IAC-24-A5.2.1.x83357

NASA's Top Human System Research and Technology Needs for Mars

Andrew Abercromby[a]*, David Baumann[a], Debbie Berdich[a], James Broyan[a], Torin McCoy[a], Sharmila Watkins[a], Neal Zapp[a]

[a] *National Aeronautics and Space Administration, United States of America,* andrew.abercromby@nasa.gov
* Corresponding Author

Abstract

NASA is working with industry and international partners to return humans to the Moon and to eventually enable humans to explore Mars. Within NASA, several organizations work together to identify, prioritize, fund, execute, and operationalize the research and technology development (R&TD) that will be necessary to enable crew health and performance (CHP) during these future missions. These organizations include flight programs, the Health and Medical Technical Authority (HMTA), the Human Research Program, the Space Technology Mission Directorate, System Capability Leadership Teams, and other organizations, many of which existed for several years prior to the creation of the Moon-to-Mars (M2M) Program Office in 2023. A variety of constructs, vocabularies, and processes exist for managing risks and supporting strategic planning across these organizations. For example, M2M objectives, program risks, human system risks, human research gaps, capability gaps, and envisioned futures are all constructs currently used within NASA to identify and prioritize R&TD needs. These strategic planning constructs are evolving to allow M2M objectives and R&TD investments to be aligned and traced at a detailed level. A recognized need exists among stakeholder organizations to identify and communicate the highest CHP R&TD priorities in a unified and digestible way that addresses the perspectives of NASA's CHP community. To achieve this, the HMTA arranged a series of discussions with representatives of NASA's CHP community, during which the 8 highest priority CHP capabilities that will enable human missions to Mars, referred to as the "top human system capability needs for Mars", were identified. The list includes Earth-independent human operations; Mars-duration food system; Mars-duration effects on human physiology; risk mitigations for vehicle atmospheres; computational injury and anthropometric models; exploration exercise countermeasures; individual variability in responses to spaceflight; and sensorimotor countermeasures. Existing tools and processes for strategic planning and risk management were evaluated, as well as the technical practicalities, cost, and schedule feasibility associated with potential R&TD investments in different capability need areas. This capability needs report is not owned by any one NASA organization and does not replace existing strategic or program planning processes; rather it aims to complement and inform them with a unified set of community generated priorities. These top capability needs will be re-evaluated periodically based on R&TD progress and the evolving M2M architecture.

Keywords: Mars; human; spaceflight; research; technology

Acronyms/Abbreviations

ADD: Architecture Definition Document
CHP: Crew health and performance
DCS: Decompression sickness
ECLSS: Environmental control and life support systems
EVA: Extravehicular activity
HMTA: Health & Medical Technical Authority
HRP: Human Research Program
HSRB: Human System Risk Board
ISS: International Space Station
MCC: Mission Control Center
PRR: Path to Risk Reduction
R&TD: Research & technology development
SCLT: System Capability Leadership Team
STMD: Space Technology Mission Directorate
M2M: Moon-to-Mars
VIS: Vibration isolation and stabilization

1. Introduction

1.1 Humans to the Moon and Mars

NASA is working with industry and international partners to return humans to the Moon and to eventually enable humans to explore Mars. The strategies for these Mars missions are being developed by NASA's Strategy and Architecture Office and are being implemented by the Moon-to-Mars (M2M) Program, and updates are published annually in the Architecture Definition Document (ADD) [1]. Significant advancements in scientific knowledge and technical capabilities are required to enable future Mars missions; the purpose of this paper is to identify and describe several specific areas of research and technology development (R&TD) that must be prioritized to ensure that the physiological and psychological health and the performance of astronauts is adequately protected during future missions to Mars. Documenting these priorities will clearly convey the highest priority capability needs from the perspective of NASA's crew health and performance (CHP) community.

NASA plans and performs R&TD in a prioritized and structured way, as described in the following section. Even so, the realities of communicating priorities clearly, concisely, and consistently within a large, distributed organization can be difficult. Collaboration and partnering with industry, academia, and NASA's international partners is critical to the M2M program and will also benefit from consistent communication and discussion of plans and priorities to ensure the most effective use of finite R&TD resources.

The capability needs report is not owned by any one organization within NASA and does not replace existing strategic or program planning tools and processes; rather it aims to complement and inform them with a unified set of community generated priorities. Anticipated users include internal NASA leaders who direct R&TD investments, as well as industry, academia, NASA's international partners, and other government agencies that are interested in using and/or contributing to R&TD in these areas: Collaboration and coordination is critical for advancing the knowledge and technology required to enable humans to explore Mars.

The capability needs identified herein are not the only important human system capabilities needed for Mars. Rather, they are the subset of important capabilities that the NASA CHP community considers to be most important when considering the variety of factors described in Section 2. The approach used to establish these high priority capabilities is described in Section 2, each of the 8 identified top capability needs is described in Section 3, and the outcome and impact of the effort is described in Section 4.

1.2 Strategic Planning for Human System Research and Technology Development within NASA

Several organizations work together within NASA to identify, prioritize, fund, execute, and operationalize the R&TD necessary to enable future missions. These organizations include flight programs, the Health and Medical Technical Authority (HMTA), the Human Research Program (HRP), the Mars Campaign Office (MCO), Biological and Physical Sciences (BPS), the Space Technology Mission Directorate (STMD), System Capability Leadership Teams (SCLTs), and the Capability Integration Team. These organizations use a variety of mechanisms to identify, fund, and execute R&TD activities according to their organization's objectives and priorities. Most of these organizations existed prior to the creation of the M2M Program Office in 2023.

The CHP community is also distributed across multiple organizations within NASA, as necessitated by the wide range of aeronautics and astronautics research, development, and operational activities requiring CHP expertise. A consequence of the distributed expertise and resources is that different processes, tools, and terminologies are used across the agency for planning R&TD. Some of these differences are intentional and reflect the varied functions, priorities, and specializations of different organizations across NASA, whereas some inconsistency is unintended, and ongoing efforts aim to synchronize strategic planning and products across the agency where appropriate. Communication and coordination among CHP R&TD organizations within NASA is important to ensure information and technology is shared, to avoid unintended duplication of effort, and to align investments with shared interests and needs, to the greatest extent practical.

The primary tools used to strategically plan R&TD within NASA's CHP community for more than decade have been the combination of human system risks managed by the Human System Risk Board (HSRB), the HRP research gaps associated with those risks, and the path to risk reduction (PRR) strategic plans, all of which are publicly accessible online via the Human Research Roadmap [2].

