Experimental Investigation of Vertical Translation Design Commonality Across Differing Gravitation Levels

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Current knowledge of human habitation in partial-gravity is limited to six brief sorties to the lunar surface. As interest in human exploration and longer-term habitation of the Moon and Mars increases, methods must be created to better understand how to design a living environment for humans in differing gravity levels. This paper presents the results of recent studies at the University of Maryland on human accessibility between different floors of a habitat in various gravity levels, based on the use of body segment parameter ballasting in the underwater environment to represent the gravitational force on each body segment in ascending and descending ladders and staircases. This has culminated in the development of a dedicated test apparatus which allows full reconfiguration of the angle and tread spacing on staircases, and can be used both underwater and in the laboratory environment. Test subjects ascend and descend the ladder at various gravity conditions to determine the effect of differing apparent gravity levels, with data collected on both performance and gaits as measured by motion capture systems. Extensions to this work are proposed that focus on part-task simulations such as servicing and repair of equipment racks, and focused studies on the habitat design implications of rotating habitats for artificial gravity.

Nomenclature

$6DOF$	=	six degrees of freedom
$C-H$	=	Cooper-Harper
CTB	=	Cargo Transfer Bag
GCS	=	global coordinate system
LCS	=	local coordinate system
NB	=	neutral buoyancy
TLX	=	NASA Task Load Index

I. Introduction

At this point in time, we have accumulated hundreds of thousands of hours of experience in microgravity habitation spread across Skylab, International Space Station, and seven different Russian stations, all in low Earth orbit. In comparison, we have less than two weeks of experience in living on the moon, with the longest single duration limited to 72 hours. This experience was achieved in a minimally-sized spacecraft optimized for minimum mass, and certainly not for habitation issues.

At the same time, we are looking ahead to long-term settlements on the moon, and ultimately on the surface of Mars. Crews traveling to and from Mars will spend roughly nine months in transit, and more than a year on the surface. Lunar crews will only have a few days of transit time, but could stay on the surface for a year or more to minimize the cost of crew rotation. In all of these cases, we will need to focus much more on habitation, particularly in the various gravity environments of the moon (0.16 Earth "g") and Mars (0.38 g), despite having almost no relevant experience to date.

For a number of years, various analog sites and simulations have focused on lunar and Mars exploration scenarios[1], including long-duration habitat living with realistic external communication time delays.[2] While each of these efforts have contributed to basic understanding of habitation design in simulated planetary surface exploration, all of them have been performed, by necessity, in Earth gravity conditions. Laboratory based simulations of partial gravity, such as weight offset systems, are limited in scope and generally restricted to only short-term EVA simulations. Underwater simulations of lunar or Mars gravity in terms of extended habitation (such as the NASA NEEMO missions) are likewise limited to EVA simulations, and have been generally performed with single-point ballasting of the test subjects rather than spreading the ballast appropriately across all major body segments.

The University of Maryland (UMd) Space Systems Laboratory (SSL) has focused on trying to obtain data on everyday internal activities inside space habitats using body parameter ballasting[3] in the underwater environment. Performing the tests in the UMd Neutral Buoyancy Research Facility (NBRF) provides a more controlled environment than the ocean location of NEEMO, and allows the use of the SSL 16-camera Qualisys motion capture system for underwater data collection on motions, gaits, positions, and velocities. As will be described in more detail in the following sections, the focus of this set of tests is on vertical access between multideck habitats, and on performance of maintenance tasks on a single rack unit.

II. Background/Rationale

With recent attention to long-term lunar and Mars human exploration, as well as habitats beyond low Earth orbit such as the Deep Space Gateway*, there is significant renewed interest in extended habitation in space. Much of the conceptualization of these new habitats also revolves around the availability of the Space Launch System for transport, resulting in 8-10 meter diameter concepts. Alternately, with the success of the Bigelow Extended Activity Module (BEAM) on International Space Station, there are also a number of inflatable concepts, also driving to larger diameters than the current standard 5-meter payload fairings.

