Technical Feasibility Study – Orbital Operations Club

1. Abstract

The Modular Lunar Augmentation System is a lower-limb platform designed to support human mobility during operations on the Lunar Gateway and the lunar surface. The system is modular, configurable either as a prosthetic limb for amputee astronauts or as a lower-limb augmentation and training system for non-amputee crew, depending on mission requirements. The core design integrates a variable-impedance knee joint, environmental protection against lunar regolith, and embedded sensing and control systems. Interchangeable proximal interfaces of either a residual-limb socket for amputees or a removable thigh-mounted frame for non-amputees allow joint mechanics, load paths, and control behaviour to remain consistent across both operations.

In the training configuration, astronauts wear the system while performing tasks in a simulated reduced-gravity environment within an immersive virtual setting, enabling evaluation of gait, balance, and movement control on flight-representative hardware prior to EVA. In the operational configuration, the system provides active load support and controlled motion, accounting for reduced gravity, abrasive regolith, and EVA suit mobility constraints for both amputee and non-amputee users. This feasibility study evaluates whether a single modular system can satisfy the structural, control, environmental, and safety requirements associated with its dual-use design.

2. Design Specification

The Modular Lunar Augmentation System prioritises load transfer, controlled articulation and robustness to meet EVA and operational requirements. Figure 1 summarises the hardware architecture, detailing the interfacing components, their functions and chosen materials.

The lower limb system consists of a modular attachment interface, an actively controlled knee joint, structural shank and prosthetic foot. The human-prosthetic interface uses either a residual-limb socket for para-astronauts or a removable thigh training frame for non-amputees, with a carbon-fibre reinforced polymer structure and space-rated silicone liner to ensure effective load transfer and comfort [1], [2]. Controlled articulation is provided by a single-axis variable impedance knee joint operated via elastic actuators connected in series to regulate stiffness and damping across different gravity environments. The knee is housed with a titanium alloy, Ti-6Al-4V, chosen for its strength, fatigue resistance and environmental durability [3], [4], [5], [6]. The lower leg structure consists of a carbon-fibre composite shank to transfer loads from the knee to a rigid carbon-fibre prosthetic foot with embedded force and contact sensors for ground reaction measurements. The shank also holds channels for cables and sensors to allow real-time data monitoring. All critical moving interfaces are protected from abrasive regolith through the use of space-rated, low-outgassing elastomeric seals.

