Human Factors and Behavioral Performance Evaluation Framework for IntraVehicular Activities(IVAs) Under Simulated Lunar Gravity: Focus on the Lunar Agriculture Module (LAM)

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Abstract

The Planetary Infrastructure Research Group at the German Aerospace Center (DLR) is developing a Lunar Agriculture Module (LAM) to support sustainable food production and provide Bioregenerative Life Support System (BLSS) functions for long-duration lunar missions. Despite various ongoing research efforts on BLSS development and lunar surface human activities, a critical knowledge gap remains regarding how reduced gravity (0.16g) impacts human factors and behavioral performance (HFBP) during intravehicular activities (IVAs) in a lunar module. To fill the existing research gap, DLR is constructing the Lunar Agriculture Module – Reduced Gravity Simulator (LAM-RGS). The LAM-RGS integrates a Mixed Reality (MR) environment – combining Physical Reality (PR) mockups and Virtual Reality (VR) systems – with a gravity offloading system and multimodal data acquisition tools. This simulator will assess task performance, workload, and biomechanics under simulated lunar gravity conditions to optimize the internal system and rack design of the LAM, minimize ergonomic risks, and improve human-system interaction.

To achieve these goals, this paper presents the experimental design and architecture of the LAM-RGS, introducing a four-pillar research framework consisting of: (1) simulator system development and experimental design, (2) system integration and validation, (3) human factors and performance assessment, and (4) data-driven design optimization. The proposed methodology provides a foundation for systematically evaluating human performance in lunar IVA operations and supports the evidence-based design of future lunar habitat systems.

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1 Introduction

Long-duration human lunar missions require advanced life support systems to sustain crews with minimal resupply from Earth. Bioregenerative Life Support Systems (BLSS) offer a lower equivalent system mass compared to traditional physicochemical systems, making them highly suitable for long-term surface operations. The German Aerospace Center (DLR) is currently developing the Lunar Agriculture Module (LAM) to enable sustainable food production and support BLSS functionality for future human spaceflight activities on the Moon.

Although numerous studies have explored BLSS development and lunar extravehicular activities (EVAs), a critical knowledge gap remains in understanding how reduced gravity (0.16g) affects human factors and behavioral performance (HFBP) during intravehicular activities (IVAs) – particularly in tasks related to plant cultivation, system maintenance, and cargo handling. In response to this challenge, DLR is developing the Lunar Agriculture Module – Reduced Gravity Simulator (LAM-RGS). This system enables systematic evaluation of human performance in a simulated lunar environment, thereby informing both hardware design and operational procedures. The LAM-RGS integrates a Mixed Reality (MR) simulation platform that combines Physical Reality (PR) and Virtual Reality (VR) environments to provide high-fidelity, cost-effective representations of plant cultivation and maintenance areas. The simulator also incorporates a gravity offloading system (hosted at the LUNA Facility in Cologne) and multimodal data acquisition tools, including wearable sensors and biosensors to capture physiological, biomechanical, and cognitive performance data under both Earth gravity (1G) and simulated lunar gravity (0.16G) conditions. This experimental facility is designed to assess task performance, workload, and biomechanical strain to optimize the LAM's internal layout and rack system, mitigate ergonomic risks, and improve human–system interaction. The main HFBP study using the LAM-RGS, scheduled for 2026, aims to address the following research questions.

- How does reduced gravity affect HFBP during IVAs related to maintenance, horticultural, and logistics tasks within the LAM?
- How does prolonged exposure to MR environments under simulated lunar gravity conditions affect skill retention and long-term cognitive adaptation?
- How can multimodal data – including task performance, workload (both physical and cognitive), and biomechanical metrics – be integrated to inform the internal layout and operational strategies of a more efficient LAM?

This paper, representing an initial stage of the broader research program, outlines the background and research gap, introduces a four-pillar research framework for the development and application of the LAM-RGS, and proposes corresponding implementation strategies and experimental designs. Furthermore, the LAM-RGS simulator is presented, followed by a discussion of the expected outcomes and recommendations for future research.

2 Background and Research Gap

Bioregenerative Life Support Systems and DLR Projects

The BLSS is a critical technology for enabling sustainable, long-duration crewed missions on the lunar surface by significantly reducing dependence on costly and logistically challenging terrestrial resupply. Accordingly, evaluating the efficacy of BLSS requires extensive testing and builds upon the foundation of numerous prior projects.The performance of BLSS components, particularly plant cultivation systems, has been assessed in various space-based platforms [25, 23], large-scale terrestrial testbeds [31, 14, 15], and mission analogs [29, 16, 7].

