost-effective since the suits are reusable and do not require custom fittings, unlike the EVA spacesuits used in previous NASA manned spaceflight programs. The shuttle EMU (1979–2002), including the life support backpack and Simplified Aid for Extravehicular Rescue (SAFER), weighs approximately 275 lb (124.7 kg) on Earth and is pressurized to 4.3 psia (29.6 kPa). The ISS EMU (2002−present), including the life support backpack and SAFER, weighs about 319 lb (145 kg) on Earth and is pressurized to 4.3 psia (29.6 kPa).

The associated physiological workloads for completing ISS-focused tasks in the EMU is well understood with respect to average and peak metabolic rates and task durations, including the differences between NBL training and in-flight, based on 30 years of NBL training and a defined process for EVA qualification. Figure 2-9 shows an example of the metabolic rate differences in the NBL versus in-flight in the EMU suit for both shuttle and ISS operations (Cox, 2024; Norcross et al., 2023).

The EMU suit imposes significant mobility limitations due to its rigid, gas-pressurized design. The suit restricts natural joint movement, particularly in the shoulders, hips, and knees, resulting in a reduced ROM. Due to the HUT shoulder design, there are imposed restrictions to nominal joint motion (e.g., scapulothoracic motion) of the shoulder during donning/doffing and specific mobility tasks. Additionally, the HUT also increases the internal rotation of the shoulder, increasing injury potential during nominal operations, both in training and in-flight (Williams & Johnson, 2003).

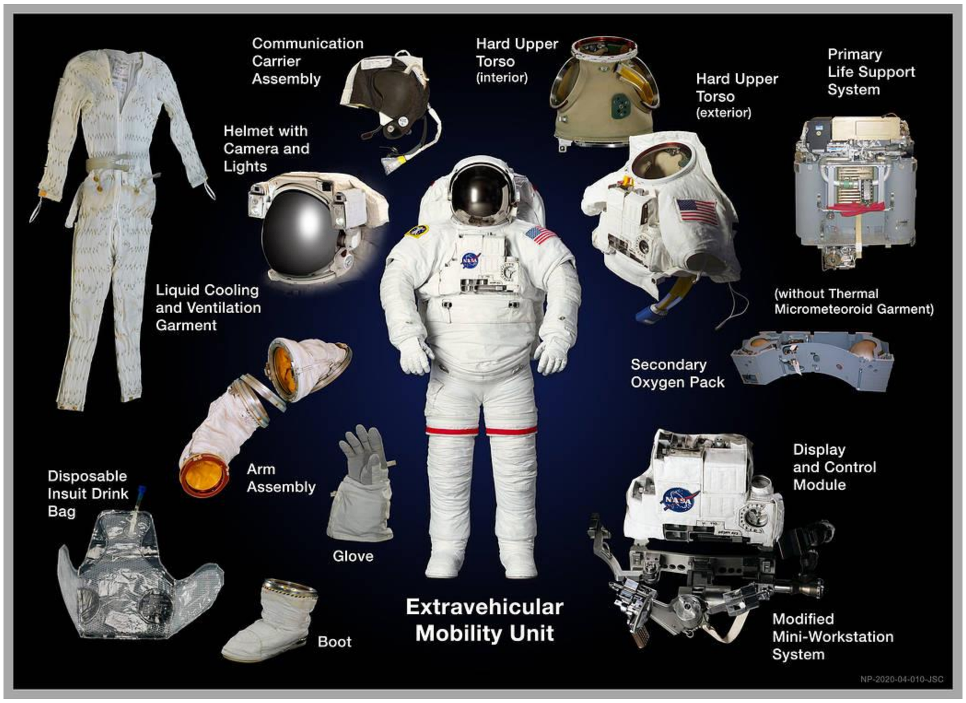


Figure 2-8. Extravehicular Mobility Unit
https://www.nasa.gov/image-article/extravehicular-mobility-unit-emu/

The suit's substantial mass and bulky structure reduces speed of movement and mobility, while the fixed helmet restricts peripheral vision and limits spatial awareness, requiring astronauts to reposition their entire bodies rather than simply turning their head. Furthermore, while weight is not an issue in microgravity, it becomes an important factor when planetary gravity is introduced. These factors collectively impair movement efficiency during EVA. During suited operations in the EMU, it becomes increasingly difficult to perform movements such as bending, or single leg kneel in the suit, actions essential for planetary surface EVAs. Sustained EVA operations last 6−8 hr, placing an astronaut under continuous physical and cognitive stress, further heightened by the resistance imposed by the pressurized suit and/or specific analogs.

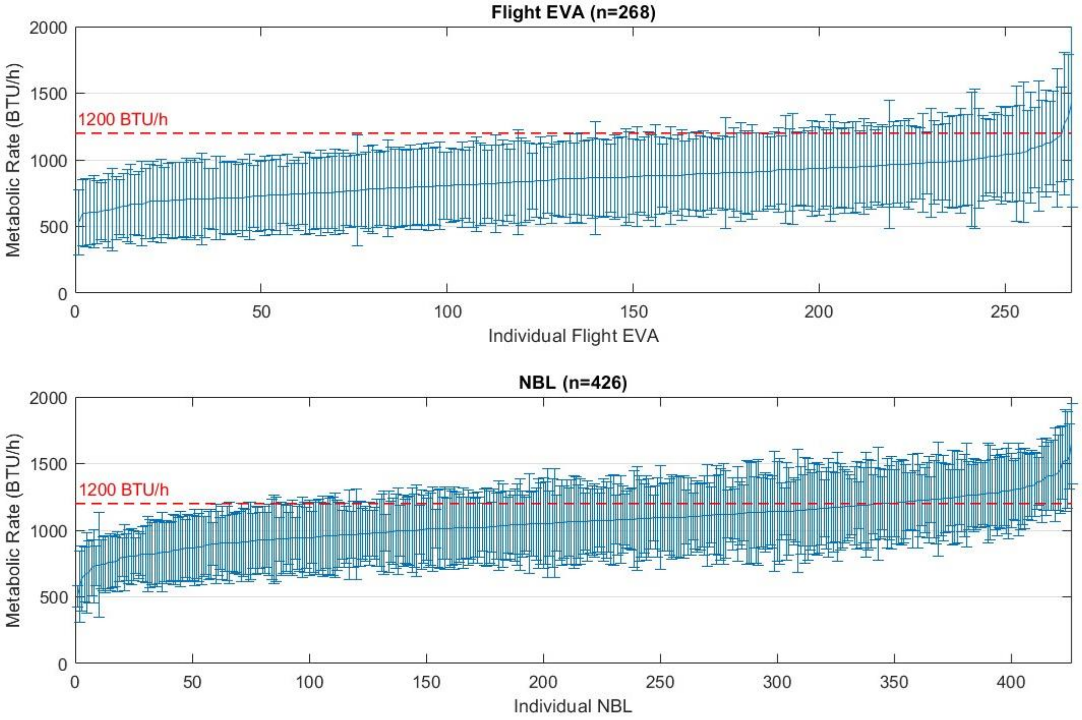


Figure 2-9. Metabolic rate differences. Top: EMU suit. Bottom: NBL training environment. Each point represents one subject. The 1200 BTU/hr. line corresponds to the xEVAS System Requirement Document (SRD) and is associated with RQMT-017.

2.2.2 Mark III

The Mark III (MK-III) was developed by ILC Dover under contract with NASA as part of the Advanced Space Suit Program (Figure 2-10). Designed as a rear-entry, hybrid hard-soft suit for planetary surface exploration and zero-prebreathe EVA operations, MK-III operates at up to 8.3 psi, a significant increase from the 4.3 psi used in the EMU. Although the MK-III was developed as a technology demonstrator and not an operational flight suit, it helped to inform the design of later spacesuit concepts such as the Z-series and the current xEMU. This suit weighs 59 kg (or 130 lb), with a 15 kg (33 lb) PLSS. The suit consists of a HUT, hard hip and waist brief, shoulder, upper arm and ankle bearings, and soft fabric joints at the elbow, knee, and ankle.

Despite incorporating hard upper and lower torso components and multiple joint bearings, the suit's hip brief assembly has limited ROM, restricting normal gait mechanics. As a result, suited subjects exhibit wider stances, reduced foot clearance, and shorter stride lengths, with resistive torques at the hip joints reaching up to 16 Nm (Cullinane, Rhodes, & Stirling, 2017). Although mobility is enhanced compared to the EMU, biomechanical modeling reveals that the MK-III still imposes elevated MSK loads, particularly in the knee flexor muscles, potentially causing increased fatigue during prolonged activity (Diaz & Newman, 2014).

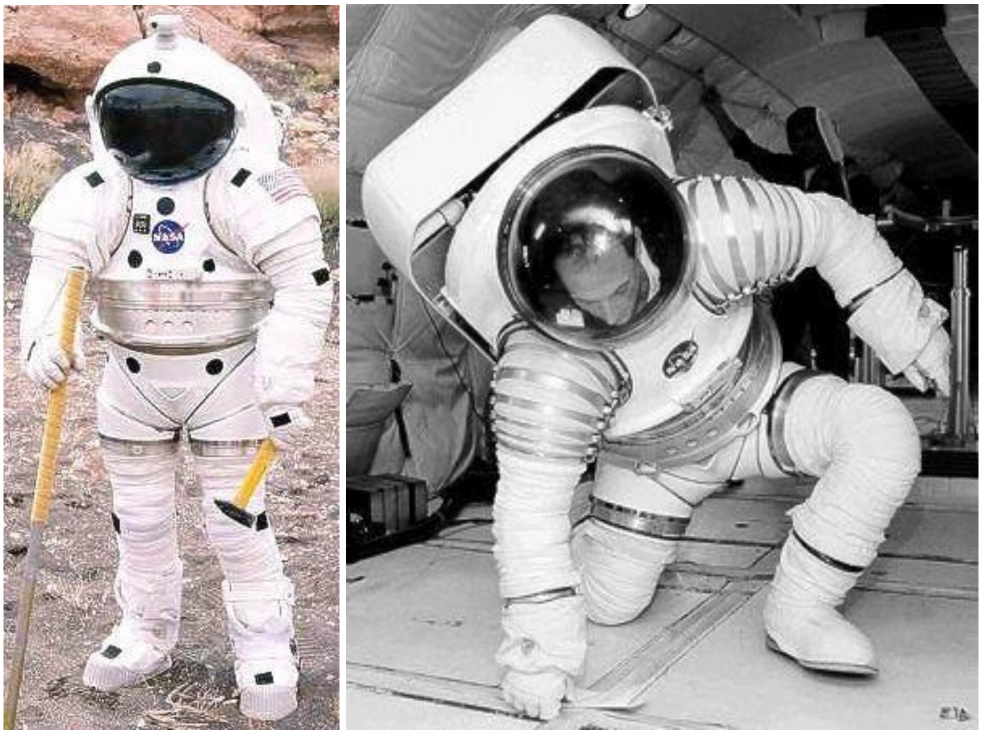


Figure 2-10. Mark III Spacesuit(MK-III) (Diaz & Newman, 2014)

Lastly there is an increased metabolic burden during level and inclined traversing and during EVA while wearing the MK-III under planetary gravity conditions compared to unsuited baseline performance (Norcross et al., 2010a, 2010b). Norcross et al. (2010b) evaluated the mobility of the MK-III planetary suit through level treadmill ambulation in POGO with variations in suit configuration, specifically changing suit pressure and locking or unlocking waist rotation. Their findings demonstrated that the suit imposes measurable restrictions to nominal gait. Specifically, internal padding reduced cadence by approximately 20% and knee ROM by 16% compared to unsuited walking. Locking the waist bearing further constrained hip rotation and increased metabolic rate. Mobility limitations were thus tied to kinematic stiffness and suit fit, with restricted articulation degrading gait efficiency and elevating exertion levels.

Norcross et al. (2010a) investigated mobility during inclined treadmill ambulation (up to 30% grade) and short exploration tasks in the MK-III suit under Lunar gravity analog conditions (in POGO). They varied suit pressure (1.0–6.5 psi) and maintained constant suit mass (of 121 kg) to isolate pressure-related effects. As incline increased, hip, knee, and ankle joint ROM all increased, with the greatest ROM occurring at the lowest suit pressure. There was a noticeable change in joint ROM particularly around 4.3 psi, suggesting altered gait mechanics. Cadence slowed and subjects adopted shorter, more frequent steps to compensate for suit inertia and stiffness. Waist-bearing movement also decreased with increasing pressure, indicating restricted torso rotation. Despite varied pressure having minimal effect on subjective rate of perceived exertion (RPE) during exploration tasks, performance metrics and mobility demands clearly varied with pressure and incline, highlighting that suit pressurization and kinematic constraints significantly influenced gait efficiency and functional mobility in reduced-gravity environments.

2.2.3 Exploration Extravehicular Mobility Unit

As a steppingstone to the Artemis mission NASA's Advanced Space Suit Team at JSC, started the development in 2019 of the Exploration Extravehicular Mobility Unit (xEMU; commonly referred to as the xPGS [Exploration Pressure Garment System]). This suit was designed to maximize planetary and microgravity mobility and enable EVAs in the harsh conditions of permanently shadowed regions on the Lunar Surface. It features a rear-entry design and incorporates a combination of soft and hard materials to balance mobility with system mass efficiency. The upper torso assembly (UTA) includes a HUT, rear hatch, rolling convolute shoulder joints, helmet, extravehicular visor assembly, EMU arms, and Phase VI gloves (Davis et al., 2020). The lower torso assembly (LTA) is comprised of a waist, brief, and hip assembly (WBH), along with EMU-style legs and planetary boots (Davis et al., 2020). The xEMU is designed to accommodate a broad anthropometric range, continuing NASA's commitment to inclusivity in suit sizing established in previous suit designs. The full xEMU weight (pressure garment system, PLSS, and informatics) planned was approximately 300–350 lb, approximately 50–58 lb in Lunar gravity. More information about this xEMU spacesuit can be found in these articles (Figure 2-11): Davis et al. (2024); Davis et al. (2020); McFarland, Campbell and Rhodes (2023); Rhodes, Flaspohler and McFarland (2023); Ross, Rhodes and McFarland (2019).

Due to the design of the joints, there is some programming required to manipulate the convolute joints to a desired position. It is often suggested that, during fit checks, the subject move each joint through its isolated ROM to get a feel for each joint's unique movement (Figure 2-12).

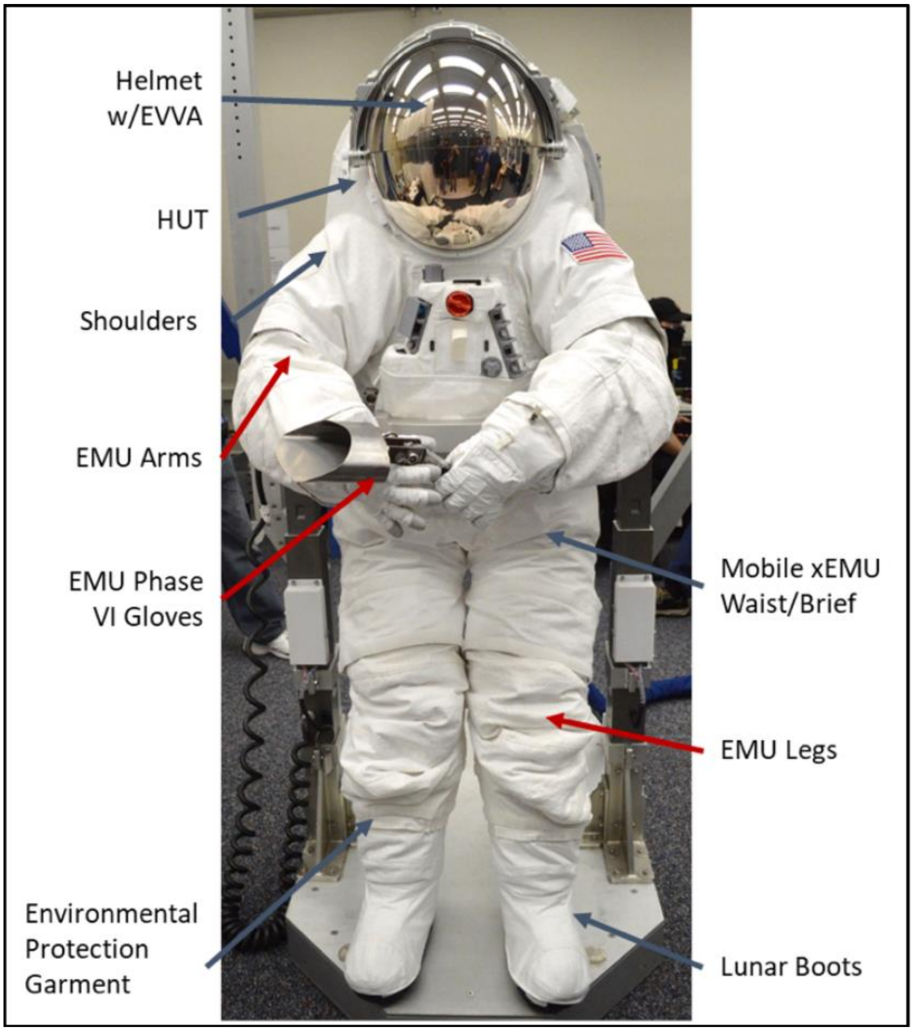


Figure 2-11. xPGS design overview

Functional mobility and ROM testing was conducted in the xEMU with seven subjects performing two different testing sessions, a familiarization (FAM) run and a data collection run. This testing was done in ARGOS with offloading to simulate Lunar gravity (1/6-g). The FAM test aimed to acclimate subjects to the suit's performance and the testing environment while optimizing gimbal settings and measuring isolated ROM and reach via motion capture. The subsequent data collection test assessed dynamic movements, functional task performance, and comfort. One notable task involved navigating a regolith trailer with scattered rocks and using geology tools. Functional task performance confirmed the suit's compliance with xEMU requirements. ROM data was collected using Vicon motion capture, although challenges such as marker obstruction by suit hardware affected data fidelity. The ROM data was exploratory, with no strict pass/fail criteria, and aimed to support future mobility optimization and suit sizing evaluation. ROM values from this testing can be found in Table 2-2.

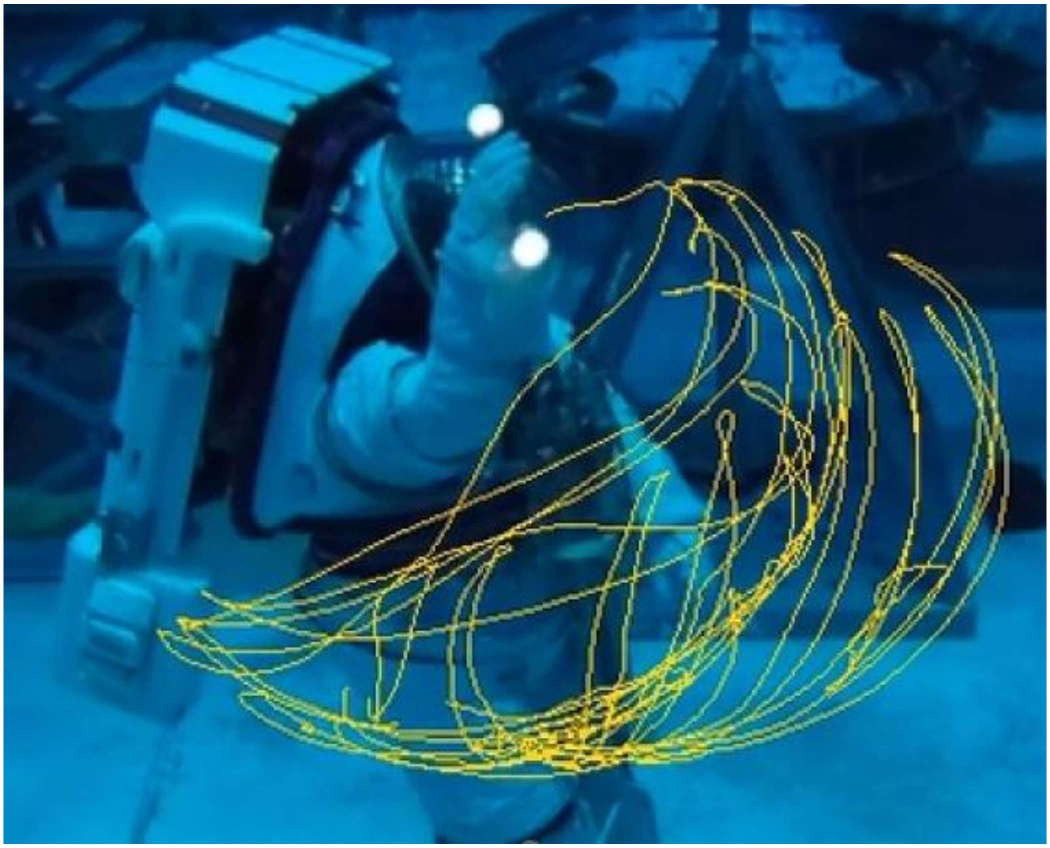
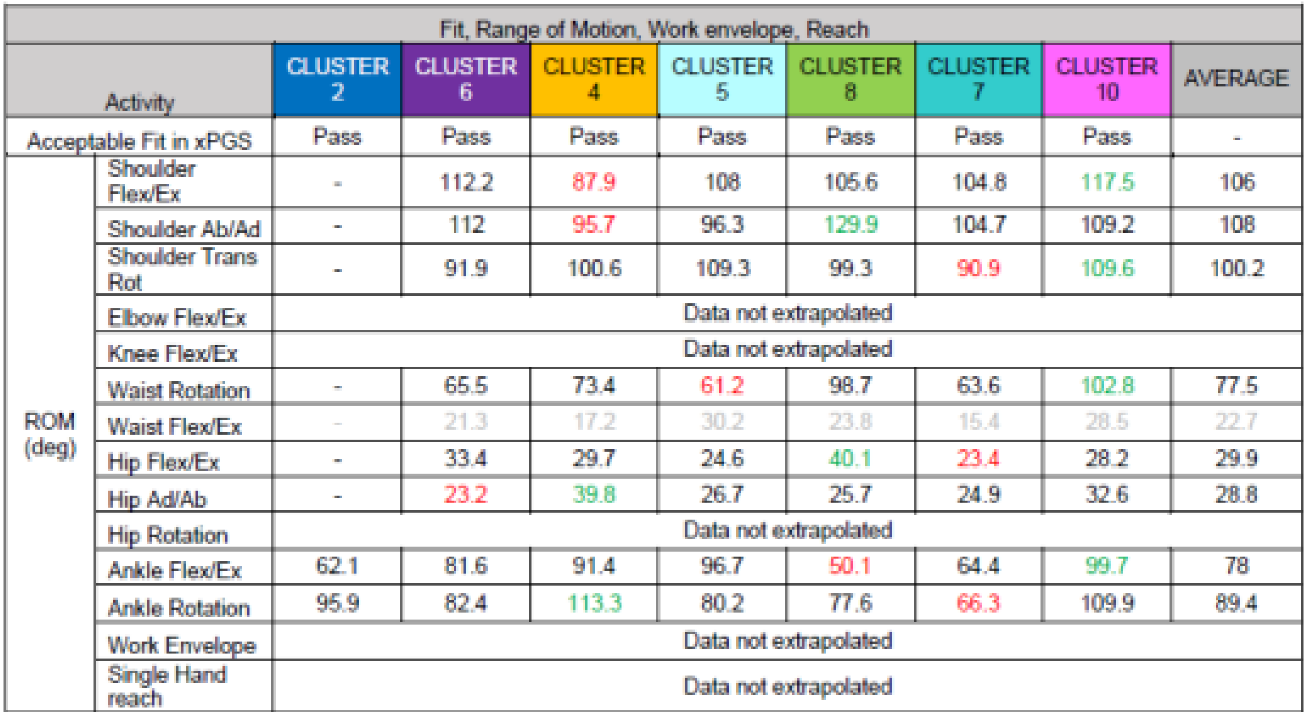


Figure 2-12. Trace lines of shoulder movement

As we advance toward the future of space exploration and adopt the vendor's next-generation spacesuit, it is imperative to rigorously characterize and investigate the metabolic, MSK, thermal, cardiovascular, and cognitive demands these systems impose on crewmembers. Comprehensive research across these domains will be essential to safeguard crew health, optimize performance, and ensure mission success.

Table 2-2. ROM for *Test* Subjects*(green = maximum value; red = minimum value (Rhodes, Flaspohler, & McFarland, 2023)).*



Fit, Range of Motion, Work envelope, Reach									
Activity		CLUSTER 2	CLUSTER 6	CLUSTER 4	CLUSTER 5	CLUSTER 8	CLUSTER 7	CLUSTER 10	AVERAGE
Acceptable Fit in xPGS		Pass	Pass	Pass	Pass	Pass	Pass	Pass	-
ROM (deg)	Shoulder Flex/Ex	-	112.2	87.9	108	105.6	104.8	117.5	106
	Shoulder Ab/Ad	-	112	95.7	96.3	129.9	104.7	109.2	108
	Shoulder Trans Rot	-	91.9	100.6	109.3	99.3	90.9	109.6	100.2
	Elbow Flex/Ex	Data not extrapolated							
	Knee Flex/Ex	Data not extrapolated							
	Waist Rotation	-	65.5	73.4	61.2	98.7	63.6	102.8	77.5
	Waist Flex/Ex	-	21.3	17.2	30.2	23.8	15.4	28.5	22.7
	Hip Flex/Ex	-	33.4	29.7	24.6	40.1	23.4	28.2	29.9
	Hip Ad/Ab	-	23.2	39.8	26.7	25.7	24.9	32.6	28.8
	Hip Rotation	Data not extrapolated							
	Ankle Flex/Ex	62.1	81.6	91.4	96.7	50.1	64.4	99.7	78
	Ankle Rotation	95.9	82.4	113.3	80.2	77.6	66.3	109.9	89.4
	Work Envelope	Data not extrapolated							
	Single Hand reach	Data not extrapolated							

2.2.4 Simulator Suits

Some simulations or research studies do not require the full fidelity of a pressurized spacesuit or are not able to provide that capability due to the environment. In these instances, suit simulators can play a large role in providing elevated simulation quality in 1-g environments. Simulator suits like the Atlas EXCON, field backpack, or hybrid spacesuit simulator (HS3) (described below and shown in Figure 2-13) provide many advantages like workload simulation, partial limitation of movement, and enhanced informatics allowing for training with increased fidelity despite lack of a pressurized spacesuit.

The field backpack is the lightweight operationally focused “suit simulator” that is used in simulated EVA field testing. The backpack is focused on operational capability, providing communication, global positioning system, lighting, and a waist belt to interact with tools. The backpack does represent some of the volumetric representation of the PLSS but largely lacks any mobility restrictions found in a spacesuit. Unloaded, the backpack weighs about 50 lb and about 70 lb when loaded with tools and equipment.

The Atlas EXCON suit was designed to provide mobility restrictions during simulated EVA field tests, with the simulator having suit-like hip, waist, and arm bearings. The EXCON suit has the capability to integrate the Lunar toolbelt and provides a strong volumetric mockup of the upper half of a spacesuit. The challenge with the EXCON suit is that while most of it is made from lightweight material, the unloaded suit still weighs close to 70 lb, increasing to about 90 lb when loaded with tools and equipment. This provides an intense workload for the subject to manage while in the field.

As part of the HHP research effort at JSC, the EVA and Environmental Physiology Laboratory (EEPL) developed the HS3 to be a low-cost physical and cognitive workload approximator that could be used by research studies or training to improve simulation quality when a pressurized spacesuit and/or partial gravity facility is not necessary or available. The HS3 consists of a soft outer suit, thermal control, gloves, boots, helmet, and integrated bioinformatics and communications. The purpose of HS3 was not to replace suited testing or other suit simulators, rather it offers increased simulation quality and relevant workload to tasks that would otherwise be tested in a shirt-sleeve environment. The EEPL team uses HS3 to evaluate hardware, develop protocols, and answer preliminary research questions that can then be applied to higher fidelity suits, simulations, and/or future missions.

While the simulator suits add some fidelity with their addition of communication systems, tools, and integrated operations, they have several limitations. Since the simulator suits operate in 1-g, they cannot fully replicate the ROM or mobility limitations observed in a pressurized suit, and the heavy external load may increase the risk of MSK injuries.

The Joint EVA & HSM Test Team (JETT) is an EVA & HSM Program (EHP) sponsored and systems engineering group comprised of testing SMEs and stakeholders from across the exploration community. The JETT focuses on developmental testing for EHP projects and testing of the CONOPS for EHP systems. JETT also develops, integrates, and executes integrated human-in-the-loop (HITL) tests and analogs related to EHP projects, including EVA, surface mobility (LTV and PR), technology development, and mission implementation. As mentioned before, testing in 1-g environments with simulators suits can be very physically demanding. Several field-based test events in Arizona, USA, and Iceland have been conducted to assess Lunar EVA concepts of operations, hardware, and science-focused integrations pertinent to execution of exploration operations. These field-based simulations often include high-fidelity tools and spacesuit simulators to best emulate Artemis-like campaign activities. One such test includes the third major integrated field test hosted by JETT (Miller, 2023), known as JETT3, which included a four-part EVA series and utilized two different suit simulator mockups: the Atlas EXCON suit simulator was used to conduct more EVA-realistic operations, while an integrated informatics field backpack was used for conducting more operational and technology-focused demonstrations. Table 2-3 shows data from JETT3 testing, where EVA 1 & 2 were in the Atlas EXCON and EVA 3 & 4 were with a backpack simulator.

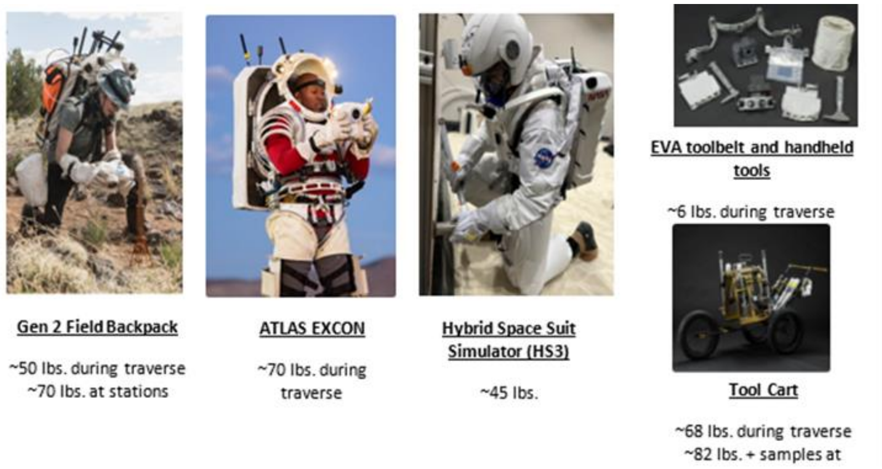
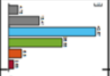
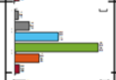
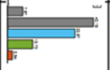
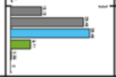


Figure 2-13. Simulator suits used in 1-g simulated EVAs

Table 2-3. Workload Data from JETT3 Field Test Series

	Heart Rate (%Max HR)	Speed (kmh)	Distance (km)	Slope Along Track (deg)	Duration (hr)	% Time spent in HR zone (median [Max])		Bedford Rating
EVA1	Avg : 63% **EVA Max : 92%**	Avg = 1.1 Mx = 4.3	3.67	Avg = 5.1 Max = 16.2	3:27		Light Zone [Max]	3
	Avg : 64% **EVA Max: 95%**	Avg = 1.1 Mx = 4.9	3.86	Avg = 5 Max = 16.2			Light Zone [Max]	6
EVA2	Avg : 54% EVA Max : 82%	Avg = 1.2 Mx = 5.2	3.84	Avg = 3.6 Max = 18.1	3:06		Mod Zone [Max]	3
	Avg : 60% EVA Max: 83%	Avg = 1.2 Mx = 6.7	3.78	Avg = 3.5 Max = 18.1			Very Light [Hard]	6
EVA3	Avg: 60% EVA Max: 89%	Avg = 1 Mx = 5.4	4.91	Avg = 9.4 Max = 32.4	4:45		Very Light [Hard]	1
EVA4	Avg : 61% **EVA Max: 92%**	Avg = 1.3 Mx = 5.5	7.81	Avg = 4.2 Max = 22.6	5:56		Very Light [MAX]	1
	Avg : 56% EVA Max : 85%	Avg = 1.1 Mx = 5.8	4.97	Avg = 3.5 Max = 11.4			Very Light [HARD]	1

Both subjects from this JETT mission saw max heart rates reach over 90% of their maximum heart rate during EVA 1. As seen in the Table 2-3, the long duration of field EVAs seem to pose a challenge for the subject physical and mental workload. The Bedford ratings of mental workload for EVAs when the subjects were in the EXCON suit were much higher than the field backpack EVAs. The volumetric mockup of the EXCON requires more attention to operate the suit, while the field backpacks were often found to feel more familiar and took less mental focus on operating. While these suits attempt to provide some simulation quality, the long duration of the simulated EVAs with the weight of the suit simulators may pose a risk of injury to the subjects. There is a constant effort from a variety of teams (Flight Surgeons, physical therapist/athletic trainers, test team, etc.) to help ensure we are keeping subjects safe when conducting operations in 1-g.

