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Water Immersion Ballasted Partial Gravity for Lunar and Martian EVA Simulation

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ABSTRACT

The University of Maryland Space Systems Laboratory is developing the capability to simulate partial gravity levels for human operational activities through the use of ballast on body segments in the underwater environment. This capability will be important as NASA prepares to return to the Moon by the end of the next decade. The paper discusses various forms of partial gravity simulation used in the past, and derives a targeted set of applications for ballasted underwater simulations. Primary application of this technique is for static or quasistatic activities, such as collecting basic anthropometric data on reach envelopes or postural control, as well as accumulating an experience base on partial gravity habitat and vehicle design and operations.

INTRODUCTION

As work begins on hardware for the next human exploration of the Moon, it would be useful to have a database on human reactions to partial gravity. This includes data such as how far someone can bend over to pick up objects, or the required size of interior passageways. The only way to collect this data before flight is through simulation. Several methods have been used in the past to simulate working on the Moon, such as parabolic flight, counterweight systems, water immersion, and 1G testing. Each method has its own set of advantages and liabilities.

Parabolic flight creates true partial gravity; it is not technically a simulation. Any gravity level between 0 and 1G can be created for a short period of time. Parabolic flight is however, not without its drawbacks. Each test last only approximately 30 seconds, followed by a 2 g pullout. This prevents testing of long tasks in a continuous manner. Accuracy of the gravity level achieved is a function of pilot skill and atmospheric conditions. Parabolic flights are extremely expensive, on the order of several thousand dollars per flight hour, and test equipment is severely restricted in size and mass due to the limitations of the host aircraft. [1]

Counterweight systems solve many of the problems inherent to parabolic flight, but substitute a new set of problems. Most counterweight systems only offset the gross weight of the test subject, not each body segment individually. This means the limb motion is generally unrealistic for the desired gravitational environment. Complex systems must be designed to keep the suspension point directly above the subject, which generally limits this method to interior simulations where a gantry or other structure supports the counterweight system. A further problem involves rotational freedom: a gimbaled harness must be designed to allow the subject to bend and rotate if those motions are to be included in the simulation. This involves meticulously placing the pivot axis exactly through the subject's center of mass, which is possible only for a single fixed pose. [1]

Water immersion uses the buoyancy of water to offset the force of gravity. The human body is close to neutrally buoyant underwater, so adding ballast can simulate any gravity level. This ballast can be distributed on each body section weighting the body proportionally. Since the ballast is placed on the subject there is no rotational constraint. The subject is free to move in all 6 degrees of freedom. Water immersion does have its drawbacks as well. The most obvious drawback is water drag. This lends water immersion most to static or quasi-static tests. Another problem is the increased mass of the test subject/ballast combination. This puts increased inertial loads on the subject. Safety is another concern due to the underwater environment. The use of safety divers and redundant air sources serves to keep the risks at an acceptable and manageable level. [1]

1G testing ignores partial gravity entirely. Testing is done with mockup hardware and other assistance to the subject. This testing is useful for procedural testing. It allows the crew to walkthrough the entire task at their own pace. This method was used for crew training during the Apollo program. [1]

For simulating partial gravity the Space System Laboratory (SSL) has chosen water immersion. This is due in large part to the fact that the SSL is based at the Neutral Buoyancy Research Facility (NBRF). The NBRF is a 7.7 meters (25 foot) deep, 15.2 meters (50 foot) diameter water tank built specifically for space research.

This unique facility makes water immersion testing the simplest choice at the SSL.

The system developed consists of a full-body harness that is outfitted with four pockets to distribute the ballast. During test runs the subject and two safety divers descend on SCUBA to the bottom of the tank. It is at this point that the subject removes their SCUBA unit and fins; the ballast is added at this point as well. The subject is able to remove their SCUBA unit because they are attached to a hookah rig. This consists of an extra long hose attached to a SCUBA cylinder that can be seen in figure 1. This allows the subject mobility without the encumbrance of SCUBA gear. Data collection begins upon completion of safety procedures and ballasting. At the end of the test the process is reversed. The ballast is removed, the subject replaces their fins and SCUBA unit and the team returns to the surface for debriefing.