Since 2015, the German Aerospace Center (DLR) has significantly contributed to this field, initiating projects such as EDEN ISS [34] in Antarctica. This project successfully demonstrated sustainable food production within a controlled environment under extreme, isolated conditions, providing valuable operational experience. Building on this foundation, DLR is advancing the development of modular BLSS testbeds – including EDEN LUNA [3], and the Lunar Agriculture Module Ground Test Demonstrator (LAM-GTD) [20, 21], collaborating with the Canadian Space Agency (CSA). These current initiatives are specifically focused on maturing technologies and operational concepts required for the eventual deployment and operation of BLSS facilities on the lunar surface.

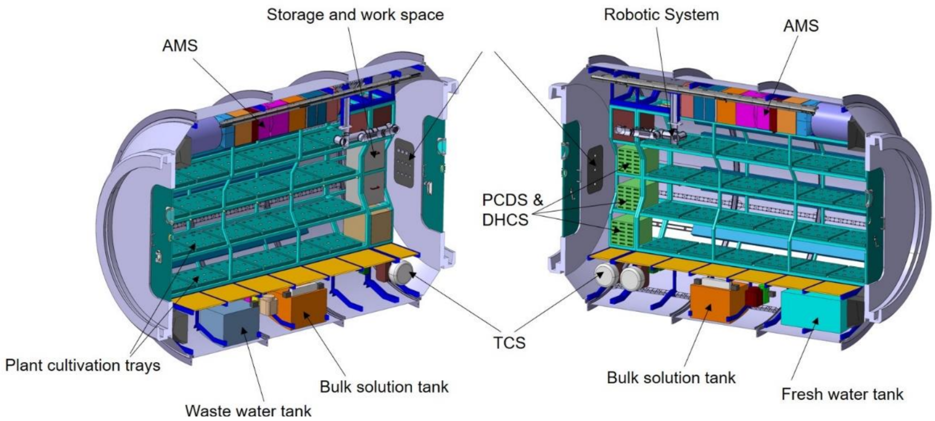

Figure 1 Cross-section of the LAM-GTD's LAM unit [21].

Limitations of Existing Research

Lunar gravity is a critical stressor that must be considered in long-duration human exploration missions. For example, movements such as walking, kneeling, and shoveling under lunar gravity are affected by shifts in the center of mass and reduced gravitational force, leading to impaired balance and increased physical exertion – indicating the need for optimized spacesuit design and appropriate safety measures [28, 4, 8].

Furthermore, the space environment, particularly factors such as altered gravity and stress, significantly impacts key human cognitive and perceptual motor performances, including spatial perception, sense of direction, and mental rotation. These changes can directly lead to a decline in mission performance capabilities and pose safety risks. Such psychomotor impairments have been identified as contributing factors in spaceflight incidents, yet it remains unclear to what extent these observed deficits may change during long-duration missions [19].

Extensive research exists on human factors and performance using various Human-in-the-Loop (HITL) approaches. These approaches utilize diverse technologies and platforms, including Physical Reality (e.g., NASA's Lunar Gateway [32], I-Hab [33]), Virtual Reality (e.g., ESA's Argonaut Moon lander VR demonstration [9], NASA's Deep Space Habitat [1]), Augmented Reality (e.g., NASA's HERA augmented reality study [5], AR-based tapping tasks [6]), and MR platforms (e.g., ISS Cold Atom Lab with MR [27]). However, relatively few studies fully account for actual lunar gravity conditions. Furthermore, even when lunar gravity simulation devices are utilized, their application has been primarily limited to evaluating extravehicular activities (EVAs) or spacesuit performance, as exemplified by NASA's ARGOS project [17].

3 Objective and Methodology

This study aims to conduct a Human-in-the-Loop(HITL) evaluation to comprehensively analyze astronaut task performance and human factors, with the goal of optimizing the operational procedures and internal system design of the LAM. The HITL evaluations are iterative assessments conducted during the design and development process to identify issues related to human systems integration. These evaluations involve user-representative participants performing tasks using representative hardware, software, and procedures [32].

The Human Factors and Behavioral Performance (HFBP) experiments using the LAM-RGS follow a progressive validation process to assess simulator fidelity. Beginning with low-fidelity mockups, the validation extends to mid- and high-fidelity configurations incorporating a 0.16G lunar gravity offloading system at the LUNA Facility in Cologne. This integration pathway allows for the direct application of ergonomics evaluation metrics across simulation stages. The approach provides a low-cost, rapid feedback incremental development strategy in the early phases and generates evidence of human–system compatibility at the final verification stage. These outcomes form a foundation for extending the findings into international design standards, such as NASA-STD-3001 [26].