The EEPL team conducted testing to evaluate the workload of specific tasks with the HS3 (Figure 2-14). This study took eight subjects with prior suited experience and ran them through a simulated 3-hr EVA in the APACHE test space while wearing the HS3. The timeline was structured so the tasks were standalone, with 3-min rest periods in between, allowing subjects to ideally achieve a steady state workload for that task. Both physiological and subjective measures were captured to characterize the physical and cognitive workloads seen during the simulated EVA.

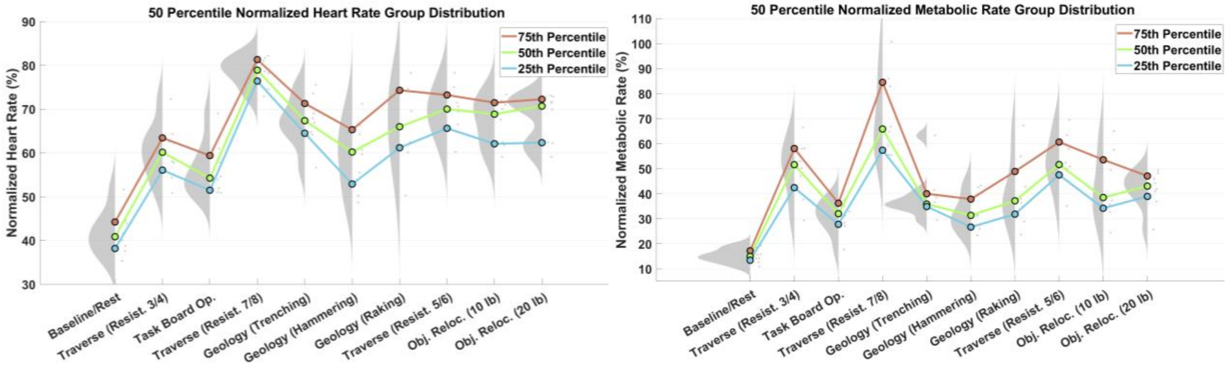


Figure 2-14. Physiologic results from HS3 Characterization Study. Left: Normalized Heart Rate. Right: Normalized Metabolic Rate

This data gave us initial ranges of expected workloads for conducting various EVA tasks in the APACHE test space. The data showed that the high resistance/incline traverse was the most demanding task in the timeline. While there are still challenges with attempting to compare this data to other suited analogs, the capability to repeat controlled tasks and studies opens the door to assessing suit simulator workloads and gaining insight into how they differ to other analog or suited environments.

2.3 Artemis Training for the Missions

Crewmembers have varying degrees of training with ISS (microgravity) and space shuttle experience. The purpose of this section is to outline the Artemis training plan for assigned crew (prime and back-up crewmembers). The training schedule will depend on the types of activities to be conducted on the Lunar Surface. The major tasks and specific postures for early Artemis missions can be broken down as follows:

EVA Prep/Post

- Fine motor skills
    - Buttons on A/L panels
    - Switches on suit
    - Configuring tools on suit
- Cross-body arm motion and extended reach
    - Servicing and cooling umbilical (SCU) disconnect/connect
    - Helmet light adjustment
- Fine body adjustments
    - Self-Egress/Ingress in don/doff stand

Egress/Ingress

- Squatting
- Ladder climb
- High leg lifts
- Arm extended reach
- Suit donning/doffing

Traverse

- Ambulating
- Pushing/Pulling
    - Ambulating with cart
- Carrying tools while ambulating

- Scrambling (all fours)

Contingency

- Prone and prone-to-recover
- Supine and supine-to-recover
- Pushing/pulling
    - Incapacitated Crew Rescue (ICR)
    - Assisted Crew Rescue (ACR) with cart

Geology

- Sample deposits in bags
- Kneeling
    - Single knee kneel
    - Double knee kneel
- Fine motor tasks
    - Closing sample bags
    - Deploying sample markers
- Science payload deployment
    - Lifting
    - Carrying at waist level
    - Pushing/pulling
- Raking and trenching
- Coring
    - Hammering with overhead motion
- Hammering
    - Standing
    - Kneeling
- Scooping while kneeling

Figure 2-15. Common suited positions

For the first Lunar Surface mission, the tentative and draft (pending approval) testing and training schedule is proposed with the following numbers:

- Suited events over a 24-month period: 32 events
  - 8 NBL runs per prime crew, 13 total runs with 4 trained crew
  - 3 ARGOS runs per crew, 12 total
  - 11 AX3S runs per crew, 13 total
  - 1 vacuum chamber per crew, 4 total
  - 2 dust mitigation operations (ops), 4 total
  - Vehicle/airlock mockup classes
    - 3 prep & posts per prime, 5 total
    - 20 HLS EVA hardware/interface classes
  - 7−10 rock yard events (Atlas EXCON/backpack); night ops
- Suit systems classes/events: 19 per crew, 91 hr
- VR/Traverse planning events: 9 per crew
- Mission-specific science ops: 20 hr per prime crew
- Photography classes: 2 per crew
- Payload classes: 3 per crew
- Science classes
  - 120 classroom hr

    - 50 fundamental science hr
- Field hours
    - 294 total hr
    - 26 fundamental hr

It is tentatively planned to prioritize NBL training to ensure the crew have accomplished their eight runs. ARGOS training will be utilized as necessary. When AX3S is available, these runs will be prioritized, due to the multiple benefits of the AX3S. The vacuum chamber exposes crew to class 1 (defined as flight certified suit that contains all the mission critical systems and components) hardware and dust mitigation ops. Crew will also have classes consisting of but not limited to vehicle, geology, navigation, hardware, tools.

During the FY 23 SERPO TIM, Dr. Harrison "Jack" Schmitt, Ph.D. (Apollo 17 Astronaut and geologist) recommended that pre-flight training focus on hands-on field-based geology to prepare the crew with adequate geology skills required for planetary surface operations.

Currently, NBL training has a well-defined schedule (8 runs) and training objectives, including planetary surface operations, HLS/EVA contingency, and notional EVA CONOPS. Initial training will target proper suit fit, suit mobility skills, and facility test environment FAM sessions, all which may affect training time. HLS/EVA runs will be utilized for contingency scenarios involving EVA-like HLS failure, incapacitated crew rescue (ICR), and other off-nominal conditions. Notional EVA timeline runs will emphasize end-to-end surface sortie execution, with a focus on two-crew interactions, payload handling, detailed test objectives, and representative science tasks. Currently, AX3S is expected to be a training location for the first Lunar Surface mission; the training schedule and objectives are still in planning phase.

3 Physical Domain

3.1 Musculoskeletal Injury Considerations

3.1.1 Historical Musculoskeletal Injury Data

Musculoskeletal (MSK) injuries within the Astronaut Corps are the primary reasons Astronauts seek care from medical. From January 1, 2009, to December 31, 2019, the incidence rates of non-surgical MSK injuries were 0.68 per person per year. Delineating this rate based on flight status timelines, there is an incident rate of 0.86 preflight, 2.06 in-flight, and 1.24 per person per year in the one year post-flight. These injuries were most notably observed in the upper extremity with a larger incidence rate in the hand, wrist, and shoulder when compared to other regions. This data was obtained from a data pull on July 2021, which included all MSK conditions from 2009–2019 (from Lifetime Surveillance of Astronaut Health). From the beginning of the Shuttle Program to 2008, there have been 88 surgeries performed, with the majority involving the shoulder. This well-established trend of increased MSK injuries led to the development of the Musculoskeletal Medicine and Rehabilitation program in 2011, which provides Sports Medicine and Rehabilitation services to the Astronaut Corps. In addition to this program, previous efforts (as discussed in section 1.1) have been made to reduce the risk of suited injury in the EMU through the Shoulder Tiger Team (Williams & Johnson, 2003), the development of the EVA Work Hardening program, and robust issue and injury tracking through the Suited User Incident Tracking System (SUITS) survey and the electronic medical record (EMR). The SUITS database has encouraged proper reporting of suit related issues across all training environments and suits. With the implementation of these programs, and the decreased volume of ISS EVA training due to operational changes, a large decrease in upper extremity injuries has been observed (Scheuring, 2013). As of 2017, new Astronaut Candidates (ASCANS) are educated at the start of their NBL and EVA training flow on MSK injury considerations and suited performance of the EMU. In addition to this training, from 2013–2017, there was an EVA syllabus overhaul that incorporates a progressive exposure to training, reducing initial training time in the suit, inverted operations, and targeting an optimal suit fit prior to progressing to full training. Although this current data reflects and mission demands of the shuttle and long-duration ISS missions, this information provides a foundation for developing sustainable programs for Artemis and future space exploration.

Musculoskeletal injuries are multifactorial and have a complex interworking of risk factors. During an extensive literature review including systematic reviews of civilian, military, and athletic populations, there were consistent trends in modifiable and non-modifiable extrinsic and intrinsic risk factors that contribute to MSK injuries. Relevant to the contents of this document, there is strong evidence to support an elevated risk of sustaining a MSK injury if there is a prior history of injury, increased training volume, lack of skill acquisition, elevated external load, and diminished total physical fitness level. Additionally, there is moderate to strong evidence to support that rapid identification, early intervention, and proper conservative management through physical therapy, athletic training, and escalation to advanced care when necessary. This is vital to reducing the severity of injury, reducing lost training time during rehabilitation or recovery, and limiting impact on the mission (Bullock et al., 2023; de la Motte et al., 2019; de la Motte et al., 2017; Hoppe et al., 2022; Kakouris, Yener, & Fong, 2021; Sammito et al., 2021; Whittaker et al., 2017).

It is understood and well-documented in the literature that other load-carrying environments including military, fire, and police have an increased risk of MSK injury. Notably, in each of these communities there is a range in incidence rate as low as 136 injuries per 1000 per year and as high as 49.5 injuries per 100-man hours. Consistently reported in each of these studies is a trend towards injuries in the lower extremity, spine, and compressive neuropathies with direct correlation to an increased risk with elevated external or applied load and frequency of training ((DCPH-A), 2024; Division; Hauschild et al., 2017; Knapik et al., 1992; Lovalekar et al., 2020; Molloy et al., 2020; Ruscio et al., 2010). Each of these tactical environments have established fitness requirements, which allows for the relationships to be observed between fitness and injury risks. Most notably cardiovascular fitness and total body strength are largely correlated to an individual's risk of developing an MSK injury (Fox et al., 2020; Hauschild, 2016; Nindl, 2015; Orr et al., 2010; Orr et al., 2016; Orr et al., 2021; Robinson et al., 2018; Shumway, 2019).

Lunar Surface EVAs will provide new challenges to performance optimization due to the complexity of pre-flight training analogs, limited in-flight exercise capabilities, transition to a novel gravitational environment, and increased operational tempo for EVAs compared to historical operations. Artemis Lunar Surface operations will present new challenges and new risks. With less comprehensive exercise countermeasures, in transit and in the HLS compared to ISS, crew may exhibit functional performance deficits on the Lunar Surface. Apollo astronauts demonstrated a range of performance decrements and MSK concerns. The Apollo crewmembers reported feeling "wobbly" when first walking on the Lunar Surface, and falls were common (Scheuring et al., 2007; Thuro & Stirling, 2021). Fatigue in the upper extremity, attributed to glove and suit design, led to difficulty with multiple gripping tasks such as unscrewing core tubes, hammering drive tube samples, and gripping the ladder. Inadequate sleep and dietary caloric intake were also identified as contributing factors to overall performance fatigue. During the approximate 80 EVA hours, there were nine MSK injuries reported on the Lunar Surface. These injuries primarily involved the hand, wrists, and shoulder.

The Apollo missions demonstrated that humans are able to work effectively with an adaptive gait and locomotion strategies effective in 1/6-g during short stays in partial gravity, but the effect of longer stays poses many unknowns (Scheuring et al., 2007). With longer transit—up to 2.5 times for Artemis missions compared to Apollo missions—there is an increased likelihood of physiological deconditioning and disorientation after Artemis crew land in the novel 1/6-g environment. Crew will require time (several hours to days) and rehabilitation to optimize their sensorimotor functions in 1/6-g; however, the necessary recovery time has not been defined and is likely to vary between crewmembers. In transit deconditioning and engaging in Lunar Surface operations prior to full adaptation could increase the risks of MSK injuries, work inefficiency, falls or fall-related injuries, and suit or vehicle damage.

3.1.2 Concerning Suited Positions

As discussed in section 2.2, planetary suits will offer a robust design for longer, independent surface operations with greater mobility and mass than the current EMU, contributing to novel movement demands required to perform nominal operations. This section will discuss the current understanding of positions that may increase injury risk during training and surface EVAs and must be fully characterized and monitored. An important consideration when observing the suited motion is what you see the suit doing is not always representative of the motion of the human inside of the suit. The inside of the suit may have a fair amount of space, depending on the subject's anthropometry and suit fit. For example, a subject with thinner legs would have more room to move around and may have more difficulty controlling the suit. In these positions the subject inside of the suit may be in a more extreme ROM than what is visible from the outside of the suit. Simulation quality of the environment may contribute to the specific position, or posture, and may not be a concern for flight. However, since most of the suited time occurs in the training environment, they must be considered to reduce the risk of training related injuries. The objectives for the following sections describe and explain the following:

- Description of the suited position and the anatomical considerations or concerns
- Load and frequency of the task and whether it is environment specific
- Incorporation of preliminary ergonomics model analysis of these positions
- Potential injuries that may incur

3.1.3 Ergonomic Task Characterization

A suited ergonomics model has been developed to characterize common EVA tasks based on suited motion capture data and suit-human mass models. The three main outputs from the ergonomics model are suit joint angles, extreme hip and shoulder postures, and static joint moments (Figure 3-1). Suit joint angles are the angles between the suit components, such as the rotation of the hip and shoulder bearings. These angles allow for the quantification of the ROM required at each suit joint to complete a task. The extreme hip and shoulder postures are the maximum angular differences from a neutral suited position at these joints. The static joint moments represent the moments required to be produced to maintain a given posture (and do not consider dynamics, which would greatly affect biomechanical demands during tasks such as hammering). The data presented in this section is sourced from a preliminary analysis of the motion capture data from Pressure Garment Subsystem Design Verification Testing (DVT) of the xEMU, in which nine subjects performed a variety of functional mobility tasks at ARGOS (1/6-g offload). Twenty-four tasks were selected for evaluation, including traverse, surface mobility, geology, and suit reach tasks. The current analysis assumes a Lunar gravity environment and doesn't account for the effects of ARGOS simulation, including the lack of limb/tool offloading.

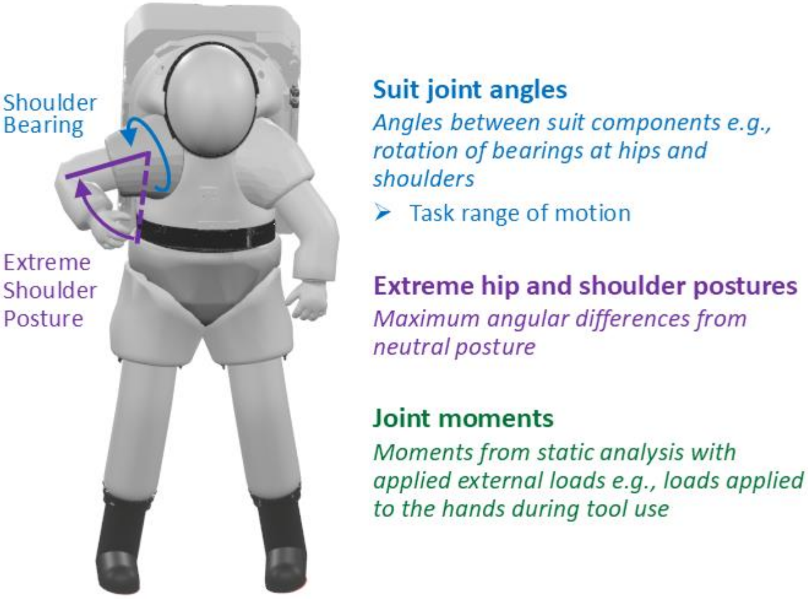


Figure 3-1. Kinematic and kinetic variables

3.1.4 Single Leg Kneel

Description of Concern

This position occurs when the crewmember is on a single knee with the other leg outstretched straight in front or rotated out to the side. Particularly in this position, the hip, knee and ankle have the potential to be at extreme angles inside of the suit. An example of the single leg kneel postures are shown in Figure 3-2. Subjects are often in the kneeling position to accomplish EVA tasks or during fall recovery. Simulation quality affects the stability and weight distribution causing various loads and/or strain on the lower extremity, depending on the subject's preferred strategy.

Due to the design of the LTA in the xEMU, crew have reported challenges with the soft goods limiting their ability to kneel, remaining in a stable position: it is difficult to bend at the waist and reach the working surface due to the CG issues contributing to a falling forward motion in specific analogs. This contributes to the subject utilizing most of their body (trunk and lower extremity) to maintain stabilization, while positioning their ankle, knees, and hips in extreme positions to increase their base of support and actively relying on trunk and core stability to counteract the effects of the CG placement.

Subjects may be required to come to stand from a kneeling position by utilizing the ankle as the primary force generator to standup. This may occur from a maximally inverted and plantar flexed position or an everted and dorsiflexed position, both of which are a concern for injury and considered an ineffective movement strategy. Due to the orientation of the hip bearings, it can be very difficult to align the knee under the base of support, requiring other joints to compensate. Additionally, the CG being high on the subject in this position causes the subject to fall forward when initiating nominal kneeling to standing mechanics and forces. Crewmembers often perform a dynamic motion to grab something on the ground—by jumping down into the kneeling position and springing back up—using the momentum of the suit to push themselves back up. This ultimately turns a static kneeling posture into an extreme dynamic explosive motion, and the CG in ARGOS does not have time to pull the subject forward. The NBL provides a different challenge in that water drag induces an opposing force (or resistance) on this motion.

Figure 3-2. Single leg kneel in ARGOS

Ergonomic Model Analysis

The model data presented in this section shows the range across the 24 EVA tasks for each output variable, represented by the blue (task ROM), purple (extreme posture), and green (static joint moment) bars, with the value for the current task in orange. Examining the relative biomechanical demands, the single kneel to recover task had very high suit joint ROM and extreme posture at the hip (Figure 3-3). The knee also had to go through a large ROM (Figure 3-3). Maintaining a single leg kneel posture with a forward-leaning torso required high hip and back moments (Figure 3-3).

Ergonomic risk factors seen for this task are awkward posture, forceful exertion, contact stresses, and prolonged static position. A combination of high lower body angles and a bent over torso puts the body in a biomechanically awkward posture (away from a neutral posture). Contact stresses and forceful exertions may be experienced when having to drive into different parts of the suit to push up off the ground. Kneeling postures may also be held for a prolonged duration while performing geology tasks, potentially increasing the injury risk.

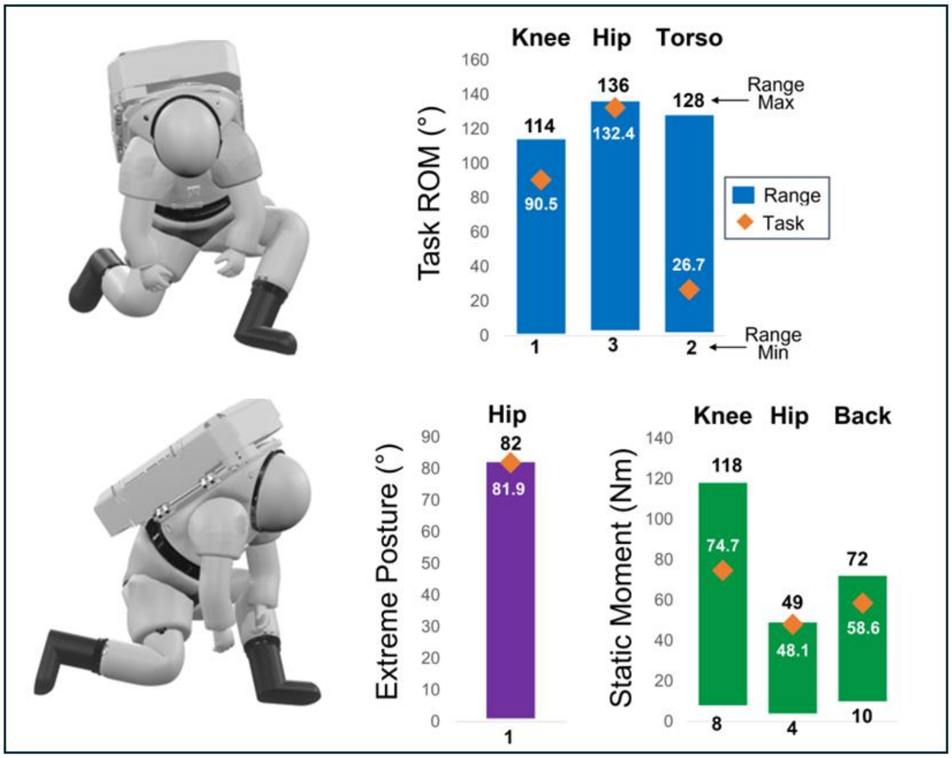


Figure 3-3. Single leg kneel task ergonomic outputs

Load and Frequency

This position is common in all training environments and seen as a high frequency event, being performed during many different tasks during geology. This is a medium to high load task in terms of stress on the joints, due to the extreme positions. This position is of potential concern across all training environments. While the Lunar Surface is largely unknown, there could still be potential issues with inertial mass versus actual mass. Even with a reduction in mass on the Lunar Surface, inertial properties will pose a different and potentially concerning strain on the human in the suit. On the Lunar Surface, we would not have the CG issue, as this is a terrestrial training environment issue only.

Potential Injuries

The areas of the body of concern during the single leg kneel task are the spine, hip, knee, and ankle. This section is taking into consideration a high frequency during the training event, with a medium to high load on the lower extremity, and the ergonomic model data. The injury watch list items for consideration when executed at a lower frequency with a higher load (e.g., jumping into positions on an inverted ankle, bent knee and externally rotated hip) could include—but are not limited to—acute, rotational injury to the ankle, knee, or hip (e.g., sprains, meniscus, etc.). For higher frequency performance, repetitive or prolonged static positions injuries such as ankle and hip impingement, knee, and spinal strains may be more common. This concern exists for both the terrestrial and Lunar Surface environment and is specifically related to the large amount of ankle rotation in the xEMU. Lastly, due to the increased fall risk in this position, there needs to be a heightened awareness for upper extremity injuries that may result from a fall on an outstretched arm (FOOSH).

3.1.5 Double Knee Kneel

Description of Concern

This position occurs when the crewmember is kneeling on both knees in a wide base of support, the knees directly aligned under their center of mass (COM), ankles in a plantar or dorsi-flexed position with/without external rotation to the foot to maintain stability (Figure 3-4). The CG remains an issue while in this position and may result in subjects falling forward, elevating the risk of injury to the upper extremity due to falling on outstretched arms. With each position there are various techniques to get into and out of each position, for example, when coming to stand subjects can either lean backwards and use an explosive force/motion or transition from a double knee kneel to the single.

In the field, while wearing the Atlas EXCON suit, it has been determined that the subject prefers to be in a double kneel position instead of a single leg kneel. The single leg kneel puts a lot of pressure on one knee, and the double kneel position is a lot more comfortable. However, due to the external load on the subject, getting down to the ground in either kneeling position is very energy inefficient. Subjects will bring all their tools with them to the ground and maintain a prolonged kneeling position to complete their tasks. Ergonomics data, load, frequency, and areas of concern will be addressed in the prone to recover section, as these sections are largely the same and involve similar biomechanics

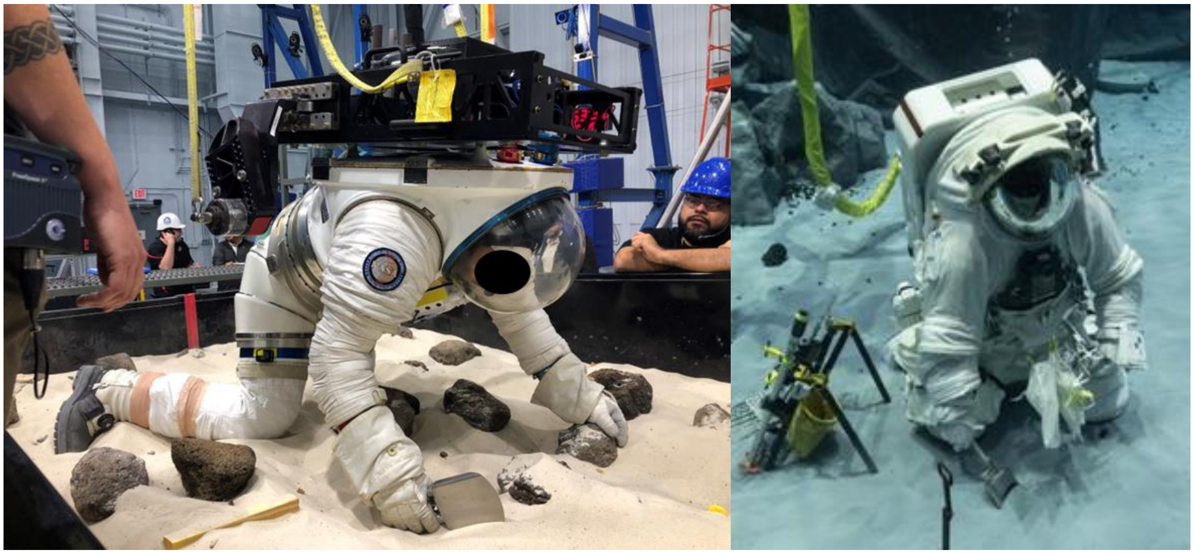


Figure 3-4. Double knee kneel position in ARGOS (left) and in the NBL (right)

3.1.6 Prone to Recover

Description of Concern

The prone to recover position is comprised of five-phases: kneeling, loading, fully prone, upper extremity recovery, and lower extremity recovery. The *kneeling phase* is when the subject falls onto both knees and the ankles are in an externally rotated position. It is important to practice falling in the suit in a controlled manner to minimize the risk of injury. The *loading phase* includes falling onto the hands with outstretched arms from the kneeling position, while avoiding helmet impact to the ground. The *fully prone phase* is when the body is lying flat in a completely face down position. The *upper extremity recovery phase* is when the subject goes from fully prone to an upright or kneeling position. The subject needs to explosively push-up to get enough distance from the ground to swing their legs under themselves to start standing or settle into the double/single leg kneeling position. This phase requires that the wrist, hands, elbows, and shoulders are strong and flexible and can provide explosive power to push up the offloaded 1/6-g weight of the suit. The subject's anthropometry (arm length) affects the spring length, so the subject would need to compensate with a greater amount of force if their arms are shorter. This part of the recovery from this position also has pivot point or CG issues, causing unrealistic heads-down moments. This moment can be really fatiguing to most subjects. Some subjects can complete recovery from push up to a fully standing position. However, depending on the subject's anthropometry, they may settle after the first phase in a double or single leg kneel position. Lastly, the *lower extremity recovery phase* is when the body goes from the double knee kneel to standing. This position is where different techniques may be performed.

Certain environment or simulations may exacerbate the amount of strength needed to get out of this position. For example, water drag in the NBL will significantly increase the amount of force needed during the *upper extremity recovery phase*.

Ergonomics Model Analysis

The ergonomics assessment for the prone to recover task showed high suit joint ROM at the knee, torso/back, and elbow (Figure 3-5). For extreme posture, the hip and shoulder fall in the middle of the overall task range (Figure 3-5). The static moments required to maintain the double kneel posture during prone recovery at the hip, knee, and back (L5-S1) are among the highest across the tasks (Figure 3-5).

Ergonomic risk factors seen for this task are awkward posture, forceful exertion, and contact stresses. Both a forward and backward torso lean cause the body to move out of a neutral posture and can increase stresses on the body and moments required to maintain stability, particularly with larger anterior/posterior shifts of the torso and PLSS CGs. Multiple forceful exertions may be required to recover-to-standing, including a push off the ground into a kneel or directly up to standing, and potentially an explosive movement up from the kneel. Contact stresses may also be experienced when pushing up off the ground and having to drive into different parts of the suit to complete this motion. If work is being performed on the ground, such as with different geology tasks, a double kneel posture may be held for an extended duration, creating an ergonomic risk of a prolonged static position.

Load and Frequency

The double knee kneel position and prone to recover tasks are high load and impart high stress on the upper and lower extremities. Double kneeling is a low frequency event due to simulation quality or CG issues, while double kneeling is a high frequency event in the Atlas EXCON during field testing geology tasks. The prone to recover position is typically a low frequency event.

Potential Injuries

The areas of the body that are of concern for potential injuries are the wrist, elbows, shoulders, knees, and spine. Items on the injury watch list for a position with lower frequency and a higher load include injuries to the upper and lower extremity such as—but not limited to—fall on outstretched hand (FOOSH), impact fractures, blunt trauma, and rotational injuries.

3.1.7 Bending Over Tasks

Description of Concern

Bending over for geology tasks such as trenching and scooping is a high metabolic rate (MetRate) activity. During trenching, the crewmember uses a long-handled geology tool (e.g., shovel or rake) to displace large amounts of sand and create a small ditch, requiring them to bend forward for leverage. This posture, combined with repetitive motion, raises concerns for fatigue and potential injury, as the crew must exert substantial sideways torque to break through the "regolith". The water drag at the NBL can further exacerbate the torque demands on the body. Trenching in the field is similarly complicated, due to digging through compact soil, requiring a high energy expenditure. The subjects with shorter arms may be at a mechanical disadvantage, as the fixed-length tool makes it more difficult to generate effective leverage. The tool handle is one length, and creating leverage for trenching will be difficult. A useful real-world comparison for studying repetitive strain in this context may be a golf swing, which similarly involves bent posture, rotational torque, and repetitive motion.

Ergonomics Model Analysis

During the bent-over trenching/raking task, while the overall motion at the torso and hips remained fairly low (Figure 3-6), the static joint moments required to maintain this posture were high with the hip joint experiencing the highest moment of all tasks analyzed (Figure 3-6). The suit joint angles and moments observed during the extended-handle scooping task were comparable to those seen in the trenching/raking task. Extreme hip posture was 60−80° across both trenching/raking and extended handle scooping tasks, depending on the technique used.