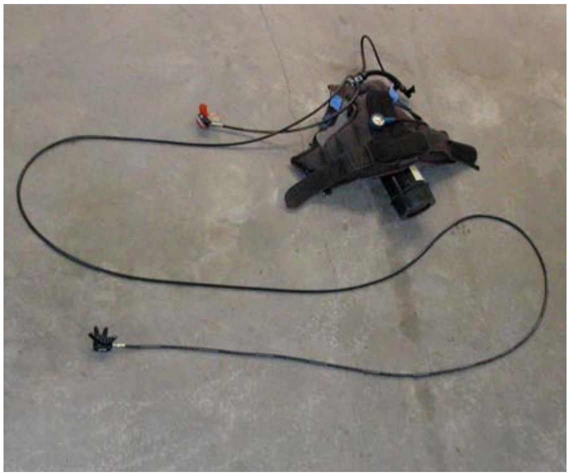

Figure1: Hookah rig

BODY SEGMENT PARAMETERS

The ballast on the subject is distributed so that each body section has an apparent weight close to what it would be in true partial gravity. This is one of the advantages that water immersion systems can have over counterweight systems. With the ballast distributed, the subject's center of gravity (CG) is maintained in the proper location. This allows the subject to bend and lift in a manner closely resembling true partial gravity. The ideal system would place a thin layer of ballast across the entire body to exactly replicate the true mass distribution. This is however not very practical. As a close approximation, ballast is placed at the CG of body segments such as the torso or upper legs. The more segments used, the more accurate the simulation. Accuracy must be balanced against safety and practicality concerns. The mass each segment contributes to the total and the locations of the segment CG vary from person to person. Models have been made to approximate these values for the general population. [2]

Body Segment	Percent of Body Mass	Lunar Mass (kg)	Martian Mass (kg)
Head/Neck	6.94	0.97	2.19
Trunk	43.46	6.08	13.69
Upper Arm	2.71	0.38	0.85
Forearm	1.62	0.23	0.51
Hand	0.61	0.09	0.19
Thigh	14.16	1.98	4.46
Shank	4.33	0.61	1.36
Foot	1.37	0.19	0.43

Table 1: Body segment parameters for 84kg man [2]

As can be seen in table 1 above, most body segments are a small percentage of the total body mass. These can be excluded and still yield a reasonably accurate simulation. For the system designed only two body segments were used, the thigh and the torso. All of the other masses were distributed proportionally between these two segments. This configuration was chosen for a number of reasons including safety, practicality, and mobility. From a practical standpoint it would be next to impossible to design a harness that placed mass at each of the points listed in table 1 and held it securely. Locations like the hands and feet must be kept free so that the subject can manipulate equipment and walk. Placing ballast at these locations would be difficult and would most likely impair the simulation. From a safety standpoint the ballast must be easily jettisoned in case of emergency. The more locations ballast is placed, the longer it would take to rescue the subject. An example of the ballast distribution chosen can be seen in table 2.

Body Segment	Percent of Body Mass	Lunar Mass (kg)	Martian Mass (kg)
Torso	75	10.5	23.63
Thigh	25	3.5	7.88

Table 2: Ballast needed for 84kg man using SSL harness

BALLAST SYSTEM DESIGN

Test subjects are completely submerged during testing, thus safety becomes a driving factor in the design of the ballast system. In the event of an incident during a test the ballast must be removed as quickly as possible to aid in the extraction of the subject. In addition, during nominal operations the ballast must be held firmly to the subject so that tasks can be carried out in a manner as close to natural as possible. In order to meet these criteria two base platforms were investigated: a harness and a full-body jumpsuit.

PLATFORM SELECTION

Jumpsuit

A jumpsuit was considered early in the design process due to its ability to hold weight easily without shifting. Pockets sewn onto a jumpsuit would not move in relation to the body provided that the jumpsuit fit well. Ultimately the jumpsuit was discarded in favor of the harness due to adjustability concerns. It would be impractical to design a jumpsuit that would fit tight enough on a wide range of subjects.