While the PRRs focus predominantly on addressing identified gaps in the research, the capability roadmaps, which are managed by the environmental control and life support systems (ECLSS)-CHP SCLT, focus primarily on technology and include a subset of the research tasks from the PRRs, particularly those tasks that directly inform subsequent technology development. Each SCLT roadmap is a multi-year plan for specific R&TD activities that are required to address or "close" a defined capability gap, i.e., an identified need for a future mission that cannot be met using current knowledge and/or technology. In the area of CHP, all capability gaps are mapped to one or more human system risks, which helps align strategic plans and integrate roadmaps between research-focused and technology-focused organizations [3].

Over the past year, additional mapping has been performed to align the CHP capability gaps with the objectives, use cases, and functions identified by the M2M program [4]. These strategic planning constructs continue to be aligned and evolved at the time of writing to allow M2M objectives and R&TD investments to be aligned and traced at a detailed level.

Reorganization of NASA's STMD has resulted in additional and ongoing efforts to align NASA's internal processes while also engaging the broader community to identify and prioritize technology development needs or "shortfalls", including a survey that was released to the public to solicit feedback and recommendations. The STMD does not traditionally invest significantly in CHP R&TD, however, the STMD survey-based approach is being aligned with other agency-identified capability needs.

1.3 Identifying Top Human System Capability Needs

Given the multitude of existing and emerging tools and processes for strategically planning R&TD, it is appropriate to question the need for another related product. The effort to identify a short-list of highest priority human system capability needs for Mars missions was prompted in-part by the recognition that the high level of detail captured in human system risks, gaps, and roadmaps that is essential for informing strategic planning also limits their effectiveness as a communication tool for certain audiences and applications. The variety and continued evolution of tools and processes to plan and prioritize technology development across NASA further contributes to the challenge of clearly and concisely communicating the highest priorities to the leaders ultimately responsible for making informed investment decisions. Finally, procurement sensitivities limit the ability to publicly share NASA's detailed technology roadmaps, which affects collaborations with industry, academia, and international partners. Publication and international collaboration on CHP technology roadmaps is being pursued and publishing these top human system capability needs for Mars is also intended to improve insight into NASA's areas of greatest need.

2. Methods

The goal of the effort described in this manuscript was to identify and communicate the highest R&TD priorities in a unified and digestible way that addresses the considerations and perspectives of NASA's CHP community. To achieve this, the Office of the Chief Health and Medical Officer arranged a series of discussions with representatives of NASA's CHP community, during which the 8 highest priority mission-enabling CHP capabilities for human missions to Mars, referred to as the "top human system capability needs for Mars", were identified.

2.1 Participating Organizations

The approach taken to identify these top human system capability needs for Mars was similar to that used by NASA's integrated product teams, wherein a small team of representatives from several organizations worked together to create a draft product that was then briefed to the leaders of their respective organizations and other stakeholder organizations and was further refined as needed. Each representative was responsible for coordinating with their home organization.

This approach developed a product within approximately 10 weeks, which ensured that it informed the following year's budget planning process. The primary organizations contributing to the initial draft of the product were the ECLSS-CHP SCLT, the HRP, the HMTA, and the HHP Directorate. Additional review and inputs were subsequently provided by the Flight Operations Directorate, the Mars Campaign Office, the Crew Health & Safety Office, and the chairs of the HSRB. An informational briefing of the product was also provided to the HSRB, although a formal HSRB review was not requested because the product is intended to reflect the consensus recommendations of the broad self-organized and self-identified "NASA CHP community", which extends beyond the membership of the HSRB.

2.2 Prioritization Criteria and Considerations

The following high-level criteria and considerations were used when determining which capability needs should be the highest priority:

- R&TD roadmaps and projected readiness levels: The extent to which credible strategic plans are already in place and funded to ensure a high likelihood of capability readiness within the necessary timeframe.

- Anticipated return on investment: A subjective assessment of the anticipated reduction in risk to CHP and/or other potential benefits to the mission architecture (e.g., a reduction in system mass or volume) if additional resources were to be used to mature a particular capability.

- Practicality: The likelihood that a feasible capability could be developed and matured within reasonably foreseeable cost and schedule constraints.

- Alignment with Mars mission needs: The identified capability needs are either extremely important or essential to enable future human Mars missions.

- Dependent vs. independent of mission architecture: The identified highest priority capabilities are likely necessary for any future Mars architecture; future evolution of the Mars architecture is unlikely to affect the importance of the identified capability needs.

Figures of merit were available for some but not all the capability needs being considered, and although figures of merit are being identified and refined where possible, the implications of some capability needs are extremely difficult to quantify. As such, a qualitative approach was used that relied on the judgment, discussion, and consensus of experts from NASA's internal CHP community.

Each representative first identified the highest priority capability needs from their organization's perspective. Representatives could use existing strategic planning products (e.g., risks, gaps) but were not constrained by them i.e., any high priority need identified by their organization could be submitted for consideration. The highest priorities identified by the participating organizations were then compared and discussed.

No significant disagreement resulted when establishing the capability needs, described in the following section. No attempt was made to further prioritize among the 8 identified capabilities in the highest priority tier; the order in which the capability needs are presented does not reflect their respective priorities.

Single-page summaries were created for each of the top capability needs, which included a description of the capability; an example of the R&TD product; the applicable capability gaps and human system risks; the associated M2M objectives; the affected Mars architecture elements; and the anticipated implementation paths for R&TD products. The package was then briefed to the leaders of the participating organizations and other stakeholder organizations. The presentation package was then refined based on feedback from these briefings, however, the identified top capability needs remained unchanged. The final presentation package was then briefed to a variety of internal NASA community forums and leaders.

3. Results: NASA's Top Human System Research and Technology Needs for Mars

3.1 Earth-Independent Human Operations

The Need: Technologies and concepts of operation to enable crews to perform under delayed and intermittent communication with Earth.

Among the most significant challenges posed by human missions to Mars is the unavoidable communication delay or latency between Earth and Mars. As the crew journey further away from Earth, the increasing distance means that the time it takes for communication signals to travel between the spacecraft and Earth increases to as much as 22 minutes in each direction when Earth and Mars are at their greatest separation. The implications of this are enormous. Furthermore, if communication relay capability is not available during solar conjunction—when the sun is between Earth and Mars and blocks direct communication—the crew must be capable of operating for several weeks without communication, monitoring, or any other support from earth.

All current and previous human spaceflight missions, including Apollo missions to the Moon, have relied heavily on large teams of engineers, scientists, physicians, and other experts in the Mission Control Center (MCC) and other ground-based locations who provide a range of critical functions including monitoring vehicle systems, detecting and diagnosing malfunctioning systems, formulating responses to anomalies, remotely guiding complicated procedures, monitoring medical issues and providing consultation, and even remotely commanding and controlling vehicle systems. The ability to talk and video-call directly with family and friends is an important source of psychological support during long-duration spaceflights. Physiological-, cognitive-, and system-monitoring and decision support during extravehicular activities (EVAs) are crucial and will become even more so for exploration EVAs because they will include increased workloads, environmental hazards, and less-structured timelines than International Space Station (ISS) EVAs.