A critical factor in habitat design is the ratio of habitable volume (i.e., the volume that the human crew can easily move through and use for everyday operations) to total pressurized volume. Analytical studies have shown that the use of multiple levels ("floors", "decks", or equivalent) are essential to take advantage of the large pressurized volume within habitats of larger diameters.[4] While Skylab used a (generally) vertical orientation for its internal layout, access between levels was simple in microgravity. All other experiences in space habitats have been (generally) horizontal orientations, which minimizes access between vertical levels, and is still simplified by microgravity.

In general, the overall desire of this research was to use underwater simulation with appropriate ballasting to provide an analogue environment to study habitat design as a function of gravity levels. The underwater test environment provides a number of advantages, including no limitations on the number of objects in the test, no restrictions on trajectories, particularly vertical transits which would be difficult in suspension systems or air-bearing facilities, and the ability to involve any number of human test subjects. At the same time, it was clear that the use of underwater testing would not allow integrated mission testing – the "day(s) in the life" sort of simulation provided in most Earth analogue tests. Instead, the effects of water immersion, along with the accompanying hydrodynamic forces, drives the simulation designer towards part-task simulations which can be bounded in both volume and time in ways more appropriate to the test environment.

Given the prior study cited leading to the adoption of multi-level habitats in the future, one of the obvious tasks in future habitats will be routine access between decks, both directly for crew and while transporting cargo. An earlier study[5] looked at this task using available hardware (a commercial extension ladder) and assessed crew mobility at stairway angles of 35^o (Figure 1), 57^o (Figure 2), 67^o, and 90^o (vertical) at microgravity, lunar, and Mars gravity levels with and without the manual transport of an appropriately-ballasted cargo transfer bag (CTB). These tests resulted in interesting observations, including the realization that the 35^o case in lunar and Mars gravity is much more similar to motion up and down a ramp under Earth gravity, and that all microgravity motion is dependent entirely on the subject's arms and hands regardless of slope. Several limitations of this impromptu test scenario also became apparent, including the fixed rung size and spacing of the ladder, and the lack of handrails to prevent the test subject from falling in the event of a lateral loss of balance.

To address these shortcomings and continue the previous research, this effort started with the design of a variable-configuration stairway which allows full control of all of the primary experiment parameters. It was designed to allow variable angles of stairway between 30^o and 90^o, with treads of variable pitch and angle as can be seen in Figure 4. Tread depth and even tread visibility factor in to the performance and safety of the task. The test apparatus was designed to be wide enough (0.75m) to allow the study of two subjects passing, and incorporated variable-position handrails for safety and increased fidelity. Figure 3 shows the design of the variable-geometry staircase. This unit was designed to be mounted to a vertical ladder permanently attached to the side of the UMd neutral buoyancy tank. In reviewing options, it was decided that it would be best to design a fixed platform to be installed a constant 3m (10ft) above the bottom of the tank, so that all test ascents and descents would be over the same height change appropriate for two adjacent decks of a multi-deck habitat.

*or perhaps "Lunar Orbital Platform-Gateway", depending on the official title this week

Fig. 1 Descending a 35° stairway in Mars gravity[5]

Fig. 2 Ascending a 57° stairway in Mars gravity carrying a cargo transfer bag (CTB)[5]

A straight stair geometry was chosen over that of a U-Shape or L-Shape staircase due to complexity of the two when trying to integrate into the current attachment points. The other two configurations utilize landings that may be useful for space savings in a habitat design. However, it is reasonable to assume that since all three configurations typically consist of rectangular treads at even spacings, that a common preference in tread spacing/size/orientation are consistent across all three options. Another common geometry for staircase is the spiral staircase. A spiral staircase may be the most space efficient, but lacks the capability to easily transfer large objects such as a triple-CTB or M03 bag. The goal is to develop the most space efficient traversal configuration that enables a subject to carry a CTB, or a pair of subjects carry an M03 bag, while appropriately loaded to the relevant gravity conditions.

