Movement in Low Gravity (MoLo) – LUNA: Biomechanical Modelling to Mitigate Lunar Surface Operation Risks

David Andrew Green
Space Medicine Team, European Astronaut Centre, European Space Agency, Troisdorf, Germany

Abstract

The Artemis programme seeks to develop and test concepts, hardware and approaches to support long term habitation of the Lunar surface, and future missions to Mars. In preparation for the Artemis missions determination of tasks to be performed, the functional requirements of such tasks and as mission duration extends whether physiological deconditioning becomes functionally significant, compromising the crew member's ability to perform critical tasks on the surface, and/or upon return to earth [MoLo-LUNA – leveraging the Molo programme (and several other activities) – could become a key supporting activity for LUNA incl. validation of the Puppeteer offloading system itself via creation of a complementary MoLo-LUNA-LAB. Furthermore, the MoLo-LUNA programme could become a key facilitator of simulator suit instrumentation/definition, broader astronaut training activities and mission architecture development – including Artemis mission simulations. By employing a Puppeteer system external to the LUNA chamber hall it will optimise utilisation and cost-effectiveness of LUNA, and as such represents a critical service to future LUNA stakeholders. Furthermore, MoLo-LUNA would generate a unique data set that can be leveraged to predict de-conditioning on the Lunar surface – and thereby optimise functionality, and minimise mission risk – including informing the need for, and prescription of exercise countermeasures on the Lunar Surface and in transit. Thus, MoLo-LUNA offers a unique opportunity to place LUNA, and ESA as a key ongoing provider of evidence to define, optimise and support crew Artemis surface missions.

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1 From Apollo to Artemis

The Artemis programme aims to place the first "boots on the Moon" since Apollo 17 in 1972. Apollo missions could be characterised as demonstration missions – dashing to the Lunar surface and back. In contrast, the Artemis programme seeks to develop and test concepts, hardware and approaches to support long term habitation of the Lunar surface, and future missions to Mars. In preparation for the Artemis missions, crew tasks need to be defined, whilst considering their functional requirements, not least because as mission durations extend physiological deconditioning may become significant, compromising a crew member's capability, and/or performance on the surface or upon return to earth [56].

Overall mission architecture including time in transit, and any stay on the Lunar Gateway must also be considered as microgravity (µg) is despite exercise countermeasures associated with multi-systems physiological deconditioning [57] – albeit with significant intra-individual variability [59]. As such it is critical to define the functional requirements of any task related to lunar surface missions (including emergency tasks), assess crew capability, predict task-relevant physiological de-conditioning, and thereby determine the potential functional

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implications prior to sustained Artemis missions. Such knowledge is critical not only to minimise task failure, but optimise task/tool design, prevent injury, and determine the need for, and if so, requirements of surface exercise countermeasures.

Initial Artemis missions are scheduled to involve Lunar surface sojourns of approximately 6 days, with the objective to extend missions as fast as supporting infrastructure and crew capabilities permit. In the Apollo mission reports, crew reported few issues post-flight, medical evaluations were relatively unremarkable, whilst aerobic capacity and orthostatic tolerance were reported to be at pre-flight levels after a couple of days [66]. However, Artemis will be in longer than Apollo missions (Apollo 17 was 12-d and 14-hrs) with longer transit times, even without accounting for a stay on the Lunar Gateway.

During transits (in the Orion capsule) crew will use a NASA Flywheel device although the exercise stimulus it will provide is incomparable to that generated by the current International Space Station (ISS) countermeasure suite provided by the Advanced Resistive Exercise Device (ARED), T2 Treadmill and the Teal ergometer [47]. Furthermore, the Flywheel cannot be used when Orion is docked to the Lunar Gateway due to insufficient vibration isolation. However, on the Lunar Gateway, albeit currently undefined ESA will provide and operate a Lunar Gateway Exercise Countermeasure Device – that will be significantly more capable than the Flywheel but again, potentially not equivalent to current ISS countermeasures [60] although a variety of optimisation approaches have been proposed [61]. Thus, exercise in µg prior to landing on the lunar surface may not entirely ameliorate deconditioning.