Most importantly, support from the dozens of highly trained flight controllers on the ground is critical for identifying and ensuring rapid and appropriate responses to emergent situations that threaten the crew and/or spacecraft, such as a failure in the life support system, a cabin depressurization, or a medical emergency.

The need for capabilities to overcome the challenge of communication latency is often referred to as crew autonomy. However, full autonomy from Earth is not the goal; it is expected that the ground will continue to provide as many functions as possible during a Mars mission. Many functions that are currently provided by Earth-based personnel and systems will be largely unaffected by the Earth-Mars communication latency, particularly if they involve monitoring systems or situations over an extended duration or with a long time-to-effect. Examples of this include support to rehabilitate from a musculoskeletal injury or monitoring the gradual degradation of solar array output over the course of a mission.

Changes to operations concepts and communication protocols can mitigate the effects of communication latency on some tasks and can preserve opportunities for ground monitoring and decision support, even during some tasks such as geological exploration during EVAs, while minimizing timeline inefficiencies [5–7]. However, new capabilities are essential to address situations requiring time-sensitive detection, diagnosis, and response, or activities that currently require significant interaction and feedback between Earth and space, such as medical imaging or troubleshooting complex systems.

To achieve this, some vehicle functions will necessarily be partially or fully automated; however, demands on crew-time are still likely to increase substantially, particularly for activities involving troubleshooting. In the event that a solar conjunction blocks communication and no relay is available, the functions that must be performed independent of Earth will increase significantly.

Instrumentation will be required to gather data regarding the vehicles' systems, the environment, and the crewmembers' health and performance, and this data must be aggregated into interpretable and actionable formats. In the MCC today, ISS telemetry from thousands of sensors is viewed continually by experts in each individual system, each with years of training and experience to interpret and appropriately respond to data trends. Biomedical engineers and flight surgeons monitor the ISS crewmembers' health and performance data; however, these data are not integrated with other data sources such as the life support systems, making it difficult to observe, understand, and appropriately respond to their interdependencies.

Although they will be highly trained and capable, Mars astronauts will not have the cognitive bandwidth, training, or available time to work in the same way that MCC operates for ISS. In-mission training will be essential to maintain proficiency in certain skills that will degrade over the course of the multi-year mission, as well as to obtain new skills or procedures that were not anticipated during Earth-based crew training. Additionally, an onboard command center will be necessary to monitor, troubleshoot, and repair vehicle and spacesuit systems, and should focus on the subset of scenarios that cannot be adequately automated or mitigated by the ground based MCC. This onboard command center must also provide capabilities to help detect and troubleshoot unanticipated scenarios. Crews will be trained to respond to a variety of time-critical medical emergencies and must be equipped with multi-functional medical devices and other diagnostic and treatment equipment that crewmembers can use without real-time remote guidance.

Psychological countermeasures will be more important during a Mars mission than during any previous spaceflight mission due to the significantly greater duration, distance from Earth, and the inability to interactively converse with family, friends, or behavioral health specialists; novel approaches are needed to maintain behavioral health and performance that account for delayed and possibly intermittent communication.

3.2 Mars-Duration Food System

The Need: Food formulation, processing, packaging, and storage solutions that meet the mass, volume, and shelf-life needs of Mars missions.

Providing food systems for Mars missions that are safe, stable, palatable, nutritious, and variable, and that minimize resources will be challenging. Astronauts on the ISS are well supplied with prepackaged food from Earth and nutritional needs are well matched to crew needs.

The standard ISS food menu consists of ~210 prepackaged items stored at ambient temperatures, which provide balanced nutritional intake. The standard foods are regularly and frequently supplemented with crew preference foods and fresh produce from Earth, which have shorter shelf-lives and can account for ~20% of a crewmember's food intake

(Figure 1). This regular resupply provides variety to the overall menu, which is important because it contributes to maintaining a high level of consumption of the standard menu items, however, this variety of food will not be possible during a Mars mission.

The shelf-life of the standard food items on the ISS is limited to ~18 months, which is well short of the 36 months (roundtrip with short surface stay) to 60 months (if food for surface stay is deployed 2 years before crew arrive) that will be required for Mars missions. Formulation, processing, packaging, and storage options are required that increase the shelf life of a variety of foods while preserving the nutritional content and palatability [8]. Cold storage may slow the degradation of nutrients, but will require more mass and power, which will limit large-scale use. Improved barrier materials, higher levels of nutrient fortification during processing, and formulations with varied levels of fat, starch, and water could preserve nutrients for longer periods, however, these solutions require additional R&TD.

Crewmembers on the ISS require 2.39 kg of prepackaged food a day, and food will represent the largest non-propellant logistical mass for a Mars mission [9]. Reducing the mass, volume, and crew time associated with food packaging and handling can therefore yield substantial mission-scale savings, meaning that the challenge of increasing shelf-life must be met while simultaneously minimizing the associated resources.

In-mission food production (e.g., crop growth) is an additional option for meeting Mars mission duration requirements, however, current capabilities in this area cannot support the caloric intake of Mars mission crews within reasonably foreseeable mass, power, and volume constraints. In-mission food production may be used to supplement shelf-stabilized foods but must be further developed to ensure efficient use of mission consumables and reliable production of foods that are safe for consumption throughout the duration of a Mars mission.

The technical challenges of reliably germinating crops, delivering water and nutrients, and controlling microbes during successive plantings are being addressed but are yet to be completely solved and demonstrated in space. Repeatable crop production and verification of food safety prior to consumption must also be demonstrated in microgravity to support development of food systems for the duration of a Mars mission.

It is not yet known whether Mars missions will require in-mission food production; Mars food system needs will be met primarily, and perhaps entirely, using shelf-stabilized foods. Although it is important, R&TD to support in-mission food production is likely mission enhancing rather than mission enabling and therefore is a lower priority than developing the shelf-stabilized foods that will provide the primary food source during a Mars mission.

An additional challenge for a Mars mission food system is that the water content of shelf-stabilized foods may have to be reduced significantly. Because the life support system on the ISS recovers ~98% of water, the water in food resupplies the life support system. The state-of-the-art Sabatier technology on the ISS currently recovers ~45% of oxygen and electrolyzes water to produce oxygen that resupplies metabolized oxygen. NASA has invested substantially in technologies that can recover >75% of oxygen during future Mars missions, which means less reliance on electrolyzing water. If prepackaged food for Mars missions contains close to 50% water content, as with the current ISS food system, excess water will result during the mission; the water content of food must be reduced to < 30% to realize the benefits of the high-efficiency water and oxygen recovery systems.