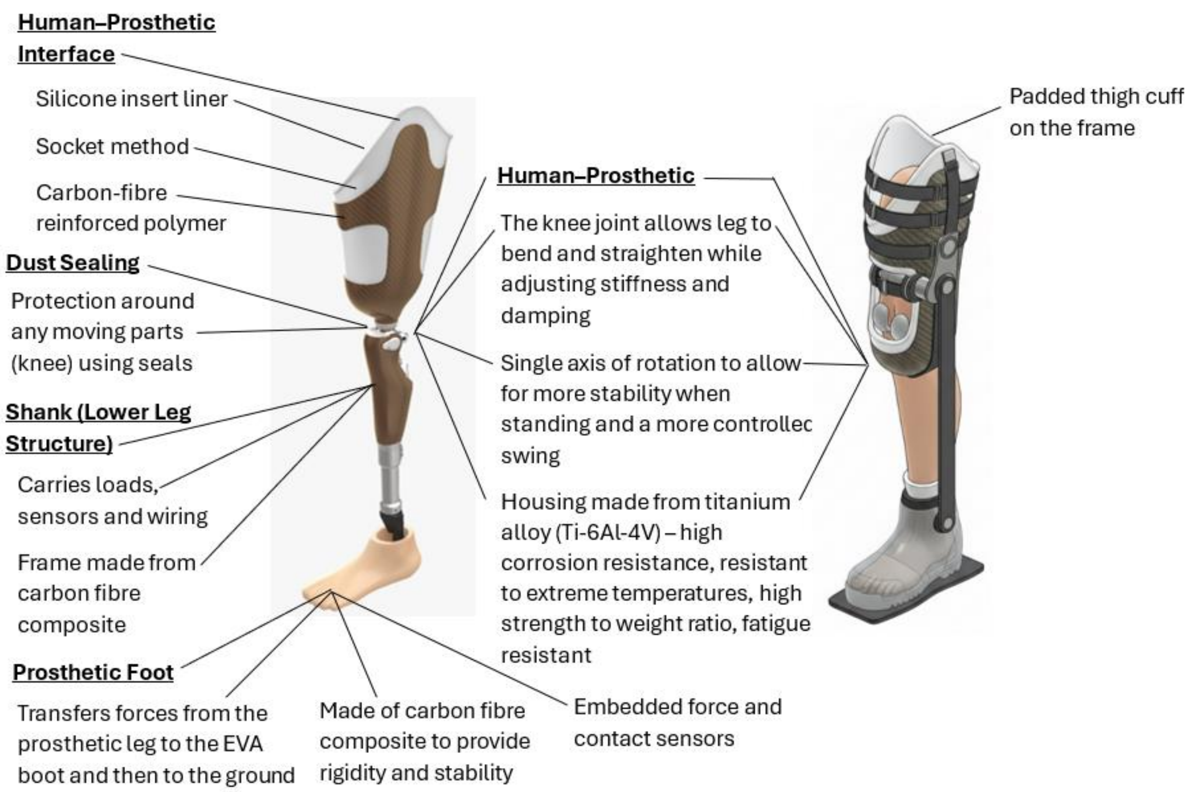

Figure 1: Space-rated Mobility Aids: Prosthetic (*left*, [7]) and Exoskeleton (*right*, generated with Perplexity AI)

3. Operational Environment Analysis

The prosthetic leg is specially reinforced to withstand the hazards of launch, the Lunar Gateway, and the lunar surface. In microgravity, the prosthetic is used primarily for translation along handrails, resistive exercise, and general mobility inside the station. To counter the natural fluid shift and residual-limb volume changes in 0 g, the active socket uses pneumatic pressure to automatically adjust grip [8]. Dual 3-axis IMUs (on the shank and pelvis) which apply microprocessor-knee sensor-fusion strategies shown to improve balance confidence and reduce falls, are used to estimate the gravity vector and motion state [9], [10]. This system enables automatic switching between Ground-Test (1 g), Lunar EVA (1/6 g) and Orbital (0 g) modes, ensuring joint stability and controlled leg motion.

During lunar EVA and partial-gravity operations, the prosthetic provides stable, low-impact gait on uneven terrain. To minimise the magnitude of impact forces, ground-reaction forces are capped by the controller, which integrates gravity estimation with foot-force sensing and dynamically adjusts damping and swing speed, while a speed governor limits walking velocity to a safe impact envelope in 1/6 g [11]. A supervisory logic layer flags excessive speed or impact events, triggering haptic feedback within the socket or boot to prompt a safer gait. This helps maintain a natural and efficient walking pattern for the astronaut and protects the suit from high-magnitude shocks [11].

Dust-proof rotary seals made from low-outgassing, space-rated elastomers protect joints from abrasive lunar dust. By combining this feature with abrasion-resistant outer materials, the system extends EVA operating life from minutes to over 100 hours [12], [13]. Additionally, the rigid carbon-fibre foot and EVA-boot interface provide a predictable load path from astronaut to ground, improving balance during hopping or loping lunar gaits in low gravity.

Across all environments, if a critical fault, sensor failure or power loss is detected, the joints default to a stable, load-bearing configuration so the astronaut can hold position or be assisted to safety [14], [15]. A mechanical quick release at the socket or training frame enables rapid prosthetic jettison in medical or suit integrity emergencies, while haptic feedback in the socket provides vibration alerts when impact forces approach unsafe levels.

4. Manufacturing, Testing and Qualification

The Modular Lunar Augmentation System employs a 'core peripherals' approach, separating flight-critical, high-value components from low-value elements to allow rigorous qualification of essential parts without unnecessary certification of replaceable ones. High-value components, which lie on the primary load path or directly influence joint control such as the knee joint, actuators, sensors, power management, electronics, and primary dust seals are manufactured, assembled, and fully qualified on Earth. They undergo static and dynamic load testing (ISO 10328), fatigue and wear assessments, biocompatibility testing [16], and environmental evaluation for thermal cycling, radiation exposure, and outgassing to meet ESA standards [17]. Actuators and sensors are also tested for response, accuracy, and fault handling to ensure a stable fail-safe in the event of power loss or sensor failure.

Low-value components, such as training frames, socket shells, and dust covers, are 3D printed aboard the Gateway's HALO. As they are mechanically isolated from the primary load path, they are verified through dimensional checks, mechanical fit, and functional inspections rather than full flight qualification. After Earth-based validation of core components, the fully assembled system undergoes integrated testing to verify coordinated performance across mechanical, electrical, and control subsystems. Sensor-driven gait control is assessed across operating modes [18], walking speed and impact mitigation are evaluated in reduced gravity [19], and joint motion is confirmed to remain compatible with EVA suits, ensuring stable, predictable system behaviour.

Prior to operational use, non-amputee trials with the removable training frame are conducted under controlled monitoring of joint loads, interface pressures, and control performance. Safe operation is confirmed through repeated testing before approval for para-astronaut use under medical supervision, with thresholds enforced to prevent excessive loading, unstable gait, or loss of control. The separation of core and peripheral components provides clear fault containment, allowing peripheral failures to be addressed without aborting EVA operations. Core failure modes are characterised on Earth, and the system is designed to default to a stable fail-safe configuration, providing a defensible, traceable pathway for demonstrating that the prosthetic is safe, reliable, and capable of supporting human EVA operations.

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