Apollo crew perfomed daily “Moonwalks” straight after 3 days in transit. Space adaptation syndrome, which includes disorientation was not reported in Apollo missions, which is surprising given its high prevalence in subsequent space programmes [33]. Nevertheless, Apollo crew stumbled and fell on the Lunar surface on several occasions, in particular when carrying a tools. Whilst, the specific cause of instability is unknown, locomotion style (i.e., “bunny hopping” [4], and/or skipping [31]) on the uneven Lunar regolith when donning Extra-Vehicular Activity (EVA) pressure suits are all likely factors.

In addition to the helmet that limited peripheral vision, the A7 EVA suits significantly restricted ankle, knee and hip mobility, compounded by the caudal and posterior displacement of the center of mass (CoM) due to the Portable Life Support System backpack [62]. In order to maintain balance crew presumably (as detailed assessment of gait biomechanics was impossible on the Lunar surface) tended to lean forward to counterbalance [22], increasing the risk of anterior-posterior, but also medio-lateral falls [67]. Restricted arm movement as well as inhibiting stability could also have contributed to the fact that having fallen, crew had great difficult in righting themselves leading to extreme stress (for the crew and mission control), elevated metabolic (and thus oxygen supply consumption), and ultimately exhaustion [66].

If more significant deconditioning is experienced in Artemis missions, a fall may become more likely, and potentially unrecoverable [15]. For instance, spinal adaptation [28], prime mover [23] and/or trunk muscle atrophy [11] combined with impaired proprioception [65] and motor coordination [64] may impair anticipatory postural adjustments [39] and postural resilience [16].

Whilst, prime movement atrophy may impair power generation required to getting back up. Furthermore, when falling there may be an increased risk of fracture [24] due to reduced skeletal integrity e.g., bone mineral density (BMD) and bone mineral content (BMC) [69], in addition to muscular or connective soft tissue injury [7], and the risk of prolapsed intra-vertebral discs which is a known risk post-flight [6].

Thus, µg and hypogravity-related deconditioning may present a significant risk to health and wellbeing, to task performance, and ultimately mission success. As a result, there is an urgent need to model the physiological deconditioning associated with exploration missions, to inform mission architecture including task definition, but also to determine the need for, and if so, definition of appropriate, and individualised exercise countermeasures.

6^o Head down tilt bed rest (HDTBR) is the pre-eminent ground-based model of µg [30], although dry immersion [52] and hyper-buoyancy floatation [8] have been suggested to induce more rapidly and/or profoundly some of the adaptions associated with µg. As such NASA recently proposed that prior to crewed surface Artemis missions that a 30-day HDTBR study be performed at :envihab a German Aerospace Centre (DLR) facility in Cologne, followed by evaluation of EVA-related task performance. Whilst, such a campaign represents a "worst-case" case scenario – i.e., where crew perform no exercise prior to "landing" – it raises the question of how to define relevant tasks, to evaluate task performance (feasibility and functionality) in a way that informs the safety and success of future Lunar surface crew.

Fortunately adjacent to :envihab DLR and NASA have recently constructed a unique large-scale Lunar-surface analogue – termed LUNA – that will facilitate high-fidelity robotic and crew operations simulation [10]. LUNA will also incorporate a ceiling-mounted "Puppeteer" gravity offloading system that will be able to offload (to 0.16g) two crew moving in any direction simultaneously. In the summer of 2025, a free-standing (frame mounted) (linear) Puppeteer prototype will be trialled to inform the final system. Fortunately, despite the absence of Apollo biomechanical data – the key requirements for the "Puppeteer" system were derived from data collected as part of the Movement in Low Gravity (MoLo) programme instigated in 2014 by ESA in partnership with DLR and with several European academic institutions.

2 MoLo – preferred locomotion

The initial MoLo objectives were to evaluate hypogravity simulations and define "preferred" movement characteristics (unencumbered by an EVA suit) in "valid" simulated hypogravity in order to act as a baseline for novel surface EVA suit concepts, and to inform surface habitat design concepts. This work was required as gait velocity is known to be reduced by offloading (via prolongation of ground contact and flight times) [68] along with reductions in oxygen consumption (cost of transport) [53] and ground reaction forces [25]. However, gait velocity interacts with key biomechanical [27] and metabolic parameters [9] – presumably to optimise gait bioenergetics in a given context [45].