Fig. 3 CAD image of variable-geometry staircase test device

Fig. 4 Closeup of the CAD of the adjustable stair treads

III. Test Setup

A. Variable-Geometry Staircase Test Rig

Design requirements for the variable staircase were based around safety and efficient use of limited test time; in particular, given the overhead on conducting underwater testing in terms of required crew size and reasonable dive durations, it was deemed critical to design a system with quick reconfigurability between test configurations. The primary options were either rapid reconfiguration of the test hardware for changing the testing parameters, or having multiple test subjects ready to run through a specific test condition one after the other prior to resetting the hardware for the next data point. The decision was made to choose the first option, focusing on one test subject per dive and rapid hardware reconfiguration, thus reducing the number of divers in the water and ensuring that all divers stay active throughout the test operations.

A variable-geometry staircase and platform combination was designed, with a strong focus on the safety of test subjects, as well as on easy and rapid reconfiguration. The hardware was created utilizing a combination of engineering prototyping extrusions and hardware from the 80/20 Corporation. Two six-meter (20 ft) 1530 extrusions were used to make the staircase's hypotenuse for stiffness and strength, and 3034-Lite profile extrusion was used to make the 90-cm wide steps. Custom brackets were designed and milled to allow the step extrusions to be permanently secured on a pivot, and a second screw moved through holes at 10^o angles to provide a range of specific tread angles from 0^o to 90^o at 10^o increments. The angle adjustment screw on each side has a large thumbwheel installed to allow convenient removal and replacement without tools underwater.

After the preliminary round of testing, rigid fiberglass panels 30cm $\times$ 90cm were attached to each step to provide a larger tread for the test subject. These panels are removed when testing at 90^o, as the "treads" transition to ladder rungs for the vertical case.Two handrails were also added for safety concerns to allow test subjects an additional gripping point in case of real or perceived need. The six meter long staircase assembly is capable of testing angles varying between 30^o and 90^o when attached to a platform three meters above the "ground". The 10^o discrete angles on the steps constrain the apparatus to seven possible test angles, which was decided to be an adequate degree of resolution for these tests. Figure 5 shows the baseline variable-geometry staircase set up in a laboratory highbay; Figure 6 shows the original form of the apparatus (prior to the installation of wider tread surfaces with anti-slip tape) in the underwater environment.

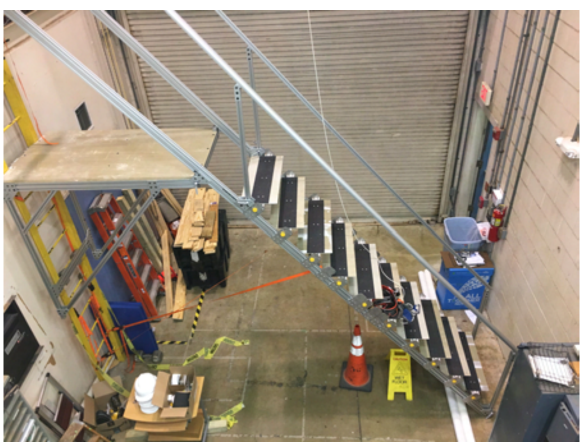

Fig. 5 Laboratory baseline setup with modified treads on staircase

Fig. 6 Original staircase set-up underwater

B. Data Collection

Test subject selection is based on University regulations for diver approval. Each test subject has diving certification and previous experience diving in the Neutral Buoyancy Research Facility. Each subject also has specialized training to enable use of a full face mask and microphone unit to allow for communication between the subject and surface crew.

The goal for testing is to collect data which will unequivocally identify the effect of staircase geometry (specifically, rise angle, step spacing, and tread depth) on test subjects' ability to successfully maneuver up and down the staircase under different gravitation conditions and with different cargo loads. Since the inter-deck height is fixed at three meters, transit time is the simplest possible metric for performance. Notation of errors (e.g., slipping off of or missing a step, loss of balance, stopping to regrasp a payload or steadying against a handrail) are performance anomalies which are of equal importance to transit time. For both of these data categories, raw data is collected in the form of video recording. The nominal recording setup is to position one camera looking down the staircase at a high enough altitude to clearly image the subject's legs and feet, as well as their overall body. A second camera is set up orthogonal to the staircase providing a full side view, which is ideal for timing the start and stop of each traverse. Test subject and test director verbal communication is audible throughout the test setup via underwater speakers for testing in that environment; this audio stream is clearly picked up by the underwater video cameras through their waterproof housings by built-in microphones. The audio tracks are used to ensure that the data collected is correctly attributed to the appropriate test number.