Harness

The harness design was chosen because it satisfied the adjustability concern mentioned. The harness would have to be a full-body style to allow ballast to be placed on the torso as well as the legs. The harness designed has ballast attached in four locations: chest, back, and both thighs. It is designed to securely hold the ballast to the subject and contains a crane attachment point for emergency extraction.

The harness, shown in figure 2, is constructed from webbing similar to that used in skydiving harnesses. The harness was designed to be modular. All of the straps in the upper harness can be separated and replaced individually. The lower harness was sewn in a manner similar to that of a rock climbing harness. This was done to achieve a robust design. Attached to the lower harness is the crane attachment point. This point would be used in a worst-case scenario to extract the subject from the water. Modularity is important for two main reasons. First, it allows the harness to be modified to fit future subjects. Secondly, modularity allows upgrades to the harness to be made to meet future experimental demands.

The harness is adjustable in a large number of ways. All of the adjustments are made using quick adjustable fittings. These allow the harness to be quickly adjusted as needed during the test. The lower harness is adjustable around each leg and at the waist. The upper harness has two shoulder straps that are adjustable to raise and lower the ballast on the torso. There is also a chest strap that runs directly behind the ballast to keep it securely in place.

Figure 2: Partial Gravity Harness System

BALLAST ATTACHMENT DESIGN

Along with the harness, a system for attaching the ballast had to be devised. The key was to design a system that was secure while at the same time allowing the ballast to be attached and removed quickly and easily. Two concepts were designed and tested: a hard plate system and a soft pocket system.

Hard Plate Release

The first system to be developed was the hard plate design shown in figure 3. It was thought that the hard plate system would prevent movement of the ballast during tests. The system consisted of an aluminum plate with a tab on one end and a through hole on the other. To this plate ballast was attached using bolts. The plate was then attached to the harness by inserting the tab into a slot on the harness and a clevis pin was inserted in the hole. A hitch pin was used to secure the clevis pin. When the hitch pin was pulled gravity would pull the plate off of the clevis pin and the plate would fall.

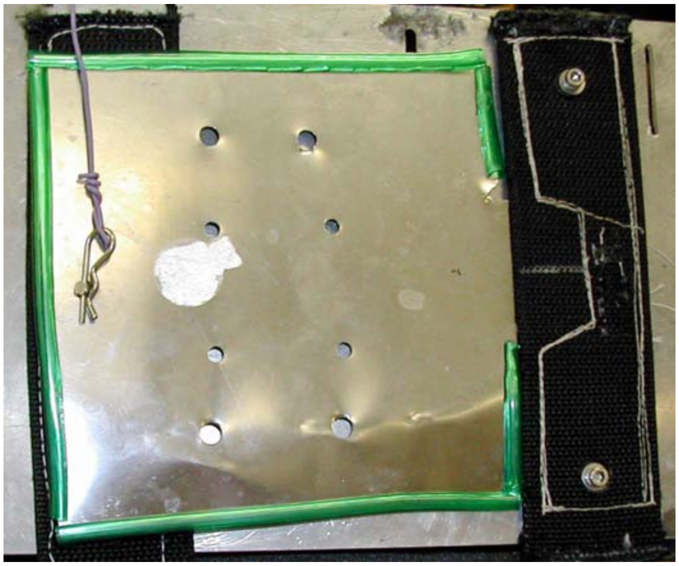

Figure 3: Hard Plate Demonstrator – Pin release located on the left side. Tab and slot located on right side.

A subscale demonstrator was built to test that the plate would not hit the subject during release. This was important as hard weights were being used. The demonstrator showed no problems and the plates seemed easy to install and release. With this positive result the plate system was installed on the full harness and was tested with a human subject. During the test the subject was wearing an AGA Full Face Mask (FFM) as did one of the safety divers. This facilitated constant communication on the progress of the test.

This test revealed numerous problems. Modifying the plate design could have solved several of the problems. Two problems that could have been solved through modifications were that the tab fit too snugly into the slot and that the plates scratched the divers. The divers were scratched in spite of the fact that there was tubing placed around the edges except on the tab. To solve these problems the tab and slot tolerances would need to be loosened and better protection installed on the plates. However two problems not uncovered by the demonstrator caused the plates to be discarded entirely. The first problem involved the fact that the plates were flat to accommodate the ballast while the areas of the body they were being attached to were curved and changed as the subject moved. The movement sometimes caused the tab to fall from the slot. This required the safety diver to assist in adjustment. This would be extremely disruptive while trying to conduct an end-to-end task. The second problem was flexibility in switching between subjects. The harness was designed so that it could fit a range of subjects. The plate design on the other hand required drilling new holes to attach different weights. This was deemed prohibitively time consuming.