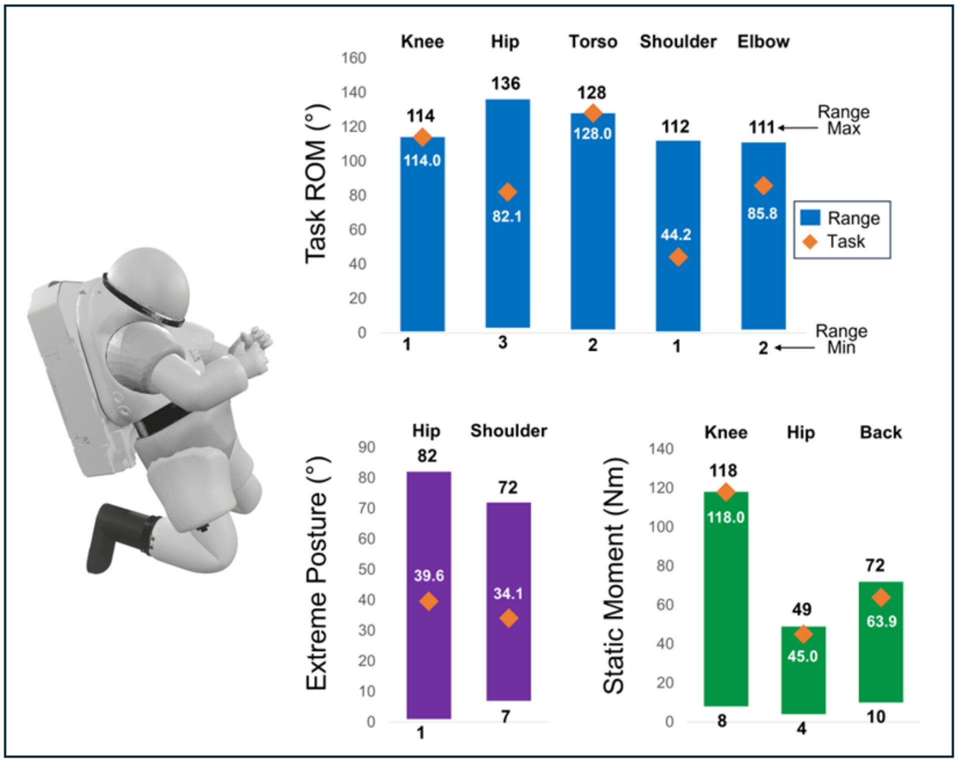


Figure 3-5. Prone to recover task ergonomic outputs

The ergonomic risk factors associated with this posture and task include awkward positioning, repetition, and forceful exertion. The raking posture involves forceful movements performed in a forward-leaning position, deviating significantly from neutral alignment. Additionally, the repetitive nature of the task may contribute to increased fatigue, cumulative stress, and a higher risk of tissue damage over time.

Load and Frequency

This task is considered low to medium frequency. It is not performed often and can be done in every training analog. The physical load depends on the specific analog and the tools used, which vary based on task, In ARGOS/POGO, tools are typically weighted to 1-g and involve moving sand, resulting in a high load. In the NBL, tools vary between 1-g and 1/6-g and encounter water drag while moving sand, also producing a high load. Finally, in field training, digging in dirt presents the highest load since it requires actual ditch excavation rather than simply moving sand.

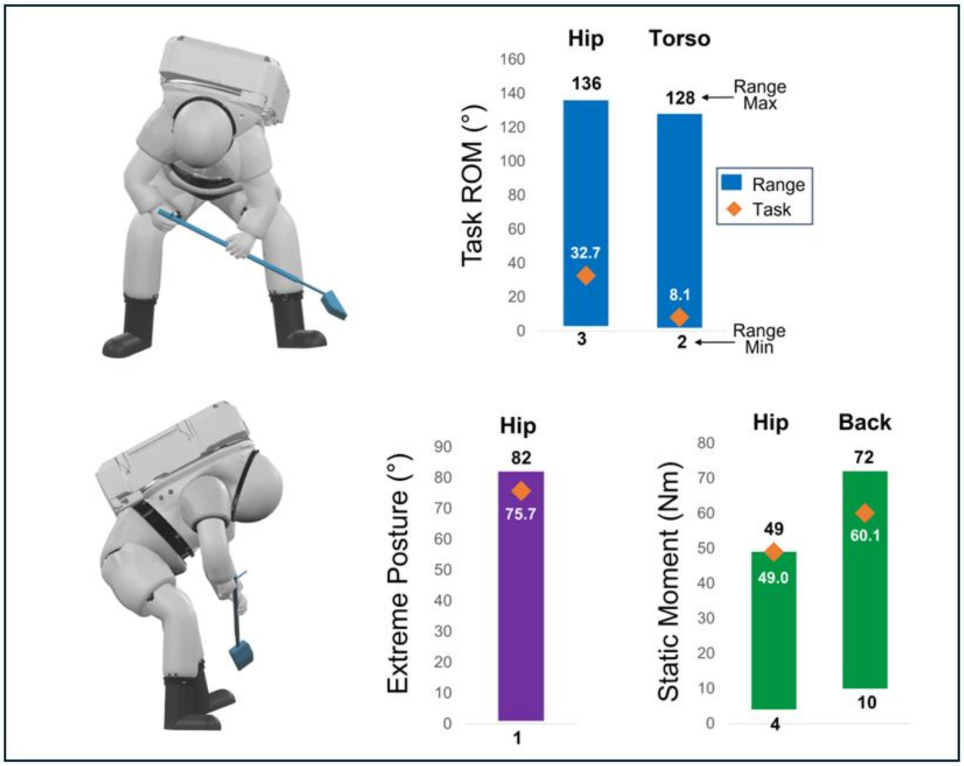


Figure 3-6. Trenching/Raking task ergonomic output

Potential Injuries

Given the higher load, lower frequency, and ergonomic data indicating prolonged high static moments, the injury watchlist shifts toward repetitive overuse injuries affecting the shoulder, elbow, wrist, hands, and spine.

3.1.8 Supine Recover

Description of Concern

Supine recovery can only be realistically practiced in the NBL, where the crewmember has ended up on their back. The first step involves swiftly swinging the legs around to roll onto their side. In the NBL, water resistance may assist slightly by providing some push once the subject is on their side. Next, the crew performs a rolling motion to reach a position resembling prone recovery, after which they use prone recovery techniques to stand up. This entire sequence requires significant exertion, as the suit's material and joints create resistance that the crew must overcome to generate enough force to lift themselves out of the supine position.

Ergonomics Model Analysis

There is currently no ergonomics model assessment of the supine recover task as there is no motion capture in the NBL. The identified ergonomic risk factors include awkward postures, forceful exertions, and contact stresses. Multiple techniques exist for transitioning from supine to prone then to standing, all of which demand high exertion from both the upper and lower body. Additionally, contact stresses are likely as the body forcefully presses against various parts of the suit to lift off the ground.

Load and Frequency

This task is a low-frequency event performed only in the NBL and involves extremely high load and exertion. Even in the NBL the task is described as "unrealistically hard".

Potential Injuries

All considerations discussed for the low-frequency single or double knee kneel or prone-to-recover task also apply here, as these movements and positions serve as the final transition after flipping or recovering from the supine position. This is an extremely challenging and demanding activity, requiring crewmembers to generate significant force through their head and trunk to come to a kneeling position. As a result, the primary areas of concern are the cervical, thoracic, and lumbar spine, and lower extremity, particularly due to the rapid rotational force generated through the spine and lower extremity when swinging the leg around to the kneeling position.

3.1.9 Repetitive Injuries

Description of Concern

Repetitive tasks in training environments are already a significant concern for injury, both during training and actual EVAs. Some analogs pose greater risks than others. With high-tempo EVAs anticipated in the near future, these concerns are amplified, underscoring the need for improved mitigation strategies. In ARGOS and POGO, the arms are not offloaded, making geology tasks significantly more taxing as the arms feel much heavier. Tools used during ARGOS training are typically weighted for 1-g to remain functional, meaning they are heavier than they would be on the Lunar Surface, compounded by the lack of arm offloading. Overhead tasks, such as hammering to drive a tube, are especially demanding; depending on a crewmember's suit and glove fit, mobility, ROM, and strength, they may need to repeat the motion multiple times to complete the task. These repetitive, high-force activities present a significant risk for injury, both during training and EVA operations. At the NBL, both the arms and tools are partially offloaded due to water buoyancy, which helps reduce the load; however, this benefit is offset by the resistance from water drag. For the drive tube task, crewmembers are now required to collect core samples on the Lunar Surface. When two drive tubes are connected to form a double drive tube, the crew must again hammer it into the ground. Regardless of a crewmember's height, the tool remains the same length. For shorter individuals, this means performing overhead hammering, requiring significant force and increasing physical strain.

Ergonomics Model Analysis

Drive tube hammering was analyzed as an example of a repetitive task, with various techniques observed that demonstrated differing degrees of shoulder and elbow motion, as well as variations in upper body posture. The technique represented in Figure 3-7 has balanced motion across the upper body joints with similar suit joint ROMs at the shoulder and elbow. Other technique variations showed primarily shoulder motion (task ROM: 26° shoulder / 8° elbow) or primarily elbow motion (task ROM: 8° shoulder / 42° elbow). The shoulder posture was high in comparison to other tasks as the arm was raised to allow bringing the hammer down onto the drive tube (Figure 3-7). Upper body joint moments are highly influenced by the training environment, specifically the lack of arm offloading in ARGOS and the added resistance from water drag in the NBL, as discussed in the previous section.

The primary ergonomic risk factors associated with this task include repetition, forceful exertion, and awkward posture. With a high work surface, the shoulder may be required to exert force while elevated above a neutral posture. Repeatedly performing tasks in this position can lead to increased fatigue and a heightened risk of overuse injuries.

Load and Frequency

This task is considered high-frequency and is performed across all training analogs. The physical load varies depending on the environment and tools used. In ARGOS/POGO, tools are typically weighted for 1-g, and they do make contact with actual surfaces (simulated or artificial rock), thus resulting in a high load due to unsupported arm motion. In the NBL, tools range between 1-g and 1/6-g and are affected by water drag, which lowers the effective load; however, force generation is limited, and no real rock is impacted. In contrast, field training involves striking and breaking actual rocks, making it the highest-load scenario due to the real impact forces required.

Potential Injuries

Similar watchlist type of injuries as to what was previously state for repetitive use. Frequent overhead activities can lead to shoulder injuries involving the subacromial space such as rotator cuff or bicep tendon issues. Additionally, repetitive gripping and hammering is a known risk factor for sustaining elbow injuries such as medial/lateral epicondylalgia or peripheral neuropathies such as carpal tunnel syndrome. Characterizing where higher metabolic and frequency tasks exist can inform mission planning to reduce these types of injuries and enable successful mission execution.

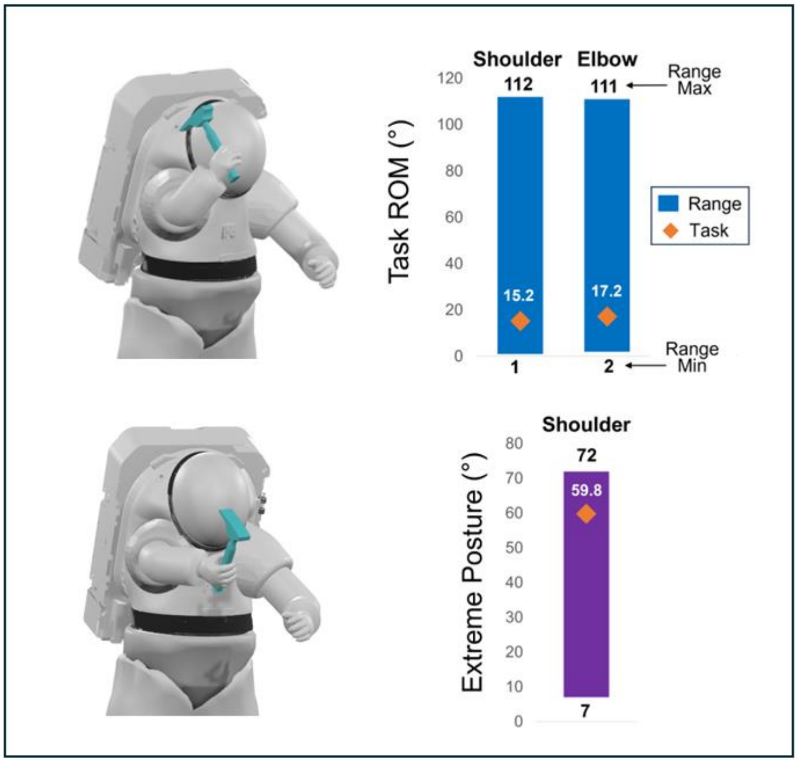


Figure 3-7. Drive tube hammering technique ergonomic output

3.2 Physiological Monitoring: Current and Future

This section describes and focuses on the physiologic monitoring associated with the human operating inside of the suit, executing simulation tasks and objectives or operating in unique testing environments and excludes human systems interaction. Human systems interaction is certainly important and warrants further investigation with respect to EVA operations but is outside the scope of the current discussion related to suited HHP optimization.

3.2.1 Why is this important?

Monitoring physical and cognitive workload is important for many different reasons but is particularly important for characterizing the human response to the operational environment, especially given that NASA is now making a major shift from the well-characterized ISS microgravity environment to exploration of the Lunar Surface and beyond. Even considering experience from the Apollo program, a vast number of significant changes and differences can be expected during the Artemis program that may impact the human interactions and responses, including new commercially developed landers and spacesuits, time in microgravity before Lunar landing, high frequency execution of surface EVAs, and charting unexplored regions of the Moon. Due to these factors and more, exploration on the Lunar Surface is going to increase both the physical and cognitive workload beyond levels previously experienced in-flight. Compared to ISS operations, crew will now be using their lower body during EVAs for ambulation and holding kneeling positions, as well as using geological tools that require significant physical exertion and wider motion demands of the upper body. Cognitive workload is expected to increase as crew may not have step by step procedures but will more likely have flexible and broadly scoped tasks that will require real time decision making and analysis. Because in-mission support will be decreased/less or delayed, human or crewmember autonomy will be increased, putting additional burden on the crew to continuously monitor the mission situation and execution. Additionally, NASA is changing the injury risk due to the increased type and number of potential injury mechanisms. Whereas microgravity EVAs are primarily reliant on use of the upper body, it stands to reason that the inclusion of full body mobility in a partial-gravity environment will likely result in an increased number of lower body and back injuries during surface EVAs. The number of back-to-back EVAs completed by the same individual astronaut is expected to vastly increase over previous missions and programs, up to 24 hr of EVA per week (EVA-EXP-0042 Rev. D), which will increase the likelihood and exposure for injury and compromised performance due to fatigue and poor recovery time. Historically, Apollo was the only program that planned to include back-to-back EVAs; however, they did during the Shuttle Program as a response to an unplanned failure or mission change. With reduced recovery time between EVAs (i.e., "higher EVA density"), possible fatigue and repetitive/cumulative effects become an increased concern. Lastly, there is uncertainty in Lunar Surface EVA CONOPS, equipment (i.e., suits, tools, etc.), and tasks based on the current state of development of these resources; subsequently, only a limited number of relevant Lunar EVA physiological datasets exist.

While demanding, EVAs are not the only important responsibility placed upon the crewmember during surface operations. The EVA days are typically expected to be a 12—13-hr workday for the crewmember, assuming nominal execution of all planned operations without unforeseen complications. An example of a Lunar Surface mission timeline is shown in Table 3-1. When considering back-to-back EVAs for 4 or 5 days, cumulative fatigue and burden both outside of and between EVAs must also be factored into determinations for readiness and performance optimization during EVAs.

From a sensorimotor perspective, there are key differences between the prior Apollo and planned Artemis missions that may significantly impact task performance during or after g-transitions, particularly during Lunar descent and landing and early EVA operations where alterations in sensorimotor function can lead to disorientation, postural imbalances, impaired locomotion, and operational challenges to manual control. The planned Artemis missions include longer transits in microgravity, potentially increasing cardiovascular and sensorimotor deconditioning effects. These missions also include differences in landing vehicle design that impact crew override capabilities and expose the crewmembers to various distinct acceleration profiles, potentially leading to disorientation and altered perceptions of motion. Mission duration and individual responses often influence both the severity of performance decrements and the variability in adaptation timelines. The individual variability related to g-transition effects adds to uncertainty around first EVA timing and content. The planned EVAs are expected to exhibit more challenging terrain and variable lighting conditions which may increase fall and injury risk when coupled with sensorimotor alterations following g-transitions. Given the high-performance physiological and functional demands of planned EVAs during these upcoming missions, there is a need to characterize EVA preparedness both early and late in-mission.

The risk of injury and compromised performance during EVA operations is highly integrated and multi-faceted, so a robust and holistic approach to characterizing demands and impacts to HHP throughout mission-relevant profiles is necessary. Results from planned EVA testing and research will support development and validation of concepts to monitor and optimize HHP on Earth, in-transit, during, and following g-transitions.

During data collection, there are many challenges which may preclude taking measures in the different analog environments or simulations. For example, it is difficult to capture standard fitness measures underwater when testing in the NBL. Depending on the specific suit, environment, and simulation content, many caveats and limitations may be associated with the data that must be recognized, understood, and accepted as-is as part of the test outcomes. Consequently, it is paramount to have good simulation content and test approaches, carefully considering the caveats of each analog suit and/or testing environment, before beginning data collections and making any data-driven claims. To conclude the preface for this section, the common phrase “train like we fly” should be kept in mind. This should also extend beyond training to “research like we train, train like we fly”, to ensure successful conduct of the most relevant and highest fidelity efforts which will best inform crew health and performance needs for training and missions alike with realistic and highly applicable data.

Table 3-1. Exploration EVA Day Timeline

Mission Activity	**Est. Duration**	**Notes/Rationale**
EVA Prep	01:30	This number is based on ISS average.
Prebreathe	00:30	Depends on cabin atmosphere and suit pressure. Can be anywhere from 00:00-02:00
Depress	00:30	Depends on vehicle capabilities and pre-breathe validation. This number is based on ISS average.
EVA	07:00	Can be up to 8 hours in duration, per ConOps
Repress	00:30	Depends on vehicle capabilities. This number is based on ISS average.
EVA Post Ops	01:30	This number is based on ISS average. This should include: • Post EVA suit inspections. • Suit cleanup and reconfiguration • Consumables Recharge (O2, water, power).
EVA PMC	00:15	Private medical conference required by Surgeons after each EVA
EVA Conference	01:00	Conference with ground team to discuss details of EVA that just occurred and changes for next EVA
Next EVA Tool Prep	00:30	Time to reconfigure tools for next day's EVA.
Next EVA Study Prep	00:45	Provide the crew time to study any changes to the plan agreed upon out of the Post EVA Conference

3.2.2 Sensors and Measurement of the Human

Currently, research and test data are primarily being collected and supported by the EVA Environmental Physiology Laboratory (EEPL), Applied Injury Biomechanics (AIB) and Anthropometry and Biomechanics Facility (ABF), the Neuroscience Laboratory (NSL), and the Exercise Physiology and Countermeasures Lab (EPC) in various suited simulation and testing efforts at the NBL, ARGOS, field-based environments, motion base and fixed base simulators, sensorimotor disorientation paradigms (e.g., centrifuges and galvanic vestibular stimulation), and virtual/hybrid-reality testbeds. The characterization of HHP during partial-g EVA simulations has many elements to consider:

- Development and implementation of appropriate ground-based EVA simulation content (e.g., EVA tasks, tools, and procedures).
- Identification of relevant health/performance measures and development of capabilities to obtain and protect for those measures.
- Detection and monitoring of likely performance decrement, sensorimotor alterations, and/or injury mechanisms during exploration EVA training pipelines and flight missions.

3.2.2.1 Core sensors and measures

EVA research and testing occurs frequently at JSC, often across a multitude of different analogs and suit simulators, with different objectives and specific aims. Therefore, different sensors and monitors may be required and must be adapted to each of the different environments. The above-mentioned labs have a multitude of methods and capabilities to measure relevant parameters in various domains of HHP. In some cases, primarily due to limitations or inaccessibility, there may be a significant gap between the volume of data we have for some of these sensors and measurements compared to other sensors and measurement. Ongoing efforts seek to remedy these issues, making provisions to include all standard measures and sensors in common suited testing simulation environments.

3.2.2.2 Primary Measures-Physical Workload

Metabolic rate/CO2

Metabolic Rate (MetRate) is an important metric during EVAs. The closed-loop spacesuits process the outputs of human metabolism, namely carbon dioxide (CO2) and heat—indicators of physical workload. Metabolic Rate measures the oxygen (O2) consumption and the output, or the CO2 production. During ground-based simulations, this is passively estimated using Peronnet equation, using the measured flow rate of air into suit and the CO2 measured downstream from suit (side-sampled at suit exhaust) using Vaisala GMP252 or similar sensors. In the field or with the HS3/simulator suits, metabolic rate is readily collected via portable metabolic analyzer (COSMED K5). In actual spacesuits during spaceflight operations, metabolic rate is measured by assessing the pressure drop of the O2 tanks, which indicate volume of O2 consumed per time.

The limiting consumable for EMU operations is “MetOx canisters” due to their limited total CO2 scrubbing capacity. Heat rejection is achieved by the LCVG performance which is constrained by PLSS feedwater supply limits and heat exchanger efficiency. Based on these suits and PLSS limitations, measures and predictions of MetRate and cumulative metabolic load is a key metric for determining EVA duration limits based on spacesuit consumables usage. The harder an individual works, the higher the O2 consumption and CO2 production that the spacesuit must provide and manage. Current EMU MetOx Canisters have an approximate capacity of about 6900 British Thermal Units (BTUs) available for EVA, with some reserve for off-nominal situations. While metabolic rates vary over the EVA, if they are managed to an average below 1000 BTU/hr. (~250 kcal/hr.), a 6.50 hr. EVA is reasonable.

In the case of exploration scenarios, it is thought that the increase in gravity (e.g., 1/6-g) relative to ISS microgravity operations will result in an increase in physical workload. The exploration PLSS is being designed to handle higher average metabolic rates and total scrubbing capacity, with 1200–1600 BTU/hr being targeted as a sustainable rate for a 6–8-hr EVA. To maximize surface time and completion of mission objectives, crewmembers will have to sustain these workloads for the expected durations.

Heart rate

Heart rate (HR) is a function of physical workload closely tied to metabolic rate and thereby can be used to estimate consumable usage. HR allows us to indicate how hard the subject/human is working while in the suit. This is typically collected locally via chest strap, often a Polar H10 or similar device. ARGOS currently has capability to wirelessly stream and view heart rate via custom internally developed app, though network firewalls and wireless restrictions in certain test environments often makes this difficult and not always possible. The same capability is being investigated at NBL but requires additional instrumentation to work underwater and transmit along the umbilical. HR monitors can also be used in “local” storage mode for field or lab-based environments but require additional postprocessing to synchronize data.

Aerobic Fitness

Heart Rate becomes even more valuable if we have data on an individual’s fitness capability, such as aerobic fitness through a VO2pk test. The local standard is to conduct cycle based VO2pk tests, coupled with a metabolic analyzer (Parvomedics TrueOne2400) and ECG monitor, which provides a normalization metric for physical workload data (e.g., MetRate and heart rate) as these are highly individualized and subject-specific. Literature indicates that ~40% VO2pk is sustainable for ~6–8 hr in tactical athletes, and this is a value that should also be considered appropriate and monitored for exploration EVA operations (Strock et al., 2023). Preliminary data from previous ground-based suited testing indicate that an average work rate of 30–40% of VO2pk is achievable and sustainable for these durations, though intermittent peaks for more difficult tasks (e.g., traverse) should be expected (Strock et al., 2023).

Thermal Loads

Thermal burden is also tied to physical workload. Completing any physical tasks requires expenditure of energy, subsequently producing heat via metabolism. This heat must then be eliminated from the spacesuit, primarily through use of the LCVG. Hence the heat load managed by suits must be understood and characterized.

Thermal information can be obtained several different ways, including the following: i) core temperature, ii) skin temperature, and iii) suit temperature. Core temperature is typically collected through an ingestible pill (e.g., eCelsius), is recorded locally, and is offloaded after the testing. Skin temperature is collected through a low-profile skin surface sensors (e.g., iButtons) and is also recorded locally and downloaded after testing. Additionally, an iButton can be placed in the suit helmet bubble for suit environment temperature and humidity. The suit temperature is measured through the LCVG inlet/outlet temps and flow rates using resistive temperature detectors and flowmeters to model heat storage. Once this information is obtained, additional relationships for measures tied to physical workload can be modeled and tied to suit consumables usage or human performance implications during EVA.

Subjective/Qualitative Feedback

In absence of quantitative measures, validated, subjective surveys can be used with appropriate language and in appropriate scenarios. As an example, Rating of Perceived Exertion (RPE) can be collected using the Borg CR10 scale to subjectively ascertain physical demand or exertion from a single task. The original Borg RPE scale and its validated variants are well-correlated with heart rate, thereby helping to indicate metabolic and thermal loading for a specific task or activity block. Related, the Bedford Workload Scale is a common survey that can be employed to subjectively assess cognitive demand and available mental capacity during any given task. Other relatively common subjective surveys that are often or typically used in the context of EVA—but are not yet well-characterized for EVA specifically—include:

- Thermal comfort and preference
- NASA Task Load Index (TLX)
- Samn-Perelli Subjective Fatigue Scale (SFS)

Kinematics

Kinematic data collection can be performed using traditional motion capture—stationary near-infrared cameras to track retroreflective markers affixed to a rigid body through space—which can inform isolated ROM testing (e.g., suit joint motions), reach envelope, and functional task completion. Markerless motion capture (MMC), building upon decades of research with marker-based motion capture systems, is an evolving technology that can revolutionize how human spaceflight data is captured during intravehicular activity by enabling unobtrusive monitoring capabilities and multi-subject tracking from onboard hardware (Weiss, Moudy, & Wood, 2025). The MMC systems eliminate the need for marker placement procedures—a relatively laborious procedure requiring marker placement on the human body to facilitate tracking human movement—and reduce hardware requirements to support data collection outside of laboratory settings. The MMC uses deep learning algorithms to provide three-dimensional human pose estimation from multiple synchronized two-dimensional camera views. Following a calibration procedure to determine the position and orientation of each camera, the deep learning algorithms are applied on a frame-by-frame basis to identify and track over one hundred distinct anatomical landmarks on the human body. MMC applied to in-cabin videos has the potential to support sensorimotor assessments, medical examinations, rehabilitation, training, behavior health, and in-flight exercise evaluations. Recently machine-learning solutions have been developed for automatic recognition of spacesuit motion from conventional video to enable quantification of suit kinematic patterns to optimize hardware and task designs during extravehicular activity and training analogs (Vu et al., 2022). One limitation of marker-based and MMC is that it does not allow for tracking of the human inside of the suit, as the human and suit are not perfectly coupled.

Alternative motion tracking devices include Inertial Measurement Units (IMUs), which are triaxial, three-part sensors (comprised of an accelerometer, gyroscope, and magnetometer) that can measure localized rigid body orientation and motion through space. These can be used when traditional motion capture is limited (e.g., mobile, field-based settings). IMUs must be calibrated and oriented correctly to provide useful results, especially when looking at the relationship between rigid bodies (i.e., across joints). While IMU sensors are relatively compact, the long-term wear may lead to discomfort, displacement of the sensors on the body, and restrictions in movement or crew behavior. While IMUs are often practical for ground-based testing, the availability of IMU sensors in-flight is limited.

Cognitive Workload, Cognitive Performance, and Cognitive Fatigue

There is a need to characterize how surface exploration EVA influences crewmember fatigue, cognitive workload, and demands on performance compared to microgravity EVA currently conducted from ISS. Toward this aim, EVA simulation and analog research can help identify which EVA scenarios and environments impact subjective and objective measures of cognitive workload, fatigue, and EVA performance.

Cognitive workload is typically measured using self-report scales such as the Bedford Workload Scale or NASA Task Load Index (TLX). The Bedford Workload Scale is a unidimensional rating scale designed to identify operator's spare mental capacity and cognitive workload level while completing a task. The level is assessed using a hierarchical decision tree that guides the operator through a ten-point rating scale, each point of which is accompanied by a description of the associated level of workload. Another method of collecting human performance data would be the NASA Task Load Index (NASA TLX), a widely used, subjective, multidimensional assessment tool that rates perceived workload to assess a task, system, team, or individual’s effectiveness or other aspects of performance (such as task loading). For optimal measurement of cognitive workload during EVA, it is recommended to ask participants to report their cognitive workload on a validated scale at periodic points during an EVA, particularly in reference to an EVA task just completed.

Cognitive performance is often measured pre- and post-EVA through a standardized battery of cognition tests on the laptop. The Cognition Test Battery was specifically designed for the high performing astronaut population. It is administered on the ISS and in multiple spaceflight analog environments including NASA’s 45-day Human Exploration Research Analog (HERA) and 378-day Mars analog Crew Health and Performance Exploration Analog (CHAPEA). The Cognition Test Battery consists of 10 cognitive subtests measuring various cognitive domains, from visual learning to emotional recognition to level of risk in decision making. Each test is brief in duration, and the whole battery on average takes about 20–30 min to complete, depending on the individual.

Currently there is an effort to develop embedded cognitive performance measures that can be deployed in a mission-realistic way during the EVA itself. For example, several EVA simulation studies to date have included an auditory adaptation of a reverse digit span test of working memory and executive function as well as an auditory psychomotor vigilance test (PVT) of vigilant attention. These adaptations use audio-based versions of the laptop testing so the assessments can be administered during an EVA, better capturing the actual cognitive loading work in the EVA. These cognitive battery tests are being collected for us to understand not only what the demand of cognitive performance is as a function of a single EVA, but the demand over the course of a mission profile, especially in the context of rapid EVAs.

It is thought that cognitive demand during EVA is a function of specific EVA tasks, while also influenced by the current physical workload and broader contextual factors (sleep decrements, high-tempo mission objectives), although more data is needed to draw meaningful conclusions.

Sleep is an example of an important factor impacting cognitive performance during EVA. Sleep duration and quality can be assessed through subjectively reported sleep diaries and objective sleep actigraphy devices. Actigraphy data collection often occurs for 7 days pre-test and 3 days post-test to establish normative baseline levels. Sleep and fatigue are currently being investigated in the context of EVA, particularly regarding the broader mission context which may include successive periods of sleep decrements due to high-tempo EVA or other mission objectives.

Hydration, Nutrition, and Waste Management Domain

Hydration, nutrition, and waste management should also be considered and characterized to determine physiologic needs associated with EVA tasks. During EVA, metabolic expenditures should be managed and/or replenished by in-suit nutrition or hydration systems to ensure that the crew has adequate energy and hydration levels to perform optimally (Dillon, 2023). The Food Systems Lab is currently collecting data related nutritional aspects, such as pre-EVA food preferences and meal timing. Future SERPO considerations would like to incorporate nutrition.

Hydration is tied to workload and performance, as well as thermal management. Several efforts are looking at in-EVA water consumption, sweat loss, and fluid loss to determine a crewmember's hydration status. It is likely tolerable for a crewmember to be in a dehydrated state for a single EVA; however, dehydration could become a problem, leading to other health impacts and issues if they are tactically dehydrating or just naturally dehydrating because of the demand for EVA and a high tempo mission. Limited data exist to date and are mostly focused on training simulations at the NBL. This data indicate substantial individual variability in terms of water management strategy during EVA and that it is relatively easy to become marginally dehydrated based on measurements of urine specific gravity (Estep, 2024). Additional hydration data can easily be collected using pre- and post-test weights of the human and various suit components (e.g., maximum absorbency Garment [MAG], disposable in-suit drink bag [DIDB]).

3.2.2.3 Physical Fatigue

Physical fatigue can be used to characterize the functional capacity associated with EVA tasks, especially when considering high tempo EVA operations. One current measure being used to assess functional capacity is grip strength, as measured by a hand dynamometer. There is a global understanding that hands are a problem area within the context of EVA due to interaction with the pressurized gloves. Grip strength dynamometry helps to assess fatigue in the most common area of injury and fatigue in suits (hands). This testing must be completed in a posture that isolates correct muscle groups (i.e., no cheating or compensating), and it can be done unsuited and suited to assess decrement strictly due to the suit. Additionally, it can be done pre/post-EVA to look at changes over time and time to recover, as a function of EVA workload and tasks. Other measures are being investigated to determine physical fitness readiness and fatigue both within and between EVAs but have not yet been validated or fully implemented in any studies to-date.