4 Mixed-Reality Simulator Design

The LAM is designed as a modular system focused on enabling scalable food production and supporting BLSS functions. Structurally, the LAM consists of a rigid cylindrical form approximately 4 meters in diameter and 6 meters in length. The internal layout is broadly divided into two functional zones: the plant cultivation section and the working area (Figure 1). The LAM design used for this HITL evaluation for HFBP can be referenced from the LAM-GTD design (Figure 1) currently under development at DLR.

The LAM-RGS platform comprises three integrated components: a Physical Reality (PR) simulator, a Virtual Reality (VR) simulator, and experimental data acquisition devices. The Mixed Reality (MR) environment combines virtual simulation with physical components to maximize the stimulation of multiple sensory channels, including visual, auditory, tactile, and proprioceptive inputs. This multimodal integration supports a more reliable and operationally representative testing environment.

Figure 2 Concept image of the Lunar Agriculture Module – Reduced Gravity Simulator (LAM-RGS).

4.1 Physical Reality(PR) Simulator

The following two hardware systems constitute the primary environment of the PR setup.

(1) A full-scale physical module of the LAM-RGS will be constructed using aluminum profile structures, not only to reduce experimental costs, but also to ensure realistic simulation quality, offering the added advantage of easy relocation and reassembly.

(2) To simulate the Moon's reduced gravity environment on Earth, the LUNA PUPPETEER [12] (Figure 3) – a gravity offloading system currently under development in collaboration with Space Applications Services as part of the jointly developed Luna Analog Facility [11] by ESA and DLR – will be utilized. The Puppeteer system, developed in collaboration with Space Applications Services. Its primary purpose is to facilitate astronaut and rover training by replicating the Moon's reduced gravitational pull. The development timeline for Puppeteer includes the release of an early version by 2025, with the final, fully refined system expected to be operational by 2026 [10].

4.2 Virtual Reality(VR) simulator

This VR test environment provides an immersive environment capable of simulating detailed IVAs within the LAM. Within the VR environment, key subsystems and equipment or subsystems required for plant cultivation and maintenance are integrated, along with environmental factors such as noise and lighting, thereby supporting a cost-effective and realistic representation of plant growth areas and operational procedures.

4.3 Experimental Data Acquisition Devices

To evaluate human factors and performance under both 1G and 0.16G conditions, data will be collected during the execution of a predefined fundamental movement battery (FMB) and functional task battery (FTB). For this purpose, portable or wearable devices and biosensors will be employed. Additionally, the collected data will be visualized on a dashboard in real-time (Figure 4), providing immediate feedback on key physiological responses, and will also be stored separately for subsequent analysis.

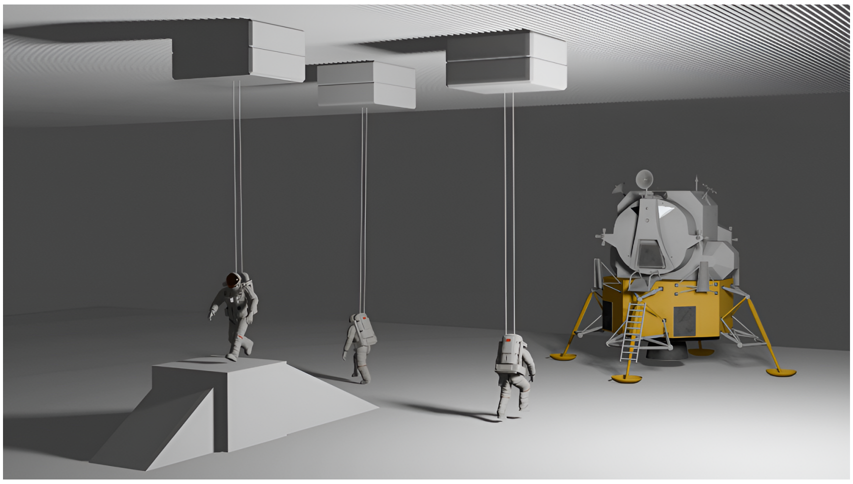

Figure 3 Conceptual image of the LUNA Gravity Offloading System, known as Puppeteer, at the LUNA Facility [12].