Test subjects were also asked for subjective evaluations of the difficulty in performing the inter-deck traverses. Over and above the subjective evaluations recorded both in real-time and during post-test formal debriefs, the test subjects are asked to provide a Cooper-Harper rating and a full set of NASA Task Load Index (TLX) evaluations for each test case. For a given staircase angle, step spacing, simulated gravitation level, and cargo load, the test subjects complete 3-5 round trips up and down the staircase, then stop to give a 1-10 rating based on a modified Cooper-Harper rating algorithm, and numerical estimates on the six NASA TLX categories of mental demand, physical demand, temporal demand, performance, effort, and frustration. This data collection protocol provides more information than a simple "satisfactory/unsatisfactory" rating would.

Ultimately, the focus of quantitative testing is on direct biomechanical data collection using motion capture camera systems. The UMd Neutral Buoyancy Research Facility is equipped with a sixteen-camera Qualisys underwater motion tracking system, which (with proper meticulous calibration) is capable of sub-centimeter position resolution on an effectively unlimited number of retroreflective targets.

While it would be ideal to obtain a complete record of all body motions of the test subjects during traverses, practical limitations of the current software supplied with the Qualisys have led to the decision to focus specifically on leg motions alone. The specific leg movements while ascending or descending stairs include lifting a leg, transferring the foot to the next step, shifting weight to the foremost foot, lifting the rear foot, transfer that foot to next step, shifting weight to the foremost foot, and repeat. Having an array of motion capture reflective markers placed strategically on the subject's legs is paramount in effectively capturing these movements, while at the same time minimizing impact on test subject comfort or range of motion.

Markers were placed on the foot (first and fifth metatarsal head and heel), calves (unique noncollinear rigid marker quad), thighs (unique noncollinear rigid marker quad), knee (lateral femoral epicondyle), and on the hips (anterior and posterior-superior iliac spine). Studying these areas of movement allows for the complete capture of a subject's gait and allows the direct comparison of results across test conditions and test subjects. For laboratory testing of the system, a separate VICON motion capture system is used, as well as a smaller (shorter) staircase test rig due to volume constraints of the laboratory test space.

IV. Testing

Laboratory and neutral buoyancy testing both utilize multiple camera motion capture systems. The laboratory testing uses an array of eight VICON cameras in a test cube of about 27m^3. The neutral buoyancy testing uses an array of up to 16 Qualisys cameras in a cylindrical area of about 1300m^3. With safety as a primary concern when doing any testing that involves climbing, a commercial fall arrestor and a two point of contact safety belt system allows subjects unimpeded movement and high levels of safety while both ascending and descending the structure.

Marker placement for proper body segment tracking required special considerations due to occlusions created by the bulky ballasting equipment. As a result, pose estimation is used to estimate joint angles based on local coordinate systems. Three or more noncollinear markers were placed on the thigh and calf of the test subject to create a local coordinate system (LCS) that could be used to calculate position in the global coordinate system (GCS).Three markers were also placed on the foot to create a coordinate system for calculating ankle angles and to estimate factors such as over or under stepping.

A. Testing Protocols

Testing generally consisted of having a test subject walk up and down the staircase at a comfortable rate. As mentioned earlier, two orthogonal video views were recorded (Figures 7 and 8) and used to measure transit time and note any off-nominal events, such as slipping or missing a step, hesitation, lateral imbalance, or changing grasps on the carried payload. Each test condition was repeated 3-5 times, after which the test subject provided a modified Cooper-Harper rating for the task, as well as the six indices of the NASA TLX protocol.