Freeze drying all food is not acceptable because many of these foods lose nutritional value and palatability. To support Mars missions, it will be necessary to develop alternative food items to reduce food water content while supporting nutritional and palatability. [10]

Figure 1. Crews are frequently provided with fresh food and preference items on the ISS; this resupply capability will not be available during Mars missions. Image credit: NASA

3.3 Mars-Duration Effects on Human Physiology

The Need: Characterization of physiological adaptations to spaceflight that occur during Mars-duration missions.

For over 20 years, the ISS has provided a platform to study how spaceflight affects human health and performance, with most ISS crews spending about 6 months in orbit. The rich dataset collected over these 20 years identifies concerning spaceflight-induced changes in physiology that appear to be dose dependent. One notable example of these adaptations is the spaceflight associated neuro-ocular syndrome that was first described by Mader et al in 2011 [11, 12]. Because roundtrip missions to Mars will take 3–5 years, NASA is assessing how the duration of exposure to spaceflight affects each physiological system.

It is unlikely that NASA will plan low Earth orbit or Artemis lunar missions that approach the 3–5 year duration of a Mars mission that can be used to fully characterize human physiology changes during these durations. To date, a handful of crewmembers have spent approximately a year on the ISS. NASA and the Russian Space Agency deliberately planned astronaut Scott Kelly’s and cosmonaut Mikhail Kornienko’s one-year mission to the ISS. Additionally, Frank Rubio and his Russian counterparts’ mission extended to a year after their Soyuz vehicle experienced a coolant leak while docked to the ISS. Other NASA astronauts have had their missions extended, providing a small preliminary cohort to assess the longitudinal effects of spaceflight beyond 6 months. These astronauts’ data are being assessed extensively to better understand the relationships between mission duration and physiological outcomes.

After the success of the joint NASA and Russian Space Agency’s first planned one-year mission and looking toward the challenge of Mars missions, NASA assembled a complement of individual investigations that spans human physiological and psychological systems: This investigation is called the Complement of Integrated Protocols for Human Exploration Research, or CIPHER. This integrative human research study will collect data on crewmembers who spend 6 months or 8–12 months on the ISS. Data collected at these different time points will determine if significantly different physiological changes occur past the 6-month timepoint. Recently, the Russian Space Agency announced that their Soyuz missions will move from 6-month rotations to 8-month rotations, so a regular pool of astronauts and cosmonauts will fly longer than previous crews.

Understanding the time course of spaceflight-induced physiological and psychological changes will be critical to extrapolate risks to human health and performance during Mars missions, the durations of which will extend beyond our experience base. These predictions will help develop requirements for a future Crew Health and Performance system.

3.4 Individual Variability in Responses to Spaceflight

The Need: Individualized prediction of physiological and psychological adaptations to spaceflight to optimize crew health and performance systems to individual astronauts' needs.

As progress continues building vehicles and planning operations for the Artemis missions to the Moon, mission planners are encountering the challenges of this resource-constrained environment. Mass, power, volume, and crew time are all carefully allocated across vehicle systems to support mission success. The resources required for these lunar missions will be more complex than resources associated with ISS missions, and the resource considerations for sending humans to Mars are staggering. Although the human system is incredibly resilient, it is also arguably the most variable system in spaceflight missions. Predictions of how individual crewmembers will adapt physiologically and psychologically during a Mars mission can be used to tailor individual countermeasures that protect the crewmember's health and performance.

Datasets collected over more than 60 years of human spaceflight indicate incredible variability exists in even this highly screened and selected population of astronauts. For example, some crewmembers gain muscle during spaceflight whereas others lose muscle. The same is seen across all physiological systems and these gains and losses are not necessarily correlated with each other.

Commercial spaceflight programs are rapidly evolving and expanding, and these programs will bring a more diverse set of humans to space. NASA is partnering with these companies to develop common research measures for all humans traveling to space. New insights are expected to be gained by studying how these diverse populations adapt and maladapt to the spaceflight environment.

The challenge of understanding interindividual variability in relation to human health is not unique to humans traveling to Mars. NASA is relying on terrestrial investigations of precision health, precision medicine, artificial intelligence, and omics research to better characterize and predict changes in individuals traveling to Mars. NASA is ensuring that the data collected from over 60 years of human spaceflight are archived in ways that will allow future scientists to compare astronaut data and trends to large terrestrial datasets and data analysis tools.

Close collaboration with those working to improve health on Earth will help tackle the challenge of predicting an individual's response to spaceflight.

3.5 Risk Mitigations for Vehicle Atmospheres

The Need: Validated tools that can estimate decompression sickness (DCS) and hypoxia risk to inform efficient and effective DCS mitigation plans including atmospheres, concepts of operation, prebreathe protocols, and treatment plans.

The cabin atmosphere during Apollo missions was 100% oxygen, which effectively eliminated the risk of DCS during EVA on the Moon at the expense of a significantly increased fire risk. The cabin atmosphere during future missions to the Moon and Mars are expected to be nitrox gas mixtures, which will be less flammable than the cabin atmosphere during Apollo missions, but will require astronauts to breathe 100% oxygen, potentially for several hours, prior to EVA to reduce the DCS risk to acceptable levels. Prebreathe protocols used on the Space Shuttle and ISS are validated for microgravity EVAs, however, the significantly increased risk of developing DCS during equivalent ambulatory EVAs make these protocols inapplicable to planetary EVA.

NASA's M2M exploration architecture, as well as the emerging commercial low Earth orbit programs that NASA is helping foster, will involve multiple different crew capsules, orbital habitats, transit habitats, landers, surface habitats, pressurized rovers, and spacesuits. Selecting atmospheres (i.e., operating pressures and constituent gasses) for each of these elements is a complex trade between hypoxia, flammability, crew time, crew workload and fatigue, consumables, ECLSS efficiency, vehicle system interoperability, and DCS risk. The trade studies that inform these highly impactful decisions are severely limited by uncertainty in existing spaceflight DCS risk models.

As an illustration of the magnitude of uncertainty in current predictions of DCS risk, expert estimates on DCS risk for the "Exploration Atmosphere" [13, 14] prebreathe validation study at the Johnson Space Center ranged from below 3% to greater than 24%. Model estimates of duration of prebreathe required before operating the initial human landing system varied by more than 100 minutes in some instances, and the engineering and fire risk implications of further enriching the oxygen content of the atmospheres are very significant, so applying conservative model estimates comes at a substantial cost.