5 Research Framework and Implementation Strategy

This section outlines the research framework and implementation strategy developed to investigate the influence of simulated lunar gravity (0.16 G) on human factors and performance during IVA tasks within the prospective LAM. Addressing research questions requires a structured methodology to handle the complex of human-system interaction in reduced gravity simulations. The framework comprises four strategic pillars, which are reflected in the research plan illustrated in Figure 5: (1) Simulator system development and experimental design, (2) Simulator system integration and fidelity assessment, (3) Human factors and performance assessment under terrestrial (1 G) and simulated lunar gravity (0.16G), and (4) data analysis aimed at optimizing internal design of LAM.

5.1 Simulator System Development and Experimental Design

The first pillar focuses on defining operational activities, designing individual LAM-RGS subsystems, and establishing the overarching experimental framework. A low-fidelity simulator prototype – excluding the gravity offloading system – will be constructed and employed in this initial phase to select reliable tasks for the main HFBP experiments and to develop corresponding experimental protocols. This phase also includes the development of data acquisition strategies and the identification and mitigation of potential system limitations that could affect data quality and task performance. These elements will be conducted through an iterative refinement process, structured as a user-centered design loop (Figure 6). The key stages are as follows:

a) **Preliminary Research:** Reviewing relevant documents, manuals, and prior findings from the EDEN-ISS and related projects.

b) **Defining Baseline of Operational Activities for the LAM and LAM-RGS:** Building on EDEN ISS procedures and the LAM-GTD Concept of Operations (CONOPS), this stage establishes the set of LAM operational activities. This includes a systematic classification of tasks encompassing both nominal and off-nominal scenarios – such as logistics handling, plant cultivation, and system maintenance. These baseline activities will serve as the foundation for the development of the FTB within the LAM-RGS framework.

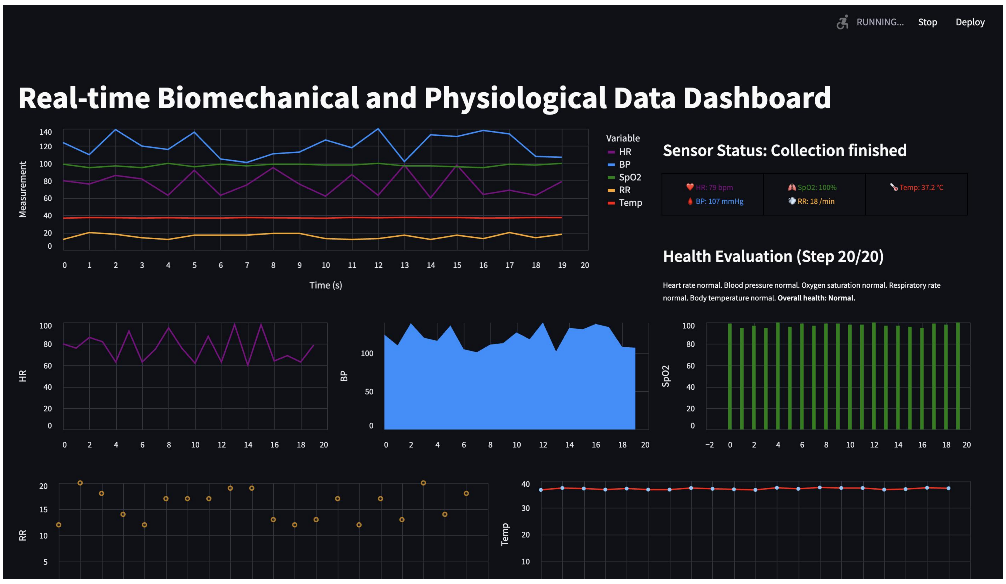

Figure 4 Concept Test of the Data Dashboard for the LAM-RGS Experiment.

c) Initial Functional Task Battery (FTB) and Experimental Protocols Development: At this stage, candidate tasks will be mapped to both VR and PR environments to support the development of a standardized Functional Task Battery (FTB) for LAM-RGS simulations. Potential constraints of the main experiment will be identified through pilot studies and user feedback. Illustrative challenges include the lack of haptic feedback in fully immersive VR environments [30, 18] and the difficulty of accurately replicating fine motor control using gravity offloading systems, as noted in evaluations of NASA's ARGOS platform [13]. Key tasks will then be selected with consideration of these limitations, followed by the development of detailed protocols to ensure simulation reliability and data quality.