Furthermore, the picture is complex as substantial differences have been reported between methodologies [5]. In fact, the majority of simulated hypogravity studies have employed fixed speeds or standardised relative gait velocity [45] based on the resultant Froude number [1] – but leads to the question of how natural is the resultant locomotion. Furthermore, vertical offloading systems are frequently uncomfortable at the points of "offloading", in particular when unloading needs to be equivalent to 0.84g to simulate 0.16g leading to stilted gait, pain and poor participant compliance [9].

As a result, our initial studies employed the Vertical Treadmill Facility (VTF) to define preferred hypogravity walk, run (and walk-run transition) velocities along with subjective metrics across a range of simulated hypogravities including 0.16g. The VTF is a vertically-mounted treadmill where participants are suspended horizontally with a multi-point harness [17] and graded constant "pull-down", or return forces towards the treadmill belt are generated via pressurised cylinders [26] in a manner similar to the T2-treadmill on the ISS [18].

The application of 0.16g axial force on the VTF was deemed to be comfortable for short periods although it is unlikely to be as well tolerated as when similar loads are generated by a graded textile-based suits which have been worn for up to 8-hrs on earth and in space [63]. Furthermore, locomotion on the VTF is “unnatural” in the sense that the leg and arm body segments must be moved vertically with respect to the (1g) gravitational vector. Whilst participants reported that this was not a significant issue – the effect of this requires confirmation in a planned ISS technical demonstration that will compare preferred walk, run (and walk-run transition) velocities along with subjective metrics at 0.16g with the VTF on earth, and the T2 treadmill on the ISS in the same crewmember. Such data is key to inform Puppeteer definition and subsequent EVA (simulator) suit concept evaluations in LUNA.

3 LUNA facility

Whilst the LUNA facility is extremely high-fidelity in terms of regolith surface characteristics (EAC-1 simulant)[20] and light conditions via a specialized illumination simulator [10], these virtues render comprehensive marker (or even marker-less) multi-camera-based (motion-capture) assessment of EVA task functionality extremely challenging. Furthermore, the generation of airborne regolith is also likely to be highly problematic to subject-mounted instrumentation unless contained within the simulator suits. However, such instrumentation will be highly restricted as it is critical that it should not affect suit performance or general mobility. In addition, setup should be simple and robust without unduly extending testing and thus potential discomfort. Furthermore, it is anticipated that due to the multi-faceted nature of LUNA, high user demand will constrain facility access time.

As a consequence, the LUNA hall is not conducive for high-fidelity biomechanical (e.g., motion) analysis, nor high-volume testing needed for iterative task development and assessment. However, evaluations of candidate Lunar EVA tasks are critical to assess feasibility, suitability, and even potential injury risk prior to their use after a HDTBR-induced deconditioning – which is known to vary between individuals [59] complicating interpretation of its relationship to functionality even though basic task function is reduced by both HDTBR and spaceflight [41].

Definition of appropriate Artemis surface EVA tasks and subsequent understanding their functional requirements is challenging [13]. For instance, on Earth even small changes in seat height can significantly affect the biomechanics of rising in healthy individuals [35]. Indeed, simple task evaluation, task completion (and time-to-completion) data and subjective ratings are of limited value in supporting future Lunar surface task development. This is because failure, or high exertion scores do not demonstrate why someone had difficulty, nor directly indicate what are the factors that underlie the difficulty whilst providing little insight into whether another individual might have similar, or different issues. Therefore, comprehensive task-based motion analysis is critical to evaluate and help support task and/or training development.

4 MoLo programme

A “classical” comprehensive multi-camera motion analysis approach was taken by the most recent phase of the MoLo programme using the L.O.O.P (Locomotion On Other Planets) facility in Milano where we evaluated locomotion at variable g levels in addition to plyometrics (hopping, countermovement and maximal jumping) at variable g levels including lunar [32]. The L.O.O.P. facility provides high-fidelity hypogravity simulation via deployment of long

(17m) twin (in series) calibrated (via electric winch) bungee cords, where the relative change of bungee length, and hence recoil force is minimised during movement. This renders near-constant offloading that appears to be facilitate natural and fluid hypogravity movement.