Furthermore, contingency scenarios involving unplanned decompression of the vehicle, habitat, or spacesuit result in significant risk of serious DCS that must be protected against for exploration missions. NASA's existing models are even more limited in their ability to predict Type II (i.e., serious) DCS under these situations, which affects the ability to make risk-informed decisions regarding the design and operation of vehicles and launch-entry-abort spacesuits.

Although many factors affect the risk of developing DCS, the most significant sources of uncertainty in current models relate to the effects of ambulation, high metabolic rates, and saturation atmospheres that have not previously been tested. Exploration spacesuits may include the capability to vary the pressure, which could significantly reduce DCS risk, but no human data exists for the ranges of pressures being considered, and biophysical models are almost completely unvalidated in these regimes. The risk of developing DCS can also be reduced if an increased level of hypoxia is accepted, however, the physiological and performance implications of increased hypoxia in the spaceflight environment are not well understood.

Validated tools to estimate DCS and hypoxia risk are essential to inform efficient and effective mitigation plans, including selecting atmospheres, and developing concepts of operations, prebreathe protocols, and treatment plans. Validated tools are also required to develop engineering and operational mitigation strategies for contingency scenarios such as cabin depressurizations, for example, identifying recommended operating pressures for launch-entry-abort suits and feed-the-leak requirements for vehicles to maintain pressure while crewmembers don suits in a contingency. Improved testing methods, materials, suppression systems, and ignition controls are also critical to characterize and mitigate flammability risk in enriched oxygen environments.

3.6 Computational Models of Injury and Anthropometry

The Need: Models to predict, monitor, and mitigate injury are needed to enable planning, training, operations, and system design for all suited phases of the mission and for all anticipated crewmember anthropometries.

Current injury incidence and inadequate spacesuit fit for smaller crewmembers represents significant risk to future exploration mission objectives. Future spacesuits and spacecraft must ensure that male and female astronauts of all shapes and sizes are not only accommodated by the hardware but can perform all necessary mission tasks without discomfort, performance decrements, or increased injury risk.

The incidence of injuries during Apollo EVAs and during ISS EVAs suggests that musculoskeletal injuries that affect mission objectives, and potentially long-term health, are not only possible but likely during long-duration planetary missions unless capabilities are developed and implemented to improve fit and mitigate injury risk [15, 13, 17]. In addition to self-reports of significant physical and cognitive fatigue, 9 injuries of varying severity were reported during the 14 total Apollo EVAs [18, 19]. Reported injuries range in severity from blisters to fingernail delamination to shoulder injuries that required surgery.

Reducing the recovery time between successive EVAs also increases the risk of an injury occurring [20]. Stays on the Moon during Apollo missions lasted up to 3 days, and astronauts wore custom-fit spacesuits while they performed up to 3 EVAs. By comparison, NASA is considering exploration missions that include as much as 24 hours of EVA per person per week throughout surface stays that will last weeks or months. Exploration spacesuits must therefore protect astronauts while they perform far more EVAs than Apollo astronauts—astronauts who will have less time to recover between EVAs than ever before.

In some cases, poor suit fit is believed to contribute to injury outcomes and is known to affect performance. The extravehicular mobility unit spacesuit used during Space Shuttle and ISS missions for over 40 years was manufactured in medium, large and extra-large sizes, meaning that it is over-sized for smaller crewmembers. Future missions are expected to enable safe and effective EVA for astronauts across a wide anthropometric range and must also account for changes in anthropometry that occur during spaceflight [21].

NASA has worked extensively with industry, academia, and other government agencies to adapt computational models of injury and anthropometry to inform the design and validation of occupant protection systems that are intended to protect crewmembers during dynamic phases of flight, and particularly during landing scenarios [22–24]. Physical interactions between the landing environment, spacecraft, spacesuits, restraint systems, and crewmembers of varying anthropometries and body compositions are complex, with many potential injury pathways that are not adequately captured by existing model capabilities. Earth-based injury models typically do not involve humans wearing spacesuits and they focus instead on improving the survivability of infrequent but very high impact events such as high-speed automotive collisions. These models are therefore developed and validated with a focus on these scenarios. By comparison, landing at the end of a spaceflight is an event that is certain to occur, and injury probabilities for each impact must therefore be very low. In addition, changes in anthropometry, and the effects of deconditioning that will occur over the course of a Mars mission all further complicate the challenge of predicting injury risk.

Models to predict, monitor, and mitigate injuries are needed to enable planning, training, operations, and system design for all phases of the missions and for all anticipated crewmember anthropometries. Ethical considerations and the near-infinite variety of possible anthropometric combinations (i.e., body shapes and sizes) make computational modelling an essential tool to develop and validate safe and effective spacesuits for all anticipated crewmember anthropometries. A combination of ergonomic, musculoskeletal, and finite-element models is required to identify and to mitigate injury-related risks either through modifications in hardware design, changes in the design of tasks and concepts of operations, and/or during training and operations. Unique sensors that quantify the motion, pressures, and forces that crewmembers experience may also need to be adapted both to validate models, and as potential sources of feedback to crewmembers.

3.7 Exploration Exercise Countermeasures

The Need: Effective and reliable exercise countermeasures and vibration isolation systems (VIS) that meet the mass, power, volume, crew time, and spacecraft structural constraints of Mars missions.

Aerobic and resistive exercise are the primary countermeasures used to mitigate physiological and psychological impacts of exposure to microgravity during spaceflight. Exercise hardware and countermeasure prescriptions have become increasingly effective at mitigating losses in muscle, aerobic fitness, and bone mineral density during long-duration spaceflights on the ISS, but significant inter-individual variability is observed among crewmembers, and some crewmembers continue to experience significant decrements in muscle mass and bone mineral density [25–29].

The substantial mass (~2,000 kg), power (~2.1 kW), and volume (19 m^3) of existing spaceflight exercise hardware can be accommodated on the ISS due to its large size and the ability to deliver large payloads to low Earth orbit on a regular basis (Figure 2). The regular resupply of critical replacement parts has also been essential to maintain exercise equipment that are heavily used and require regular maintenance and repair [30, 31].

Figure 2. ISS exercise equipment such as the ISS treadmill are important for protecting crew health and performance but require significant mass, volume, crew time, and vibration isolation. Image credit: NASA

Vehicle ECLSS must be designed to accommodate the high thermal and metabolic loads associated with exercising crewmembers. More significantly, the loads and dynamics associated with exercising in microgravity can damage the spacecraft without appropriate VIS hardware, which limits the forces imparted into the spacecraft by the exercising crewmembers. The current VIS approach involves using very large masses (e.g., tungsten), which is an effective and proven technological solution, but is extremely inefficient in terms of mass and volume, especially if multiple exercise devices are required, as on the ISS, each with unique VIS characteristics and requirements.