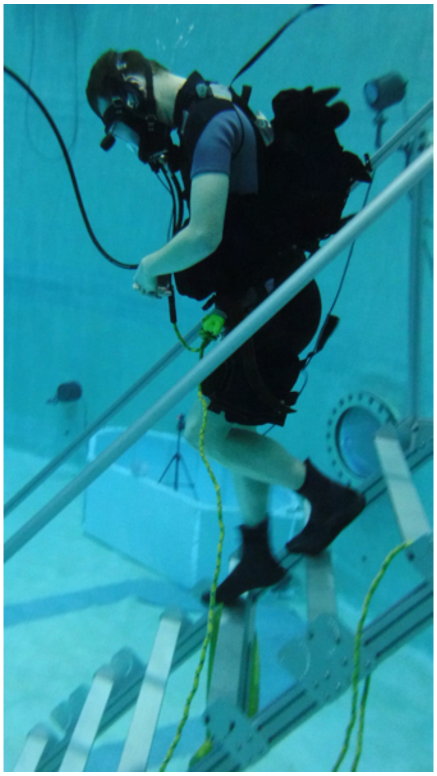

Fig. 7 Side view of test subject descent

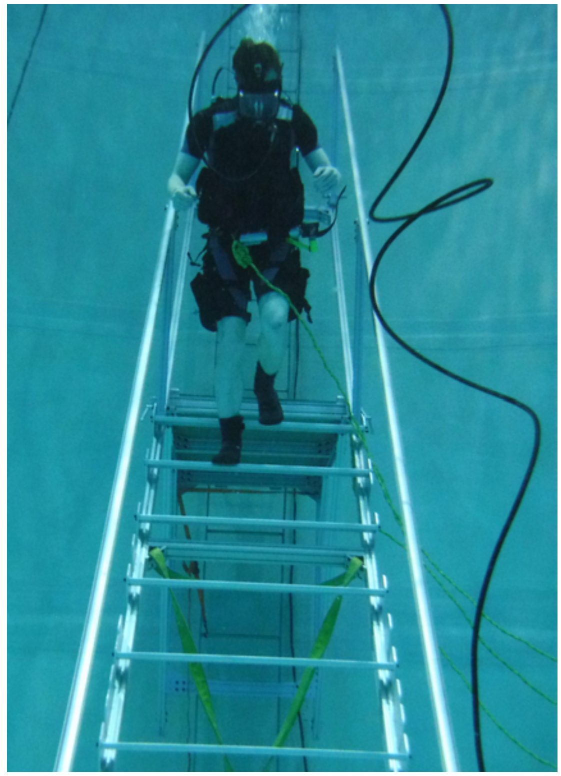

Fig. 8 Front view of test subject descent

B. Laboratory Testing

The main concern in terms of data fidelity is the effect of hydrodynamic drag in a neutral buoyancy testing environment. Having baseline measurements is critical to developing useful results. As a result, tests were done in a 1g environment with a VICON motion-capture system to capture each individual's climbing technique. This was repeated for each test setup of staircase angle and tread spacing so that the results can be directly compared to their respective ballasted partial gravity case.

The Qualisys underwater motion capture systems has a work area of roughly 1300m^3, but the dry land VICON test setup is much more compact. As a result, a compact version of the test rig was built with a platform height of 0.91m as can be seen in Fig. 9. This setup is identical to the one used in the water, aside from the platform height, resulting in a shorter ladder with fewer treads needed.

Test subjects were equipped with a total of 11 motion capture reflective spheres per leg, placed strategically along feet, tibia, above/below knee, femur, and hips as described in the testing protocol. Fig. 10 shows the issue of occluding the hip markers. As can be seen in Fig. 11, this marker placement allowed for the creation of a coordinate frame at the foot, calf, thigh, and hips. The large coordinate frame at right of Fig. 11 is the top of the platform which is used as a global reference fixed coordinate system. This allows for full motion capture of leg movements in a three-dimensional space with a reference frame to the staircase. A separate global reference frame is placed on the floor in order to track any errors that might appear between the fixed floor and fixed staircase frames.

Initial testing used the VICON "Tracker" software as seen in Fig. 11 but later testing utilized "NEXUS", which is designed for biomechanics studies. Selected test subjects also performed underwater testing while ballasted to their full Earth weight, to provide a direct comparison to stairclimbing with and without hydrodynamics drag.