Soft Pocket Release

After testing the hard plate system and declaring it unsuitable, the soft pocket system was implemented. The pockets offered a few notable advantages over the plate system. First any amount of ballast can be added that will fit in the pocket and the amount can be adjusted quickly. Next the ballast used comes in lead shot bags. This means that if the ballast hits the subject during jettison there is a low risk of injury.

The pockets were designed to have a Velcro® flap on top to allow for ballast to be added or removed without disturbing the release mechanism. The release mechanism is designed such that the ballast pushes the bottom of the pocket out of the way. Two types of releases were designed for the pockets: Velcro® and ripcord. The Velcro® release consists of a flap on the front of the pocket with Velcro and a D-ring handle. The flap attaches to the bottom panel of the pocket with Velcro® securing it in place. When the D-ring is pulled up the Velcro® separates leaving nothing holding up the bottom of the pocket. The ballast then pushes the bottom of the pocket out of the way due to gravity as illustrated by figure 4.

Figure 4: Thigh Ballast Pocket with Shot Bag – Flap has been pulled and Shot Bag is sliding out.

The ripcord release replaces the Velcro with a hinge style design. The bottom flap and front flap would be joined like two sides of a hinge. The pin in the hinge would have a handle, when this handle was pulled the hinge would come apart and the ballast would be released. This design was not constructed because the Velcro pockets worked up to expectations and a replacement was not needed

PROCEDURES DEVELOPMENT

Designing safe hardware is only half of the battle; the other half is developing procedures to cover all foreseeable contingencies. As in any system, developing these procedures starts with analyzing the possible failures that can occur.

EMERGENCY PROCEDURES

The most obvious failure when operating in an underwater environment is loss of breathing gas. In this emergency, the first priority is to restore air to the subject. This can be done by utilizing a 3.0-ft^3 tank attached to the harness or the safety diver's secondary regulator. Once the situation is stabilized, the ballast is removed and the subject assisted to the surface by the safety divers. With a breathing gas failure, once air is restored the extraction can proceed at a normal pace. If for any reason the ballast could not be separated from the subject and there were no other problems the subject could climb out of the tank using the installed ladder as seen in figure 5.

Figure 5: Demonstration of Ladder Extraction

If the subject was unable to assist in their extraction and the safety divers were able to remove the ballast then the subject could be extracted by the safety divers, which is shown in figure 6. The subject is still extractable even in the worst-case scenario of stuck ballast and subject incapacitation. In this case the subject would be hooked to the overhead crane by the harness lift point and extracted by crane as shown in figure 7. The subject is not swum out due to amount of ballast worn. Swimming a fully ballasted subject has been shown to be extremely difficult during testing.

Figure 6: Demonstration of Swimming Extraction

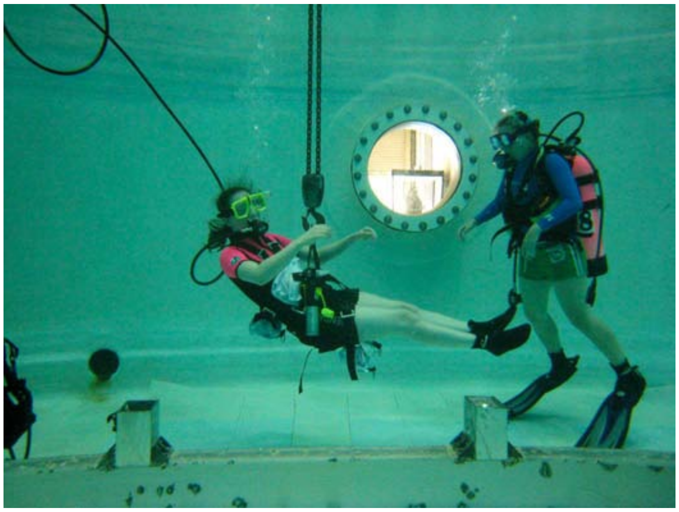

Figure 7: Demonstration of Crane Extraction

Before declaring the partial gravity system operational the emergency procedures must be extensively tested. This testing will ensure that all of the systems work as designed and that all of the procedures are feasible. Once this testing is completed safety divers will be selected and trained. Training will include an orientation to the hardware as well as all of the procedures. Subjects will be required to demonstrate that they can bailout to both the onboard safety bottle as well as the safety diver air supply.

