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HOW MEASUREMENTS FROM HYPOGRAVITY LOCOMOTION STUDIES CAN INFORM THE ARCHITECTURAL DESIGN OF PLANETARY HABITATS

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Abstract

How high do we jump on the Moon? Should we build architecture with steps or should we support different ways of moving, e.g. climbing? The reduced gravity will lead to a loss of muscular mass and stiffness of the legs, negatively affecting a person's balance: Yes, we can climb, but we can also easily lose our balance and trip up against the surrounding architecture. To avoid all of this, we need to better understand and address human walking behavior and balance on the Moon and Mars in the design already.

A number of studies already exist on simulation of hypogravity locomotion, but how we can use results from hypogravity simulation studies to inform the architectural design of Moon or Mars habitats?

This paper addresses how measurements from hypogravity locomotion studies can inform the architectural design of planetary habitats. To better understand human walking behavior, one key factor to consider that is addressed here for the first time is the effect of deconditioning and the countermeasures applied to the subject to decrease this deconditioning. Once these factors are under control, the data needed for defining the interior design are kinematic variables of joints or body segments, such as speed, step extent, direction of movement, sight line, variation of altitude, typology of walk, posture, and balance. Finally, the data need to be communicated in an interdisciplinary manner using a common language between the physiological and design fields.

The ideal research methodology is presented here, which investigates how to measure and share variables of gait and body movement in order to apply the results to the design of Moon and Mars architectures.

I. INTRODUCTION

How high do we jump on the Moon? Will we be walking, or rather hopping about? How high should a hallway be, should we build architecture with steps, or should we support different ways of behaving?

Currently, lower ceilings will allow easily launching a module with limited cost and volume that could be built using the current launch technology, but which does not appear to take into account the jump walk art of the Apollo astronauts; so if we were to walk as spontaneously as the astronauts did back then, we would hit our heads on the ceiling!

On the other hand, instead of jumping, we can use the reduced gravity to easily climb; however, the same reduced gravity will lead to deconditioning, resulting in a loss of muscular mass, stiffness of the legs, and vestibular system dysfunction. Finally, all these factors will negatively affect a person's balance: Yes, we can climb, but we may also easily lose our balance and trip up! To avoid all of this, we need to better understand human behavior on the Moon and finally address it in Moon architecture and mission plans.

I. BALANCE

On the Moon, it is very important to avoid tripping by increasing one's balance in order to assure the safety required in these extreme contexts. Balance is a factor that depends on many variables, such as:

- visual field,
- somatosensory system,
- vestibular system.

These variables are all affected by the different environmental constraints of Moon and Mars environments (1, 2, 3, 4).

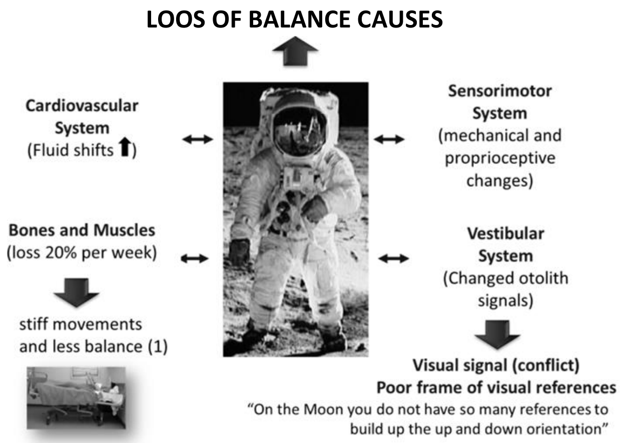

Fig. 1. Factors that influence balance in hypogravity. *(Scema manipulated and implemented by Schlacht with courtesy communication of Prof. Rittweger (Workshop EAC 15.2.2016). Original scema credits: "Effects of Microgravity on the Human Organism" Clément (2005) as used in Seminar Raumfahrtpsychologies of Prof. Manzey, Microgravitation 3, TU-Berlin.)* Central image © NASA.

Motivated by this foreword, in 2009 part of this group of researchers investigated human movements and balance in Moon gravity. The research – conducted using images and videos from NASA's Apollo missions (5) – shows that when we walk on the Moon using one of three modalities – modified walk, hop, side step (6) – the different walking patterns have an impact on the visual field. In particular, the head is tilted more downwards; as a consequence, our eyesight is lowered and we see a narrower visual field. This could, for example, reduce the perception of obstacles and decrease our balance. In other words, while we walk, we cannot see so far, which makes it more difficult to avoid obstacles and increases the possibility of tripping up (7, 8).

Our balance is usually supported by the vestibular system; however, this could be affected by hypogravity just as it happened in microgravity. In particular, in microgravity movement orientation is based only on the visual system.