As shown in Figure 5, the complete 3 m staircase was set up in the NBRF high bay to allow performance testing of

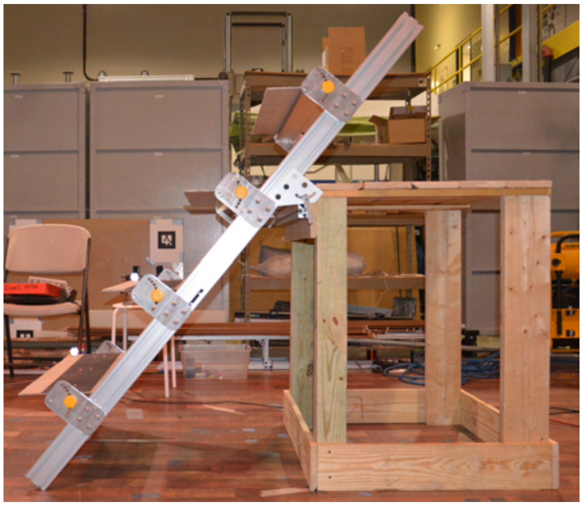

Fig. 9 Laboratory baseline setup with modified staircase

Fig. 10 Marker placement on a test subject

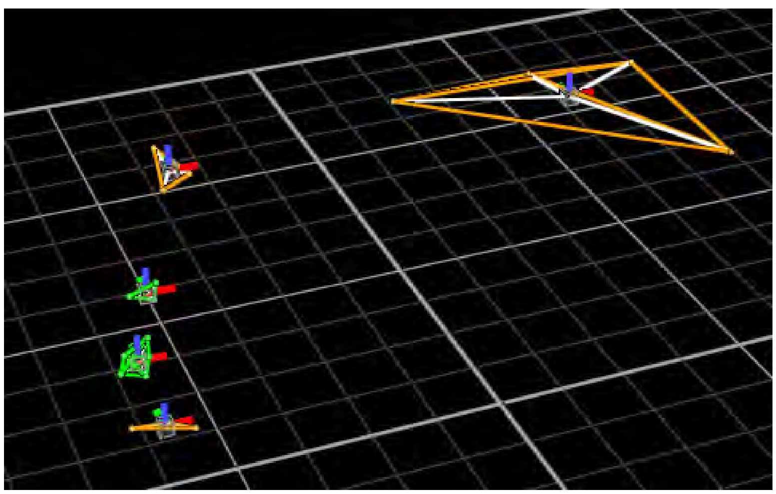

Fig. 11 VICON Coordinate Frames

subjects in their natural 1-g stairclimbing motion. This was not instrumented via motion capture, but was used to find a control case for nominal performance at varying angles and stair pitch values.

C. Neutral Buoyancy Testing

The upper platform utilized for testing (representing a ten foot elevation change vertically) was mounted directly to a fixed vertical ladder in the tank. The variable-geometry staircase then mounted to two locking pivots located on the platform, allowing the ladder to slide up and down through the pivots to adjust the effective length of the hypotenuse of the right triangle we have created. After the ladder structure is moved to the specific angle desired, equal step distances (of varying intervals per angle) must be positioned by divers, and finally each step must be adjusted to be parallel with the floor plane.

Ballasting test subjects to their Martian and lunar equivalent masses is accomplished through positioning lead weights on their chest, back, upper leg, and lower leg areas proportionally. Utilizing body segment mass percentages from published literature, it is possible to derive the equivalent required mass densities and locations for each subject based on their weight and the desired gravitational conditions. By ballasting each body segment proportionally, the apparent gravitational down-force is appropriate for each segment of the body.[3] Since the focus of this testing is on legged locomotion, the arm segment masses are lumped into the ballast mass of both the torso and head combined, which is then evenly split between the chest and back ballast sites. The test subject wears a commercial “tactical” vest, with ballast spread over the numerous pockets built into the unit. Upper leg weights are placed in pouches strapped to the outside of the thighs, but attached to the vest to prevent slipping. Lower leg weights are placed in multisegment weight pouches which are strapped around the ankles.

Ballasted test subjects wear full-face masks with two-way audio communications to the test director and test conductor. To eliminate inertial errors due to the mass of a pressurized air tank normally worn on the back, the test subjects are attached to “hookah” rigs: 10-20 meter long air hoses attached to scuba bottles near the test site. Each test subject has a dedicated safety diver to monitor their activities and initiate emergency response upon need. Utility divers change the test hardware to the proper settings for the next test case, monitor the functioning of the data collection video cameras, and take still photos for documentation.