(i) **Task Mapping for VR- and PR-Based Simulations:** Baseline LAM-RGS operational activities will be mapped to VR or PR environments based on task characteristics (e.g., physical logistics to PR for biomechanical assessment). This allocation is based on the Mixed Reality–Virtual Reality Immersion Rating Criteria (MR–VR IRC; as shown in (Table 1)), which classifies tasks according to their degree of VR integration. The rating table was developed with reference to Milgram's Reality–Virtuality Continuum [22]. To address VR's haptic limitations, Level 3 tasks (full VR) will be re-evaluated in pilot studies. For critical tasks highly reliant on haptics, simple physical mock-ups will be created to allow reclassification to Level 2 (mixed reality), or pseudo-haptic techniques will be used for tasks remaining in Level 3. Tasks critically dependent on unresolved haptics will be excluded from the FTB.

(ii) **Pilot Study for FTB Selection:** All LAM-RGS operational activities will be tested with users, applying the evaluation criteria outlined in Table 2. Through quantitative scoring and analysis of task-specific characteristics, this process aims to finalize the selection of activities to be included in the FTB used in the LAM-RGS.

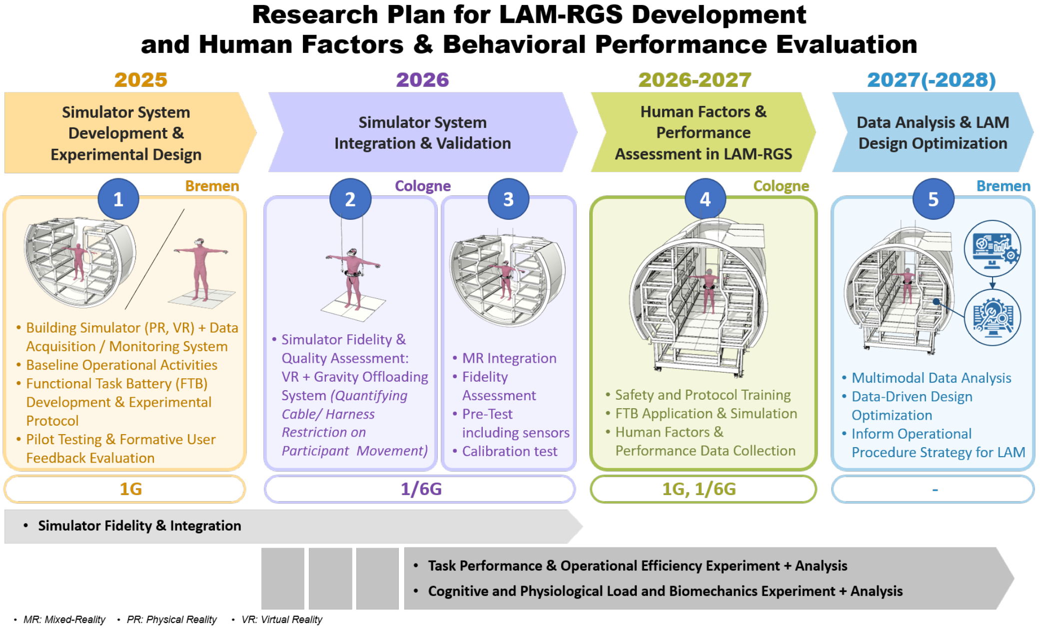

Figure 5 Research Plan for LAM-RGS Development and Human Factors and Behavioral Performance Evaluation.

To address the limitations of VR-based simulation – particularly the lack of haptic feedback – each task is rated for its level of haptic dependency. Initial simulation quality assessments incorporate proxy indicators for this dependency and include participants' subjective evaluations of realism, control difficulty, and sensory discomfort.

In addition, given the inherent limitations of the current gravity offloading system – particularly in replicating fine motor control and joint-specific kinematics – this pilot study includes monitoring of body segment engagement across activities to assess fine motor skill dependency and system-induced limitations. Consequently, this study is structured to address current technological limitations by prioritizing the assessment of gross motor functions – such as overall body coordination, postural stability, workspace utilization, and movement efficiency – over fine joint-level measurements.

(iii) **Key Tasks Selection for FTB:** User feedback data will yield quantitative scores to prioritize activities for the FTB.

(iv) **Detailed Experimental Protocols Development:** Each FTB task follows a structured protocol outlining procedural steps, tool setup, performance criteria (e.g., time, accuracy, error types), and pass/fail conditions. It also defines environmental settings and includes risk mitigation measures to ensure safety and data reliability.

d) **First-Stage Expert Review:** Protocols will be reviewed by experts to ensure validity and relevance, followed by revisions.

e) **Second-Stage Validation:** Each FTB task will have a documented protocol detailing procedures, tools, performance criteria, and risk mitigation.

f) **Final Version Approval for the Main Experiment:** Pre-tested protocols meeting safety and operational relevance criteria will be approved for 0.16G trials.