In the case of the Moon, even the visual system will not help us that much. Indeed, if we consider EVA (extra vehicular activity), the desert of Regolith on the Moon does not have so many references that will allow us to build up our up and down orientation based on our visual field.

Fig. 2. Apollo astronaut tripping © NASA (Image elaboration I.L. Schlacht and T. Umhof)

These are some of the reasons why we can find many videos where the astronaut loses his balance and trips up (9,10).

II. HUMAN FACTORS

To truly understand human walking behavior, we need to take a step back and also thoroughly consider the context and the influence of human factors.

Space radiation, differences in gravity, a rarified or very tenuous atmosphere, extreme temperatures, and isolation characterize the Moon and Mars as extreme work environments. In these environments, the human biorhythm, its sensory perception, and its entire psycho-physiological system are severely challenged. This affects human subjects' perception, deambulation, motion, and general interaction with the environment. To create future Moon and Mars habitats based on "human-centered design", we will have to investigate all the human factors that impact human interaction to try to increase the safety, productivity, and comfort of the astronauts. In this perspective, we are focusing on the investigation of anthropometrical data and interaction movements to address the walking patterns and the interactions of the astronauts inside and outside the habitat.

But which data do we need in order to understand interaction behavior and walking patterns? Which factors influence the body's decision to make a movement in respect to another one?

The walking pattern is a factor that is determined by all the human factors in relation to the system:

- **Physiological factors** (the configuration and the state of the body impact the walk, e.g., weight, muscular mass, stiffness of the legs, age, eyesight, perception of gravity and verticality…)
- **Psychological factors** (the personal approach and the psychological feeling impact the walk, e.g., being tired, afraid, happy, late, ..)
- **Operational and technical factors** (the task that we are approaching impacts the walk, e.g., carrying material, over short distances, over long distances, outside, inside, with extra vehicular suits, without EVA, …).
- **Environmental factors** (the environmental characteristics that influence the walk, e.g., mechanical properties of the soil, partial gravity, temperature, light, bare visual surroundings with no reference, interior habitat crowdedness, gravity, radiation, …)
- **Socio-cultural factors** (your culture in relation to social aspects influence the walk, e.g., you are alone, in a group, on vacation, in a work context, with background music, …)(11).

This means that in order to truly understand walking patterns, we should analyze them during a space mission. To conduct a Moon mission, however, we should have already collected these data, which is why we need to apply different solutions to collect the data, simulating the conditions of a space mission and trying to get as close as possible to the real factors.

III. HYPOGRAVITY AS THE KEY ELEMENT

It is always important to keep a holistic vision of what we are investigating and the final purpose of the application; however, isolating a determining analysis factor could also help to achieve better results. For example, focusing the research on the interaction between walking and the effects of reduced gravity may help to understand a specific aspect. Later this will then need to be validated in relation to the influence of all the other factors (psychological, operational, etc.). Gravity is indeed a highly important aspect. This is also validated by considering that the gravity acceleration *g* is acting on the vestibular system, in particular on the *maculae* of the *utriculus* and *sacculus* inner ear gravity and motion sensors (12). This influence is an unavoidable element of their mathematical functions.

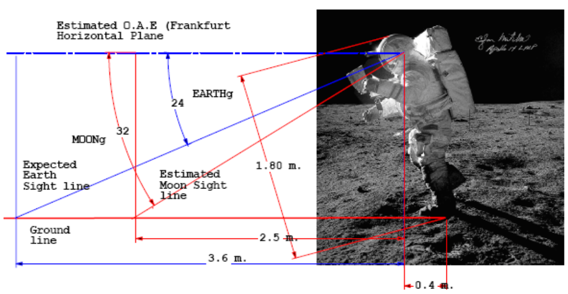

Fig. 3. Interpretation of Moon walking posture and sight-line image. Apollo 14, 1971 © NASA & M. Masali.

IV. DATA NEEDED

Focusing on the somatosensory system, we have analyzed the current bibliography on Apollo missions and on research and experiments regarding Moon and Mars gravity. In particular, we found different relevant experiments that applied instruments applicable in our research, such as a vertical treadmill with weight suspension (13, 14, 15). Usually these experiments addressed, for example, speed, metabolism, or motivation, while no information is reported on step extent, direction of movement, sight line, variation of altitude, typology of walk, and other data needed for architecture design in hypogravity.

Moreover, no experiments have been conducted that considered physical deconditioning, hypogravity, and countermeasures such as artificial gravity. For example, one excellent experiment conducted after Mars 500 investigated maximum jump height, but without simulating hypogravity and without a control group or a significant number of subjects (16).