3.2.2.4 Sensorimotor Assessments

Exploration class missions will require crew to be able to self-assess and treat any sensorimotor dysfunction after transit and gravity transitions to the Lunar Surface. The severity of motion sickness, disorientation, and instability that may be experienced by the Artemis crew is unclear, but it is expected that there will be an increase in incidences as the transit times increase which could impact operational performance, increasing instability, resulting in a greater number of falls, and ultimately increasing fatigue in early EVAs. Initial Artemis surface missions commit the crewmembers to over twice the dwell time in microgravity prior to transitioning to the 1/6-g Lunar

Surface environment when compared to Apollo (~8 days in microgravity is the shortest Artemis timeline currently supported, with periods up to 17+ days possible); neurovestibular adaptation to microgravity will be more significant than experienced by Apollo crewmembers.

As part of the "Sensorimotor Assessments” study, a set of sensorimotor assessment tasks are being developed to be performed prior to the crew’s first planetary surface EVA. The sensorimotor assessment test battery is based on lessons learned from Apollo and feedback from the Flight Operations Directorate (FOD) Flight Surgeons and astronaut representatives, Astronaut Strength and Conditioning Rehabilitation trainers (ASCRs), and relevant NASA internal and external SMEs. The assessment will include the following: 1) mimic body maneuvers such that crew can self-assess their potential ability to complete operational tasks; 2) provide opportunities to develop strategies to recover from off-nominal body positions; and 3) aid in progressive adaptation to the novel gravitational environment. Further, the sensorimotor assessment test battery meets logistic constraints of minimal up mass available—completable in a small space—and does not impact cognitive or physical reserves required for EVAs. Finally, the test battery is ordered from least to most provocative for the sensorimotor system such that an onset or increase in motion sickness symptoms during a specific task would suggest an aversive threshold was reached and task performance should end. Following a period of recovery, the task set can be attempted again. This serves two purposes: 1) minimize movement above an aversive threshold to accelerate recovery (Rosenberg et al., 2022), and 2) ensure crewmembers are confident in their movement base through progressive adaptation to movement in Lunar gravity prior to the introduction of the pressurized EVA suit and mission requirements. The current assessment test battery (Figure 3-8.) was down-selected after testing in various ground analogs (e.g., following sustained 3Gx centrifugation) and receiving subjective feedback from previously flown crewmembers to include the tasks that are most sensitive to changes in sensorimotor disorientation and best able to predict operational task performance (Moudy et al., 2025). The implementation of these assessment tasks in early Artemis missions will help refine the thresholds of performance needed to make operational GO/NO-GO decisions.

Subjective and quantitative performance from the assessment tasks should be shared with the crew medical team as additional information on crew capabilities prior to EVAs. Performing the test battery soon after landing (i.e., prior to the first EVA) is critical for determining the extent of g-transition-induced sensorimotor disorientation that result from longer microgravity transits. Later testing throughout the Lunar Surface stay will help track the combined impacts of sensorimotor recovery and cumulative fatigue from the planned high tempo surface EVA operations.

3.2.2.5 Current and Future Testing

To date, exploration EVA-relevant data have been quite limited. The capabilities now exist and are more refined to allow collection of these data simultaneously and relatively unobtrusively in a well-synchronized fashion to provide the most accurate depiction of the crewmember's state. MetRate data from key NBL training events are collected, allowing us to predict readiness for an upcoming ISS EVA including what the MetRate and consumable impact will be for each individual on a per-task basis. These prediction pipelines can be enhanced as we look towards exploration-focused training by collecting more data from more environments using the measures described to not only consider the suit consumables, but to also consider the cost and impact to the human. Ultimately, these data will allow the research and operational support teams to get a better snapshot of the human state and the associated cost of conducting EVAs.

The Crew State and Risk Model (CSRM) will provide individualized modeling of the EVA crewmember's physical and cognitive parameters, as well as predictions of crew state and associated risk based on the EVA task(s) and scenarios. Each of the underlying models in CSRM will first be developed, tested, and validated as individualized, task-specific models. This capability will also be used to provide probabilistic risk estimates and crew state predictions for development of mission architectures and concepts of operation via Personalized EVA and Informatics Decision Support (PersEIDS). CSRM is effectively the future exploration-focused basis for MEDB report/analyses. These parameters will fuel development of seven core models, which will be developed and validated 1−2 at a time: Metabolic Rate, Heart Rate, Inspired CO2, Human Thermal Regulation, Hydration, Nutrition, and Waste Management (HNW), DCS, Fatigue (Cognitive and Physical), and Traverse (Metabolic cost of ambulation). Additional models may be incorporated or developed in the future.

Humans are complex, and there exist a plethora of markers that are tied to HHP or that could be indicators of capabilities or HHP. Future work seeks to continue to expand our "arsenal" of sensors, measures, and the like to ensure we can capture the most comprehensive view of human state with the most optimal (i.e., fewest) possible infractions onto the suited system. Of note, there are several key sensors and measures being targeted for further investigation that have not been mentioned here: respiratory rate, continuous glucose monitoring (CGM), and goniometry. Other measures in the HHP domain certainly exist that have merit in the context of determining performance during EVA and been suggested or will be assessed in future studies, including stress, satiety, teamwork, team coordination (or lack thereof), and immunological alterations.

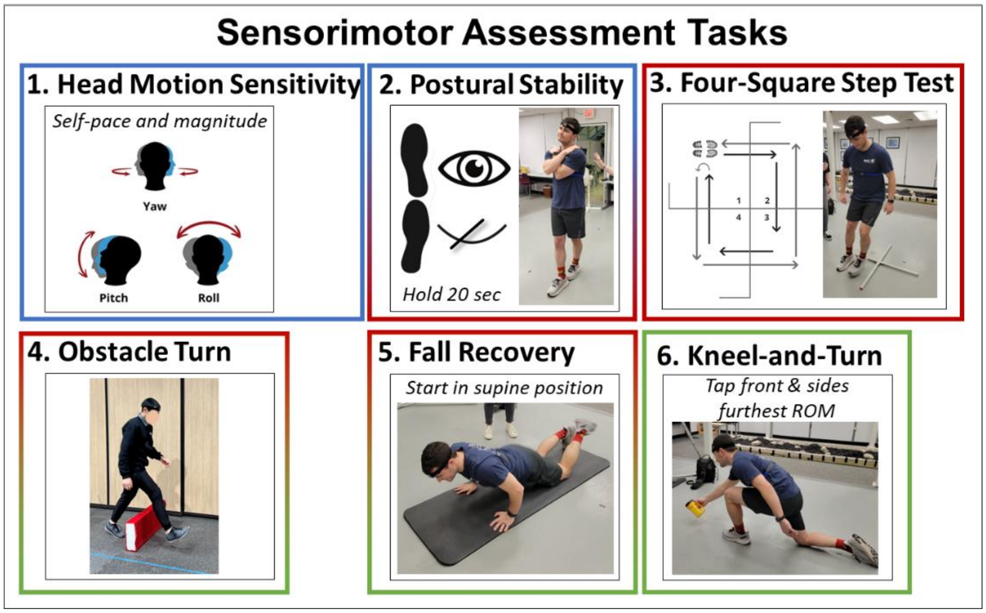


Figure 3-8. Sensorimotor test battery presented in expected performance order. Colored borders represent the primary inclusion reason: blue = progressive adaptation, red = sensorimotor validation (i.e., sensitive to sensorimotor disruptions), green = mimic movements needed during an EVA.

Artemis EVA Operations come with increased risk of injury and compromised performance; this requires a highly integrated approach. This risk drives the need to characterize demands and impacts on performance and provides insights how these may change based on factors such as EVA frequency and complexity. The joint SERPO team serves to infuse HHP monitoring, prediction, and optimization tools into EVA operations and workflows. As they develop more sensors, models, capabilities, and the like, through various efforts, HHP labs will integrate these functions into EVA testing, training, and operations. It is paramount to collect the right data, process and report it with the appropriate context, and ultimately determine what's going on at the human level and how can we best promote, preserve, protect, and optimize crew health and performance.

3.2.2.6 Additional Considerations

Galvanic vestibular stimulation (GVS) has been used to disrupt vestibular input and mimic astronaut postflight task performance after both short and long duration missions (Moore et al., 2006; Moudy et al., 2024). The application of GVS within simulation environments could provide higher fidelity training scenarios and better understanding of performance capabilities in early planetary surface EVAs following short or long duration transits. GVS is a portable system that can be worn while ambulating and applies a temporary disruption with quick dissipation of disorientation. While GVS can be implemented in most of the simulations, it does apply an electrical current and therefore would not be feasible in the NBL environment. While all environments are beneficial for providing mission-relevant data, it is very challenging to compare across different testing environments. Multiple environmental factors play a role in the workloads experienced in the different environments. Inconsistency between task execution across environments and lack of standardization make it challenging to compare. Additionally, very limited sample sizes for analysis makes it difficult to draw conclusions on comparing data from one environment to another without accounting for the confounding variables.

3.3 Physical Preparedness

Physical preparedness, viewed as a dynamic process within the broader human performance framework, is a structured, evidence-based strategy aimed at developing or restoring operational readiness. It systematically introduces task-specific physical and psychological demands to build resilience and reinforce essential capabilities. Unlike general fitness or injury-prevention routines focused solely on risk mitigation, physical preparedness targets the integrated performance systems needed to operate effectively in high-risk, high-demand environments. Its goal is not just to avoid breakdown, but to enhance the physical and cognitive attributes that underpin performance. When executed correctly, it becomes a high-impact intervention by strengthening adaptability, accelerating skill acquisition, and reducing vulnerability through progressive, deliberate exposure.

This concept is grounded in the principle of specificity, as emphasized by Kraemer and Szivak (2012), who advocates for conditioning strategies that mirror the demands of the job. Physical preparation is supported by multiple disciplinary inputs from strength & conditioning professionals, athletic trainers, scientists, physical therapists, medical doctors, and occupational health SMEs. Objective assessments guide this approach to identify performance gaps and training needs accurately, with the goal of creating a more resilient and operationally capable human system.

It is critical to distinguish physical preparedness from frameworks built on overcautious or arbitrary routines focused solely on injury prevention. Programs that rely heavily on passive modalities or low-skill activities often underestimate the human body's adaptive capacity and fail to drive meaningful progress. As Volpi et al. (2022) demonstrated, the spike in NFL injuries following an attenuated preseason was not due to a lack of mobility or balance work, but rather the absence of high-exertion, skill-integrated gameplay, underscoring that essential elements of preparation cannot be replaced with low-fidelity substitutes. Similarly, physical preparedness restores readiness by deliberately reintegrating the physiological, mechanical, and cognitive demands that define operational performance.

3.3.1 A Dynamic Blueprint for Readiness: Training as a Living System

Within the framework of physical preparedness, a critical objective is to establish a comprehensive and sustainable approach to physical preparation. This is best accomplished through a six-phase, stepwise model grounded in scientific principles and structured periodization, both sequenced and cyclic. The phases follow a deliberate progression that repeats over time, supporting continuous adaptation to feedback, evolving mission demands, and individual physiological changes. This approach reflects a dynamic and responsive (living) system built on decades of applied human performance science and practice.

Step 1 anchors the entire framework by defining the physiological and psychological demands of the target environment. This phase involves a detailed characterization of biomechanical loading, movement patterns, energy system contributions, fatigue profiles, and relevant environmental stressors. The precision of this step directly shapes the relevance and effectiveness of all downstream programming. In familiar domains (such as traditional sport), this analysis may confirm or refine established training models. However, in novel or evolving environments such as spaceflight or tactical operations, this step becomes indispensable. Without a historical blueprint, we must rigorously define what success looks like and what the human system must be capable of achieving. This phase provides a quantitative understanding of the destination: the specific physical and cognitive traits required for effective performance under mission conditions.

As emphasized by Suchomel, Nimphius and Stone (2016), identifying which physiological traits drive adaptation is essential for maximizing performance outcomes. Similarly, Kamandulis et al. (2018) demonstrated that task-specific repeated sprint training, consisting of three rounds of 14 sets of 3-s all-out punching efforts with only 10 s of rest between efforts, produced significant improvements in both upper-body aerobic power and punching performance in experienced amateur boxers. Despite the extremely short work durations, the specificity and intensity of the protocol were sufficient to drive measurable neuromuscular and aerobic adaptations. This reinforces the principle that aligning training stressors with the actual demands of performance is critical to eliciting meaningful improvements. Ultimately, understanding which traits matter and why is not optional. It forms the foundation of a targeted, effective, and evidence-based training process.

Step 2 is implementing a tiered assessment strategy that progresses from foundational biomotor capacities to job-specific function and, ultimately, operational readiness. Expressed across three tiers—further explained in section 3.3.3—this approach begins with *Tier 1*, which evaluates core physical qualities such as strength, power, endurance, and coordination using validated tools like the isometric mid-thigh pull (IMTP), vertical jump, and aerobic capacity tests. *Tier 2* introduces functional tasks that reflect occupational demands, performed under load, constraint, or fatigue, and are supported by research linking them to operational outcomes. *Tier 3* simulates real-world performance in high-fidelity environments, incorporating cognitive and psychological stressors. As demonstrated by Acevedo, Zeigler and Melton (2024) and Grier et al. (2024), no single test can independently predict readiness. However, when traits like aerobic capacity and relative strength are assessed together and interpreted in context, they offer valuable insight into physical potential and task-specific performance. Importantly, *Tier 1* tests remain the most precise indicators of physical capacity and are essential for informing effective training prescriptions.

Step 3 is the development of the training program itself, grounded in the core principles of specificity, progressive overload, and recovery, structured through the science of periodization. Once the demands of the task and mission are clearly understood, and the current physical state of the individual is assessed, we can objectively determine whether the performance goal is realistic, how far we are from it, and what training process is required to close the gap. Periodization provides the framework for this process through the systematic variation of training volume and intensity to drive targeted adaptation. This structure may include both vertical integration and horizontal sequencing, two complementary strategies for long-term development that Ian Jeffreys popularized and later published in the work from Alvar, Sell and Deuster (2017), specifically in Greg Haff's chapter on periodization. Vertical integration involves shifting the emphasis of physical qualities across phases while maintaining exposure to all traits. For example, developing maximal strength early supports later gains in power or speed. Horizontal sequencing leverages training residuals, allowing adaptations from one phase to influence the next. As described by Bompa and Buzzichelli (2024), Turner (2011), and Mujika et al. (2018), it is the timing, sequence, and interaction of these elements that determine whether qualities develop synergistically or interfere with one another. In addition to its physiological benefits, structured periodization enables alignment with operational realities such as travel, compressed timelines, or high-tempo pre-mission schedules.

Step 4 is the continuous monitoring and reassessment stage. This is not a periodic check-in; it is a real-time feedback system integrated into the training lifecycle (a living process). Monitoring spans across all assessment tiers, tracking biomotor outputs (e.g., force, power, velocity), functional performance under operational constraints, and psychological or cognitive readiness for task execution. This includes the use of objective tools such as force platforms, isometric testing, and functional task assessments, alongside subjective inputs like session RPE and recovery ratings. Merrigan et al. (2022) emphasize that consistent monitoring is critical to maintain alignment between physiological state and training prescription, ensuring that adaptation remains intentional, data-driven, and not just preference-based.

Step 5 is responsive adaptation. It represents a return to the training design process (Step 3), now informed by the insights gained through continuous monitoring (Step 4). This phase is not about arbitrary adjustments; it is about deliberately evolving the training prescription based on real-time data. Adjustments to variables such as volume, intensity, frequency, and emphasis are made in response to the current physiological and psychological status of the individual. This ensures that progression remains aligned with actual readiness, rather than predetermined timelines or subjective preference. As Mujika et al. (2018) emphasized, periodization is best viewed as a steering strategy, a flexible framework that adapts to emerging feedback, both objective and subjective. This reinforces the concept of structured flexibility, where training is not static but is continuously reshaped by ongoing assessment to maintain purposeful progression.

Step 6 involves performance execution and feedback. This phase tests the preparation, whether through simulation or high-stakes tasks. Execution serves as the final proof of the program's effectiveness. Post-performance feedback, both subjective and objective, is not the end but the beginning; it must be recorded, analyzed, and used to improve the original demand profile. In doing so, the system completes its cycle and resets for the next round. Optimization is not a fixed goal; it is an ongoing process of continuous reassessment and improvement, where physical preparedness is judged by how well training translates to performance in complex, unpredictable environments.

3.3.2 Characterizing Physical and Psychological Demands

Characterizing the actual demands of Artemis and space exploration missions requires more than assuming they resemble existing spaceflight profiles or past Apollo missions. As discussed in previous sections, these missions are centered around surface EVA operations, which introduce a fundamentally new set of physical and psychological challenges. This includes long-duration activity in partial gravity, frequent and high-tempo EVA tasks, repetitive ingress and egress from rovers and habitats, manual tool use in suits, navigation across uneven terrain, and autonomous decision-making without real-time ground support. The cumulative physical and cognitive load imposed by these elements must be precisely defined and quantified. Doing so is essential to inform training design, suit development, and physical preparedness strategies that reflect the actual conditions crew will face on the Lunar Surface.

General fitness is a prerequisite, it provides the foundational capacity to tolerate training, recover from stress, and perform basic tasks; however, exploration missions demand a much deeper understanding of how performance degrades under mission-relevant conditions. This means mapping the biomechanical, physiological, and psychological stressors that define the work. Characterization must go beyond subjective impressions or assumptions. It requires measurable indicators of workload, strain, efficiency, and resilience under specific task conditions.

Laboratory-based testing plays a foundational role in this process. Metrics such as peak force, rate of force development, aerobic capacity, and movement efficiency establish baselines for how the body generates, sustains, and recovers from work. However, lab metrics alone are insufficient. Real performance on the Lunar Surface will occur under fatigue, in suits, across unstable terrain, with elevated psychological demand and minimal recovery time. Therefore, the physical requirements must be tested and refined in analog environments that faithfully replicate those mission constraints.

The previously discussed analogs like the NBL, ARGOS, and others enable high-fidelity simulation of constrained environments. These setups help uncover how task demands change with increasing complexity and sheds light on the real costs of work. For example, a task that seems easy under normal gravity might become metabolically costly or mechanically risky when performed in a pressurized suit on the Lunar Surface. The goal of characterization is to identify these inflection points, where the task shifts from manageable to fatiguing, from efficient to requiring compensation, and from safe to high risk.

This extends to cognitive and psychological load as well. As operational autonomy increases, so does the demand for decision-making under stress. Fatigue, time pressure, novelty, and isolation all degrade cognitive bandwidth. As Pinder et al. (2011) emphasize, experienced performers demonstrate movement efficiency that minimizes muscular effort and reduces overall cost. This efficiency is not only physical but also mental as it frees attention and improves adaptability. Poor motor control, on the other hand, amplifies stress and increases risk, especially when combined with environmental constraint or equipment interference.

Traditional models such as the Wildland Firefighter Pack Test (WFPT) and the Army Combat Fitness Test (ACFT) provide valuable measures of functional task performance. However, they offer limited insight into why performance succeeds or fails. Without *Tier 1* assessments to quantify underlying physical capacities or *Tier 3* simulations to reveal how those capacities hold under operational constraints, these tests alone cannot fully characterize readiness. A modern approach integrates biomechanical and physiological data to explain both outcomes and limitations. Grier et al. (2024) found a strong relationship between relative strength and performance across all six ACFT events. Likewise, Acevedo, Zeigler and Melton (2024) demonstrated a moderate association between aerobic capacity and overall ACFT performance. While no single trait can determine success, muscular strength—particularly when scaled to body mass—and aerobic fitness consistently emerge as the most influential contributors to physical task execution. These traits support force production, endurance, and resilience under fatigue, and must be interpreted together to understand performance in context.

Therefore, characterization must examine how traits like strength, power, and endurance are expressed under varying loads, environmental constraints, and cognitive demands. Muscular strength, for example, is consistently identified as a protective trait. Lauersen et al., (2014, 2018) showed that strength training is more effective at reducing injury risk than flexibility or balance training, particularly in sports populations. Suchomel, Nimphius and Stone (2016), along with Kraemer and Szivak (2012), emphasize that strength contributes to joint stability, neuromuscular control, and tissue resilience, especially when individuals are fatigued or under load. But recognizing its importance is not enough. For exploration surface operations, we must define the actual thresholds needed to perform key tasks safely and efficiently. That is the role of demand characterization.

Ultimately, this process is not simply about whether a person can complete a task. It is about quantifying how hard the task is, what it costs physiologically and psychologically, and which traits determine whether it can be performed reliably over time. This includes not just force production and oxygen use, but also attentional demand, cognitive workload, and fatigue accumulation. Characterizing demand is the first step in developing an evidence-based roadmap for exploration mission preparation. It provides the foundation for targeted training, meaningful assessment, and performance prediction. Without this foundation, we are preparing for a mission we do not fully understand.

3.3.3 Tiered Evidence-Based Assessment Strategies

In section 3.3.1 an evidence-based approach to assess and monitor the complex physical and cognitive demands of exploration missions is outlined. While this structure has long guided operational practice and training decisions, we now formalize it as the ASCR-TAP Method, a Tiered Assessment Protocol (TAP) that establishes a common language and scalable framework for understanding physical preparedness.

This layered model differentiates potential from performance, supports targeted interventions, and allows for consistent monitoring from lab to mission. By officially naming the *ASCR-TAP Method*, we offer a standardized, scalable framework that roots all aspects of physical preparedness in real-world demands, bridging the gap between capacity, application, and sustained mission readiness. This model organizes performance evaluation across three progressively integrated tiers.

Tier 1: Foundational Physical Qualities isolate and quantify fundamental biomotor traits, such as strength, power, endurance, and mobility, using low-skill, high-validity tests that minimize technical variability. Standard tools include grip strength, the IMTP, isometric bench press (IBP), countermovement jump (CMJ), squat or static jump, and maximal oxygen uptake (VO_2pk). Together, these measures create a physiological profile that supports task execution and tailored training prescription and enables deeper interpretation of performance across mission phases.

The IMTP is widely used as a surrogate measure of lower body strength. In collegiate athletes, it has shown strong correlations with dynamic strength tests such as the one-repetition maximum (1RM) back squat ($r = 0.87$) and deadlift ($r = 0.81$), confirming its value as a high-validity proxy (McGuigan & Winchester, 2008). When paired with force platforms, both IMTP and CMJ provide additional insight into neuromuscular function such as rate of force development, bilateral asymmetries, and fatigue status (Haff & Nimphius, 2012). These tools form the analytical backbone of the current ISS Functional Fitness Assessment (FFA) and the proposed Artemis FFA, which is currently employed to monitor performance in support of mission physical preparedness. As emphasized by Comfort et al. (2015); Kraemer and Szivak (2012), as well as Bompa and Haff (2009), strength, power, and aerobic capacity are not merely desirable outcomes; they are foundational traits that underpin the ability to perform and tolerate high-demand tasks. Bottom line up front: the *Tier 1* defines the individual's *physiological foundation* by measuring key traits like strength, power, endurance, and movement quality. These data points reflect the *biological or pathological state* of the system and serve as a starting point to map and tailor the training process. It answers, *"What is their system capable of, and how do we build from here?"*

Tier 2: Functional Task Assessments evaluate whether the physiological traits measured in *Tier 1* result in actual performance during complex, mission-relevant tasks and demands. These assessments mimic real operational stressors such as fatigue, external load, limited mobility, and cognitive demand to create a performance environment that better reflects real-world conditions. In doing so, they uncover constraints that isolated capacity tests often overlook.

Tools like the ACFT and the WFPT, weighted mobility drills, repeated-effort circuits, and structured movement screens offer meaningful complexity. They evaluate how strength, endurance, power, and motor control interact under constrained physical and environmental conditions. However, their value depends on being anchored to validated performance predictors. For example, it was found that peak force from an isometric deadlift was a moderate predictor of casualty drag performance ($R^2 = 0.365$), while rate of force development showed no meaningful relationship, emphasizing that maximum strength—not explosiveness—was the limiting factor in that task.

While *Tier 2* outcomes are often interpreted considering *Tier 1* capacity, the relationship is dynamic, not strictly hierarchical. In some cases, individuals may perform well in *Tier 2* despite low *Tier 1* scores, suggesting the use of compensatory strategies, inefficient strategies, or a task with a relatively low physical threshold. This scenario helps clarify how much reserve capacity is required for success and supports a more nuanced understanding of physical preparedness. Performance is not solely defined by what someone possesses but is shaped by how they apply it under real-world constraints.

Ultimately, *Tier 2* assessments do more than just record outcomes, they help explain them. A poor result on a cone drill or loaded carry doesn't just show failure; it prompts analysis of what caused it. Was the issue due to low relative strength, limited aerobic capacity, or poor coordination under stress? Monteiro et al. (2024) found that law enforcement officers' performance on occupational tasks was predicted by a mix of physical traits, including lower body power, grip strength, and aerobic capacity, with no single trait alone explaining performance. This highlights the importance of interpreting *Tier 2* results with a multifactorial approach. By pinpointing the specific gaps that affect task performance, *Tier 2* assessments offer practical insights to improve training and ensure physical preparedness matches operational needs. Bottom line up front: the *Tier 2* evaluates how well *Tier 1* traits are expressed in complex, task-relevant movements. It bridges training science and application, clarifying whether individuals can apply their physical qualities under operational constraints. It answers, *"Can they apply what they have in a way that reflects the demands of the task?"*

Tier 3: Real-World Transfer (Analog and all high-fidelity environments) Assessments validate whether training adaptations hold under real-world mission conditions. This includes environments like EVA mockups, the NBL, or field-based load carriage drills where physical execution is influenced by fatigue, cognitive demand, spatial constraints, and time pressure. *Tier 3* isn't about isolated capability, it's about performance under pressure. A strong example of this concept comes from Silva et al. (2021), who examined how weekly high-speed running and acceleration loads during training related to actual match performance in professional soccer players. They found moderate associations between the training exposures and in-game execution of those same physical demands, reinforcing the idea that practice-based metrics can predict real operational output when matched correctly. This mirrors the logic of *Tier 3*: we do not just train and assess in isolation—we verify that those traits translate to meaningful, stress-tested performance. Bottom line up front: the *Tier 3* measures real-world execution under operational constraints. It validates whether physical capacity, task skill, and decision-making hold up when tested by actual mission demands. *Tier 3* ultimately answers, "*Can they perform the task when it counts—in context, under load, and without margin for error?*"

3.3.4 Summary & Key Monitoring Considerations

All assessment data must be interpreted within context. Variables such as age, sex, MSK history, and biomechanical profile significantly influence both the outcomes of assessments and the implications drawn from them. Subjective inputs, like session RPE or ease-of-task ratings, are only meaningful when paired with objective measures that quantify load, capacity, or output (Helms et al., 2016). The ASCR-TAP framework helps clarify these relationships (Figure 3-9). *Tier 1* defines the physiological foundation and explains the "why" behind a person's capacity. *Tier 2* evaluates how those traits are functionally expressed under structured, task-relevant conditions. *Tier 3* validates performance in operational settings, confirming whether capabilities transfer under real-world constraints. Together, these tiers shift assessment from static checklists to dynamic, actionable profiling. They enable performance professionals to link data with training and outcomes, ensuring that physical preparedness is built on both measurable capability and individualized context.

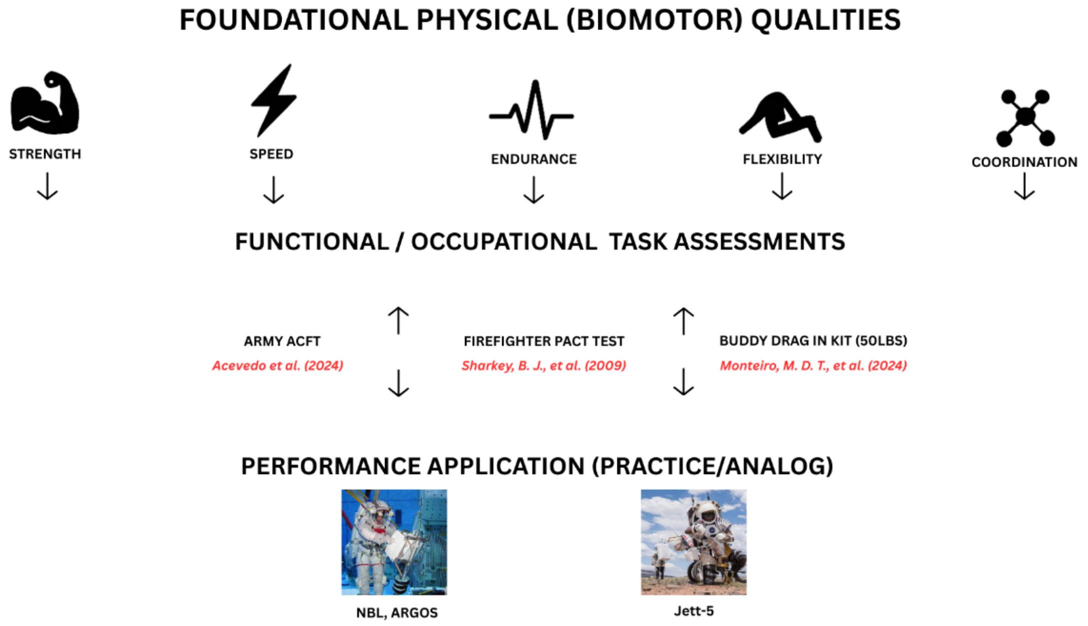


Figure 3-9. ASCR-TAP Method

3.3.5 Development of a comprehensive training program

In developing a comprehensive training plan, we must begin with the right perspective: exercises are tools, nothing more. They are not the plan itself, nor are they the solution to every performance gap. Training only becomes effective when it is grounded in a clear understanding of what we are trying to develop. One of the most counterproductive mistakes is to analyze task demands (step 1) and assess individual capacity (step 2), then resort to stringing together a checklist of exercises without context or structure. That shortcut does not reflect how people train, and it rarely produces meaningful adaptation. Without intent and progression, such programs become irrelevant, impractical, and ultimately ignored.

What is often missing in the physical preparedness conversation is a recognition of the biological cost of task completion. That is where sound training must begin. The process must follow this logic:

- *Understand the cost.* What does the task demand?
- *Assess the individual***.** What traits do they currently express, and what needs to be developed?
- *Training plan/select the right tools*. Choose exercises that specifically develop those traits, delivered through structured and periodized training.

The goal is not just to build capacity, but to build the *right* capacity in the proper *sequence*. Programs that do not do this usually fail to translate to operational performance. Artemis preparation requires a training model built on two anchors: (Step 1) mission demands, and (Step 2) the crewmember's physiological profile. These define the performance gap. The training strategy must then close that gap within real-world constraints: limited time, medical considerations, and restricted recovery bandwidth. Adaptation is not infinite. Planning must respect that.

That is where periodization becomes essential. Strategic planning through training *phases* ensures that traits identified in *Tier 1* assessments are emphasized when needed, maintained when possible, and never neglected. Muscular strength, for example, is a foundational trait that supports all others including speed, power, coordination, and resilience under load (Suchomel, Nimphius, & Stone, 2016). Issurin (2008) further underscores that you cannot train everything at once and expect meaningful adaptation. Prioritization and sequencing are required. Two principles guide this process:

- *Vertical integration* ensures that no trait is ever completely removed. Even when a certain quality is not the current priority, it is maintained at a dosage that preserves function. This guards against regression and supports the interdependence of physical systems (NSCA, 2017).
- *Horizontal sequencing* ensures that each training phase builds logically on the last. Foundational traits like strength or aerobic capacity enhance the body's ability to benefit from later phases, emphasizing speed, agility, or power. This reflects the principle of *phase potentiation* and the biological concept of *residual training effects*, which define how long adaptations last after the stimulus ends (Issurin, 2008).

In Artemis preparation, this structure is not optional, it is critical. It provides clarity, direction, and measurable progression. Without it, programming becomes vague, reactive, and inefficient.

