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One giant leap
Helping astronauts walk safely on the Moon

Humans walk differently on the Moon, risking musculoskeletal injuries affecting the safety of all crew members. **Jesse Rhoades** and **Thomas Geijtenbeek** explain how a new approach to data analysis could reduce this risk for astronauts in NASA's current Moon exploration programme Artemis

Fifty years ago, Apollo placed humans on the Moon. Over the next decade, Artemis will return us to the lunar surface. Yet a new generation of explorers will be confronted by complications the Apollo astronauts did not fear. A particularly important one is long-term exposure to the Moon's reduced gravity, for which our bodies have not evolved over the past 6 million years.

Walking on the Moon

Apollo astronauts, in total, spent 80 hours and 32 minutes on the lunar surface,[1] an average of 13 hours and 25 minutes for each astronaut who stepped on the Moon during the Apollo missions. Artemis missions, in contrast, will require up to 24 hours of extravehicular activity (EVA) per week;[2] in addition, each week, they will experience 112 waking hours of general exposure to lunar gravity. Even inside their lunar habitat, Artemis astronauts will move around, exposing themselves to ambulation under lunar gravity. This increase in exploration and exposure will substantially benefit our planetary sciences; however, it will exact a price on these explorers.

Bipedal gait has been a crucial part of the human experience. Humans are among the few animals on Earth to develop this gait pattern[3] that reduces ambulation stability through alternating phases where a single limb provides body support and frees up our hands for essential tasks, such as using tools. Our species has mastered this odd way of moving, a tight-knit series of coordinative structures always just a whisper from complete instability.

Most importantly, bipedal gait was developed for life on Earth, and we will take this evolutionary gift with us when we leave. As such, it is both a blessing and a curse. Human evolution has fine-tuned our muscles, bones, and joints for bipedal ambulation's repetitive wear and tear within the normal pull of gravity on Earth, known as "1g". Additionally, this fine-tuning has developed specific motor patterns for efficient ambulation within this gravitational constraint.

It is conceivable that the motor patterns produced on Earth may not be the most efficient within the fractional gravity of the Moon. If this is the case, new motor patterns will emerge in astronauts within the lunar environment. The problem is that alterations to the repetitious nature of gait motor patterns can produce severe consequences. Slight changes in pressure centres within joints, or vectors of force on bones, could initiate chronic repetitive injuries.

Chronic injuries are often observed when an individual injures a leg or foot. These injuries frequently necessitate a shift of weight bearing, causing secondary injuries up the kinetic chain as joints are loaded in novel asymmetric ways. On Earth, these chronic secondary injuries will generally require downtime for rehabilitation and

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Thomas Geijtenbeek has a PhD in biomechanical engineering from the Delft University of Technology and is the creator of the biomechanics software Hyfydy and SCONE.

recovery. On the lunar surface, however, where each crew member is responsible for mission-critical tasks that ensure the health and well-being of their crewmates, chronic skeletal muscular injuries can threaten the lives of all crew members. Additionally, several studies have found that asymmetric gaits will emerge as preferable under lunar gravity,[4,5] precipitating situations where chronic kinetic chain injuries may occur. Thus, experiments to identify emergent motor patterns before astronaut exposure are crucial. Identifying these motor patterns will allow for specific training protocols and mediation strategies.

Since the 1960s, several studies have been conducted examining fractional gravity effects on walking and running gait. Two of the most recent studies to be carried out under simulated lunar gravity have found specific issues that will emerge as motor patterns. First, it was found that unilateral skipping is a preferred mode of ambulation under lunar gravity[4] (something astronauts also observed during the Apollo landings). The findings were confirmed in a follow-up study, which broke down the walking and running trials from the initial study using principal component analysis (PCA). Component analysis through a biomechanics lens operates from the perspective that biological movements are too complex to describe through simple variables. Too much occurs during any given biological movement to provide an adequate description. PCA is a mathematical process that takes motion capture data and breaks a movement into components. It allows us to see a movement as a series of discrete parts, simplifying movements into discrete elements. PCA analysis on lunar gait data confirmed the emergence of asymmetric gait under lunar gravity.

Secondly, this study identified the emergence of a skipping component within *running* trials under lunar gravity. This is to say that the preference for skipping on the lunar surface was so strong that it emerged as an individual component within another motor pattern.[5] While these two studies demonstrated that we are making strides in understanding gait under lunar gravity, they also illustrate that these studies have limitations. Specifically, the above studies used six participants. This limited number of participants raises questions about the representativeness of the samples.