In addition to derivation of 3D kinematics, an instrumented treadmill provided ground reaction forces (GRFs) that allowed the tracking of segmental and overall Centre of Mass (CoM; and its acceleration) with respect to Cente of pressure (COP) [32]. We consider this to be a key variable to evaluate the risk of instability during simulated hypogravity locomotion, and during plyometric motion. Plyometric jumping is being considered for inflight exercise – following amelioration of multisystem deconditioning in HDTBR [36] – with spring-based systems proving to be not only be feasible in µg [49], but with mass-balancing potentially implementable without requiring a vibration isolation system [12]. Furthermore, plyometrics is a candidate surface exercise modality with, or without a device [70], although in the latter prolonged flight times make CoM control (including "inflight" yaw rotation), and thus safe and controlled landings potentially difficult [29]. Having developed data pipelines to tracking this movement we hope to apply our approach to complex multi-directional body motion as will be performed in LUNA, and on the Lunar surface.

However, whilst CoM and movement kinematics characterise movement – it does not tell us about the "work" associated with the movement, nor the forces generated within, and exerted upon the body structures – key to understanding the demands (and risks) of a task. Indeed, vertical ground reaction forces (zGRFs) are considered to represent a key mechanical stimuli promoting "normal" lower limb musculoskeletal regulation. Indeed, on Earth zGRFs approximate 105% of an individual's body weight when walking, rising to almost 200% during running [19]. However, it is now thought that GRFs are complemented by other forces such as torsion [40], in addition to forces (loading, strain and strain rates) generated by muscles and propagated to the bone and across joints via muscle insertions / tendons [51]. Whilst complex, a multi-faceted relationship would be consistent with the strong association between "physical activity" and bone status in healthy individuals [44].

For instance, a reduction in forces acting through the Achilles Tendon may play a key role in the significant loss of BMD and BMC observed in the calcaneus [2]. Interestingly, we have demonstrated differential modulation of joint kinematics and contractile behaviour at simulated Lunar and Martian gravities [50]. Kinetics such as external work have also been shown to be reduced when walking, running and skipping at speeds representative of those observed (0.56 to 3.6 m/s) in simulated hypogravity [46, 45].

Furthermore, application of inverse dynamics from kinematic and kinetic data the forces and moments experienced at joints, muscles, muscle-tendons, and at the bone can be derived [21]. However, the relationship between external kinetics and internal forces requires computational musculoskeletal (MSK) modelling that represents local skeletal anatomy and relevant muscle-tendon unit physiology [54]. When combined with optimisation techniques, MSK modelling can yield estimates of muscle activation patterns (that can be verified with EMG) and internal kinetics, which are not currently measurable in vivo [3]]. Whilst this approach can distinguish between populations and exercise modalities [55] although it has only recently been applied to hypogravity simulation [42], including within the MoLo programme [14].

Applying optimisation framework modelling to L.O.O.P data hip, knee and ankle net joint moments were shown to decrease in proportion with simulated hypogravity during walking [5]. This approach has now been extended to simulated lunar gravity for walking, running, and jumping/hopping. The data processing is ongoing but novel data pipelines have been built to determine concurrent motion kinematics, CoM tracking in addition to the modelling of internal and external forces that can be used to determine the functional requirements of a given movement – scaled to an individual's anthropometrics.

5 MoLo-LUNA programme

Thus, we propose to leverage the kinematic, kinetic and MSK modeling approach developed for MoLo-Milano but extend it to evaluate tasks to be performed in LUNA in the forthcoming HDTBR studies. The initial step will be to optimise and run the multi- camera motion capture data pipelines for MoLo-Milano hopping and locomotion data (across 1g, 0.16g and 0.37g) to determine the effect of hypogravity upon CoM (with respect to base of support), internal and external work, MSK loading a during hopping and locomotion.

Then, by acquiring the free-standing Puppeteer prototype and housing it in a location in Cologne (termed MoLo-LUNA-LAB) we can comprehensively evaluate the conditions performed in L.O.O.P – which can support finalisation of the main Puppeteer system. Following this we propose to evaluate candidate EVA tasks prior to their performance post HDTBR. Continuing this work initially external to the LUNA simulation hall will allow completion of data collection in "shirt-sleave" mode to act as a baseline for subsequent suit-based evaluations. This would also allow the modelling pipelines to be optimised to support rapid task performance tracking and reporting coupled with complex (cloud-based) kinetics and MSK modelling.