The mass, power, and volume of current ISS exercise hardware are incompatible with Mars missions. Mass, power, and volume will be severely constrained on Mars missions, and resupply capability will be effectively non-existent once the Mars transit habitat departs cis-lunar space. As such, exercise countermeasures for Mars missions must not only be at least as effective as the exercise countermeasures on the ISS in protecting CHP, but they must do so while using substantially less mass, power, and volume.

Ensuring the reliability of exercise hardware throughout missions that last years will be a significant challenge. The mass and volume of spare parts necessary to ensure continued operation of critical systems on crewed Mars missions will be substantial [32], meaning that the design and operation of hardware and the mission design must incorporate a maintenance, repair, and sparing strategy based on robust reliability data.

Each crewmembers exercises for 2 hours per day on the ISS is significant. This large amount of exercise time can be accommodated because the crew size is large (typically at least 6) and because most systems on the ISS are monitored and controlled real-time by ground support personnel, freeing up enough crew time for exercise. On crewed Mars missions, the shift toward increasingly Earth-independent operations due to communication latency (see Section 3.1) will require the crew to perform more nominal and contingency functions, which could make crew time potentially even more constrained than on the ISS. Developing and validating exercise modalities and protocols that protect CHP while reducing crew time and minimizing forces imparted to the spacecraft will benefit mission operations and reduce vehicle mass.

3.8 Sensorimotor Countermeasures

The Need: Validated methods for assessing, predicting, and expediting sensorimotor adaptation to altered gravity environments, and specifically the phases associated with landing on Mars and landing back on Earth.

Astronauts experience nausea and significant decrements in functional performance for days or even weeks after experiencing gravity transitions [33, 34], such as landing back on Earth after an extended duration in microgravity, while the sensorimotor system adapts to the new gravity environment. Examples of performance decrements include significant difficulty performing simple tasks such as walking, balancing, standing upright after lying on the ground, and simulated driving. Decreases in muscle strength and aerobic fitness after extended duration exposure to microgravity can contribute to these performance impacts, however, adaptation of the sensorimotor system to the new gravity environment is the primary driver of these performance decrements. Exercise countermeasures are largely effective at mitigating losses in muscle mass and aerobic fitness that occurs with exposure to microgravity, but exercise is not effective at mitigating the effects of sensorimotor readaptation.

After returning to Earth from extended duration ISS expeditions, crewmembers are immediately assisted in egressing their capsules and provided medical supervision and support as needed. Upon landing on Mars, this support will not be available and the inability to perform critical tasks during and immediately after landing poses risk to the crew and the mission. Inability to safely perform EVA for several days after landing on Mars would mean that the severely mass-constrained lander vehicle must accommodate crewmembers for several days to allow adaptation to the Mars gravity environment. Alternatively, the Mars lander and a Mars pressurized rover must be capable of pressurized docking and crew transfer, which will have substantial mass, volume, and complexity implications. In either scenario, precious time on the surface of Mars, potentially several days, would be spent rehabilitating unless countermeasures can be developed and implemented to accelerate the adaptation process.

Astronauts are not normally required to autonomously egress the vehicle after landing on Earth, but if a landing is off-nominal and requires the crew to self-egress, particularly in a water landing situation, then the performance decrements due to sensorimotor adaptation pose increased risk to crewmembers.

An additional concern is the ability of astronauts to manually pilot landing vehicles when the automated landing systems must be over-ridden for any reason. This concern, while important, depends on the architecture of the mission and it is not yet known whether a future human Mars lander will incorporate manual override capability.

4. Discussion

4.1 Impact of Identifying the Top CHP Capability Needs for Mars

A driver for implementing the lean and rapid approach described herein was to generate an integrated and actionable product in time to inform NASA's annual budget planning process for Fiscal Year 2024. This was achieved, and the top CHP capability needs were presented and submitted to leaders of the organizations that are most directly involved in the funding of CHP R&TD. Details of internal NASA funding decisions are not included in this paper; however, overall investment in these top capability needs is estimated to have increased by approximately 35% in FY24—a period during which overall budgets for Mars-focused R&TD were reduced.

Investments in the identified top CHP capability needs have been maintained or increased and the ADD has been updated since the release of the initial capability needs report. After discussion in early 2024, it was agreed that (1) the ADD updates would not change the top capability needs, and (2) the increased investments—while very helpful—had not yet enabled maturation of R&TD products to such a level that they would reduce the importance of any previously identified top priorities. It was therefore decided that a reassessment of the top human system capability needs for Mars was unnecessary to inform the FY25 budget planning process.

The capability needs report was also used to respond to various prioritization-related requests internal to NASA as well as the STMD technology shortfall survey in 2024 [35], which was distributed for responses both internal and external to NASA.

4.2 Interpreting NASA's Top CHP Capability Needs for Mars

The top capability needs identified in this paper are based on the consensus inputs of a subset of CHP-focused organizations within NASA and they are considered the highest priorities with respect to a specific set of criteria and considerations. A different set of criteria and considerations could yield a different set of priorities, and investments in other areas may be important and appropriate. Developing and retaining technologically and scientifically advanced workforces and facilities being one such important reason to consider R&TD investments in areas that may not be as important regarding the architecture of a Mars mission.

The top CHP capability needs identified in this paper are not the only high priority CHP capability needs for Mars. Many other gaps in knowledge remain and many other technological capabilities are required for future Mars missions; comprehensive lists of human system risks and capability gaps are publicly available [2, 36–38] and continued investment in these areas is critical. The decision to limit the list of top CHP capability needs to the 8 listed in this paper was intentional to emphasize the subset of important capabilities that require additional visibility and prioritization, internal and external to NASA.

Radiation countermeasures are important capabilities not included in this list of top CHP capability needs for Mars. The crew health and performance risk associated with chronic and acute (e.g., solar particle events) radiation exposure during Mars missions is significant [39]. Continued research on the physiological and cognitive effects of space radiation exposure is important, as is technology development to address radiation detection, shielding, and space weather forecasting. However, active radiation shielding for a Mars transit habitat does not appear to be practical in terms of budget, schedule, or architecture (i.e., mass, power, volume, complexity) implications. Most importantly, the potential reduction in risk of radiation countermeasures is considered beneficial but is not essential to enable a human Mars mission. In other words, not developing additional radiation detection, shielding, and/or countermeasure capabilities beyond those already available or in development is not expected to preclude a human Mars mission. Regular health monitoring of crewmembers after the mission will be critical for managing radiation risks. It is important to stress that this conclusion regarding radiation countermeasures assumes that current investments in this area continue, however, significant increases in investment are likely to yield a lower return in this area than equivalent investments in the other identified top CHP capability needs.