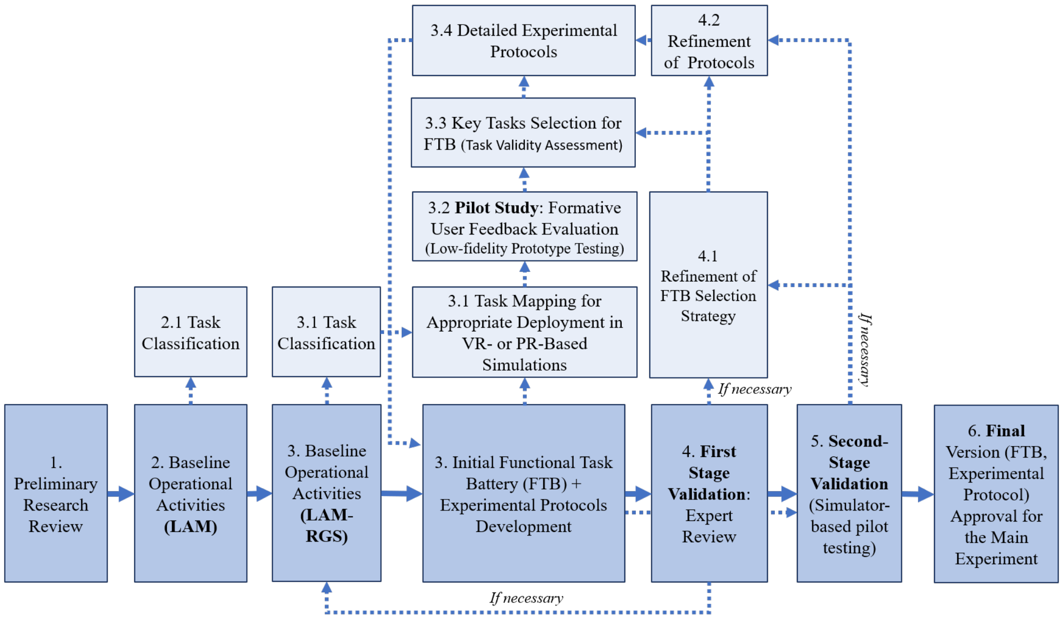

Figure 6 Functional Task Battery (FTB) and Experimental Protocol Development Process for the Main Experiment of LAM-RGS.

5.2 Simulator System Integration and Fidelity Assessment

This phase aims to validate and refine the low-fidelity MR modules, FTB, and experimental protocol to develop a mid-to-high fidelity LAM-RGS, ensuring consistent task execution and reliable multimodal data collection. As shown in Figure 5, this pillar has two validation stages: VR-Puppeteer Integration Test and MR-Puppeteer Integration Test. These steps are assigned not only to achieve seamless and rigorous system integration, but also to evaluate the fidelity and functional limitations of the gravity offloading system itself. This dual objective is critical, as previous EVA and spacesuit simulation studies utilizing gravity offloading technologies have shown that harnesses and suspension cables may either restrict natural motion or introduce artificial movement artifacts [13]. Therefore, minimizing such constraints is essential to preserving the validity of movement performance data in simulated partial gravity environments.

a) VR–Puppeteer Integration Test: The LUNA facility's gravity offload system will be integrated with a Virtual Reality (VR) environment for preliminary testing. This test aims to evaluate potential movement and task execution constraints imposed by the system's cable and harness on participants. A Fundamental Movement Battery (FMB), adapted from NASA's ARGOS project [13], will be employed for this assessment. The FMB comprises representative full-body tasks, including ambulation and gait assessment, kneeling and recovery, prone-to-stand transitions, object retrieval, target reaching, and torso rotation.

Data from evaluating the harness's impact on individual FMB movements will serve two key functions. Firstly, it will act as a diagnostic tool to identify and manage potential data distortions in similar movements during the subsequent FTB execution, guiding decisions on data exclusion or analytical weighting. Secondly, this dataset will be used to quantitatively assess the influence of the Puppeteer offloading system on fundamental anthropometric and kinematic parameters (e.g., joint angles, range of motion) under simulated 0.16G conditions. This evaluation will establish a system fidelity baseline and aid in interpreting biomechanical data from the main experimental phase.

Table 1 Simulation Modality Levels for Task Evaluation in Mixed-Reality Environments.