Another key aspect that must be considered is the "functional delta" relating to the deconditioning expected at a given time in a mission. At present we have no defined valid way of evaluating functionality prior to missions. Furthermore, the deconditioning that may occur on the Lunar surface is entirely unknown. An approach to resolve this conundrum and to estimate expected deconditioning on the Lunar surface prior to Artemis missions is to determine the work (for aerobic fitness) and forces/loads required to perform defined activities in high-fidelity simulated hypogravity i.e., LUNA – and calculate the delta to that in 1g. By looping back to the individual tasks – via generation of a biomechanical digital twin [38] one can evaluate the predicted "functionality delta" for a given individual crew member which will vary according to many factors including size [58] and gender – with small females whilst potentially not as physically strong representing lower resource consumption [57]. This approach could be concurrent with digital twining to generate movement avatars within augmented/virtual reality [43] to promote real-time task performance [48] and training.

Furthermore, from the onset, the MoLo programme has sought to incorporate candidate "low-footprint", and thus potentially LUNA-compatible technologies/approaches. Several of these devices could be integrated into the simulator suit and form part of routine data capture as part of a "low-footprint" sensor matrix. However, such approaches must be validated with respect to an appropriate gold-standard methodology – i.e., multi-camera motion capture and demonstrated to be practical.

For instance, implementation of a single-camera approach is of substantial interest this is far more plausible in LUNA, in Lunar habitants, and even on the Lunar surface. In fact, single-camera approaches are increasingly being employed in professional sports – including by members of the MoLo consortium – based on standard camera video to not only track athletic performance but also to provide automated actionable insights for the coach.

This approach, if valid and applied to all LUNA EVA-simulation tasks, would facilitate the building of models that could determine the expected deconditioning for a defined mission architecture (vs. equivalent time period active in 1g), for a given individual. If one loops back to the functional requirements for a task, this approach can then be used to determine the "functional delta" between an individual at a specific point in a mission and the functionality they require for safe and effective completion of a given task.

Whilst these models are initially focused on EVA's modelling will need to consider that missions will evolve to include intermittent EVAs, and periods of habitat dwelling. Approaches such as those proposed in Lunar Life where intravehicular activity can be simulated in part by $+9.6^o$ Head Up Tilt Bed Rest (HUTBR) and Short arm centrifugation with 0.16g at the CoM [37]. However, Lunar habitats are also likely to involve elements such as stairs or ladders to access storage/sleeping areas, move between habitat levels, and potentially move between the habitant, and to the surface [29]. In fact, on Earth, stair climbing ability is considered a key risk factor for falls [34] and was a major concern for Apollo mission control. This highlights the need for the definition of optimal (or at least careful consideration of Lunar habitat ergonomics.

Finally, utilising a "low-footprint" sensor matrix in a way that is compatible with valid modelling on the Lunar surface enabling characterisation of activity vs. predicted capabilities to provide real time operational mission support, but also provide data to validate or optimise the deconditioning models built on earth. Thus, over time they could provide individualized functionality guidance to inform task performance, exercise definition, and prescription on the Lunar surface, but also potentially during transit and/or on the Lunar Gateway.

6 Conclusion

Thus, the MoLo-LUNA – leveraging the Molo programme – could become a key supporting activity for LUNA incl. validation of the Puppeteer offloading system itself via creation of a complementary MoLo-LUNA-LAB. Furthermore, the MoLo-LUNA programme could become a key facilitator of simulator suit instrumentation/definition, broader astronaut training activities and mission architecture development. By employing a Puppeteer system external to the LUNA chamber hall it will optimise utilisation and cost-effectiveness of LUNA, and as such represents a critical service to future LUNA stakeholders. Furthermore, MoLo-LUNA would generate a unique data set that can be leveraged to predict de-conditioning on the Lunar surface – and thereby optimise functionality, and minimise mission risk – including informing the need for, and prescription of exercise countermeasures on the Lunar surface, and in transit. Thus, MoLo-LUNA offers a unique opportunity to place LUNA, and ESA as a key ongoing provider of evidence to define, optimise and support crew Artemis surface missions.

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