Lastly, tailored intervention or individualization must be evidence-based and grounded in a clear understanding of Steps 1 and 2. Otherwise, it becomes a catchall term to justify programs that lack structure, progression, or physiological benefit. Ultimately, a well-developed training roadmap ensures that every exercise has purpose, every phase has intent, and every adaptation moves the individual closer to the mission's demands (Figure 3-10). That is the difference between training for fitness and training for function.

3.3.6 Ongoing Physical Assessments

As previously outlined, physical preparedness is not a fixed trait, but a dynamic state influenced by training load, recovery status, environmental stress, and skill level. In the context of Artemis preparation, maintaining and advancing physical preparedness requires more than periodic testing. While pre- and post-assessments can track physiological changes over time, they cannot fully capture an individual's readiness to perform in real conditions. This is why a comprehensive, tiered, and evidence-based monitoring system is essential. Real-time monitoring ensures that training dosage aligns with current physical capacity and mission demands, enabling more precise adjustments and timely interventions when needed. Rather than reacting to outcomes after the fact, this approach supports continuous alignment between training, recovery, and the evolving requirements of the task.

To meet this need, physical assessments must be conducted during operational exercise training and mission training. As outlined by Merrigan et al. (2020), monitoring should occur across three nested time scales:

- *Macro-level monitoring (3–12 months)* evaluates long-term program effectiveness by linking periodized training phases to outcome metrics like strength or aerobic capacity.
- *Meso-level monitoring (8–12 weeks)* aligns with specific training phases (e.g., strength or power mesocycles) and includes re-assessments such as the IMTP or CMJ to confirm intended adaptations.
- *Micro-level monitoring (weekly or intra-weekly)* targets acute shifts in physical preparedness, capturing neuromuscular fatigue, detraining indicators, and recovery status. This level allows real-time adjustment of daily loads based on objective markers of preparedness.

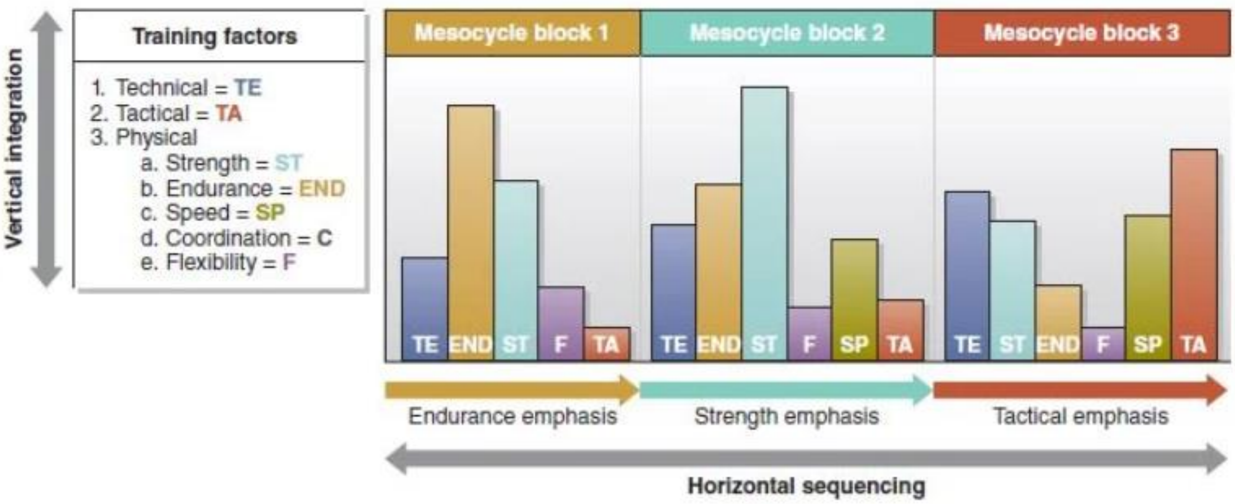


Figure 3-10. Tactical strength and conditioning mesocycle blocks (Alvar, Sell, & Deuster, 2017)

This time-scale-based monitoring strategy does not replace the *Tier 1, 2, and 3* assessment model: it enables it, while the tiered model defines what to assess. For example, the monitoring framework defines how often, at what resolution, and for what purpose assessments are applied to foundational physical capacity in *Tier 1*, functional task performance in *Tier 2*, and operational validation in *Tier 3*. In that sense, monitoring functions as the operating system behind the assessment framework. It ensures that data from each tier is captured at the appropriate interval, interpreted in context, and used to drive meaningful decisions.

For example, tools like the CMJ, IMTP, and squat jump (SJ), which are central to *Tier 1* assessments, are also highly effective at meso- and micro-level time scales. These tests reliably capture neuromuscular qualities such as peak force, rate of force development, and impulse (Comfort et al., 2015; McGuigan & Winchester, 2008). When embedded within a layered monitoring system, they do more than benchmark capacity. They help track adaptation over training cycles, inform daily adjustments, and support physical preparedness determinations that directly influence *Tier 2* and *Tier 3* task execution.

In *Tier 3* environments like the NBL and the ARGOS, additional physiological indicators such as metabolic rate, hydration status, and heart rate provide deeper insight into real-time operational readiness. When combined with *Tier 1* and *Tier 2* data, these metrics help align training with the actual demands astronauts face in high-fidelity, load-bearing simulations. However, despite their importance, the lack of an integrated monitoring platform and dependence on fragmented data systems still limit their full usefulness.

As mentioned earlier, monitoring cannot be limited to just pre- and post-testing. While helpful for measuring changes, this method only reveals what changed, not why or when. As Merrigan et al. (2020) point out, readiness should be viewed as a dynamic process, not a static checkpoint. Without continuous tracking, practitioners must rely on guesswork about adaptation, recovery, and workload. This is especially problematic during the tightly scheduled Artemis preparation cycles, where recovery time is limited.

Ultimately, this monitoring framework is not an addition to the tiered model; it is essential to its function. It turns static assessments into dynamic, actionable insights. By integrating time-sensitive data across all three tiers, this system ensures that physical preparation stays aligned with individual capacity, physiological state, and the actual demands of the mission.

3.3.7 Reworking the Plan: Training Progressions and the Limits of Specificity

As data from tiered assessments and ongoing monitoring accumulate, the next step is to rework the training plan based on what those insights reveal. This does not simply mean adjusting sets, reps, or increasing volume. It requires deliberate refinement of training progressions and a critical evaluation of how exercises are categorized and applied, especially in relation to the demands of suited EVA activity for Artemis missions.

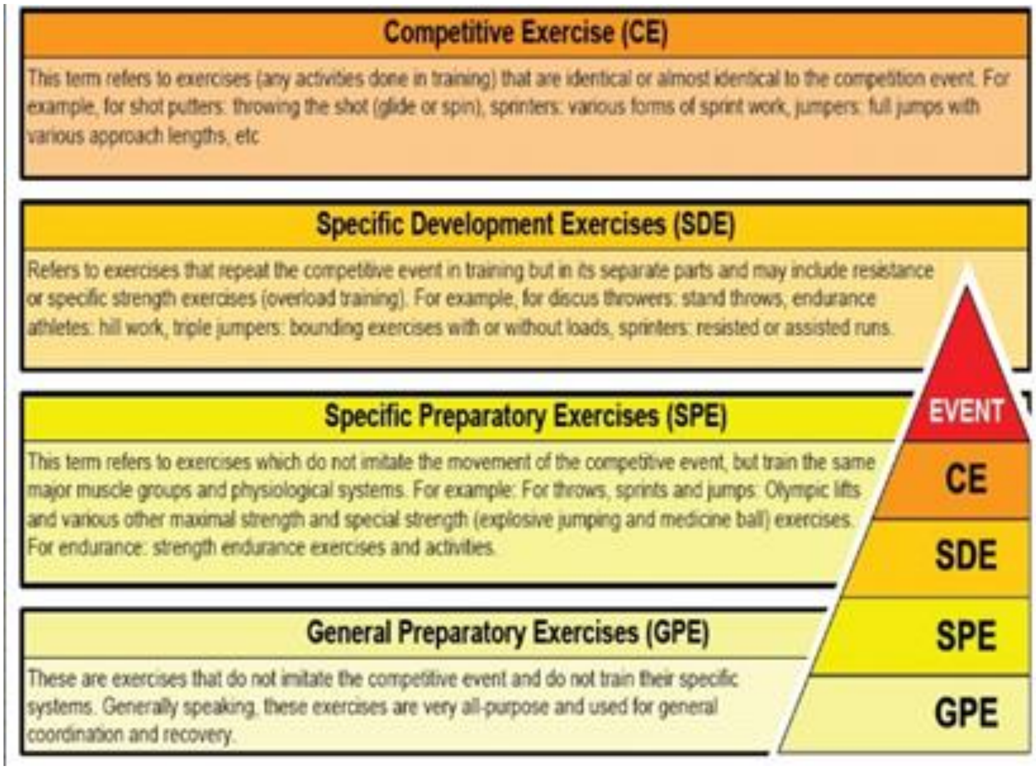
The principle of specificity tells us that training adaptations are directly related to the types of movements, speeds, forces, motor patterns, and energy systems used. This concept is formalized in Anatoliy Bondarchuk’s classification model, which organizes exercises into four categories of increasing specificity: General Preparatory Exercises (GPE), Specific Preparatory Exercises (SPE), Specific Developmental Exercises (SDE), and Competitive Exercises (CE). Each level signifies a closer mechanical and neurological resemblance to the actual task. In traditional athletics, this framework connects physical preparation to technical execution. When applied to suited EVA preparation; however, the model reveals a fundamental limitation.

The suit itself transforms how movement occurs. It adds resistance at the joints, reduces ROM, shifts load paths, alters neuromuscular control, and degrades proprioceptive feedback. These changes make EVA tasks functionally distinct from anything performed in a terrestrial gym.

No matter how an exercise is loaded or cued, it cannot be classified as an SDE or CE. At best, gym-based movements belong in the GPE or SPE categories, where they build force capacity and tissue resilience but do not replicate the neuromuscular patterns used in a pressurized suit.

This distinction is essential. Without a sound understanding of specificity, it becomes easy to mislabel exercises as mission-specific based on superficial joint similarity. But similarity in appearance does not guarantee skill transfer, as Cronin and Hansen (2005) clearly illustrate. Their study found that traditional strength tests, like a 3RM back squat, did not correlate with sprint performance in trained rugby athletes. In contrast, dynamic movements such as SJs and CMJs, which better matched the timing and neuromuscular demands of sprinting, showed meaningful relationships with sprint speed. Their findings emphasize that training must reflect the mechanical and neural properties of the task to achieve effective transfer.

Figure 3-11. Bondarchuk exercise categorization model



Competitive Exercise (CE)

This term refers to exercises (any activities done in training) that are identical or almost identical to the competition event. For example, for shot putters: throwing the shot (glide or spin), sprinters: various forms of sprint work, jumpers: full jumps with various approach lengths, etc

Specific Development Exercises (SDE)

Refers to exercises that repeat the competitive event in training but in its separate parts and may include resistance or specific strength exercises (overload training). For example, for discus throwers: stand throws, endurance athletes: hill work, triple jumpers: bounding exercises with or without loads, sprinters: resisted or assisted runs.

Specific Preparatory Exercises (SPE)

This term refers to exercises which do not imitate the movement of the competitive event, but train the same major muscle groups and physiological systems. For example: For throws, sprints and jumps: Olympic lifts and various other maximal strength and special strength (explosive jumping and medicine ball) exercises. For endurance: strength endurance exercises and activities.

General Preparatory Exercises (GPE)

These are exercises that do not imitate the competitive event and do not train their specific systems. Generally speaking, these exercises are very all-purpose and used for general coordination and recovery.

Figure 3-12. Bondarchuk exercise categorization definitions

This does not reduce the importance of the weight room. In fact, it confirms its value. The gym is where foundational traits are developed, such as load tolerance, fatigue resistance, and force production. These are essential attributes for physical preparedness. However, the gym is not the place to develop operational skill. As Volpi and colleagues stated in 2022, even highly fit individuals will struggle to perform if they are not adapted to the constraints of the operational environment. For astronauts, technical rehearsal in high-fidelity environments like the NBL and the ARGOS is not optional. These analogs are equivalent to practice for athletes. Just as athletes who skip practice suffer performance consequences, astronauts who miss exposure to realistic EVA simulations increase their risk during critical tasks.

Reworking the plan involves understanding what adaptations can and cannot happen in the gym. Specificity does not diminish the value of gym work; it clarifies its purpose. Strength training aims to develop capacity, which is then challenged through targeted tasks in *Tier 2* and validated in mission-relevant simulations in *Tier 3*. Without this comprehensive sequence, no training program can be considered fully operational.

Specificity should not be misused to justify incorrect conclusions. It is a principle that helps us differentiate between preparation and performance. The goal is not to make every exercise mimic EVA, rather to ensure the underlying physiology is strong, adaptable, and prepared. Effective training respects these differences. It recognizes the limitations of each setting and uses each tier appropriately. Only then can adjustments be made that genuinely enhance performance and support mission success.

3.3.8 Performance Execution: Monitoring as a Living System

Performance is not confirmed in the lab. It is demonstrated in the field. In Artemis preparation, that field is the analog environment, where physical demand, environmental constraint, and operational complexity come together. Facilities like the NBL, the ARGOS, and other mission-specific platforms are the most authentic settings to evaluate whether training transfers to operational tasks. These are not just simulations. They represent the highest level of physical preparation, similar to preseason training for athletes, where physical preparedness is revealed under realistic conditions.

Within these environments, monitoring becomes essential. To understand how training is expressed as performance, we must track both external load—what was done—and internal load—how the body responded. External load includes measurable outputs such as volume, time, or distance. Internal load reflects the physiological cost of that work, captured through heart rate, perceived exertion, and markers of stress or fatigue. The relationship between these two reveals how demanding the task was and how well the individual tolerated it.

This is not a simple check. It provides the clearest view into how astronauts apply their physical capabilities in context. Two individuals may complete the same task, but the cost to do so can vary widely. Without monitoring during analog sessions, we lose the opportunity to understand how training holds up under stress. As supported by Mujika (2017), internal response is a key factor in understanding risk and adaptation. Monitoring gives us that visibility. To be effective, *Tier 3* monitoring must be continuous, integrated, and guided by context. It cannot be occasional or static. It must operate as a dynamic system that links assessment with the training effect. The goal is not only to confirm task completion but to understand how it was achieved and what that tells us about readiness to progress.

In the end, this step brings everything into focus. Performance and monitoring within *Tier 3* allow us to observe how well someone executes, how they respond, and what that reveals about the training behind it. This is the point where preparation and assessment meet. It is where training becomes performance. Moreover, it is where physical preparedness becomes living.

3.3.9 The Workout

All training should start with a proper warm-up. The warm-up is not an optional or improvised element of training, it is a structured, evidence-based system designed to prepare the body and brain for physical performance. When practitioners dismiss warm-ups as “personal” or “intuitive”, they demonstrate a fundamental misunderstanding of both their physiological function and their educational value. This is problematic in high-stakes, autonomous environments like spaceflight, where individuals must prepare without direct supervision. A warm-up created from scratch each day is not an example of individualization; it is improvisation without a framework. Instead, we implement a programmatic and educational system that promotes both immediate preparedness and long-term autonomy. The Raise, Activate, Mobilize, and Potentiate (RAMP) framework, developed by Jeffreys (2007), provides the foundation for this approach, ensuring that warm-ups serve not only to prepare for the task at hand but also to teach transferable principles of movement preparation. Girginer et al. (2025) found that athletes who used a RAMP-based warm-up experienced meaningful improvements in both vertical jump height and 30-m sprint performance compared to static stretching and no warm-up. These performance gains reflect improvements in neuromuscular facilitation, motor unit recruitment, and elastic energy transfer; qualities essential for athletic and mission-critical tasks alike. In the spaceflight context, the RAMP framework equips astronauts with a reliable and repeatable system for preparing their bodies in the absence of external coaching, making it an essential component of both physical preparedness and training literacy.

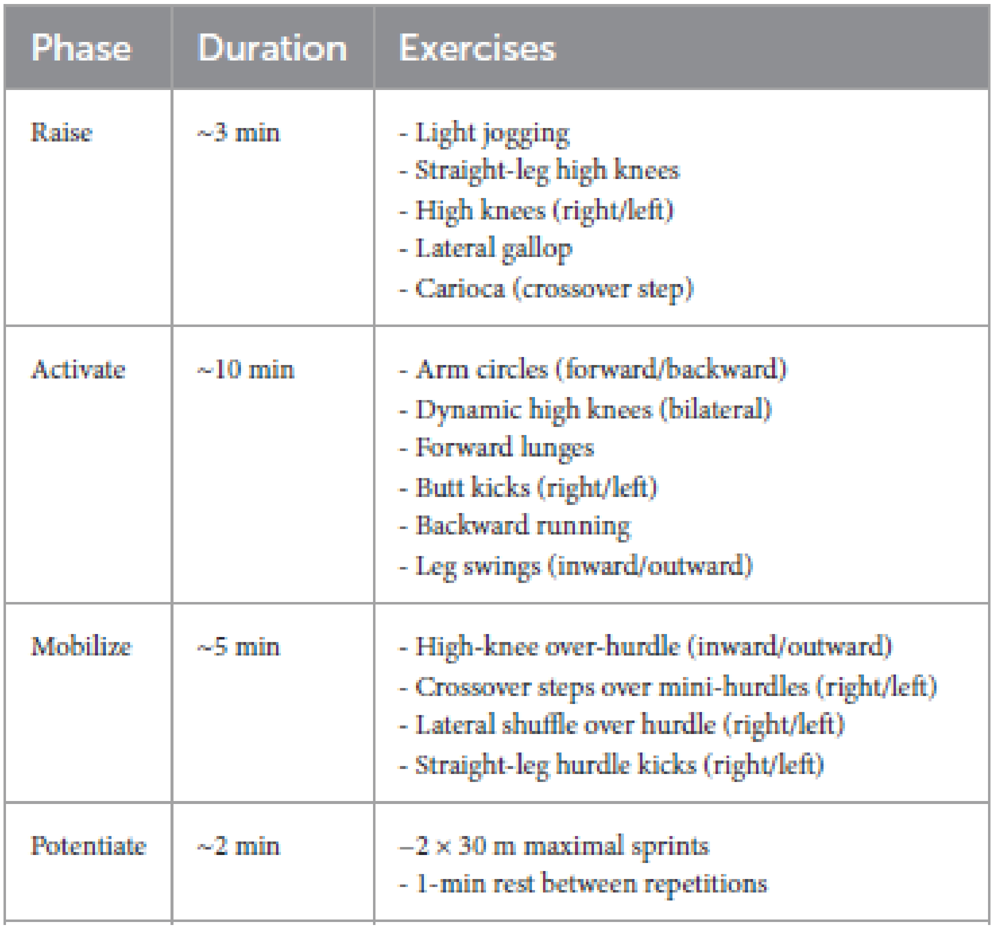
3.3.9.1 The RAMP Framework

RAMP stands for Raise, Activate, Mobilize, and Potentiate: a progressive sequence designed to prepare the neuromuscular system for high-intensity output (Table 3-2).

- **Raise:** Elevate core temperature, heart rate, respiration, and blood flow. Jeffreys cautions against wasting this phase with generic jogging; instead, practitioners should use it to reinforce movement patterns relevant to the task ahead.
- **Activate and Mobilize**: Though grouped together, these functions serve distinct purposes.

    - *Activate* targets key muscle groups (e.g., glutes, deep core, rotator cuff) to improve recruitment and joint stabilization.
    - *Mobilize* improves joint function and dynamic ROM through movement-based drills: avoiding the performance decrements associated with static stretching.
- **Potentiate**: Prepare the neuromuscular system for peak performance through task-specific, explosive efforts (e.g., loaded jumps, short sprints, progressive lifts). This phase leverages post-activation potentiation (PAP) to optimize force production without inducing fatigue.

Table 3-2. RAMP Warm-Up Protocol

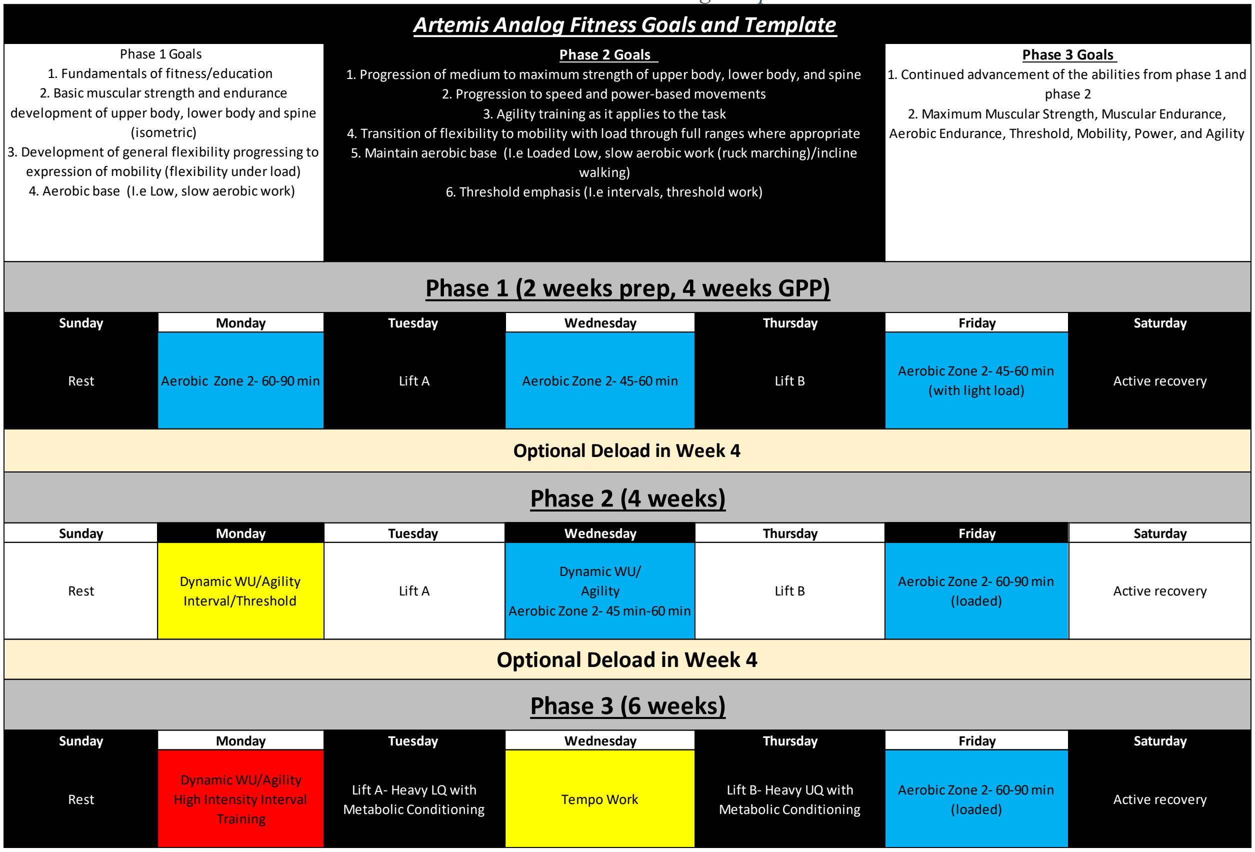


Phase	Duration	Exercises
Raise	~3 min	- Light jogging - Straight-leg high knees - High knees (right/left) - Lateral gallop - Carioca (crossover step)
Activate	~10 min	- Arm circles (forward/backward) - Dynamic high knees (bilateral) - Forward lunges - Butt kicks (right/left) - Backward running - Leg swings (inward/outward)
Mobilize	~5 min	- High-knee over-hurdle (inward/outward) - Crossover steps over mini-hurdles (right/left) - Lateral shuffle over hurdle (right/left) - Straight-leg hurdle kicks (right/left)
Potentiate	~2 min	–2 × 30 m maximal sprints - 1-min rest between repetitions

3.3.9.2 Sample Mesocycle Template

This sample mesocycle training template clearly demonstrates periodization, vertical integration, and horizontal sequencing, all designed to support gradual adaptation for Artemis's physical preparedness. Periodization is shown through a structured progression across three phases: starting with general physical preparation, moving into more specific loading, and ending with high-intensity, task-focused outputs (Table 3-3). Each phase builds on the previous one. Vertical integration is reflected by the consistent presence of multiple fitness qualities, strength, aerobic capacity, mobility, agility, and threshold conditioning, in all phases, rather than treating them as separate blocks. Horizontal sequencing appears in the weekly structure, where early exposure to mobility and aerobic work transitions into threshold intervals and loaded strength sessions, which then advance to metabolic conditioning and operational movement patterns. These strategies ensure training is progressive, integrated, and relevant to real mission demands.

Table 3-3. Phased Training Template



Artemis Analog Fitness Goals and Template

Phase 1 Goals	**Phase 2 Goals**	**Phase 3 Goals**
1. Fundamentals of fitness/education 2. Basic muscular strength and endurance development of upper body, lower body and spine (isometric) 3. Development of general flexibility progressing to expression of mobility (flexibility under load) 4. Aerobic base (I.e Low, slow aerobic work)	1. Progression of medium to maximum strength of upper body, lower body, and spine 2. Progression to speed and power-based movements 3. Agility training as it applies to the task 4. Transition of flexibility to mobility with load through full ranges where appropriate 5. Maintain aerobic base (I.e Loaded Low, slow aerobic work (ruck marching)/incline walking) 6. Threshold emphasis (I.e intervals, threshold work)	1. Continued advancement of the abilities from phase 1 and phase 2 2. Maximum Muscular Strength, Muscular Endurance, Aerobic Endurance, Threshold, Mobility, Power, and Agility

Phase 1 (2 weeks prep, 4 weeks GPP)

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Rest	Aerobic Zone 2- 60-90 min	Lift A	Aerobic Zone 2- 45-60 min	Lift B	Aerobic Zone 2- 45-60 min (with light load)	Active recovery

Optional Deload in Week 4

Phase 2 (4 weeks)

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Rest	Dynamic WU/Agility Interval/Threshold	Lift A	Dynamic WU/ Agility Aerobic Zone 2- 45 min-60 min	Lift B	Aerobic Zone 2- 60-90 min (loaded)	Active recovery

Optional Deload in Week 4

Phase 3 (6 weeks)

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Rest	Dynamic WU/Agility High Intensity Interval Training	Lift A- Heavy LQ with Metabolic Conditioning	Tempo Work	Lift B- Heavy UQ with Metabolic Conditioning	Aerobic Zone 2- 60-90 min (loaded)	Active recovery

The sample Phase 1 resistance training sessions (Lift A and Lift B) reflect a structured general physical preparation (GPP) approach, emphasizing movement quality, volume accumulation, and foundational strength across the entire body. Each session begins with a RAMP warm-up, aligning with Jeffreys' evidence-based framework to raise core temperature, activate key musculature, and potentiate performance (Table 3-4).

The exercise selection targets all major movement patterns: squat or hinge (Primary Leg, Posterior Chain), push and pull (Vertical and Horizontal Press/Pull), and includes core circuits to enhance trunk stability. The volume is consistent across muscle groups, three sets of twelve reps, providing a hypertrophy-oriented base to build muscular endurance and joint resilience.

Progressive overload is implemented through weekly progression in RPE and intensity. Weeks 1 and 2 emphasize technical rehearsal using sets at a controlled 5 RPE, while Weeks 3 and 4 increase to 6 and then 8 RPE, transitioning toward moderate intensity without excessive fatigue. The use of session RPE tracking helps guide autoregulation and monitor perceived exertion across the training phase.

This structure allows for high-quality movement under manageable loads, preparing the astronaut or tactical athlete for more complex or intense loading in later phases. It is a textbook example of periodized GPP: laying the physiological and technical foundation before higher-intensity demands are introduced.

Table 3-4. Phase 1 Strength Template

Phase 1																										
Lift A			**Week 1**				**Week 2**				**Week 3**				**Week 4**				**Week 5**				**Week 6**			
EXERCISE (60s rec)	**Sets**	**Reps**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**
RAMP Warmup	**10min**																									
Primary Leg	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Posterior Chain	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Upper Warm-up	**2**	**12**	5rpe	5rpe			5rpe	5rpe			6rpe	6rpe			6 rpe	6 rpe			6 rpe	6 rpe			6 rpe	6 rpe		
Vertical Press	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Vertical Pull	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Core Circuit	**10 min**																									
Cool Down	**5 min**																									
			Session RPE =				**Session RPE =**				**Session RPE =**				**Session RPE =**				**Session RPE =**				**Session RPE =**			
Lift B			**Week 1**				**Week 2**				**Week 3**				**Week 1**				**Week 2**				**Week 3**			
EXERCISE (60s rec)	**Sets**	**Reps**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**
RAMP Warmup	**10min**																									
Primary Leg	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Posterior Chain	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Upper Warm-up	**2**	**12**	5rpe	5rpe			5rpe	5rpe			6rpe	6rpe			6rpe	6rpe			6rpe	6rpe			6rpe	6rpe		
Horizontal Press	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Horizontal Pull	**3**	**12**	5rpe	5rpe	5rpe		5rpe	5rpe	5rpe		6rpe	6rpe	6rpe		8 rpe	8 rpe	8 rpe		8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe	8 rpe
Core Circuit	**10 min**																									
Cool Down	**5 min**																									
			Session RPE =				**Session RPE =**				**Session RPE =**				**Session RPE =**				**Session RPE =**				**Session RPE =**			

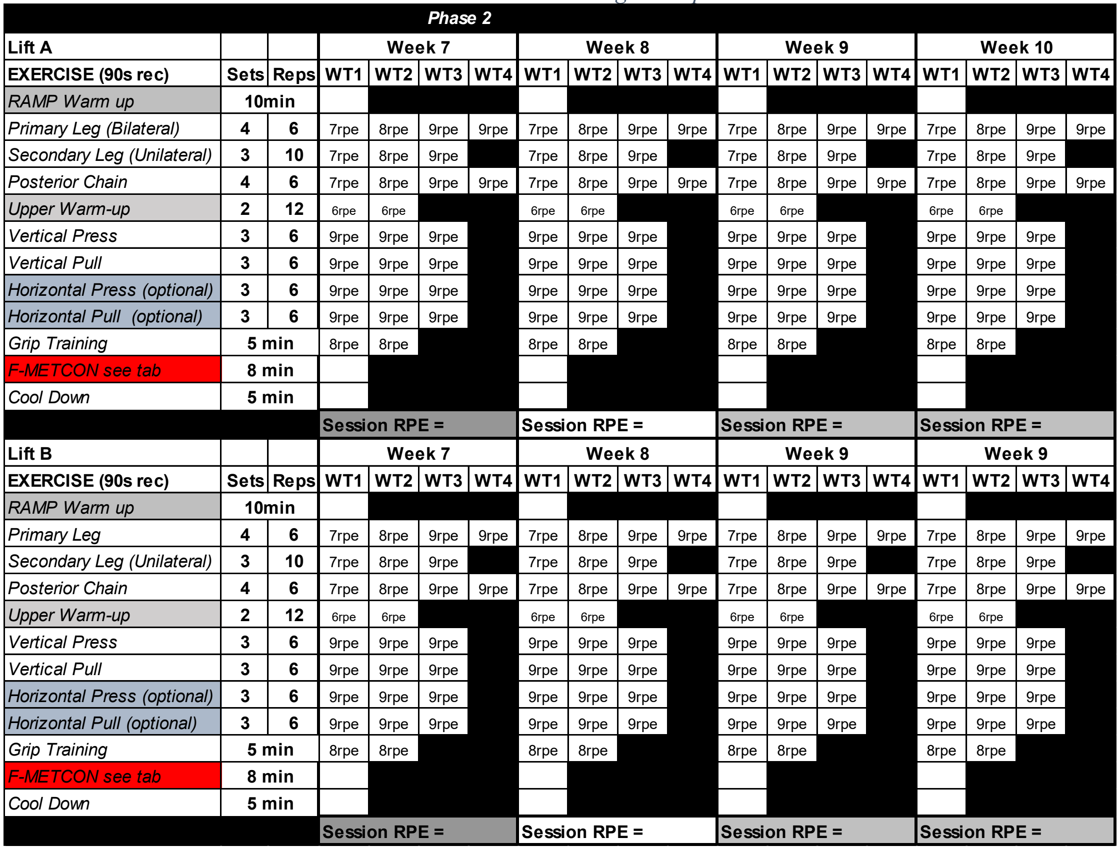
The sample ***Phase 2*** of the resistance training program reflects a deliberate shift from general preparation to intensification and complexity, increasing both load and movement specificity (Table 3-5). Compared to *Phase 1*, the volume and intensity rise, and the program introduces unilateral lower body work, optional horizontal plane pressing and pulling, and grip-specific training, signaling a move toward performance-related qualities. The RPE progression (from 6 to 9 RPE across weeks) guides a nonlinear but progressive overload model, allowing autoregulation while still raising training stress. The expanded rest intervals (90 s) support higher output per set, enabling heavier loads and emphasizing quality under fatigue. Importantly, this phase improves bilateral-unilateral integration, enhancing coordination, single-limb stability, and asymmetry control, all of which are relevant to spaceflight populations navigating unpredictable environments.