Even during the Apollo missions, there was not enough time to address this factor as they were short-duration missions. Moreover, mainly only four subjects were investigated: two from Apollo 15 and two from Apollo 16 (17,18).

In conclusion, detailed biomechanical data and correlated studies on balance are missing. There are no experiments

- after deconditioning and countermeasures to prevent deconditioning
- in combination with a collection of anthropometrical and behavioral data from a relevant number of subjects.

This could result in two risks: a low level of safety and an incompatible habitat design. The solution is to carry out a dedicated analysis that addresses:

- Deconditioning (e.g. with bedrest)
- Deconditioning countermeasures (e.g. with artificial gravity: AG)
- Control group (e.g. without AG)
- Hypogravity (e.g. using a vertical treadmill)
- Collection of data to define the interaction with the architectural environment
- Communication of data using an interdisciplinary language

V. THE IDEAL METHODOLOGY

An ideal methodology for obtaining data for architectural design will be to use bedrest, AG, and a vertical treadmill, with a statistically significant number of subjects and a control group.

Subjects who will undergo three different conditions should be compared (parallel-group design): sixty days of -6° head down tilt (HDT) bedrest only (Ctrl), 60-day HDT with continuous AG, and the same with intermittent AG. The data collected will be anthropometrical and biomechanical data during walking and running in simulated hypogravity using a vertical treadmill.

Fig. 4. Frame from a preliminary test video of the vertical treadmill with I. L. Schlacht as subject (© I.L. Schlacht, and K. Yilmaz, 2016)

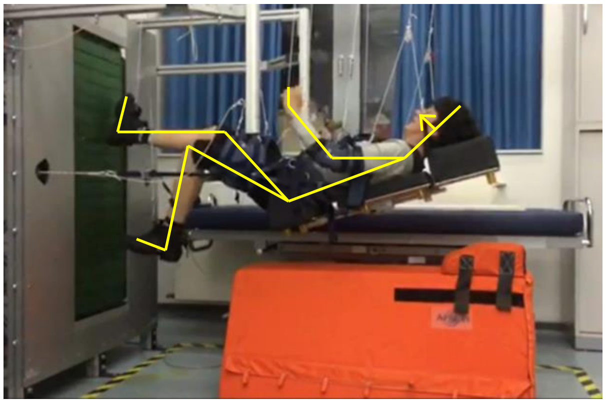

Fig. 5. Example of video analysis with I. L. Schlacht as subject (© I.L. Schlacht, and K. Yilmaz, 2016)

The vertical treadmill is a special instrument developed at DLR to simulate hypogravity in a subject while the subject is running. On the vertical treadmill, the subjects will be suspended by a belt system to simulate different degrees of hypogravity. An accelerometer (tested also in hypogravity ([19], [20])) will measure speed, step extent, direction of movement, variation of altitude, typology of walk, and balance.

The recording of video data will support research into the line of sight to derive the direction of the vestibular plane. The data will be collected three times: at the baseline, a few days after 60 days of bedrest, and after recovery. After the subjects have warmed up by running an initial seven minutes, the following videos could be collected in random order, apart from task 1 for warming up:

Table 1. Tasks for ideal data collecting

Task	Km/h	Gravity	Weight	Treadmill	Goal
1)	4	Earth	1/1	inclined	Warm-up
2)	2.5	Moon	1/6	inclined	Data
3)	2.5	Mars	1/3	inclined	Data
4)	2.5	Hypog.	1/2	inclined	Compare
5)	2.5	Earth	1/1	inclined	Compare
6)	2.5	Earth	1/1	normal	Control

Having applied this methodology, we will have data from the accelerometer that could be simply compared between Moon and Earth gravity and with the control group.

We will also have video data that need to be analyzed to identify data that cannot be registered by the accelerometer, such as changes in altitude, posture, sight line, or walk typology. Finally, all the subjects together could discuss the walking patterns and the recorded data in a debriefing, which will produce qualitative data for the improvement of the definition of hypogravity walking patterns.

The video data need to be collected while the subject is directly parallel to the camera without applying any foreshortening position. The camera should always be at the same distance and position (at least 3 meters from the subject; optimal distance would be 11 meters, but the most important factor is that the distance is kept the same in every test) and positioned such that the subject is right in the middle in the video.