4.3 Limitations and Forward Work

The product described in this paper has already helped identify specific areas that require more investment, but the limitations of this report should be acknowledged.

The top capability needs report does not identify areas in which investment could or should be decreased; excluding a capability from the list identified here does not imply a lack of need. However, given resources available for R&TD are finite, it will be important to identify investments that are lower priority or not necessary. Additionally, it is common to pursue multiple technological solutions to meet a high priority capability need. Parallel technological approaches are often desirable, however, spreading limited resources across multiple technologies that address the same capability need can limit the ability to sufficiently mature any single technological solution in the necessary timeframe. Each of the identified top capability needs for Mars are broadly defined in terms of their necessity without prescribing a specific solution or implementation for meeting the need.

The report was developed relatively rapidly to ensure it was delivered in time to inform the budget planning process, and all organizations supported release of the final version. It is recognized, however, that the lean approach used to generate this report also limited the ability of the broader CHP community to participate early in the process, and future revisions will aim to ensure earlier inputs from all appropriate stakeholder organizations. It is also acknowledged that this product reflects the perspectives of the internal NASA CHP community, and human missions to Mars will not be possible without industry, academia, and international partners. Publication and presentation of this product at the 2024 International Astronautical Congress is intended to promote collaboration and discussion, especially in any areas where perspectives and priorities may differ.

In addition to this paper, the most recent versions of NASA's CHP technology development roadmaps have been publicly released and can be found at humanresearchroadmap.nasa.gov/CHP_roadmaps.pdf. In some instances, external R&TD projects are already reflected on roadmaps, such as the European Space Agency-provided E4D exercise device technology demonstration. Coordination on future roadmap updates and prioritization discussions may help to identify additional areas of collaboration.

4.4 M2M CHP Decision Roadmap

Several future known decision points are significant drivers for CHP R&TD investments and the M2M architecture. Decisions on the necessity of capabilities such as a treadmill, crop growth, manual spacecraft control, sensorimotor countermeasures, lower body negative pressure, refrigeration, and radiation shielding are just a few examples.

Some decisions are highly dependent upon specific architectural implementations and cannot be made until higher-level decisions such as crew size and mission duration have been made, which is the focus of the Mars Architecture Decision Roadmap [40]. However, some investment-driving decisions can be made relatively independent of the eventual Mars architecture. For example, requirements for atmospheric monitoring, or crew selection based on predisposition to certain medical outcomes, are decisions that could affect the prioritization of investment, and are mostly independent on the final vehicle or mission design.

The M2M CHP Decision Roadmap is a pilot effort, modelled loosely after the Mars Architecture Decision Roadmap, that helps planners identify and make (or schedule) decisions about the M2M CHP architecture that enables more targeted investment of limited R&TD resources. Stakeholders across NASA are being invited to propose CHP-focused decisions that, once made, could substantially affect R&TD investments and/or the M2M architecture.

During the current pilot phase of this approach, a subset of these candidate decisions will be selected, some of which will be addressed in the near-term, and others that will be scheduled as future decision points. The value in identifying future known decision points is that R&TD roadmaps and associated investments may then be updated as necessary to support those future decisions with the best possible data and technological options.

The authority to make specific decisions and the appropriate participating stakeholder organizations will depend on the specific decision being made. Once made, those decisions will be communicated internally and externally, and NASA R&TD roadmaps will be updated accordingly.

Acknowledgements

The authors would like to thank Kerry George for her valuable assistance in technical editing of this manuscript.

References

[1] Moon to Mars Architecture - Architecture Definition Documents https://www.nasa.gov/moontomars architecture/ (accessed 04.09.24).
[2] Human Research Road Map. https://humanresearchroadmap.nasa.gov/ (accessed 04.09.24).
[3] A. Abercromby, G. Douglas, K. Kalogera, J. Somers, R. Suresh, M. Thompson, et al., NASA Crew Health & Performance Capability Development for Exploration: 2021 to 2022 Overview, 51st International Conference on Environmental Systems, St. Paul, Minnesota, USA, 2022, 10-14 July.
[4] Architecture Definition Document (ADD) Objective Mapping Tables https://www.nasa.gov/moonto marsarchitecture-architecturedefinitiondocuments/ (accessed 04.09.24).
[5] S.L. Cady (ed), Special Collection: BASALT Research Program, Astrobiology 19(3) (2019).
[6] M.J. Miller, D.S. Lim, A.L. Brady, Z. Cardman, E. Bell, W.B. Garry, et al., PLRP-3: Operational Perspectives Conducting Science-Driven Extravehicular Activity with Communications Latency, IEEE Aerospace Conference (pp. 1–13), Big Sky, Montana, USA, 2016, 5-12 March.
[7] S.P. Chappell, T.G., Graff, K.H.. Beaton, A.F. Abercromby, C. Halcon, M.J. Miller, et al. NEEMO 18–20: Analog Testing for Mitigation of Communication Latency during Human Space Exploration. IEEE Aerospace Conference (pp. 1–12), Big Sky, Montana, USA, 2016, 5-12 March.
[8] G.L. Douglas, S.R. Zwart, S.M. Smith, Space food for thought: challenges and considerations for food and nutrition on exploration missions., J. Nutr. 150 (2020) 2242–2244.
[9] C.S. Lynch, K.E. Goodliff, C. Stromgren, J. Vega, M.K Ewert, Logistics Rates and Assumptions for Future Human Spaceflight Missions Beyond LEO, ASCEND, 10.2514/6.2023-4617, Las Vegas, USA, 2023, 23–25 October.
[10] G.L. Douglas, M. Johnson, J. Broyan, Space Food System Water Content: Considerations for ECLSS Water System Closure, 50th International Conference on Environmental Systems ICES-2021-130, Virtual, 2021, 12–15 July.

[11] T.H. Mader, C.R. Gibson, A.F. Pass, L.A. Kramer, A.G. Lee, J. Fogarty, et al., Optic disc edema, globe flattening, choroidal folds, and hyperopic shifts observed in astronauts after long-duration space flight, Ophthalmology, 118 (2011) 2058–2069.

[12] A.G. Lee, T.H. Mader, C.R. Gibson, W. Tarver, P. Rabiei, R.F. Riascos, et al., Spaceflight associated neuro-ocular syndrome (SANS) and the neuro-ophthalmologic effects of microgravity: A review and an update, NPJ Microgravity 6 (2020) 1–10.

[13] A.F. Abercromby, J. Conkin, M.L. Gernhardt, Modeling a 15-min extravehicular activity prebreathe protocol using NASA′ s exploration atmosphere (56.5 kPa/34% O_2), Acta Astronaut. 109 (2015) 76–87.