The optional press/pull variations let coaches customize movement focus without disrupting the program structure, demonstrating horizontal sequencing within the mesocycle. Additions like grip training and F-METCON (functional metabolic conditioning) prepare for more advanced metabolic and task-specific phases in *Phase 3*, making this block a bridge between structural development and mission-specific readiness. The structure maintains vertical integration by continuing to address strength, endurance, and motor control simultaneously, but with increased complexity and purpose.

The sample ***Phase 3*** marks the final stage of the training cycle, focusing on maximum strength, power development, and functional specificity as it applies in the weight room (Table 3-6). The structure shifts from general preparation to task-oriented performance, involving high intensities (up to 94% 1RM), explosive movements, and integrated conditioning, key components of spaceflight readiness training. The warm-up and plyometric sections continue to follow the RAMP principle, now combined with specific movement preparation (e.g., medicine ball throws, loaded jumps). Plyometric exercises are paired with upper and lower body efforts, enhancing intermuscular coordination and rate of force development. The “Triple Extension” segment targets hip-knee-ankle synchronization, essential for dynamic locomotion tasks like ladder work, EVA ingress/egress, or load carriage. Heavy compound lifts are performed across 3–4 sets with 3–4 reps, progressing from 82% to 94% of 1RM.

This represents a classic intensification phase, peaking neuromuscular output before transitioning to real-world functional tasks. Grip-specific work is maintained to preserve mission-relevant endurance and control. Including metabolic conditioning (METCON) finishers ensures aerobic and anaerobic capacities are sustained even under high neuromuscular fatigue, mirroring in-mission scenarios. The dual-session format (Day 1 and Day 2) maintains movement balance and phase-specific variation, ensuring horizontal sequencing while integrating all key physical qualities: strength, power, endurance, and control throughout the cycle. This phase is not just a peak; it's a rehearsal. Every element is deliberately designed to mimic the physical complexity and intensity astronauts might face in constrained, high-stakes environments.

Table 3-5. Phase 2 Strength Template



Phase 2																		
Lift A			**Week 7**				**Week 8**				**Week 9**				**Week 10**			
EXERCISE (90s rec)	**Sets**	**Reps**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**
RAMP Warm up	**10min**																	
Primary Leg (Bilateral)	**4**	**6**	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe
Secondary Leg (Unilateral)	**3**	**10**	7rpe	8rpe	9rpe		7rpe	8rpe	9rpe		7rpe	8rpe	9rpe		7rpe	8rpe	9rpe	
Posterior Chain	**4**	**6**	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe
Upper Warm-up	**2**	**12**	6rpe	6rpe			6rpe	6rpe			6rpe	6rpe			6rpe	6rpe		
Vertical Press	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Vertical Pull	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Horizontal Press (optional)	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Horizontal Pull (optional)	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Grip Training	**5 min**		8rpe	8rpe			8rpe	8rpe			8rpe	8rpe			8rpe	8rpe		
F-METCON see tab	**8 min**																	
Cool Down	**5 min**																	
			Session RPE =				**Session RPE =**				**Session RPE =**				**Session RPE =**			
Lift B			**Week 7**				**Week 8**				**Week 9**				**Week 9**			
EXERCISE (90s rec)	**Sets**	**Reps**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**
RAMP Warm up	**10min**																	
Primary Leg	**4**	**6**	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe
Secondary Leg (Unilateral)	**3**	**10**	7rpe	8rpe	9rpe		7rpe	8rpe	9rpe		7rpe	8rpe	9rpe		7rpe	8rpe	9rpe	
Posterior Chain	**4**	**6**	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe	7rpe	8rpe	9rpe	9rpe
Upper Warm-up	**2**	**12**	6rpe	6rpe			6rpe	6rpe			6rpe	6rpe			6rpe	6rpe		
Vertical Press	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Vertical Pull	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Horizontal Press (optional)	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Horizontal Pull (optional)	**3**	**6**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Grip Training	**5 min**		8rpe	8rpe			8rpe	8rpe			8rpe	8rpe			8rpe	8rpe		
F-METCON see tab	**8 min**																	
Cool Down	**5 min**																	
			Session RPE =				**Session RPE =**				**Session RPE =**				**Session RPE =**			

This ***Cardiovascular/Cardiorespiratory Fitness Training Model*** provides a periodized framework that scales intensity, volume, and specificity across three progressive phases. It integrates aerobic base development, threshold conditioning, and high-intensity interval training (HIIT) to systematically build cardiorespiratory fitness aligned with mission demands and physiological readiness (Table 3-7).

Aerobic Conditioning (blue section) begins with unloaded, even-terrain work targeting Zone 2 heart rate (HR), gradually increasing duration and intensity across phases. This foundational work builds oxidative capacity, recovery efficiency, and long-duration stamina.

Suggested modes include biking, running, rucking, and stairmaster, with conversational pace guidelines reinforcing autoregulation.

Threshold Training (yellow section) is introduced in Phase 2 and emphasized in Phase 3. It targets the upper boundary of aerobic capacity—typically around 80% max HR or race pace effort—through 20 to 30-min sustained efforts. The focus is on elevating lactate threshold and delaying fatigue onset, using cycling and running modalities.

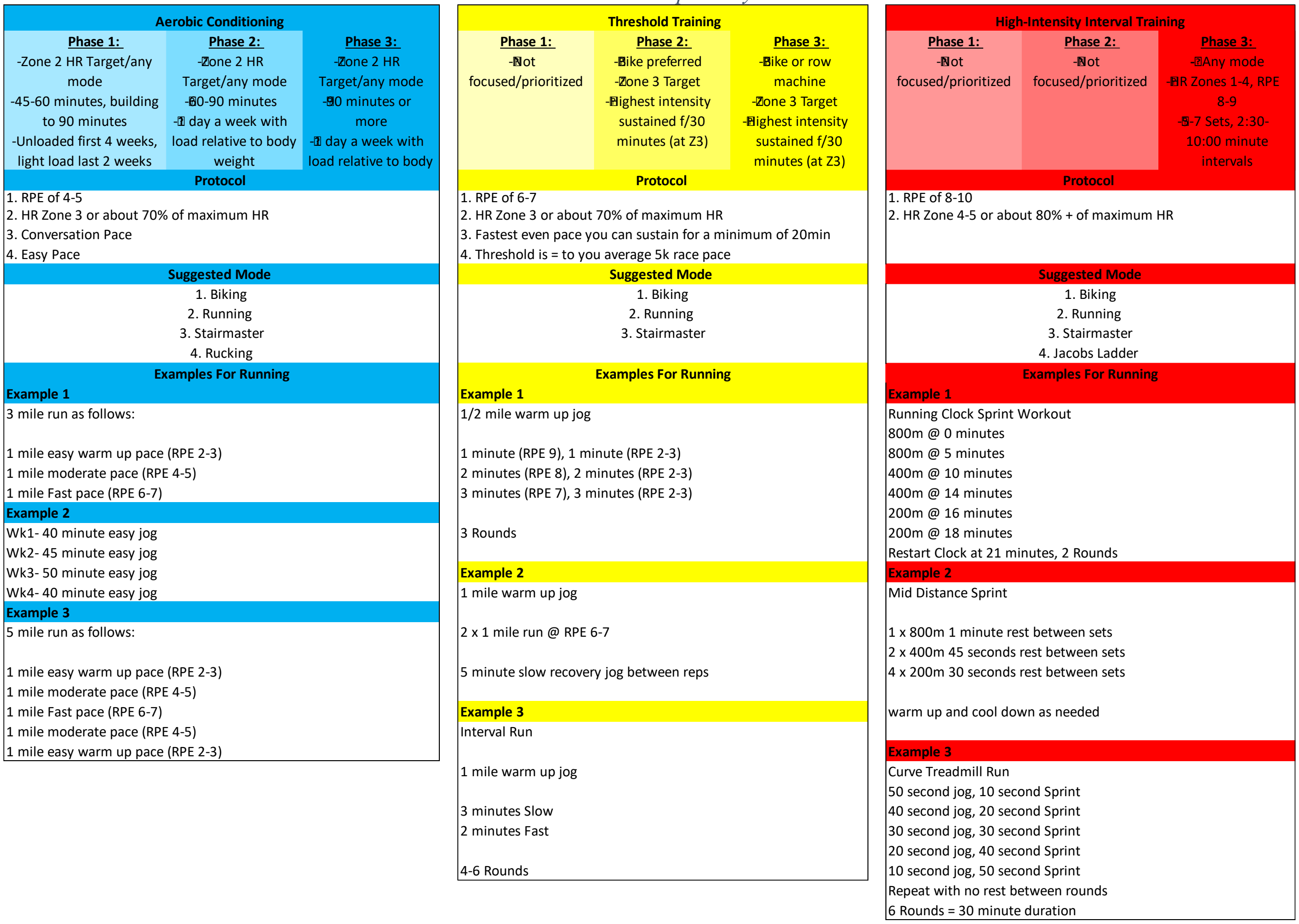
Table 3-6. Phase 3 Strength Template

Phase 3																		
Lift A			**Week 11**				**Week 12**				**Week 13**				**Week 14**			
EXERCISE (90s rec)	**Sets**	**Reps**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**
RAMP	**10min**		4rpe	4rpe			4rpe	4rpe			4rpe	4rpe			4rpe	4rpe		
Primary Leg (Bilateral)	**4**	**6**	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max
Posterior Chain	**4**	**6**	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max
Hamstring	**3**	**6**	8rpe	8rpe	8rpe		8rpe	8rpe	8rpe		8rpe	8rpe	8rpe		8rpe	8rpe	8rpe	
Upper Warm-up	**2**	**12**	5rpe	5rpe			5rpe	5rpe			5rpe	5rpe			5rpe	5rpe		
Vertical Press	**3**	**8**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Vertical Pull	**3**	**8**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
F-METCON see tab	**15 min**		9rpe				9rpe				9rpe				9rpe			
Cool Down	**10 min**																	
			Session RPE =				**Session RPE =**				**Session RPE =**				**Session RPE =**			
Lift B			**Week 11**				**Week 12**				**Week 13**				**Week 14**			
EXERCISE (90s rec)	**Sets**	**Reps**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**	**WT1**	**WT2**	**WT3**	**WT4**
RAMP	**10min**		4rpe	4rpe			4rpe	4rpe			4rpe	4rpe			4rpe	4rpe		
Primary Leg (Unilateral)	**3**	**10**	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max
Posterior Chain	**3**	**10**	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max	7rpe	8rpe	9rpe	Max
Hamstring	**3**	**10**	8rpe	8rpe	8rpe		8rpe	8rpe	8rpe		8rpe	8rpe	8rpe		8rpe	8rpe	8rpe	
Upper Warm-up	**2**	**12**	5rpe	5rpe			5rpe	5rpe			5rpe	5rpe			5rpe	5rpe		
Horizontal Press	**3**	**8**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
Horizontal Pull	**3**	**8**	9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe		9rpe	9rpe	9rpe	
F-METCON see tab	**10 min**		9rpe				9rpe				9rpe				9rpe			
Cool Down	**10 min**																	

High-Intensity Interval Training (HIIT) (red section) enters in Phase 3 to sharpen anaerobic capacity, improve speed, and enhance VO_2 kinetics. It employs short work-rest intervals (e.g., 1:1 or 2:1) across 5–7 rounds, keeping heart rate in Zones 4–5. RPE targets range from 8–10, pushing near-maximal effort. Sprint-based running formats and aggressive cycling sessions are central.

Collectively, this model embodies horizontal sequencing by introducing each energy system component when it is most developmentally appropriate and vertical integration by retaining a thread of aerobic work even as threshold and high-intensity intervals are layered in. It ensures conditioning remains mission-relevant while respecting physiological progression and managing fatigue. Just as important, this model is not standalone; it is married to the resistance training framework as part of a concurrent training approach. All stress comes from the same bucket, so aerobic, threshold, and anaerobic loads must be planned in coordination with lifting to avoid interference, support recovery, and drive targeted adaptation.

Table 3-7. Cardiovascular/Cardiorespiratory Fitness Model



Aerobic Conditioning		
Phase 1:	**Phase 2:**	**Phase 3:**
-Zone 2 HR Target/any mode -45-60 minutes, building to 90 minutes -Unloaded first 4 weeks, light load last 2 weeks	-Zone 2 HR Target/any mode -60-90 minutes -1 day a week with load relative to body weight	-Zone 2 HR Target/any mode -90 minutes or more -1 day a week with load relative to body
Protocol		
1. RPE of 4-5 2. HR Zone 3 or about 70% of maximum HR 3. Conversation Pace 4. Easy Pace		
Suggested Mode		
1. Biking 2. Running 3. Stairmaster 4. Rucking		
Examples For Running		
Example 1		
3 mile run as follows: 1 mile easy warm up pace (RPE 2-3) 1 mile moderate pace (RPE 4-5) 1 mile Fast pace (RPE 6-7)		
Example 2		
Wk1- 40 minute easy jog Wk2- 45 minute easy jog Wk3- 50 minute easy jog Wk4- 40 minute easy jog		
Example 3		
5 mile run as follows: 1 mile easy warm up pace (RPE 2-3) 1 mile moderate pace (RPE 4-5) 1 mile Fast pace (RPE 6-7) 1 mile moderate pace (RPE 4-5) 1 mile easy warm up pace (RPE 2-3)		

Threshold Training		
Phase 1:	**Phase 2:**	**Phase 3:**
-Not focused/prioritized	-Bike preferred -Zone 3 Target -Highest intensity sustained f/30 minutes (at Z3)	-Bike or row machine -Zone 3 Target -Highest intensity sustained f/30 minutes (at Z3)
Protocol		
1. RPE of 6-7 2. HR Zone 3 or about 70% of maximum HR 3. Fastest even pace you can sustain for a minimum of 20min 4. Threshold is = to you average 5k race pace		
Suggested Mode		
1. Biking 2. Running 3. Stairmaster		
Examples For Running		
Example 1		
1/2 mile warm up jog 1 minute (RPE 9), 1 minute (RPE 2-3) 2 minutes (RPE 8), 2 minutes (RPE 2-3) 3 minutes (RPE 7), 3 minutes (RPE 2-3) 3 Rounds		
Example 2		
1 mile warm up jog 2 x 1 mile run @ RPE 6-7 5 minute slow recovery jog between reps		
Example 3		
Interval Run 1 mile warm up jog 3 minutes Slow 2 minutes Fast 4-6 Rounds		

High-Intensity Interval Training		
Phase 1:	**Phase 2:**	**Phase 3:**
-Not focused/prioritized	-Not focused/prioritized	-Any mode -HR Zones 1-4, RPE 8-9 -5-7 Sets, 2:30-10:00 minute intervals
Protocol		
1. RPE of 8-10 2. HR Zone 4-5 or about 80% + of maximum HR		
Suggested Mode		
1. Biking 2. Running 3. Stairmaster 4. Jacobs Ladder		
Examples For Running		
Example 1		
Running Clock Sprint Workout 800m @ 0 minutes 800m @ 5 minutes 400m @ 10 minutes 400m @ 14 minutes 200m @ 16 minutes 200m @ 18 minutes Restart Clock at 21 minutes, 2 Rounds		
Example 2		
Mid Distance Sprint 1 x 800m 1 minute rest between sets 2 x 400m 45 seconds rest between sets 4 x 200m 30 seconds rest between sets warm up and cool down as needed		
Example 3		
Curve Treadmill Run 50 second jog, 10 second Sprint 40 second jog, 20 second Sprint 30 second jog, 30 second Sprint 20 second jog, 40 second Sprint 10 second jog, 50 second Sprint Repeat with no rest between rounds 6 Rounds = 30 minute duration		

3.4 Performance and Injury Surveillance

As stated in section 3.3, an evidenced based and systematic approach is crucial for assessing health and fitness, comprehending the body's response to training stimuli, and optimizing the performance through appropriate exercise intensity all while mitigating the risk of overtraining/inducing injury. Physical assessment and monitoring can occur around three different time points for different reasons and priorities. Macro-level monitoring occurs during the 6−12-month timeframe and serves to understand the effectiveness of the program and gross training adaptations. This would include the entire test battery listed in section 3.3. Meso-level monitoring occurs during the 8−12-week timeframe and is scheduled around pre-post periodization schemes (priorities of training) and feeds into the macro-level training program. Micro-level monitoring can occur bi-weekly, weekly, or intra-weekly and serves as system to observe neuromuscular fatigue or detraining, feeding into the macro-level training program. On the microlevel scale, it is recommended for ongoing physical assessments through the medical/MSK team to be performed prior to every suited event, immediately post, and again at the 48–72-hr time points. This micro-level monitoring would include all aspects of the SUITS survey, a physical assessment including a detailed movement assessment, and should consider fatigue monitoring through grip strength, CMJ, and blood-based biomarkers. This approach not only allows for adequate monitoring and characterization of potential issues and injuries related to suited training environments, it also allows for rapid identification and early intervention of issues and injuries from the MSK team (ASCRs and Doctor of Physical Therapy) and Flight Surgeons. Rapid identification and early intervention are vital to reducing lost duty time and returning to prior level of activity and operational status as quickly as possible after sustaining an MSK injury.

3.4.1 Feedback Loop for Physical Cost Characterization

There is currently no identified pathway to translate physiological data from various suited testing events to the Flight Surgeons or ASCR/MSK team for operational awareness and decision making around exercise prescription. SERPO serves as a continuous platform for multidisciplinary collaboration and information sharing on a continual basis to translate physiological data collected in the suit for research and operations to inform more specific exercise prescription related to a subject’s performance. SERPO aims to have quarterly meetings where physical and cognitive workload are discussed to continue to feed the living, comprehensive training plan. However, this approach does not allow for real time assessment that may lead to initiating modifications of a training program. Additionally, the absence of a centralized data platform, microlevel monitoring and feedback system also limit the ability to make frequent, up-to-date assessments—and potentially changes—to programs that are tailored to the individual’s performance in the suit (*Tier 3* assessments).

3.4.2 Additional MSK Screening/Monitoring

In addition to the need to fully characterize the physical and mental workload to develop a training plan is the need to robustly identify trends of potential MSK injury regions, locations, and further characterize the types of injury (bone versus soft tissue, etc.). Utility of the Suited User Incident Tracking System (SUITS) database will be vital to this endeavor, in addition to the physical assessment performed by the medical/ASCR MSK team. Movement-based assessments that identify pain and dysfunction in specific regions can serve as a baseline to identify regions of potential injuries and issues. Blood-based biomarkers are well utilized and understood in other human performance communities and can serve as a tool to monitor nutrition and metabolic health, hydration status, muscle status, endurance performance, injury status and risk, and inflammation, each being a vital component to understanding injury risks (Lee et al., 2017). Furthermore, ultrasound has the ability to play a pivotal role for the identification, monitoring, and management of MSK injuries, allowing for rapid on the spot assessment and time series evaluation to understand the bodies healing response to an injury or heavy stimulus (Paoletta et al., 2021). Once specific regions and locations are identified, the types of injuries can be further monitored and quantified through the use of diagnostic ultrasound.

3.4.3 Suited User Incident Tracking System Database

The SUITS database (formerly known as the Exposure Incident System [EIS]) was created in the early 2010s at NASA to track issues that crew experienced during suited exposures, specifically during NBL training and other “high risk” exposures. The *EMU Shoulder Injury Tiger Team* report (Williams & Johnson, 2003) identified the need for injury surveillance and recommended the immediate implementation of an integrated system for recording EVA training-related symptoms and injuries. Additionally, the *EMU Training Suit Symptom Study Report* (Strauss, 2004) cited an action for JSC to continue surveillance by the NBL Flight Surgeons to monitor significant EMU medical issues, including trends and additional recommendations that may emerge. Surveillance is also needed to track the effectiveness of injury mitigations and other interventions, reinforcing the actions cited in these reports.

Over the years this surveillance has expanded to include all ground-based analogs and pressurized suited environments. The most recent expansion of tests covered was in March 2024, allowing collection of suited test data for unpressurized suits and simulator/mockup suits. Criteria for inclusion of these test conditions includes use for an extended duration and/or the crew or test subject bearing high loads. Additionally, pressurized component testing for an extended duration (e.g., glove box testing) has been identified as a test event that should be included in the database. Data is collected and input into the database for crew and test subjects.

Surveillance takes the form of captured data within the SUITS Database while the same questions are available on the SUITS questionnaire, a physical form. Data collection takes approximately 10 min in total (5 min pre- and 5 min post-testing) to obtain and enter the information into the online database or in hardcopy. The database has automated follow-up functionality such that the subject or crew can input information on any issues encountered beginning 48 hr after the exposures using a secure link sent via email. The purpose of this data collection includes i) enabling improvements in human/suit interactions by real-time and post-collection; ii) identifying trends over time, across suit/analog types, test types, etc.; and iii) documenting issues encountered by crew from an occupational surveillance standpoint. The SUITS Questionnaire contains the information shown in Figure 3-13.

3.4.4 Suited Anomaly Assessment Team

The main consumer of SUITS data is the Suited Anomaly Assessment Team (SAAT), created with the purpose of communicating suited trends and suited anomalies with a controlled group of EVA stakeholders to ensure solutions could be derived in a multidisciplinary manner. The SAAT was approved by the Astronaut Occupational Health Management Group (AOHMG) in 2022, with the following charter: *"To communicate human-suit anomalies to all critical EVA stakeholders to evaluate and develop solution strategies where needed for the purposes of suit design, EVA operations optimization, injury characterization and mitigation, and personalized improvements for human-suit interactions."* The AOHMG endorsed "Need to Know" access for SAAT members related to occupational health for Privacy Act-protected data. The SAAT meets on a quarterly basis to review SUITS data to provide the team with situational awareness (SA), track effectiveness of any implemented improvements, and review actions from past meetings. The SAAT will also meet on an ad hoc basis when there is a suited anomaly, with the purpose of reviewing a description of the incident, discussion of cause and any planned mitigations, and a review forward work. (Please note that SUITS data can only be shared outside of the SAAT provided it is not identifiable information.)

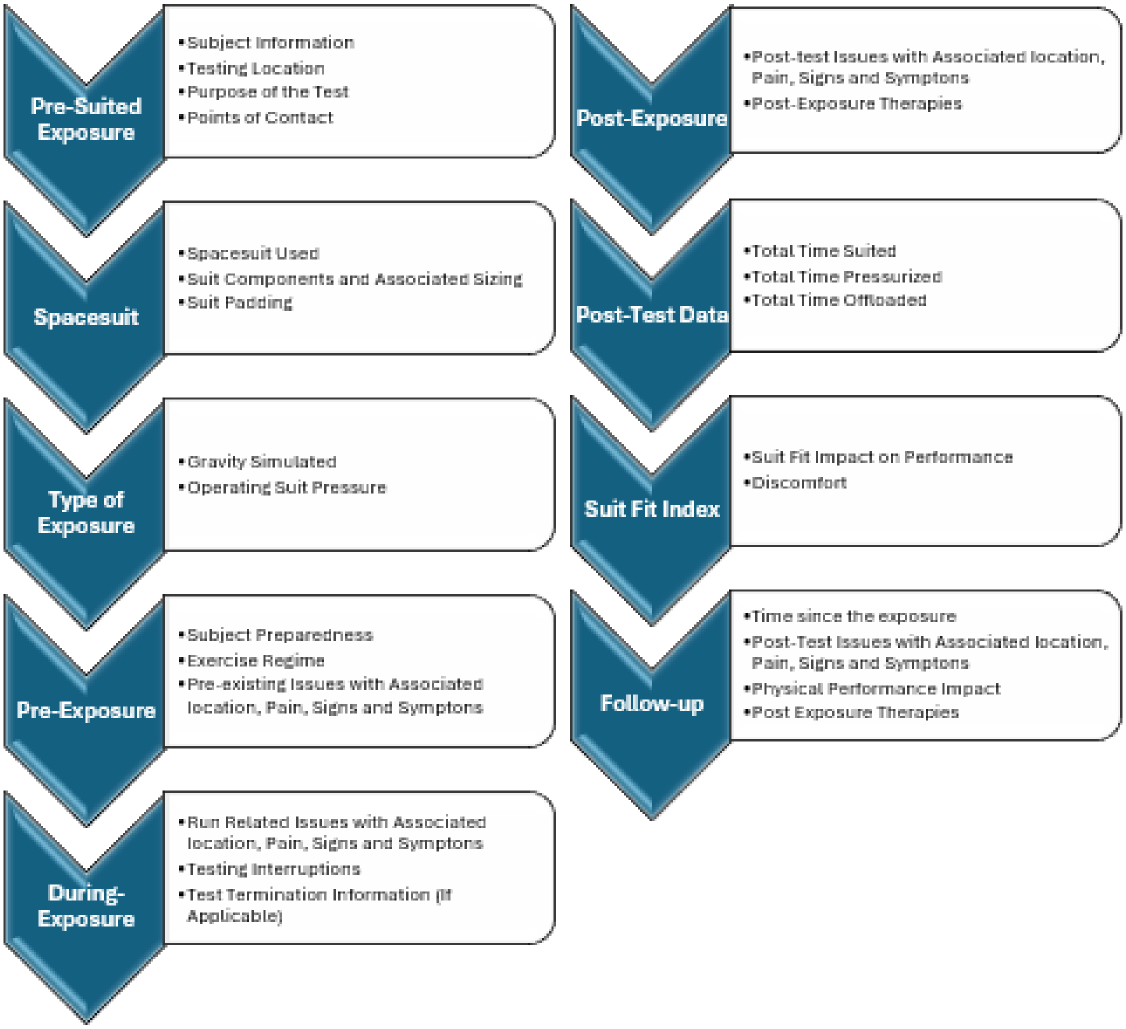


Figure 3-13. Information collected during SUITS Survey

A specific analysis shows the types of analyses and visualizations the SAAT performs at quarterly meetings. Key to contextualizing the analysis and accompanying visualizations is the distinction between an *exposure* and an *issue*. The diagram is included in Figure 3-14. An *exposure* is an instance of a suited subject (test subject or crew) getting into a suit for a purpose. An *issue* is a complaint that has an affiliated major and minor location on the body. An *issue* can be described with signs, symptoms, pain scale, and whether it is off-nominal for the person. An *issue* can be assigned during the pre-, during, post, and follow-up phases of testing.

Table 3-8. ARGOS Data

Quick Look – ARGOS	
Total Exposures	161
Num Exposures w/ Issues	62
Total Issues	160

Table 3-8 depicts the total number of exposures occurred at the ARGOS facility at JSC and the pie chart (Figure 3-15) depicts the spread of suits that have been used at that facility for testing. Since data collection began, there have been 161 exposures in ARGOS, with the majority being in the xPGS (or xEMU), followed by the MK-III suit.

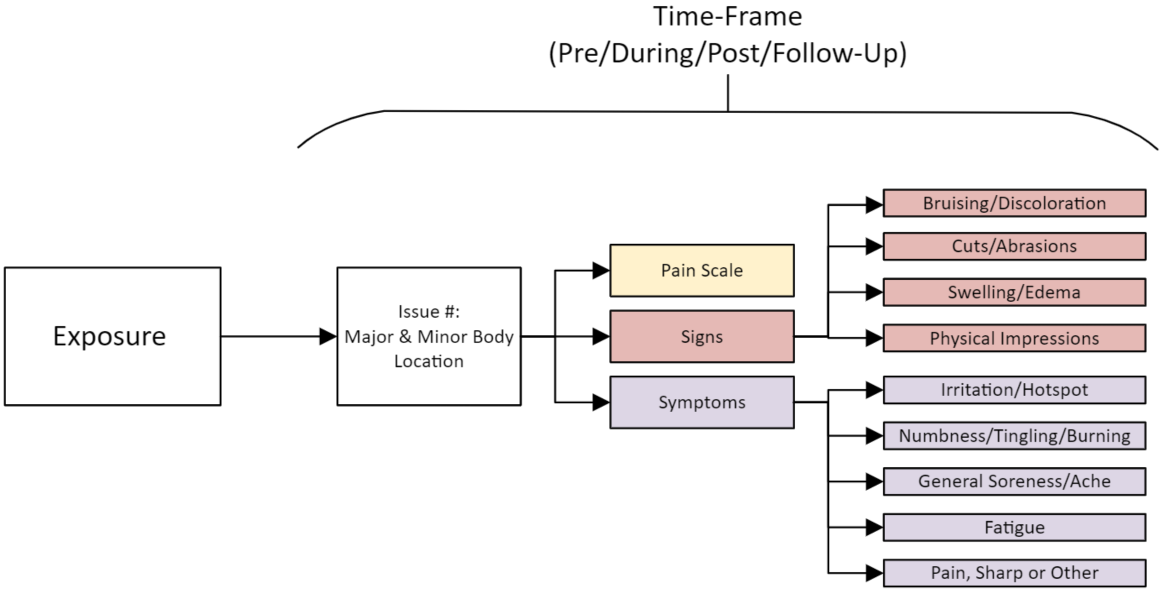


Figure 3-14. Relationship between an exposure and issues in SUITS database

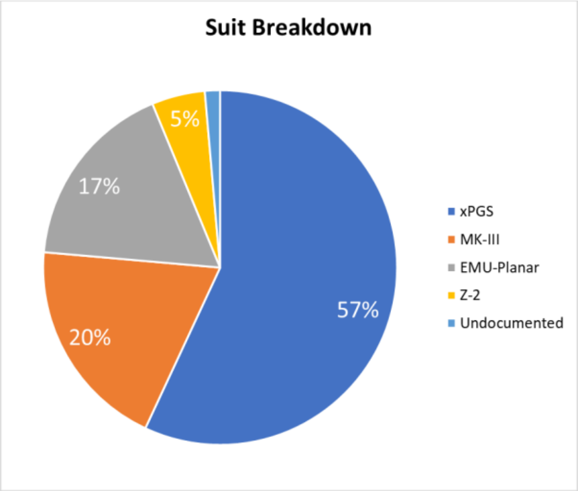


Figure 3-15. ARGOS data and accompanying spread of suits used at the facility

Given that most exposures have been in the xEMU, the next item of interest is where any specific issues have occurred for test subjects and crew. The plot given in Figure 3-16 depicts the spread of issue locations as well as their assigned pain scale. Issues have predominantly occurred in the torso and legs, followed by the feet and hands. This is a shift when comparing to historic data collected from EMU dives that show issues predominantly occurring in the shoulders and hands.