A problem

Statistical analysis plays an essential role in our daily lives. The undercurrent of this discipline runs throughout our world, protecting us from unseen harms, guiding our decisions, and allowing us to navigate an uncertain world. A constant probabilistic roulette game is being played every day of our lives, and inferential statistics provides a guidebook for this game. Richard Branson once said, "Space is hard, but it is worth it." This phrase, while endearing and genuine, benefits from a subtle omission. Calculus can be challenging, professional baseball is hard, and competing in the Olympics is demanding, but their difficulty is not accompanied by the genuine possibility of death. The simple act of getting to orbit requires that we accelerate our astronauts to 29.78 kilometres per second,[6] a speed that is exceptionally unforgiving. Even simple health issues in space can become life-threatening in these extreme environments. The probabilistic game of chance in these environments can turn deadly at a frightening pace, and our guidebook for these environments must be subject to the highest rigour.

Inferential statistics generally rely on an appropriate sample size. A sample size large enough to capture how different environments affect individuals with various physical characteristics is vital in understanding how these environments affect everyone exposed to them. Fractional gravity simulations, and subsequent research using these simulations, are typically limited in the number of recruited participants, for a litany of reasons.

Bringing the Moon to Earth

Simulation of the lunar environment is necessary for astronauts to train effectively for lunar exploration. Additionally, research is required to assess long-term habitation and activities of daily life. High-fidelity simulations, such as fractional gravity research, are expensive and dangerous.[7]

Generally, there are three methods of creating a gravity offload simulation. The first is the use of a counterweight system. These systems will allow the individual being tested or trained to experience a simulated amount of fractional gravity while still working within the Earth's gravitational constraint. These offload systems have advanced substantially since the 1960s when offload was often achieved through a pendulum system that mimicked lunar gravity. In recent years, the offload has instead been achieved through computerised robotic lifts, like the Partial Gravity Simulator (POGO) or the Active Response Gravity Offload System (ARGOS).[8] These systems use advanced robotics to mimic gravitational constraints with high fidelity.

A second method of fractional gravity simulation is underwater training in NASA's Neutral Buoyancy Laboratory (NBL), which is often used to simulate total weightlessness or fractional gravity based on the participant's weighting to offset the water's buoyancy. This method involves safety issues in that life support systems must be used during these simulations. Additionally, this method requires a large support staff for safety. Consequently, due to safety and cost issues, this method of reduced gravity training is almost exclusively reserved for astronaut training.

The final method is referred to as parabolic flight. In this case, the simulated gravitational environment is achieved by placing an aircraft into freefall.[9] Essentially, this type of simulation subjects the participant to a high-fidelity simulation of 0g or fractional g based on the plane's dive trajectory. This simulation, however, is limited by the amount of time available. Generally, participants are limited to around 25 seconds of altered gravity per cycle.[9]

All three of these method types are generally high fidelity in that they provide an excellent approximation of the effects of fractional gravity on gait or other activities. However, they have significant drawbacks, reducing the number of participants in any research study. First, access to these facilities is highly controlled. The POGO, ARGOS, and NBL are NASA facilities that are difficult for general researchers to access. Even within NASA, gaining time in these apparatuses is difficult. Secondly, facilities to simulate fractional gravity are extremely expensive; POGO, ARGOS, NBL and parabolic flight cost several thousand dollars per hour. This cost is generally prohibitive for any large-scale research.

Finally, the high-fidelity simulations for fractional gravity carry a more significant risk to participants. This increased level of

Above: Astronauts experience weightlessness in the KC-135 in 1978. Credit: NASA via Picryl.com

risk will generally increase the time needed to secure permission for these facilities and reduce the number of participants available for any study. Additionally, many of the researchers interested in this field of study hail from commercial entities and universities, both of which have limited funding. Further compounding the restricted access to these facilities, much of the simulator time is split between astronaut training and research projects. Due to these issues, simply collecting a larger sample of data is impracticable and will not be a possibility in the near future. These factors will significantly limit the generalisability of the findings of this research.

Computational simulations

Over the past decade, significant advances have been made in simulation software for capturing and analysing biological movement data.[10] Open-source biomechanics software has begun to open up large-scale simulation environments, and one of its biggest advantages is the rapid advances that can be made through a group-based iterative process. This software allows users to capture motion data, feed it into computer environments, and simulate muscle activation and force production at joints and muscles.[10] These retrospective simulations have opened up a variety of assessment techniques for movement.

Further, the open-source movement within research software has allowed for a significant increase in the distribution of the research workload across universities and research entities. This improved distribution makes it easier to compile, cross-reference, and peer-review data across the scientific community. This movement is an excellent asset to scientists.

Most interesting, however, are the latest advances in computational simulation technology: the arrival of predictive algorithms for assessing hypothetical environmental conditions. A leader in this type of software is a program called Simulation and CONtrol Environment (SCONE). This software is based on OpenSim, which allows seamless reciprocal analysis between software platforms.[11]

Simulation and CONtrol Environment (SCONE)

SCONE is open-source software for performing predictive simulations of biological motion. It uses a model of the human, a controller that generates input for model actuators, and an objective that describes the goal task for which you wish to optimise through a weighted combination of measures. In other words, SCONE can be regarded as an optimiser that determines the optimal values for the free parameters in a scenario to meet a specific objective.