V. Preliminary Testing Results

The first iteration of the reconfigurable staircase had narrow treads and smooth surfaces that slowed down testing and had unpredicted outcomes of subjects missing the treads altogether. However, the qualitative data still gives interesting results. A 95th percentile male test subject showed a preference for a 44cm vertical between treads as opposed to the 30cm or 61cm at a 60° incline. This can be seen in Fig. 12 where the the apparent effort, mental and physical demand, and frustration all have local minimum at the 44cm setup. The collected data for the 5th percentile male did not have any apparent minimum effort/demand solutions in the tested regime. Laboratory testing created a baseline for the 95th and 5th percentile male at 50° and 60° inclinations. Both setups had 10 treads with a vertical of 27cm between treads. The baseline times for the 95th percentile male is shown in Table 1. This data was collected using the setups shown in Fig. 5 and Fig. 6.

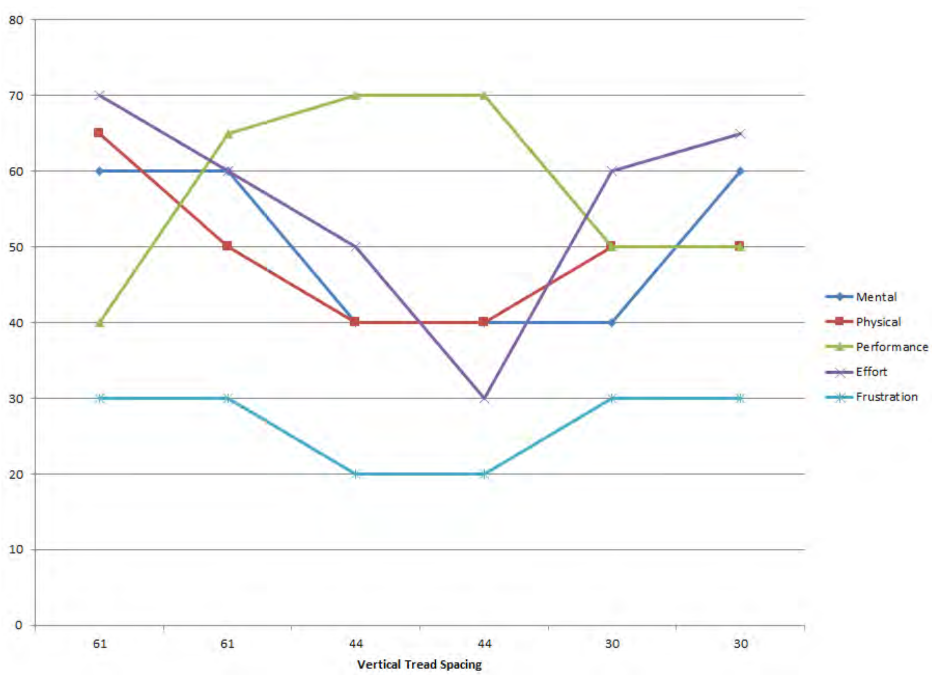

Fig. 12 TLX for 60° incline and 95th percentile male

For the 50° incline, the 95th percentile male had an average task time across ten trials of 6.34 seconds without a 2.75kg CTB and 6.5 seconds with the CTB in hand. The 5th percentile male had an average task time of 6.8 seconds and 6.6 seconds respectively. For the 60° incline, the 95th percentile male had a task time of 6.2 seconds without the CTB and 5.5 seconds with the CTB. 5th percentile male had a time of 4.8 seconds and 5.5 seconds respectively. These data points bring up an unexpected trend: in most cases, the subject moved faster while carrying a CTB.

Table 1 95th Percentile Male Climbing Times (Seconds)

1G (Dry)		w/o CTB	w/ CTB
50° Incline	Up	6.58	6.70
	Down	6.10	6.31
60° Incline	Up	6.63	6.04
	Down	5.75	4.86

Lunar (Ballasted)		w/o CTB	w/ CTB
50° Incline	Up	20.59	16.61
	Down	14.17	12.68
60° Incline	Up	17.17	13.14
	Down	9.47	9.85

Laboratory testing with the VICON system has created a baseline to allow for ballasted data to be more accurately interpolated into representative data for atmospheric environments. Initial testing showed that occlusions of the foot LCS are hard to avoid without camera redistribution or a change in natural gait. As a result, the calf and thigh LCS were proven to be much more useful and reliable for baseline measurements.