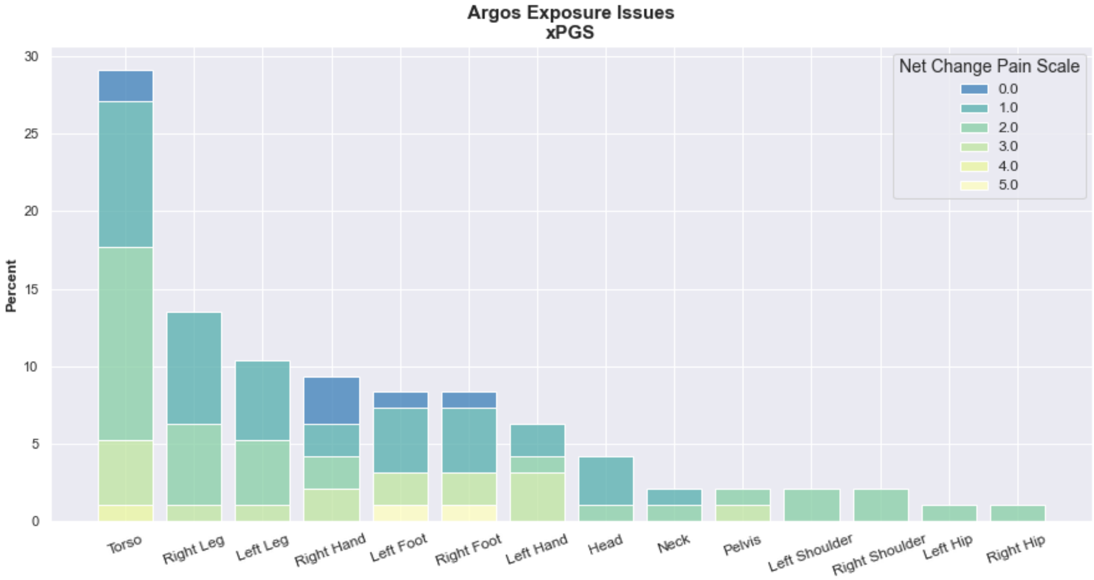


Figure 3-16. Issues occurring for ARGOS exposures in the xEMU (or xPGS)

The pie charts in Figure 3-17 show the most reported locations within the torso (chest), leg (knee), and foot (top of). This information can inform improvements in suit fit and recommended watch areas specific to analog environments.

Analyses and visualizations are only as good as the underlying data, so it is critical to acknowledge the factors that influence reporting of the data contained within SUITS. The data collector, method of collection, comfort/trust in the data collector, access to the database to input data, and perceived importance of the surveillance effort are all contributors to data quality. To improve data quality and strengthen the conclusions drawn from analyses, ongoing efforts are focused on refining the SUITS questionnaire and enhancing the associated database.

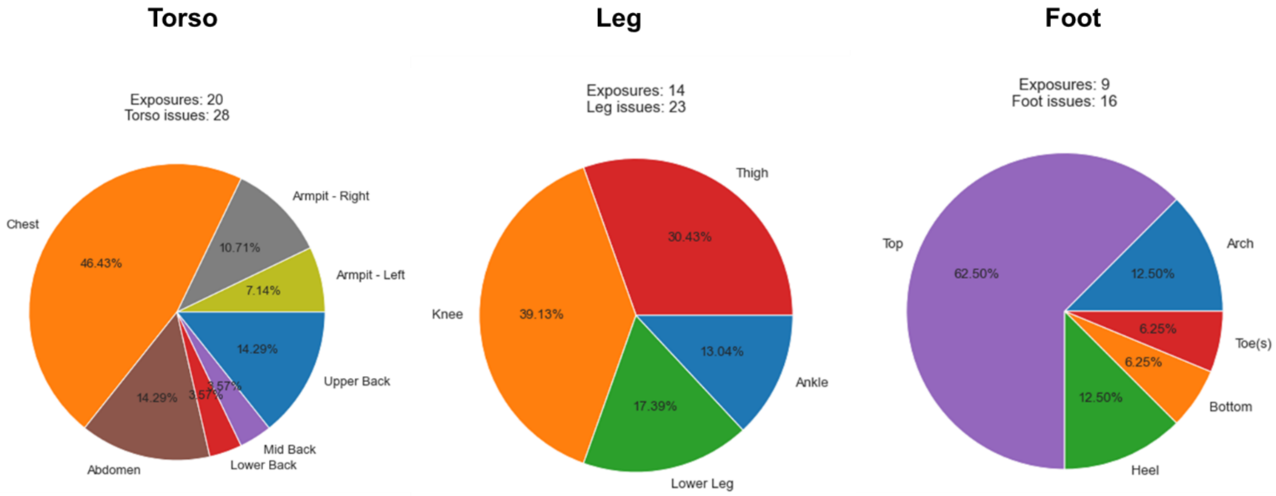


Figure 3-17. Distribution of subregions associated with reported issue

4 Cognitive Domains

There has been a lack of data on which cognitive domains are most important for conducting mission critical decisions with crew safety implications during EVA, much less during surface EVA. Although decrements in cognitive performance present an important risk to crew safety during exploration mission class EVA, the cognitive capabilities that will be required of crewmembers to maintain crew safety during exploration EVA, and the characterization of crewmembers' cognitive workload and performance around exploration EVA, is still not well understood. Connecting to broader goals of the SERPO group, physical workload and pain should also be recognized as factors that can impact cognitive performance and managed accordingly prior to, during, and following EVA

The cognitive domain of surface EVA has only recently been characterized in EVA simulation and analog research. Examples of surface EVA data speaking to the cognitive domain include data from the Mars Desert Research Station, in which surface EVA resulted in increased mental and physical workload (Rai, Kaur, & Foing, 2012). Novel gait patterns associated with partial gravity, such as during surface exploration EVA on the Moon or Mars, was found to increase cognitive load in the form of increased prefrontal cortex activity and reduced memory recall in a separate study (Smith, Segovia, & Salmon, 2023). In simulated EVA conducted in water submersion, response accuracy during inhibition and switching cognitive tasks was lower during EVA compared with a control condition, while reaction times for the inhibition task were faster during EVA (Möller et al., 2023). In a simulated EVA study conducted in NASA's ARGOS, a trend suggested decrements in vigilant attention and processing speed following two simulated EVAs conducted over a 3-day period (Schlotman et al., 2023). Despite these findings, there is a need for more data to characterize cognitive performance prior to, during, and following EVA.

The cognitive and physical demands of surface exploration EVA conducted in partial gravity environments like the Moon and Mars are likely to be higher than microgravity EVA currently conducted from the ISS. Developing a long-term presence on the Moon and exploring Mars will furthermore require more frequent and extended EVA compared to EVA conducted during the Apollo era. In addition to important considerations of the physical workload and capacity required to complete exploration EVA, there must be a commensurate consideration of the cognitive capabilities that will be required to complete the complex science and infrastructure goals of future surface exploration missions. Since initiation of the SERPO group, NASA's Behavioral Health & Performance (BHP) Laboratory has made significant progress toward characterization cognitive considerations during surface exploration EVA. Progress from specific projects is described below.

4.1 Surface EVA Cognitive Task Analysis

A recently conducted surface EVA cognitive task analysis (CTA) aimed to characterize the procedures, cognitive demands required, and the critical safety decisions associated with decrements in cognitive performance during surface EVA. The CTA was conducted with 15 astronauts and SMEs in EVA operations and research. Interviews focused on surface exploration EVA and elicited feedback from experts on the cognitive domains required for specific EVA tasks, including cognitive strategies, critical cues, and decision-making strategies. The information from the surface EVA CTA identifies the specific cognitive challenges that astronauts are likely to encounter during surface exploration EVA and provides the foundation for (1) prioritized and targeted cognitive performance measurement and functional performance tests, (2) EVA simulation design at varying levels of cognitive workload, and (3) the development of training and other technologies that can inform NASA standard and guidelines for medical operations and EVA planning in future Artemis missions to the Moon and Mars.

Several recommendations for future surface EVA operations and research were generated by the CTA:

- The importance of cognitive workload in off nominal or contingency scenarios. Crew pre-mission training should include off-nominal and emergency scenarios such as an Incapacitated Crew Rescue (ICR) to prepare for low-likelihood but cognitively challenging and high consequence events. Physical workload and pain should be recognized as factors that can impact cognitive performance and managed accordingly prior to, during, and following EVA.
- Factors that need to be included in EVA research and training, including SA, sleep, and communication delay need to be systematically measured in EVA research. For example, to keep communication effective during Lunar communication delays, there should be effort in ground simulations and training to implement consistent procedure words (e.g., “over”, “copy”).
- EVA planning and technology considerations. During Lunar or Mars surface geological operations, cue cards on astronaut cuffs should include reminders of geological terms to reduce cognitive workload associated with geology callouts. MCC should consider offloading some of the operator tasks of EVs while performing field geology to maximize the quality of science conducted on the Lunar Surface. Crewmembers should be given extra time for suit mobility adaptation at the start of EVA operations given the cognitive workload associated with this EVA task. If extra time for suit adaptation is not built into the EVA timeline—separate from traverse given the cognitive workload associated with that EVA task—there is likely to be increased cognitive workload early in the EVA as

crewmembers adapt to moving in the suit in partial gravity. Consideration of suit adaptation over the course of multiple mission phases is also critical.

- Teamwork can be an effective countermeasure in surface EVA. To maximize the cognitive offloading of effective teamwork, crews should receive training to learn about cognitive offloading after flight selection, in addition to training on managing different work styles, managing cognitive workload through teamwork, developing SA, and other aspects of effective teamwork for surface EVA.

4.2 APACHE Cognitive Workload Study

The APACHE testing environment (Figure 4-1a) has the capability to simulate exploration EVA in a controlled environment where the subjective and objective correlates of physical and cognitive workload can be extensively characterized. The APACHE Cognitive Workload Study was completed from December 2024 to April 2025 in the APACHE High Bay space at NASA JSC. The study was initiated to conduct a technology demonstration for integration of an omnidirectional treadmill (Figure 4-1b) within APACHE for the purpose of enabling higher fidelity characterization of cognitive workload and performance at different levels of EVA task difficulty, as well as for identification of the underlying physiological correlates of cognitive workload during EVA. The specific aims of this study were to 1) characterize the effects of integrated VR and omnidirectional treadmill on cognitive workload and performance during simulated EVA, 2) characterize self-reported and objective measures of cognitive workload and EVA performance at different levels of cognitive task difficulty in a high-fidelity VR EVA environment, and 3) preliminarily validate embedded cognitive measures that could be deployed in future surface exploration EVA.

Technical issues during data collection necessitated a switch to a passive treadmill and sandbox configuration (Figure 4-1c) for the remainder of testing. Although not the original study goal, this switch allowed for a fuller comparison between the two different types of treadmills in terms of how they impact cognitive and physical workload during simulated surface EVA. The results of the APACHE Cognitive Workload Study demonstrated the integration of a new omnidirectional treadmill into APACHE for the purpose of testing its capability for increasing fidelity of simulated surface EVA. Participants who completed the study on the omnidirectional treadmill (N = 8) rated it as less comfortable, less realistic, less usable, more disorienting, more frustrating, more nauseating, but also more immersive compared to participants who completed the study on the passive treadmill (N = 6). The omnidirectional treadmill was associated with higher subjectively rated cognitive workload, lower ratings of team functioning, but with no difference in EVA performance, compared to the passive treadmill and sandbox configuration.

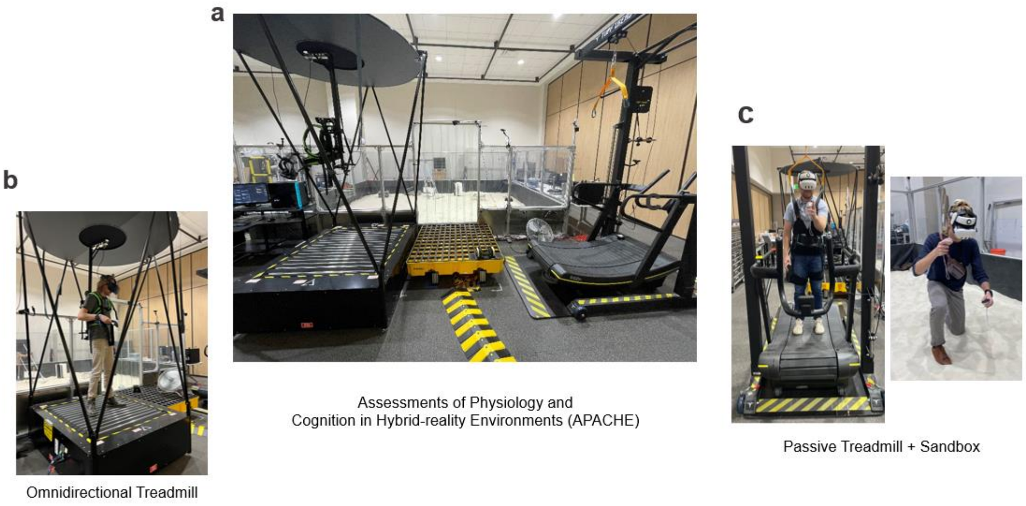


Figure 4-1. APACHE with integrated treadmill

Toward the study's aim of characterizing cognitive workload at different levels of surface EVA task difficulty, cognitive workload was manipulated during geology sample identification by changing the spread of rock sample element composition values, thus impacting how cognitively demanding it was for participants to identify which rocks were most valuable to sample. Results indicated that the cognitive workload manipulation successfully increased subjective and objective measures of cognitive workload. In terms of the primary EVA task of geology sampling, participants performed significantly worse in terms of the quality of their geology sampling during the high cognitive workload condition when compared to low cognitive workload condition. Participants also had significantly less efficient geology sampling and a steeper decline in situational awareness (SA) to the secondary EVA task of suit temperature monitoring over time in the high compared to low cognitive workload condition. Self-reported mental demand (NASA-TLX) was significantly higher in the high cognitive workload condition when compared to low cognitive workload condition. In addition, performance on a cognitive task of working memory (reverse Auditory Digit Span Test) was significantly worse during the high cognitive workload condition when compared to low cognitive workload condition. Examining physiological impacts of cognitive workload, participants' heart rate (HR) during geology was significantly higher in the high cognitive workload condition when compared to low cognitive workload condition.

Taken together, these results demonstrate evidence for a relationship between cognitive workload, EVA performance, self-reported mental demand, and physiological correlates of cognitive workload. Results suggest cognitive workload during surface exploration EVA may be an important consideration for EVA schedulers and monitoring for critical mission tasks (NASA STD-3001 V1 4011; M2M-40005 Baseline, AMMERD 3.4 Cognitive and Vigilance Assessments). The results of the APACHE Workload Study have implications for EVA planning, EVA simulation research, and cognitive monitoring for future missions to the Moon and Mars. The study demonstrated the feasibility of integrating a treadmill into VR environments for future EVA simulations, while also highlighting limitations of an omnidirectional treadmill. In addition, the cognitive workload data in the study was designed to be integrated into CSRM effort to inform future EVA decision-support tools (PersEIDS).

4.3 Developing Embedded and Unobtrusive Cognitive Measures

An important secondary aim of the APACHE Cognitive Workload study was to provide initial validation of embedded cognitive measures in a surface EVA simulation environment and point to the need for future validation in other high-fidelity simulation environments including ARGOS, NBL, and field tests for eventual integration into spaceflight settings. The APACHE Cognitive Workload Study provides a foundation for cognitive monitoring tools in missions to the Moon and Mars that can be completed unobtrusively and concurrently with EVA objectives. Examples that have been tested in EVA simulation environments including NBL and APACHE include an auditory adaptation of a reverse digit span test of working memory and executive function, as well as an auditory psychomotor vigilance test (PVT) of vigilant attention.

The Auditory Digit Span Test (DST) adapted for using during EVA simulation is a modified version of the validated neuropsychological test from the Wechsler Memory Scale - Fourth Edition (WMS-IV) (Wechsler, 2009). During traverse to geology sites at the NBL (Figure 4-2a), subjects were presented with a series of computer-generated digits in increasing order. Subjects were instructed to repeat the strings of numbers in the order that they were heard (forward span). Outcomes included mean reaction time, accuracy, and lapses. A further iterated version of the auditory digit span test was deployed in APACHE (Figure 4-2b), during which the test conductor playing the role of intravehicular (IV) crewmember verbally administered the increasing digits to the extravehicular (EV) subject and instructed them to repeat the numbers back in reverse order (backward span).

The auditory PVT developed for EVA simulations was modified from the classic Wilkinson Auditory Vigilance Test (Wilkinson, 1968). In the NBL, suited subjects listened to series of 500 ms auditory tones during traverse to geology sites, with a pseudorandomized inter-stimulus interval of 1–2 s. Subjects were instructed to reply "*Test*" when they heard the tone, at which point the speech recognition capability in the stimulus presentation software would record their response. Outcomes includes included mean reaction time, accuracy, and lapses. These adaptations use audio-based versions of the laptop testing so the assessments can be administered during an EVA, better capturing the actual cognitive loading work in the EVA. These cognitive battery tests are being collected for us to understand not only what the demand of cognitive performance is as a function of a single EVA, but also over the course of a mission profile, especially in the context of high-tempo EVA.

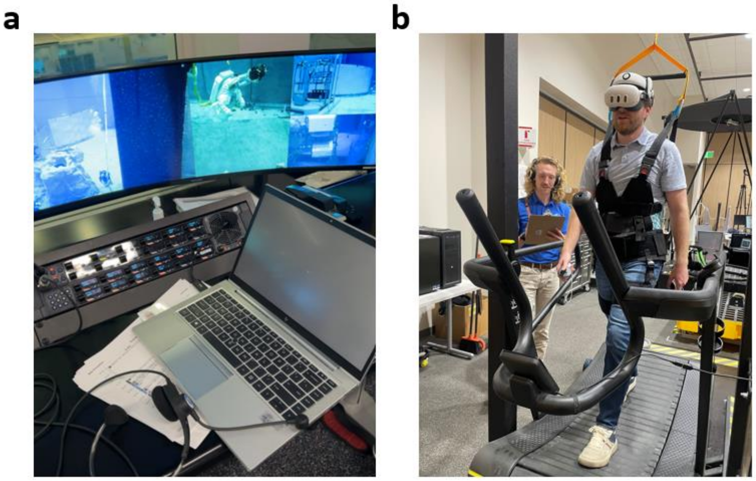


Figure 4-2. Auditory cognitive performance measuresembedded during EVA in NBL (a) and APACHE (b)

5 Future Considerations

5.1 Holistic HHP Considerations—An Injury Risk Reduction Strategy

The contents of this document are heavily focused on understanding the physical workload of the training environment and structuring a comprehensive program to enhance physical preparedness. In addition to these considerations, there are several recommendations outlined below to target additional injury risk reduction strategies. Additionally, to further capitalize on HPO from a holistic lens and a means to reduce the risk of sustaining an MSK injury, other areas of human performance must be considered and addressed. Specifically, the areas of cognitive performance and nutrition have a direct and well-established relationship with optimizing human performance and reducing the risk of MSK injury. Future considerations of the SERPO initiative should follow a similar six-step process as outlined in the physical domain aspect of human performance to fully understand the cognitive workload and nutritional demand. This process would allow for effective countermeasures to be implemented in the preflight training flow related to cognitive and nutritional need and further contribute to the holistic health and HPO strategy to reduce risk of MSK injuries.

5.2 Comprehensive Model of Optimizing Performance

The Comprehensive Model Optimization & Performance (CMOP) is a new initiative designed to integrate astronaut health and performance into a single interdisciplinary framework. While not yet fully established, its purpose is clear: to unite diverse SMEs under a structured model that strengthens collaboration, reduces silos, and aligns expertise with the dynamic demands of human spaceflight. Instead of collecting parallel inputs from separate fields, CMOP seeks a coordinated system where medical, physiological, behavioral, nutritional, engineering, and research expertise converge in real time to enhance and sustain astronaut readiness. The strength of this approach rests on SMEs, whose depth of knowledge cannot be replaced by surface familiarity. Historically, this community has often treated injury prevention as the primary focus, at the expense of broader performance preparation. While injuries do diminish performance, reduce operational potential, and increase the cost of maintaining a qualified workforce, prevention alone creates too narrow of a lens. It risks leaving crew underprepared for the physical demands of spaceflight and can even foster psychological hesitation, where astronauts grow overly cautious each time they enter a spacesuit. Such fear undermines confidence and performance. True readiness requires more: resilience, adaptability, and preparation for the full scope of mission demands. This is why SME expertise is indispensable. Just as a primary care physician and a neurosurgeon are both trained in medicine but uniquely equipped to solve different problems, each discipline in spaceflight contributes irreplaceable knowledge that cannot be generalized away. When those skills are integrated, astronauts benefit from solutions that no single field could achieve alone. But when expertise is siloed, dismissed, or overshadowed by what can be termed discipline dominance, the assumption that training in one area confers authority across others, vulnerabilities emerge. CMOP counters this tendency by fostering a culture where every discipline is treated as mission-critical, ensuring astronaut readiness reflects both physical resilience and psychological confidence.

To operationalize this vision, CMOP draws from the science of team science. Stokols et al. (2008) emphasize that silos, lack of shared language, and undervaluing contributions undermine integration, while structured frameworks foster collaboration. Choi and Pak (2006) distinguish three modes: multidisciplinary efforts work in parallel, interdisciplinarity fosters interaction while preserving disciplinary depth, and transdisciplinary synthesizes knowledge into shared frameworks. CMOP is deliberately interdisciplinary, integrating specialized knowledge while preserving integrity, so astronaut care adapts to operational demands rather than defaulting to a single perspective.

Within this framework, the Flight Surgeon serves as chief medical authority, accountable across mission phases. This role is not about overshadowing other SMEs or mastering every domain, but about coordinating expertise so astronaut care reflects the full system of knowledge. Inputs from nutrition, behavioral health, musculoskeletal health and science, and physiology all feed into the Flight Surgeon's knowledge in real time, ensuring resources are available when operational decisions are required. Effective leadership relies on humility—recognizing when another discipline's expertise carries greater weight—and on fostering interdependence, trust, and respect rather than disciplinary dominance, conceptually supported by Bennett and Gadlin (2012).

The CMOP highlights adaptability as its core strength. Influence must shift flexibly based on astronaut needs. Sometimes medical oversight takes priority; at other times, expertise in musculoskeletal, nutritional, behavioral, or cognitive areas must lead. When each discipline is empowered to guide within its domain, under the authority and coordination of the Flight Surgeon, the system stays balanced and adaptable. Without this flexibility, interdisciplinary work risks splitting into disconnected inputs that fail to meet mission demands.

As discussed in Section 3.3.3, the ASCR TAP offers a clear example of how this integration can be organized. TAP demonstrates how readiness can be evaluated across layers of capacity, function, and operations. Importantly, surveillance is incorporated at every tier, not confined within a single discipline. Strength, aerobic capacity, neuromuscular control, sleep, nutrition, behavioral health, cognitive performance, and biomarkers are all monitored simultaneously. This concurrent surveillance ensures that insights combine into a unified picture of astronaut readiness, rather than remaining isolated within separate domains.

Tier 1 – Foundational Capacity establishes the physiological and behavioral baseline through:

- Strength, aerobic fitness, and neuromuscular control testing
- Nutrition monitoring of hydration, energy intake, and recovery
- Sleep and circadian rhythm tracking
- Psychological health and resilience screening

Tier 2 – Functional Performance evaluates integration of multiple systems as astronauts execute real tasks, including:

- Movement efficiency, coordination, and fatigue monitoring
- Cognitive function under workload
- Stress and emotional regulation
- Musculoskeletal and cardiovascular medical assessments
- Operational risk monitoring from safety/engineering perspectives

Tier 3 – Operational Simulation adds full mission context and complexity through:

- EVA and habitat simulations
- Cognitive decision-making and SA
- Biomarkers of stress and adaptation (e.g., cortisol, IGF-I, immune function)
- Team performance and communication under pressure
- Integration of engineering, human factors, and mission control inputs

This example framework illustrates how concurrent monitoring across disciplines produces a multidimensional picture of readiness. Critically, readiness cannot be reduced to a single measure. For example, Monteiro et al. (2024) demonstrated that aerobic capacity, relative strength, and agility each uniquely predict Army Combat Fitness Test performance, reinforcing that readiness emerges only from the integration of multiple assessments.

Together, CMOP and ASCR TAP create complementary frameworks. CMOP supports interdisciplinary integration, while TAP organizes assessment through a tiered system. Together, they coordinate astronaut health and performance into a cohesive model where each discipline's contribution is clear yet harmonized. Ultimately, the key that unites CMOP and TAP into a dynamic, functional system is a data integration platform. Without shared surveillance and synchronized data streams, disciplines risk becoming isolated despite good intentions. A unified platform ensures that inputs from physiology, medicine, behavioral health, engineering, and operations are not just gathered but combined into a single, accessible view of astronaut readiness. This integration turns CMOP and TAP from theoretical frameworks into practical systems that can adapt in real time to the needs of human spaceflight.

5.3 Integrated Data Limitations

The current data management system houses silos of information on several platforms, including—but not limited to—the EMR (which includes medical and performance data); SUITS; Information Management Platform for Analytics and Aggregation (IMPALA); Multidisciplinary Analytics, Visualization, and Reporting Interface for Integrated Countermeasures (MAVRIIC); Lifetime Surveillance of Astronaut Health (LSAH); and variations within individual communities (Anthropometry, MSK injury tracking, etc.). The silos of information limit the capability to fully comprehend the physical and cognitive demand in training environments, relationships between performance and medical assessments as they relate to analog training events, and limit ability to identify where interventions could be applied early to optimize performance, reduce risk of injury, and establish specific trends related to performance and MSK injury profiles. Future considerations of the SERPO project should identify potential solutions either internal at JSC or through leveraging technology that is well understood in other HP communities (e.g., Smartabase, Spear).

5.4 Operational Consideration for Future Space Exploration

Not all-encompassing, this summary highlights key operational considerations and changes for upcoming Lunar Surface missions. Space exploration is entering a new era in which absolutely every single aspect of EVA is evolving, from landing locations and environmental conditions to suit design, prebreathe protocols, and operational timelines. When compared to the Apollo A7L, modern reference designs such as NASA's xEMU have a greater mass (approximately 181 kg for the EVA configuration versus 91 kg for the Apollo A7L). Though the xEMU does have enhanced mobility, CG optimization, and rear-entry self-donning capabilities. Operating suit pressures are expected to be higher (~5.2 psi versus Apollo's 3.7 psi), introducing new trade-offs between performance, fatigue, and injury risk.

Planetary EVA will occur in more extreme thermal ranges and lower lighting conditions, with longer surface durations than historically observed during the Apollo missions. Artemis missions, particularly the first Artemis Lunar landing mission, will feature extended transit times, longer dwell periods in microgravity, and higher decompression sickness (DCS) risk thresholds, all of which influence prebreathe requirements, mission cadence, and metabolic demands. Apollo EVA challenges—such as slope navigation, limited torso flexion, hand and forearm fatigue, and optical illusions from Lunar lighting—are likely to manifest differently at the Lunar south pole, where terrain, shadowing, and contrast will present novel hazards. Operational timelines will shift from Apollo's aggressive descent-to-EVA approach to a slower ramp-up, with more EVAs overall but longer recovery intervals. The Artemis surface profile includes increased traverses, heavier sample return loads (~100 kg), and new contingency planning, such as incapacitated crew rescue for steep terrain. Collectively, these differences create unknowns in performance, efficiency, injury patterns, and physiological adaptation, underscoring the need for robust data collection, ongoing trade studies, and adaptive operational planning.

6 Recommendations

This section outlines recommendations resulting from biweekly and annual TIMs. These recommendations are independent of suit design and CONOPS and will be refined as additional insights are gained. They are not intended to be exhaustive and are summarized here for the purposes of this report.

6.1 Physical Preparedness and Training Plan Recommendations

Comprehensive physical training programs are most effectively implemented and sustained when grounded in a cyclical, six-step framework:

1. Identification and understanding of the physical and mental demands associated with the activity or performance (i.e., suited training);
2. Initial evidence-based assessments to objectively quantify current capability and fitness levels relative to the identified demands;
3. Development of a comprehensive, and demand-driven training program;
4. Ongoing physical assessment and performance monitoring;

5. Systematic modification and progression of the training program based on assessment and outcomes; and
6. Performance execution.

Comprehensive physical training plans should be mandatory and formally scheduled during the duty day for crew members. A minimum training frequency of three sessions per week, each lasting approximately 1.5 hours, is recommended. An additional two training sessions per week, each of approximately one hour, may be required based on the objectives and priorities of the training plan. Effective training cycles require sufficient time for adaptation and should be appropriately periodized to support performance optimization and injury risk mitigation. Although this is not currently a capability at NASA JSC, it is important that test subjects adhere to the same framework and physical training plans for the suited environment.

Routine physiological monitoring, including sleep, nutrition, and performance metrics, should be integrated into the comprehensive training plan for both crew and non-crew test subjects to support individualized program adjustments and long-term health outcomes.

Optimizing human health and performance during the preflight, in-flight, and postflight mission phases should incorporate interdisciplinary collaboration and data integration between Flight Surgeons, Physical Therapists, Athletic Trainers, Strength and Conditioning Specialists, Behavioral Health Specialists, Nutritionists, and research SMEs (e.g., exercise physiology, bone health, nutritional biochemistry, etc.).

6.2 MSK Injury Risk Management Recommendations

Medical and ASCR/MSK support are critical across all suited testing environments for both crew and non-crew test subjects. Such support is essential to ensure physical preparedness, enable accurate characterization of issues and injuries, support early identification and treatment of MSK conditions, and advocate for injury risk reduction strategies.

An interdisciplinary team approach, including the crewmember, Suit Test Engineer, Flight Surgeon, and ASCR/MSK team, is essential to ensure comprehensive subjective (e.g., SUITS feedback, prior injury history) and objective (e.g., movement-based assessments) evaluations are conducted both pre- and post-suited events. This approach facilitates an accurate understanding of injury risk, fitness for duty, and early implementation of appropriate mitigation strategies.

A objective of this interdisciplinary approach is to improve transparency in MSK injury reporting without negatively impacting the crewmembers' ability to perform their job duties (e.g., flight status, training). Enhanced transparency is expected to improve the accuracy of reporting and overall awareness of suit-related MSK injuries and performance-limiting issues.

Contractual agreements will be required to establish funding mechanisms for ASCR/MSK support of non-crew test subjects. Injury risk reduction should be prioritized for everyone, and lessons learned in both crew and non-crew subjects can inform and support continuous refinement of ASCR/MSK physical training and/or injury prevention strategies.

As a result of the SERPO recommendation, MSK assessment and support were implemented during recent testing series. This capability provided a critical communication gateway between crewmembers and relevant personnel, enabling rapid identification of MSK issues and injuries and establishing a structured pathway for communication with the test team. This pathway expedited discussions related to the test plan, suit fit, and day-of-test preparation, and supported implementation of the RAMP preparation framework described in section 3.3.

6.3 Analog Training Recommendations

Prior to analog training events, test subjects should receive comprehensive briefings addressing high-risk suited positions, unstable postures, explosive movements, and identified watch-list injury regions. Suboptimal task execution strategies, such as explosive movements to transition from compromised ankle positions, should be avoided. If a task cannot be completed without compromising safe and effective positioning, alternative solutions such as suit design adjustments or tool aids must be considered (e.g., tools to assist standing out of a kneeling position). Clear and continuous communication between the test subject and test team is essential to support these risk mitigation strategies.

A closed-loop, three-step communication and decision-making process should be employed during all analog training activities:

1. Instruction of test subjects on extreme or high-risk positions and postures prior to task execution;
2. Real-time assessment and communication during task performance, incorporating subjective feedback from the test subject; and

3. Termination or deferral of tasks when completion requires the test subject to assume extreme or ineffective positions that elevate injury risk.

This closed-loop communication process should be continuously reinforced throughout the duration of testing, including during the final hours of training events. Pre-suit activities incorporating the RAMP program, in-suit functional movement assessments, and structured communication protocols have already been implemented during select testing campaigns and have resulted in early task termination to prevent injury. These practices should be expanded and standardized across future analog environments and testing campaigns (e.g., ESP, Hi-Tempo).

Training protocols should aim to minimize cumulative exposure to 1-g tool use outside of optimal biomechanical positions (e.g., overhead, extended away from the body). Low-cost training approaches using suit simulators to support proper skill acquisition should be carefully evaluated and incorporated where appropriate. Analog training environments should consider adopting a "practice like you fly" philosophy, with test plans designed to closely replicate surface EVA CONOPs.