[14] A. Garbino, M. Hew-Yang, P. Estep, B. Siders, L. Dillon, C. Ramsburg, et al., Development, Validation and Approval of a Planetary Extravehicular Activity Prebreathe Protocol: NASA Exploration Atmosphere Tests 1 & 2. In 94th Aerospace Medical Association (AsMA) Annual Scientific Meeting, Chicago, Illinois, USA, 2024, 5-9 May.

[15] Risk of Injury and Compromised Performance Due To EVA: Evidence Report Operations, humanresearchroadmap.nasa.gov/Evidence/reports/EVA.pdf (accessed 04.09.24).

[16] Human Research Road Map: Risk of Injury and Compromised Performance Due to EVA Operations, https://humanresearchroadmap.nasa.gov/Risks/risk.aspx?i=84 (accessed 04.09.24).

[17] L. Stirling, P. Arezes, A. Anderson. Implications of pace suit injury risk for developing computational performance models. AMHP, 90 (2019) 553–565.

[18] R.A. Scheuring, C.H. Mathers, J.A. Jones, M.L. Wear, Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts, Aviat. Space Environ. Med. 80 (2009) 117–124.

[19] R.A. Scheuring, J.A. Jones, J.D. Novak, J.D. Polk, D.B. Gillis, J. Scmid, et al., The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations, Acta Astronaut. (2008) 980–987.

[20] R. Scheuring, P. McCulloch, M. Van Baalen, R. Watson, S. Bowen, T. Blatt, Shoulder Injuries in US Astronauts Related to EVA Suit Design. In 83rd Aerospace Medical Association (AsMA) Annual Scientific Meeting. JSC-CN-26251, Atlanta, Georgia, USA, 2012, 13-17 May.

[21] K.S. Young, K.H. Kim, S. Rajulu, Anthropometric changes in spaceflight. Hum. Factors *65* (2023) 977–987.

[22] J.T. Somers, R. Scheuring, B. Granderson, J. Jones, N. Newby, M. Gernhardt, Defining NASA risk guidelines for capsule-based spacecraft occupant injuries resulting from launch, abort, and landing. NASA Technical Memorandum (2014). NASA/TM-2014-217383.

[23] N. J. Currie-Gregg, C. Lawrence, J. Somers, Occupant Protection Modeling and Injury Prediction for NASA Human Exploration Spacecraft, In Advances in Human Factors in Simulation and Modeling: Proceedings of the AHFE 2017 International Conference on Human Factors in Simulation and Modeling, 8 195–206, Los Angeles, USA, 2017, 17–21 July.

[24] J.B. Putnam, J.T. Somers, J.A. Wells, C.E. Perry, C.D. Untaroiu, Development and evaluation of a finite element model of the THOR for occupant protection of spaceflight crewmembers. Accid. Anal. Prev. 82, (2015) 244–256.

[25] C. Krittanawong, N.K. Singh, R.A. Scheuring, E. Urquieta, E.M. Bershad, T.R. Macaulay, et al., Human health during space travel: state-of-the-art review, Cells, 12 (2022) 40.

[26] S.M. Smith, M.A. Heer, L.C. Shackelford, J.D. Sibonga, L. Ploutz-Snyder, S.R. Zwart, Benefits for bone from resistance exercise and nutrition in long-duration spaceflight: evidence from biochemistry and densitometry. JBMR 27 (2012) 1896–1906.

[27] A.D. Moore Jr, M.E. Downs, S.M. Lee, A.H. Feiveson, P. Knudsen, L. Ploutz-Snyder, Peak exercise oxygen uptake during and following long-duration spaceflight. J. Appl. Phys. 117 (2014) 231–238.

[28] J.M. Scott, A.H. Feiveson, K.L. English, E.R. Spector, J.D. Sibonga, E.L. Dillon, et al., Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts. NPJ Microgravity, 9 (2023) 11.

[29] M. Shen, W.H. Frishman, Effects of spaceflight on cardiovascular physiology and health. Cardiol. Rev. 27 (2019) 122–126.

[30] C. Moore, R. Svetlik, A. Williams. Designing for Reliability and Robustness in International Space Station Exercise Countermeasures Systems. In IEEE Aerospace Conference, pp. 1–20, Big Sky, Montana, USA, 2017, 4-11 March.

[31] C. Moore, R. Svetlik, A. Williams, Practical Applications of Cables and Ropes in the ISS Countermeasures System. In 2017 IEEE Aerospace Conference, pp. 1–15), Big Sky, Montana, USA, 2017, 4-11 March.

[32] A.C. Owens, W.M. Cirillo, N. Piontek, C. Stromgren, J. Cho, Analysis and Optimization of Test Plans for Advanced Exploration Systems Reliability and Supportability. In International Conference on Environmental Systems, Virtual, 2021, 12–15 July.

[33] A.P. Mulavara, B.T. Peters, C.A. Miller I.S. Kofman, M..F Reschke, L.C. Taylor, et al., Physiological and functional alterations after spaceflight and bed rest. MSSE 50 (2018) 1961–1980.
[34] T.K. Clark, Effects of spaceflight on the vestibular system, in: Y. Pathak, M. Araújo dos Santos, L. Zea (Eds.), Handbook of Space Pharmaceuticals, Springer Cham , 2022, pp.273–311.
[35] Civil Space shortfall ranking, July 2004 https://www.nasa.gov/wp-content/uploads/2024/07/civil-space-shortfall-ranking-july-2024.pdf?emrc=66d103c42346f (accessed 04.09.24).
[36] A. Abercromby, G. Douglas, K. Kalogera, J. Somers, R. Suresh, M. Thompson, et al., NASA Crew Health & Performance Capability Development for Exploration: 2021 to 2022 Overview, in 51st International Conference on Environmental Systems, St. Paul, Minnesota, USA, 2022, 10-14 July.
[37] A. Abercromby, G. Douglas, K. Kalogera, K. Marshall-Goebel, J. Somers, R. Suresh, et al., (NASA Crew Health & Performance Capability Development for Exploration: 2022 to 2023 Overview. In the International Conference on Environmental Systems, Calgary, Alberta, Canada, 2023, 16-20 July.
[38] E.L. Antonsen, E. Connell, W. Anton, R.J. Reynolds, D.M. Buckland, M. Van Baalen, Updates to the NASA human system risk management process for space exploration. NPJ Microgravity 9 (2023) 72.
[39] S. Freese, A.P. Reddy, K. Lehnhardt, Radiation impacts on human health during spaceflight beyond Low Earth Orbit, Reach 2 (2016) 1–7.
[40] Mars Architecture Decision Roadmap: Moon to Mars Architecture 2023 https://www.nasa.gov/wp-content/uploads/2024/01/key-mars-architecture-decisions.pdf?emrc=d2385f (accessed 04.09.24).