This computational software allows researchers to examine hypothetical environments based on specific inputs. In the case of space research, this software can allow for the assessment of gait within lunar gravity while wearing a space suit outfitted with a portable life support system. The simulations work on iteratively predicting how a model will interact with its environment. Positive and negative feedback from the environment is fed into the model, which, over many iterations, will evolve towards a goal state. With gait, the goal state would be efficient forward ambulation. Thus, the software can take the environmental constraints and predict the most efficient motor patterns for forward ambulation.

However, these models can also allow several model parameters to be drawn randomly based on population means and variance through the introduction of random "seeds". This introduces a random element into the simulations, allowing us to model outcomes under natural variations one will encounter in real life.

Additionally, many other parameters can be modified: body height and weight, muscle properties, and neurological variations. Using variation in these model parameters, in addition to random seeds, will allow for variation to emerge within the simulations. These modifications will elicit varying behaviours from the models within the environmental constraints that have been programmed. Considering these computational simulations of a complex adaptive system, slight input changes can produce nonlinear changes; small changes can have significant effects. Thus, through this forward simulation, we can artificially amplify the sample size of the computational study with slightly changing initial conditions. Essentially, every random seed or other parameter alteration would represent unique observations. Thus, a sample size necessary for rigour can be accomplished using these software packages.

SCONE allows for a more representative sample; however, the apparent issue is that these data are computational; they have no actual human data. Essentially, with humans in the loop for testing, we cannot achieve enough participants to establish representativeness, but with computer simulations, we leave the human element out of the equation. At this point, we propose that a combined effort may provide an avenue for experimentation.

A cyborg option

Human testing will always be the gold standard for providing quality data to decision-makers regarding astronaut training and mission activities. However, computer simulations can offer distinct advantages in providing the large sample sizes required for accurate prediction. We propose a hybrid tactic for examining lunar gait, combining the benefits of both approaches. A hypothetical tactic in combining human and simulated data elements would require three distinct stages. During the initial stage, we conduct testing on humans with specific small-sample statistical analysis, concentrating on increasing the power of the samples, for instance, using within-subject designs that eliminate person-to-person differences. Running these simple statistics will provide us with hypothesis-testing data for this smaller group. We should be able, with a degree of confidence, to assess that the results represent the small sample we have taken.

During the second stage, we employ a large-scale computational analysis. At this phase, environmental variables are fed into the analysis, and a large number of random seeds or other unique parameter alterations are run to provide a larger sample size for the computational analysis. Gait, in particular, is a great candidate for predictive simulations due to the mechanistic properties of human gait. Examining the gait as a system of interconnected muscles, bones, and joints allows for specific predictions about how the gait changes over time due to environmental constraints. SCONE data could then be run through standard inferential statistics to answer the pertinent research questions examined during the first phase.

During the final stage of this analysis, comparisons would be made between the human in the loop data, and the computational study. These comparisons would assess any relationships between the two data sets. If the computational data are consistent with the human results, an assumption of representativeness could be made for the computational results. The human data provides us with a degree of ecological validity, while the computational data provides representativeness. Of course, this process needs to be carefully validated. A lack of fit between the human and computational data would indicate questionable validity for this technique. During the initial implementation of such a strategy, a feedback mechanism needs to be developed to allow for technique modification.

Test flight

The three-phase method we propose has shown some initial positive results. Previous studies have identified that, under lunar gravity, skipping is an optimum gait technique.[4,5] During the Apollo missions, skipping spontaneously emerged among astronauts during lunar excursions. We studied SCONE-generated gait patterns under lunar gravity to examine this phenomenon further. Specifically, forward ambulation was simulated with SCONE under lunar gravity. In this initial test run, 100 random seeds were run for the simulation. In those simulations, skipping emerged nearly every time as the optimum gait pattern. This brief examination and initial results demonstrate that SCONE simulations possibly represent an alternative avenue for research on lunar gravity. While these results are initial, they indicate that this method should be examined further.

Stepping into the future

Simulations limit people's exposure to the danger of an actual environment. In the case of aircraft, for example, we create simulators so that neophyte pilots are not killed with every mistake. Simulations also allow for a better understanding of those environments through experimentation. Lunar gait research has an access problem; simulation of the lunar gravitational environment on Earth is expensive, and available facilities are limited, resulting in studies with very low sample sizes. The proposed method could provide a viable alternative for this critical research and essential data for our brave astronauts. Let us help the Artemis explorers understand how to explore the Moon safely, and enjoy its exquisite beauty without stepping too close to the precipice. ■

Disclosure statement

Thomas Geijtenbeek is the author and proprietor of the Hyfydy simulation engine, which was used to generate the motion data for this study.

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