Additionally, RGA flights remain a critical capability accurately understanding and characterize the CG effects in analog environments and for reducing the risk of training-related injuries. Leveraging historical operational data and physiological datasets can enhance analog training design, planning, and execution. Video analysis of Apollo-era operations, combined with in-suit physiological monitoring during task performance, can further inform operational and mission planning, including task sequencing, workload management, and break scheduling.

6.4 Suit Recommendations

The demands placed on the human within a spacesuit differ substantially between microgravity and the Lunar Surface. On the lunar surface, the combined effects of sloped terrain, inertial mass, and lunar regolith increase the likelihood of nominal slips, trips, and falls, as well as the potential for more severe, currently unquantified rotational injury mechanisms. Given that majority of historical suited operational experience comes from microgravity environments, additional testing is needed to inform understanding of the human-to-suit interaction and human movement within the suit under planetary surface conditions.

Research efforts should assess the effects of the suit design on the human body, including the relationships to individual physical preparedness and the correlation with the suited environment. While Apollo crews reported minimal lower extremity injuries, modern planetary suit designs incorporate increased joint mobility and design changes, which may introduce new injury risks. Identifying injury mechanisms where limiting suit joint ROMs along specific planes may help reduce risk. For tasks requiring kneeling or transitions to and from the ground, appropriate hip and ankle kinematics are critical; inadequate ROM or improper joint mechanics may impose elevated injury risk from these positions.

Future space exploration is moving towards a rear entry hatch, where self-donning and doffing of the suit changes and elevates the injury potential for the shoulder. The positioning required by a rear entry suit and any donning/doffing aids, with the crewmember often reaching up and behind, places the shoulder in extreme postures and may elevate injury risk. Suit design modifications and donning/doffing aids must therefore be systematically evaluated to quantify impacts on human performance and musculoskeletal injury risk. SMEs should leverage NASA's extensive experience from Apollo, Space Shuttle, and subsequent programs to assess these risks and inform optimization of suit design, human performance, and operational procedures.

Hand and forearm fatigue and injury were nominally reported during Apollo lunar surface operations. As exploration missions return to the Moon and progress toward Mars, increased emphasis on glove design and fit is essential to optimize dexterity, mobility, and tactile feedback while minimizing injury risk. Testing should evaluate methods to reduce unnecessary force and strain to the forearm through active or passive offloading strategies. The use of customized gloves will enable performance optimization and decrease injury potential by addressing fit-related issues.

Given the reliance on repetitive gripping tasks during lunar surface operations and in-flight exercise (e.g., Orion), incorporation of a soft-goods glove strap or comparable design modification is strongly recommended to assist in maintaining a closed-grip posture and mitigating repetitive motion fatigue. This consideration is particularly important as elevated suit pressure (ESP) configurations remain under evaluation, which may further increase localized pressure points and musculoskeletal loading.

6.5 Tool Recommendations

Tools need to be designed and selected for multiple purposes, including, but not limited to, optimizing task performance, serving as mobility aids (e.g., recovering from falls, ambulation), enhancing ergonomics to limit concerning suited positions (e.g., extended handle tools), limiting grip fatigue, and providing fatigue mitigation when no other options are available (e.g. benches). Careful consideration is required for the weight and design of 1-g tools versus 1/6-g tool simulations during training events, as well as tool shape to improve ergonomics (e.g., different shovel heads would make tasks easier). Collaboration with industry partners should be explored to innovate ergonomic tool design.

Specific tool recommendations include:

- **Walking poles**: Incorporate attachment points that avoid repetitive gripping and are integrated into the gloves, suit, or PLSS (e.g., ski pole-style straps around wrist). Lengthen tools to avoid kneeling or bent over positions. Provide bench items for fatigue mitigation.
- **Trenching tools**: Ensure tools replicate 1/6-g weight and avoid 1-g tool weight where not necessary for analog training.
- **General tool design**: Consider longer-handled tools and worksite magnification capability in the lower helmet Field of View (FOV) to reduce the need for kneeling.

6.6 Cognitive Domain Recommendations

Environmental factors that contribute to cognitive workload during surface EVAs must be thoroughly evaluated, particularly the ease or difficulty of achieving geology science objectives. To support this, EVA simulation studies should implement clearly defined and standardized EVA performance metrics. Embedded cognitive measures, including both self-report and objective measures, should be integrated into these studies to characterize cognitive performance under different conditions and validate the measures for operational monitoring use on the Moon and Mars. The baseline impact of new EVA simulation technologies on cognitive workload, cognitive performance, and overall EVA performance need to also be evaluated. In addition, reliable and effective navigation aids must be developed and tested, as Apollo surface crews frequently experienced disorientation during physically demanding translations.

6.7 Summary of Recommendations and Path Forward

Collectively, these recommendations emphasize a proactive, interdisciplinary approach to human health and performance optimization, and injury risk reduction across training, testing, and operational environments. Implementation of these strategies will enhance understanding of human-to-suit interactions, inform suit and tool design decisions, and support safe, sustainable mission execution as exploration activities progress from analog testing to Lunar and future planetary operations.

7 SERPO Strategy & Roadmap

The following strategy is not all-encompassing but is intended to provide a clear overview of the SERPO process and facilitate understanding of its approach. The SERPO framework is designed as a dynamic, cyclical process in which all components are interconnected and can be pursued concurrently to optimize human performance across mission timelines.

Foundation & Assessment establishes a baseline understanding of risks, current practices, and interdisciplinary needs across all human performance domains. Historical and current research, including findings from the Shoulder Injury Tiger Team and Apollo-era suit recommendations, are reviewed to identify knowledge gaps and unimplemented improvements. Injury trends and risk factors in EVA and NBL training data are analyzed. The scope of HPO is defined, key domains and their interactions (e.g., fatigue influencing decision-making and injury risk) are mapped, stakeholders are engaged, and a centralized collaboration platform is implemented to facilitate interdisciplinary alignment.

Task & Environment Characterization identifies specific EVA tasks, environmental factors, and equipment considerations that influence performance and injury risk. This includes cataloging pre-flight, in-flight, and exploration EVA tasks, analyzing their biomechanical, cognitive, and physiological demands, and highlighting high-risk maneuvers. Environmental and equipment assessments evaluate planetary suit designs, training venues, and surface conditions on the Moon and Mars, while risk mapping prioritizes interventions based on MSK and cognitive injury potential.

Develop Evidence-Based Training Programs focuses on creating training curricula grounded in research and HPO principles. Preflight and pre-mission education, critical for enabling in-flight autonomy on Mars-class missions, includes strength and conditioning, nutrition, and acute

MSK injury management, as well as competency assessments to prepare crew for progressively autonomous operations.

Integrated Human Performance Optimization establishes SERPO as a central interdisciplinary hub for collaboration, data collection, and dissemination. Real-time and post-training monitoring captures physical and cognitive metrics, while injury and performance data collected across training venues and mission phases inform updates to protocols, interventions, and suit designs. Cross-domain coordination aligns nutrition, fatigue management, and cognitive support with physical training objectives, enhancing decision-making and overall mission performance.

Validation, Evaluation, & Continuous Improvement ensures ongoing assessment of training and intervention effectiveness. Pilot testing through analog simulations evaluates injury mitigation and performance outcomes, while key performance indicators (KPIs) for injury rates, physical readiness, cognitive workload, and mission success are measured. Iterative refinement updates FCEs, training programs, Work Hardening protocols, and operational guidance, incorporating lessons learned into SERPO recommendations. Program sustainability, funding, and logistical support are maintained to enable continuous improvement.

Mission Integration embeds SERPO guidance throughout all mission stages. Pre-flight, FCEs, Work Hardening, and domain-specific training prepare crew and align cross-disciplinary readiness. In-flight and exploration EVA operations are monitored for performance and injury indicators, with real-time guidance for task prioritization, fatigue management, and injury prevention. Post-mission, performance and injuries are evaluated, and training protocols, rehabilitation strategies, and databases are updated to incorporate lessons learned and further optimize future mission readiness.

Together, these components form a cyclical and iterative process in which data, insights, and interventions continuously feed back into one another. Multiple components can progress simultaneously, enabling proactive identification of risks, rapid implementation of improvements, and ongoing optimization of human performance for exploration-class missions.

References

(DCPH-A), D. C. f. P. H.-A. (2024). U.S. All Services Injury Surveillance 2021 Summary. *Defense Safety Oversight Council (DSOC) Military Injuries Working Group (MIWG)*. https://ph.health.mil/PHC%20Resource%20Library/cphe-ip-all-services-injury-surveillance-2021-summary.pdf

Acevedo, A. M., Zeigler, Z., & Melton, B. (2024). Maximal Aerobic Capacity as a Predictor of Performance on ACFT Total Score of ROTC Cadets. *Int J Exerc Sci*, *17*(4), 429-437. https://doi.org/10.70252/rjam3514

Alvar, B. A., Sell, K., & Deuster, P. A. (2017). *NSCA's Essentials of Tactical Strength and Conditioning* (First Edition ed.). Human Kinetics.

Bennett, L. M., & Gadlin, H. (2012). Collaboration and team science: from theory to practice. *J Investig Med*, *60*(5), 768-775. https://doi.org/10.2310/JIM.0b013e318250871d

Bompa, T. O., & Buzzichelli, C. A. (2024). *Periodization: Theory and Methodology of Training* (Sixth Edition ed.). https://doi.org/10.5040/9781718225435

Bompa, T. O., & Haff, G. G. (2009). *Periodization: Theory and Methodology of Training* (Vol. 5th ed.). Human Kinetics, 2009.

Bullock, G. S., Dartt, C. E., Ricker, E. A., Fallowfield, J. L., Arden, N., Clifton, D., Danelson, K., Fraser, J. J., Gomez, C., Greenlee, T. A., Gregory, A., Gribbin, T., Losciale, J., Molloy, J. M., Nicholson, K. F., Polich, J. G., Räisänen, A., Shah, K., Smuda, M., . . . Rhon, D. I. (2023). Barriers and facilitators to implementation of musculoskeletal injury mitigation programmes for military service members around the world: a scoping review. *Injury Prevention*, *29*(6), 461-473. https://doi.org/10.1136/ip-2023-044905

Choi, B. C., & Pak, A. W. (2006). Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. Definitions, objectives, and evidence of effectiveness. *Clin Invest Med*, *29*(6), 351-364.

Comfort, P., Jones, P. A., McMahon, J. J., & Newton, R. (2015). Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: test-retest reliability. *Int J Sports Physiol Perform*, *10*(1), 58-63. https://doi.org/10.1123/ijspp.2014-0077

Cox, L. (2024, July 29-August 1, 2024). EVA Planning: Using Neutral Buoyancy Laboratory (NBL) training to predict inflight energy expenditure. International Space Station Research and Development Conference (ISSRDC), Boston, MA.

Cronin, J. B., & Hansen, K. T. (2005). Strength and power predictors of sports speed. *J Strength Cond Res*, *19*(2), 349-357. https://doi.org/10.1519/14323.1

Cullinane, C. R., Rhodes, R. A., & Stirling, L. A. (2017). Mobility and Agility During Locomotion in the Mark III Space Suit. *Aerosp Med Hum Perform*, *88*(6), 589-596. https://doi.org/10.3357/amhp.4650.2017

Davis, K., Nguyen, D., Siddiqui, Z., Tejral, Z., & Stockfleth, S. (2024, 21-25 July 2024). *Measuring xEMU Loads Through Shoulder Straps* 53rd International Conference on Environmental Systems, Louisville, Kentucky. https://ttu-ir.tdl.org/server/api/core/bitstreams/89543d8d-a154-42e1-bef9-2c43aac19b0b/content

Davis, K., Rhodes, R., Kim, H., Benson, E. A., Hernandez, Y., Vu, L., & Sudhakar, R. (2020). xEMU Lower Torso Assembly (LTA) Brief Fleet Sizing Study. 2020 International Conference on Environmental Systems,

de la Motte, S. J., Clifton, D. R., Gribbin, T. C., Beutler, A. I., & Deuster, P. A. (2019). Functional Movement Assessments Are Not Associated with Risk of Injury During Military Basic

Training. *Military Medicine*, *184*(11-12), e773-e780. https://doi.org/10.1093/milmed/usz118

de la Motte, S. J., Gribbin, T. C., Lisman, P., Murphy, K., & Deuster, P. A. (2017). Systematic Review of the Association Between Physical Fitness and Musculoskeletal Injury Risk: Part 2-Muscular Endurance and Muscular Strength. *Journal of Strength and Conditioning Research*, *31*(11), 3218-3234. https://doi.org/10.1519/JSC.0000000000002174

Diaz, A., & Newman, D. (2014). *Musculoskeletal human-spacesuit interaction model* IEEE Aerospace Conference, Big Sky, MT.

Dillon, L. (2023, 7-9 Feb. 2023). Recommendations for Developing Space Suit Integrated Food Systems and Delivering Nutrition Before, During, and After Lunar EVA. 2023 Human Research Program (HRP) Investigators' Workshop (IWS), Galveston, TX, USA.

Division, A. F. H. S. DOD Health of the Force 2021. . https://www.nami.org/NAMI/media/NAMI-Media/Research/DOD-Health-of-the-Force-2021.pdf

Estep, P. (2024). *Human Performance in Spacesuits and Exploration Operations* Spaceflight Human Optimization and Performance (SHOP) Summit, Houston, TX.

Fox, B., Judge, L., Dickin, D., & Wang, H. (2020). Biomechanics of military load carriage and resulting musculoskeletal injury: A review. *Journal of Orthopedics & Orthopedic Surgeons*, *1*(1), 6-11.

Girginer, F. G., Seyhan, S., Açar, G., Bilici, M. F., Bilici Ö, F., & Soylu, Ç. (2025). Acute effects of the RAMP warm-up on sprint and jump performance in youth soccer players. *Front Physiol*, *16*, 1612611. https://doi.org/10.3389/fphys.2025.1612611

Grier, T., Benedict, T., Mahlmann, O., & Canham-Chervak, M. (2024). Relative Strength and Physical Performance in US Army Male and Female Soldiers. *J Strength Cond Res*, *38*(8), 1479-1485. https://doi.org/10.1519/jsc.0000000000004823

Haff, G. G., & Nimphius, S. (2012). Training Principles for Power. *Strength & Conditioning Journal*, *34*(6), 2-12. https://doi.org/10.1519/SSC.0b013e31826db467

Hauschild, V. (2016). Foot marching, load carriage, and injury risk. *Technical Information Paper (Army Public Health Center)*.

Hauschild, V. D., Hauret, K. G., Richardson, M. D., Jones, B. H., & Lee, T. J. (2017). A Taxonomy of Injuries for Public Health Monitoring and Reporting. https://api.semanticscholar.org/CorpusID:80429997

Helms, E. R., Cronin, J., Storey, A., & Zourdos, M. C. (2016). Application of the Repetitions in Reserve-Based Rating of Perceived Exertion Scale for Resistance Training. *Strength Cond J*, *38*(4), 42-49. https://doi.org/10.1519/ssc.0000000000000218

Hoppe, M. W., Brochhagen, J., Tischer, T., Beitzel, K., Seil, R., & Grim, C. (2022). Risk factors and prevention strategies for shoulder injuries in overhead sports: an updated systematic review. *Journal of Experimental Orthopaedics*, *9*(1), 78. https://doi.org/10.1186/s40634-022-00493-9

Issurin, V. (2008). Block periodization versus traditional training theory: a review. *J Sports Med Phys Fitness*, *48*(1), 65-75.

Jeffreys, I. (2007). Jeffreys I (2007) Warm-up revisited: The ramp method of optimizing warm-ups. Professional Strength and Conditioning. (6) 12-18. *Professional Strength and Conditioning*, 12-18.

JSC, N. (2019). Extravehicular Mobility Unit. In N. J. S. Center (Ed.), (Vol. FS-2019-07-JSC-EA010): JSC Engineering Directorate.

Kakouris, N., Yener, N., & Fong, D. T. P. (2021). A systematic review of running-related musculoskeletal injuries in runners. *Journal of Sport and Health Science*, *10*(5), 513-522. https://doi.org/10.1016/j.jshs.2021.04.001

Kamandulis, S., Bruzas, V., Mockus, P., Stasiulis, A., Snieckus, A., & Venckunas, T. (2018). Sport-Specific Repeated Sprint Training Improves Punching Ability and Upper-Body Aerobic Power in Experienced Amateur Boxers. *J Strength Cond Res*, *32*(5), 1214-1221. https://doi.org/10.1519/jsc.0000000000002056

Knapik, J., Reynolds, K., Staab, J., Vogel, J. A., & Jones, B. (1992). Injuries associated with strenuous road marching. *Military Medicine*, *157*(2), 64-67.

Kraemer, W. J., & Szivak, T. K. (2012). Strength training for the warfighter. *J Strength Cond Res*, *26 Suppl 2*, S107-118. https://doi.org/10.1519/JSC.0b013e31825d8263

Lauersen, J. B., Andersen, T. E., & Andersen, L. B. (2018). Strength training as superior, dose-dependent and safe prevention of acute and overuse sports injuries: a systematic review, qualitative analysis and meta-analysis. *British Journal of Sport Medicine*, *52*(24), 1557-1563. https://doi.org/10.1136/bjsports-2018-099078

Lauersen, J. B., Bertelsen, D. M., & Andersen, L. B. (2014). The effectiveness of exercise interventions to prevent sports injuries: a systematic review and meta-analysis of randomised controlled trials. *British Journal of Sports Medicine*, *48*(11), 871-877. https://doi.org/10.1136/bjsports-2013-092538

Lee, E. C., Fragala, M. S., Kavouras, S. A., Queen, R. M., Pryor, J. L., & Casa, D. J. (2017). Biomarkers in Sports and Exercise: Tracking Health, Performance, and Recovery in Athletes. *Journal of Strength and Conditioning Research*, *31*(10), 2920-2937. https://doi.org/10.1519/JSC.0000000000002122

Lovalekar, M., Hauret, K. G., Roy, T., Taylor, K., Blacker, S. D., Newman, P., Yanovich, R., Fleischmann, C., Nindl, B. C., Jones, B., & Canham-Chervak, M. (2020). Musculoskeletal injuries in military personnel-Descriptive epidemiology, risk factor identification, and prevention. *Journal of Science and Medicine in Sport*, *24*(10), 963-969. https://doi.org/10.1016/j.jsams.2021.03.016

McFarland, S. M., Campbell, D. H., & Rhodes, R. A. (2023, 16-20 July 2023). *NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2023* 52nd International Conference on Environmental Systems, Calgary, Alberta, Canada. https://ntrs.nasa.gov/api/citations/20230006720/downloads/ICES-2023-121%2C%20NASA%20Advanced%20Space%20Suit%20Pressure%20Garment%20System%20Status%202023%20-%20FINAL.pdf

McGuigan, M. R., & Winchester, J. B. (2008). The relationship between isometric and dynamic strength in college football players. *J Sports Sci Med*, *7*(1), 101-105.

Merrigan, J. J., Rentz, L. E., Hornsby, W. G., Wagle, J. P., Stone, J. D., Smith, H. T., Galster, S. M., Joseph, M., & Hagen, J. A. (2022). Comparisons of Countermovement Jump Force-Time Characteristics Among National Collegiate Athletic Association Division I American Football Athletes: Use of Principal Component Analysis. *J Strength Cond Res*, *36*(2), 411-419. https://doi.org/10.1519/jsc.0000000000004173

Merrigan, J. J., Stone, J. D., Hornsby, W. G., & Hagen, J. A. (2020). Identifying Reliable and Relatable Force-Time Metrics in Athletes-Considerations for the Isometric Mid-Thigh Pull and Countermovement Jump. *Sports (Basel)*, *9*(1). https://doi.org/10.3390/sports9010004

Miller, M. (2023). *Extravehicular Activity (EVA) & Human Surface Mobility (HSM) Program (EHP) Joint EVA & HSM Test Team (JETT) Field Test 3 (JETT3) Report*.

Möller, F., Hoffmann, U., Vogt, T., & Steinberg, F. (2023). Exercise-Related Effects on Executive Functions During a Simulated Underwater Extravehicular Activity. *Hum Factors*, *65*(6), 1014-1028. https://doi.org/10.1177/00187208211032868

Molloy, J. M., Pendergrass, T. L., Lee, I. E., Chervak, M. C., Hauret, K. G., & Rhon, D. I. (2020). Musculoskeletal Injuries and United States Army Readiness Part I: Overview of Injuries and their Strategic Impact. *Military Medicine*, *185*(9-10), e1461-e1471. https://doi.org/10.1093/milmed/usaa027

Monteiro, L., Santos, V., Abel, M. G., Langford, E. L., Martinez, G. J., & Massuça, L. M. (2024). Biomotor Abilities for Law Enforcement Officer Readiness. *Applied Sciences*, *14*(7), 3004. https://www.mdpi.com/2076-3417/14/7/3004

Moore, S. T., MacDougall, H. G., Peters, B. T., Bloomberg, J. J., Curthoys, I. S., & Cohen, H. S (2006). Modeling locomotor dysfunction following spaceflight with Galvanic vestibular stimulation. *Exp Brain Res*, *174*(4), 647-659. https://doi.org/10.1007/s00221-006-0528-1

Moudy, S. C., Peters, B. T., Clark, T. K., Schubert, M. C., Weiss, H., & Wood, S. (2025). *Development and Validations of Sensorimotor Assessment Tasks Using Spaceflight Analogs* Human Research Program Investigators' Workshop (HRP IWS), Galveston, TX.

Moudy, S. C., Peters, B. T., Clark, T. K., Schubert, M. C., & Wood, S. J. (2024). Development of a ground-based sensorimotor disorientation analog to replicate astronaut postflight experience. *Front Physiol*, *15*, 1369788. https://doi.org/10.3389/fphys.2024.1369788

Mujika, I. (2017). Quantification of Training and Competition Loads in Endurance Sports: Methods and Applications. *Int J Sports Physiol Perform*, *12*(Suppl 2), S29-s217. https://doi.org/10.1123/ijspp.2016-0403

Mujika, I., Halson, S., Burke, L. M., Balagué, G., & Farrow, D. (2018). An Integrated, Multifactorial Approach to Periodization for Optimal Performance in Individual and Team Sports. *Int J Sports Physiol Perform*, *13*(5), 538-561. https://doi.org/10.1123/ijspp.2018-0093

Nindl, B. (2015). Physical Training Strategies for Military Women's Performance Optimization in Combat-Centric Occupations. *Journal of Strength and Conditioning Research*, *29*, S101-S106.

Nindl, B. C., Jaffin, D. P., Dretsch, M. N., Cheuvront, S. N., Wesensten, N. J., Kent, M. L., Grunberg, N. E., Pierce, J. R., Barry, E. S., Scott, J. M., Young, A. J., O'Connor, F. G., & Deuster, P. A. (2015). Human Performance Optimization Metrics: Consensus Findings, Gaps, and Recommendations for Future Research. *The Journal of Strength & Conditioning Research*, *29*, S221-S245. https://doi.org/10.1519/jsc.0000000000001114

Norcross, J., Scheuring, R., Sanders, R., & Murray, J. (2023). *Updates to the Risk of Injury and Compromised Performance due to EVA Operations* (CR: SA-06425).

Norcross, J. R., Clowers, K. G., Clark, T., Harvill, L., Morency, R. M., Stroud, L. C., Desantis, L., Vos, J. R., & Gernhardt, M. L. (2010a). Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit. *NASA/TP-2010-216125*. https://ntrs.nasa.gov/api/citations/20110003409/downloads/Norcross%20et%20al%202010%2C%20Metabolic%20costs%20%26%20biomech%20of%20inclined%20ambulation%20%26%20exploration%20tasks%20in%20a%20planet%20suit.pdf

Norcross, J. R., Clowers, K. G., Clark, T., Harvill, L., Morency, R. M., Stroud, L. C., Desantis, L., Vos, J. R., & Gernhardt, M. L. (2010b). Metabolic Costs and Biomechanics of Level Ambulation in a Planetary Suit. *NASA/TP-2010-216115*.

https://www.lpi.usra.edu/lunar/artemis/NorcrossEtAl_NASA-TP-2010-216115_PlanetarySuitMetabolicCosts.pdf

Orr, R., Coyle, J., Johnston, V., & Pope, R. (2010). Load carriage: Minimizing soldier injuries through physical conditioning – a narrative review. *Journal of Military and Veterans' Health*, *18*(3), 31-38.

Orr, R., Coyle, J., Johnston, V., & Pope, R. (2016). Self-reported load carriage injuries of military soldiers. *International Journal of Injury Control and Safety Promotion*, *24*(2), 1-9.

Orr, R., Pope, R., Lopes, T., D., L., Blacker, S., Bustillo-Aguirre, B., & Knapik, J. (2021). Soldier load carriages, injuries, rehabilitation and physical conditioning: An international approach. *International Journal of Environmental Research and Public Health*, *18*(8), 4010. https://doi.org/10.3390/ijerph18084010

Paoletta, M., Moretti, A., Liguori, S., Snichelotto, F., Menditto, I., Toro, G., Gimigliano, F., & Iolascon, G. (2021). Ultrasound Imaging in Sport-Related Muscle Injuries: Pitfalls and Opportunities. *Medicina (Kaunas)*, *57*(10), 1040. https://doi.org/10.3390/medicina57101040

Pinder, R. A., Davids, K., Renshaw, I., & Araújo, D. (2011). Representative learning design and functionality of research and practice in sport. *J Sport Exerc Psychol*, *33*(1), 146-155. https://doi.org/10.1123/jsep.33.1.146

Rai, B., Kaur, J., & Foing, B. H. (2012). Stress, workload and physiology demand during extravehicular activity: a pilot study. *N Am J Med Sci*, *4*(6), 266-269. https://doi.org/10.4103/1947-2714.97205

Rhodes, R., Flaspohler, C., & McFarland, S. (2023, 16-20 July 2023). *Testing Fit, Mobility, and Comfort of the Exploration Pressure Garment Subsystem (xPGS)* 52nd International Conference on Environmental Systems, Calgary, Canada. https://ttu-ir.tdl.org/server/api/core/bitstreams/60dd1b98-5dbd-4d6a-8390-6ffb27f51fd2/content

Robinson, J., Robers, A., Irving, S., & Orr, R. (2018). Aerobic fitness is of greater importance than strength and power in the load carriage performance of specialist police. *International Journal of Exercise Science*, *1*(11), 987-988.

Rosenberg, M. J., Reschke, M. F., Tomilovskaya, E. S., & Wood, S. J. (2022). Multiple field tests on landing day: Early mobility may improve postural recovery following spaceflight. *Frontiers in Physiology*, *13*. https://doi.org/10.3389/fphys.2022.921368

Ross, A., Rhodes, R., & McFarland, S. (2019, 7-11 July 2019). *NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2019* 49th International Conference on Environmental Systems, Boston, Massachusetts.

Ruscio, B. A., Jones, B. H., Bullock, S. H., Burnham, B. R., Canham-Chervak, M., Rennix, C. P., Wells, T. S., & Smith, J. W. (2010). A process to identify military injury prevention priorities based on injury type and limited duty days. *American Journal of Preventive Medicine*, *38*(1 Suppl), S19-33. https://doi.org/10.1016/j.amepre.2009.10.004.

Sammito, S., Hadzic, V., Karakolis, T., Kelly, K. R., Proctor, S. P., Stepens, A., White, G., & Zimmermann, W. O. (2021). Risk factors for musculoskeletal injuries in the military: a qualitative systematic review of the literature from the past two decades and a new prioritizing injury model. *Military Medicine*, *8*(1), 66. https://doi.org/10.1186/s40779-021-00357-w

Scheuring, R. (2013). *NASA EVA Funcational Capacity Evaluation (FCE) and Work Hardening Program Development Effort Summary* (NASA EMU Shoulder Injury TIM, December 2012, Issue.

Scheuring, R., J Jones, J., Polk, J., Gillis, D., Schmid, J., Duncan, J., Davis, J., & Novak, J. (2007). The Apollo Medical Operations Project: Recommendations to Improve Crew Health and Performance for Future Exploration Missions and Lunar Surface Operations. *NASA STI, NASA/ TM–2007–214755*.

Schlotman, T. E., Cox, L. I., McGrath, T. M., Baughman, A. J., Estep, P. N., Siders, B. A., Abercromby, A., & Somers, J. (2023, 4-11 March 2023). A Preliminary Assessment of Physical Demand during Simulated Lunar Surface Extravehicular Activities. 2023 IEEE Aerospace Conference,

Shumway, J. (2019). Injury prevention for tactical personnel – Compiling the evidence and lessons learned. *TSAC Report*, *52*(1).

Silva, R., Camões, M., Barbosa, A., Badicu, G., Nobari, H., Bernardo, A., Carvalho, S. A., Sant'Ana, T., Lima, R., Bezerra, P., & Clemente, F. M. (2021). Relationship between training load and match running performance in men's soccer. *Journal of Men's Health*, *17*(4), 92-98. https://doi.org/10.31083/jomh.2021.082

Smith, C. M., Segovia, M. D., & Salmon, O. F. (2023). Impact of reduced weight on motor and cognitive function in astronaut analogs: A simulated lunar gravity workload study. *Acta Astronautica*, *206*, 18-29. https://doi.org/https://doi.org/10.1016/j.actaastro.2023.02.014

Stokols, D., Hall, K. L., Taylor, B. K., & Moser, R. P. (2008). The science of team science: overview of the field and introduction to the supplement. *Am J Prev Med*, *35*(2 Suppl), S77-89. https://doi.org/10.1016/j.amepre.2008.05.002

Strauss, S. (2004). Extravehicular Mobility Unit Training Suit Symptom Study Report. *NASA/TP–2004–212075*. https://ntrs.nasa.gov/api/citations/20060017061/downloads/20060017061.pdf

Strock, N. C., Frisco, D., Dillon, E. L., Estep, P. N., Norcross, J., Prejean, B. J., Fincke, R. S., & Marshall-Goebel, K. (2023, 2023 Feb 7). Evaluation of Aerobic Standards for Lunar Surface Extravehicular Activities. Human Research Program (HRP) Investigators' Workshop (IWS), Galveston, TX.

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The Importance of Muscular Strength in Athletic Performance. *Sports Med*, *46*(10), 1419-1449. https://doi.org/10.1007/s40279-016-0486-0

Thuro, A., & Stirling, L. (2021). *Characterization of the Apollo Astronaut Lunar Extravehicular Activity Falls and Near-Falls* 2021 IEEE Aerospace Conference, https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9438263

Turner, A. N. (2011). The Science and Practice of Periodization: A Brief Review. *Strength and Conditioning Journal*, *33*(1), 34-46. https://doi.org/10.1519/SSC.0B013E3182079CDF

Volpi, A., Haselman, W., Photopoulos, C., & Banffy, M. (2022). Regular-Season Injury Rates in the National Football League After an Attenuated Preseason Due to COVID-19. *Orthop J Sports Med*, *10*(11), 23259671221133776. https://doi.org/10.1177/23259671221133776

Vu, L., Kim, H., Gordon, A., & Rajulu, S. (2022). Machine-learning Solution for Automatic Spacesuit Motion Recognition and Measurement from Conventional Video. *51st International Conference on Environmental Systems*.

Wechsler, D. (2009). Wechsler Memory Scale (4th ed.). *San Antonio, TX: Pearson.*

Weiss, H. M., Moudy, S. C., & Wood, S. J. (2025). *Unobtrusive Monitoring of Sensorimotor Performance in Ground-Based Functional Tasks* 2025 IEEE Aerospace Conference, Big Sky, MT, USA.

Whittaker, J. L., Booysen, N., de la Motte, S. J., Dennett, L., Lewis, C. L., Wilson, D., McKay, C., Warner, M., Padua, D., Emery, C. A., & Stokes, M. (2017). Predicting sport and occupational lower extremity injury risk through movement quality screening: a systematic review. *British Journal of Sport Medicine*, *51*(7), 580-585. https://doi.org/10.1136/bjsports-2016-096760

Wilkinson, R. T. (1968). *Sleep deprivation: Performance tests for partial and selective sleep deprivation*.

Williams, D. R., & Johnson, B. J. (2003). *EMU Shoulder Injury Tiger Team Report*. https://ntrs.nasa.gov/api/citations/20040200968/downloads/20040200968.pdf