Level	**Type**	**Description**	**Examples of Expected Task**
Level 1	Non-VR (Physical Reality Only)	No VR implementation required. 100% physically executable. No VR interaction	Basic button/switch operation tests, Simple ergonomic evaluations, Hardware usability tests, Simple physical item movement.
Level 2	Partial-VR (Mixed physical+virtual interaction)	PR-based with key virtual subsystems or elements. PR–VR interaction with PR essential for tasks. VR Dependence (Task Time/Elements): 10-90%<	Accessibility, reachability & posture check during VR interaction, Supply Management, Workspace and layout Design Verification across VR tasks, Repairs, Cleaning
Level 3	Full-VR (High Immersion)	Almost entirely VR-based experiment, excluding minimal PR. Suitable for evaluating/training complex/hazardous scenarios hard to replicate physically. Physical Execution: Impractical/Impossible. VR Dependence (Task Time/Elements): >90%	Simulation of complex operational tasks, Emergency Response(Fire, leak), Complex system diagnostics, System maintenance/monitoring, Plant growth, Operating robotic arm

This stage also incorporates verification and adjustments to ensure consistent harness conditions across 1G and 0.16G environments. This consistency is critical for reliable relative comparisons of human factors and performance metrics in later research stages. Any identified inconsistencies or suboptimal harness fit will be addressed through corrective actions, such as adjustments in harness placement.

b) MR–Puppeteer Integration Test: The complete simulator configuration (MR simulator, Puppeteer, data acquisition components) will undergo final validation. This focuses on verifying system interoperability and synchronization, iteratively refining fidelity and usability using quantitative metrics and qualitative user input under 1G and 0.16G conditions. Despite efforts to minimize fine motor skill dependency, the offloading system is expected to have limitations in fully replicating lunar conditions for all FTB fine motor activities. This final validation aims to identify remaining limitations and inform necessary adjustments to the research strategy.

5.3 Human Factors Assessment Under 1G and Simulated 0.16G Conditions

The third pillar constitutes the main experimental phase of the study and investigates the effects of gravitational loading on task performance, cognitive and physiological workload, and biomechanics. These factors will be measured during the execution of the FTB under both Earth gravity (1G) and simulated lunar gravity (~ 0.16G). The primary goal under 0.16G is to assess absolute changes in human factors and performance, while the 1G condition

Table 2 Evaluation Criteria for Functional Task Battery selection.

Evaluation Domain	Description
Task Completion Time	Indicator of task complexity and procedural efficiency.
Task Stability	Captures errors and balance instability events.
Biomechanical Load	Frequency of gravity-sensitive postures; rated for fine/gross motor dependency (High/Med/Low).
Workspace Usage	Extent of movement and identification of key tactile interaction points.
Subjective Workload	Mental, physical, and temporal demands (NASA-TLX / DLR-WAT).
Simulation Acceptability	Quality and realism ratings via Likert scales and user interviews.

serves as a baseline for evaluating relative differences in cognitive load, musculoskeletal strain, task efficiency, and ergonomic strategies across gravity environments. Quantitative and qualitative data will be collected across the following key domains as follows.

a) Task Performance and Operational Efficiency

(i) **Objective Performance Metrics:** Data will include task completion time, error rates (categorized by type and severity), success/failure rates, task-specific accuracy, and behavior-based indicators such as the frequency of specific postures, idle time, or repetitive motions.

(ii) **Subjective Workload and Usability Measures:** Participants will complete validated post-task surveys (e.g., NASA-TLX [24] or DLR-WAT [2]), and the System Usability Scale (SUS). These will measure perceived mental demand, physical effort, time pressure, and frustration, providing insight into how reduced gravity affects perceived workload and usability.

b) Cognitive, Physiological, and Biomechanical Data Collection

(i) **Cognitive Assessment:** Electroencephalography (EEG) will be used to monitor cognitive load, attention shifts, and mental fatigue. Analyses will focus on frequency bands (e.g., theta, alpha) associated with task engagement and working memory.

(ii) **Physiological Monitoring:** Real-time physiological parameters will be collected, including heart rate, heart rate variability (HRV), estimated CO_2 metabolic expenditure, and muscle activation via surface electromyography (EMG). These data will be used to assess energy expenditure, stress responses, and localized muscle fatigue during task performance.

(iii) **Biomechanical and Anthropometric Analysis:** A motion capture system for human body posture recognition will be used to track macroscopic kinematic variables such as joint angles (at segment level), segmental velocities, movement trajectories, postural stability, and workspace utilization. Given the limitations of simulating fine motor control under partial gravity conditions, emphasis is placed on whole-body coordination patterns and gross movement dynamics, which serve as more robust indicators of functional performance and ergonomic risk in this context. These measures will support the identification of compensatory or altered movement strategies used to maintain task stability in reduced gravity.