The km and the type of gravity should be pronounced and recorded clearly. The subject should wear markers on key joints and body points, such as

- shoulders,
- elbows,
- wrists,
- hips,
- knees,
- ankles,
- face: Frankfurt plane

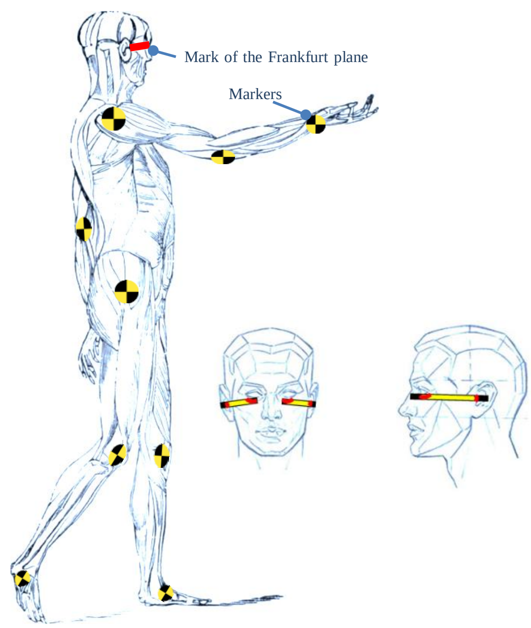

Fig. 6 Draft plan for body markers and mark of Frankfurt plane (background human: (21), computer manipulated by I.L. Schlacht).

If the videos are collected without markers, they can be processed afterwards with special video analysis software, such as Kinovea and iPi Recorder. Based on the tracked joint and body points, a simple human behavior model can be presented visually.

The final results need to be visualized in a way that is easy to understand by both experts in the field and non-experts, and the description must be coherent with current bibliography (22, 23).

Fig. 7 Example of result visualization (Image computer manipulated by I.L. Schlacht)

VI. DATA FOR ASSESSING INTERACTION

Coming back to our goal of measuring the impact of gravity on the motoric behavior of interaction with the environment, we know now that key factors to consider are the effect of deconditioning as a result of hypogravity, the countermeasures applied to the subject to address this deconditioning, and finally the simulation of hypogravity. But having achieved this ideally with our "Ideal Methodology", what do we need to measure?

First of all, we will need to measure anthropometric and motion (considering also angular values) elements of gait. Here, the key variables are:

- speed,
- step extent,
- direction of movement,
- amplitude of movement,
- sight line,
- variation of altitude,
- typology of walk,
- posture,
- balance.

These parameters form the basis of the architectural design. However, other data may also be of interest: for example, gait smoothness may also be an important parameter, as well as endurance (apart from speed) and the ability to react to rapid changes (which will probably reduce the risk of falls).

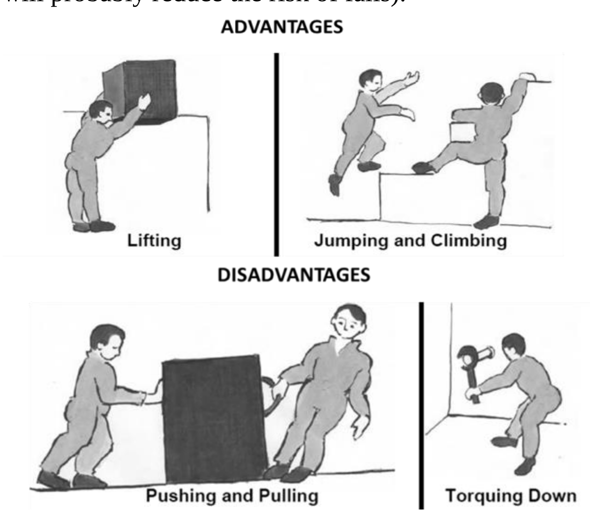

Fig. 8 Advantages and disadvantages in Moon gravity (c) SICSA

Moreover, to define the interaction with the architectural environment, it is very important to measure not only the gait, but also the variables of gait and balance as well as other motoric behavior, with priority on determining the speed, force, extension, and amplitude of movements that are influenced by hypogravity, including advantages such as:

- Lifting
- Jumping and climbing

or disadvantages such as:

- Pushing and pulling
- Torquing

After this has been achieved, it will also be important to study the dimension of fine movements from an anthropometrical perspective, such as work desk interaction movements: e.g., sitting posture, pressure on keyboard, stability of objects on desk, pouring of liquids, in order to learn about the effects on everyday needs like drinking a coffee cup on the Moon.

CONCLUSION

The ideal research methodology presented here investigates how to measure kinematic variables of joints or body segments that impact an astronaut's balance and gait structure in order to apply the results to the design of Moon and Mars architectures.

A very important element of this research is to support communication between physiological research and design. Indeed, one great shortcoming of a lot of studies is that the data collected are not understandable to people outside the field and are not applicable in other fields. In our case, the results will be visualized, which supports easy communication and interdisciplinary application. Hopefully we will be able to develop habitats on the Moon with the right ceiling measurements to prevent hitting our heads on it while making kangaroo jumps.

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SUGGESTED READINGS

On line on www.extreme-design.eu

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