PLANNED EXPERIMENTS

As mentioned due to drag, water immersion testing lends itself to tests, which are static or quasi-static such as posture or stability. Static studies can help discover important information for space suit and facility design. Basic information such as the angle of a ramp or the size of a step that is well quantified on Earth is likely to change on the Moon or Mars. With NASA's desire to explore these locations for long periods sub-optimal designs could lead to loss of productivity, irritation to the crew, and possible safety issues.

The first test that is planned for the partial gravity system is a ramp stability study. During this study the subjects will stand on a ramp placed at different angles to determine the steepest useful ramp. The subject will be asked to stand on the ramp facing in different directions to determine how stable they are. The subjects will also pick up objects while on the ramp to simulate sample collection on a slope. The ramp will allow the study of handrails. At what ramp angle do they become necessary? What is the optimal height for the rail? Should the ramp be narrow enough to grab both rails or is one sufficient?

Space suit design parameters will also be studied. What is the best location for the CG of the space suit backpack? What overall backpack mass is acceptable? In the future a backpack will be designed that allows for mass to be added and its location adjusted. With the backpack in place the ramp experiment will be repeated. The data will be compared to determine the effect the backpack has on stability.

Other ideas for future experiments include hatch design. How big of a hatch is needed in partial gravity? What is the optimum size and shape of a suitport for donning/doffing a space suit?

FUTURE WORK

Once the system is operational and initial experiments are completed, lessons learned from this system can be applied to more ambitious systems. While certain experiments on space suit design can be conducted with the current system the dynamics of a pressure suit are not simulated. The SSL is also developing a project known as the MX-2 shown in figure 8. This is a low cost space suit simulator. Currently the MX-2 focuses on simulating microgravity operations. These two projects could be combined to work on simulating planetary suits. This would allow research to be done on the mobility required to perform planetary exploration tasks.

Figure 8: MX-2

The SSL also conducts research in dexterous and planetary robotics. In the future collaborative studies could be conducted to study humans and robots working together. What types of robots are best suited for assisting astronauts in planetary exploration? What tasks are best done by humans, robots, or human-robot teams?

CONCLUSION

As humans return to the Moon and move on to Mars intelligent decisions need to be made when designing the hardware and infrastructure. The best way these decisions can be made is with supporting research. Simulations such as the water immersion system outlined are one way to conduct this research. The sooner this research is started the better prepared we will be to design exploration hardware when the time comes.

ACKNOWLEDGMENTS

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REFERENCES

1. Braden, Jeffrey R., Akin, David L., "Ballasted Underwater Simulation for Partial Gravity Operations", *Workshop on Analog Sites and Facilities for the Human Exploration of the Moon and Mars*, Colorado School of Mines, 2003.
2. De Leva, Paolo, "Adjustment to Zatsiorsky-Seluyanov's Segment Inertia Parameters", *Journal of Biomechanics*, Vol. 29, No. 9, Pgs. 1223-1230, Elsevies Science, Great Britain, 1996.
3. Newman, D.J., Alexander, H.L. and B.W. Webbon, "Energetics and Mechanics for Partial Gravity Locomotion", *Aviation, Space, and Environmental Medicine*, 65: 815-823, 1994.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

Bailout: To transfer from a primary air source to a secondary source

CG: Center of Gravity

FFM: Full Face Mask

NBRF: Neutral Buoyancy Research Facility

SCUBA: Self Contained Underwater Breathing Apparatus

SSL: Space Systems Laboratory

Suitport: A hatch to enter a rear entry space suit attached to the outside of a habitat or rover