5.4 Multimodal Data Analysis and LAM Internal System Design Optimization

The final pillar of the framework integrates and analyzes diverse datasets to derive evidence-based recommendations for LAM design and operational concepts.

a) **Cross-Environment Comparative Analysis** The objective of this analysis is to compare and analyze differences in task performance and cognitive/physiological responses when identical tasks are performed across two different environments. The focus is on variations in execution strategies, performance outcomes (e.g., speed, accuracy, error rates), cognitive load, physiological, and biomechanical responses. Statistical methods such as ANOVA, t-tests, or nonparametric equivalents will be used to compare.

b) **Multimodal Data Integration** To investigate both short-term responses and long-term human adaptation under simulated lunar gravity, this study adopts a multimodal analytical framework that integrates temporally synchronized data streams of HFBP. With the analytical framework still in the planning stage, the study is exploring advanced multivariate statistical techniques designed to address the anticipated complexity and high dimensionality of the data. (Table 3) outlines the potential domains for comprehensive evaluation through integrated, correlation-based analysis.

Table 3 Potential Domains for Evaluation and Multimodal Data Integration in LAM-RGS.

Domain	Potential Data Integration	Application Objective
Human-System Interaction Optimization	Behavioral performance, biomechanical data	Design guidelines for safe internal layout and workspace configuration.
Task Efficiency Improvement	Cognitive workload, physiological signals	Development of efficient task protocols & OPS under lunar gravity.
Ergonomic Risk Management	Posture analysis, motion patterns, EMG, cognitive load	Prediction of ergonomic risks and injury prevention strategies.
Training Optimization and Metrics Development	Performance scores, cognitive and physiological metrics	Mission capability assessment and training proficiency criteria.
Adaptation Pattern Identification	Performance scores, physiological signals cognitive workload, biomechanical data	Understanding long-term behavioral/cognitive adaptation in MR and lunar gravity.

Machine learning techniques, such as clustering and pattern recognition, may be employed to identify complex behavioral profiles or fatigue-related trends. However, the primary analytical emphasis remains on interpretable statistical methods that align with human factors and ergonomic research objectives.

c) Human Factors Engineering for LAM Design Improvements Based on integrated data analysis, this study offers evidence-based design recommendations to optimize the LAM's internal systems. Key suggestions include refining workspace layout, adjusting work surface heights, and repositioning controls and interfaces to reduce physical and cognitive workload, lower error risks, and enhance user safety and operational efficiency. These findings will enrich the broader human factors knowledge base for lunar surface operations and inform standardized design guidelines for critical off-world infrastructures, such as habitats and laboratories.

6 Conclusion and Potential Applications of the Simulator

This paper has presented the LAM-RGS, an experimental platform currently under development at DLR to address a critical knowledge gap in human factors and performance research for IVAs within a lunar BLSS, specifically the LAM. The simulator integrates a MR environment, experimental data acquisition systems, and a dynamic gravity offload system (Puppeteer) to enable mid- to high-fidelity evaluation of astronaut behavior and performance under simulated lunar gravity (0.16G).

By moving beyond traditional EVA and habitat studies, this research targets the underexplored domain of IVA-related agriculture and logistics tasks in partial gravity. The LAM-RGS facilitates comprehensive multimodal data collection – encompassing objective and subjective task performance, efficiency, and workload under both terrestrial (1G) and simulated lunar (0.16G) conditions. The anticipated outcomes include data-driven insights into human performance limitations, adaptation strategies, cognitive and physiological workload, and biomechanical responses associated with performing essential tasks in a partial gravity environment. These findings are expected to inform evidence-based design recommendations for optimizing internal layout, ergonomic interfaces, and operational procedures within the LAM. Ultimately, this study aims to contribute substantially to the human factors knowledge base required for long-duration lunar missions.

The LAM-RGS platform is envisioned as a versatile and mid-to high-fidelity testbed with multiple potential applications. The simulator may support iterative design validation of BLSS systems, astronaut training in lunar-specific IVAs, and refinement of nominal and off-nominal operational procedures. Furthermore, the platform enables advanced investigations in human–system integration, ergonomic assessment, and technology evaluation under partial gravity conditions relevant to lunar surface operations.

In conclusion, future research will focus on implementing and refining the proposed framework, completing the development of the LAM-RGS simulator by 2025, and executing the planned experimental campaigns. This work is expected to advance our understanding of human performance and system interaction in reduced gravity and provide the methodological foundation necessary to enable sustainable human exploration and habitation on the Moon.

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