An unexpected observation was that test subjects were consistent in descending so that both feet hit each tread. On the other hand, when ascending, some trials had both feet hit each tread, and others would see subjects stepping so that only one foot hit each tread. That inconsistency can be seen in Figure 13 and the occlusion issues for the foot LCS can be seen in Fig. 14. The horizontal lines with red squares represent tread locations, and the lone red square is at the height of the platform. These are the estimated locations due to issues with the tracking software. Ballasted underwater motion capture should show us how the drag element and different simulated gravity levels effect the climbing profile.

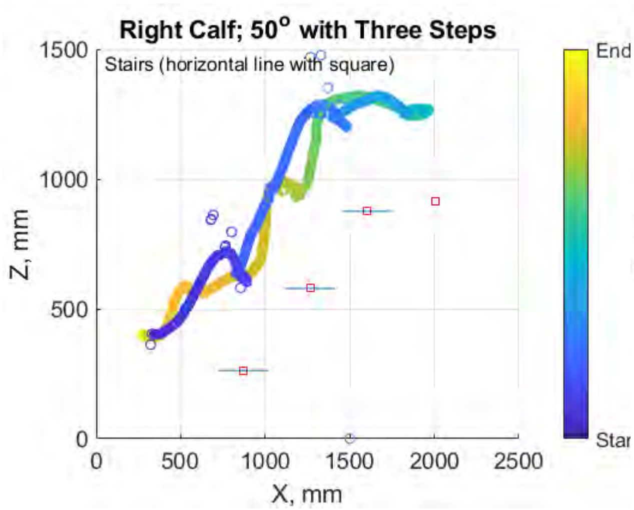

Fig. 13 Motion Capture Data for Calf LCS

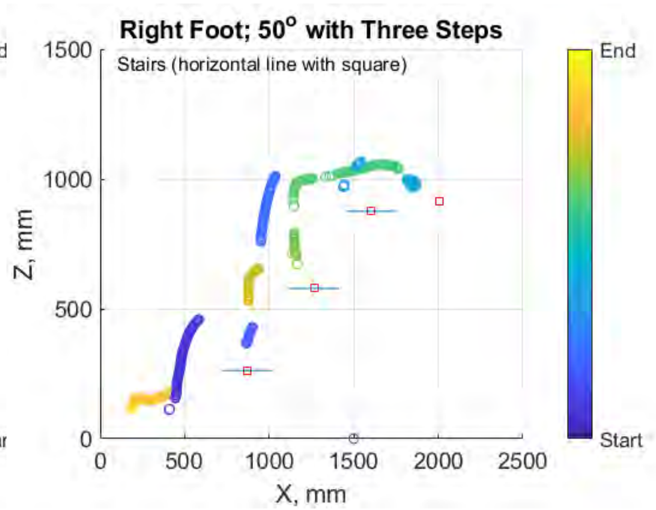

Fig. 14 Motion Capture Data for Foot LCS

VI. Related Work

In certain situations vertical ladder use is unavoidable. For example, rotating habitats to produce artificial gravity almost always feature a cylindrical "transfer tunnel" from each habitat module to a central module in microgravity. It is presumed that the crew can use ladders within the vertical transfer tunnels to move between habitat modules, and to move logistics stored in microgravity or delivered to a despun docking interface in the central module.

To evaluate this scenario we looked at a cylindrical transfer tunnel 1.5m in diameter. This diameter can be thought of as the size of the hole needed to go between floors, so a smaller hole means less space dedicated to the ladder. Ladder placement withing this tube is critical. Climbing a ladder while carrying any object is unsafe due to the inability to maintain three points of contact. Therefore, either a backpack or pulley system is needed. Central ladder placement allows for two people to simultaneously interact with the ladder, but limits the maximum object size to that of less than a M03 bag. To allow for enough room to carry a CTB as a backpack or use a pulley to transfer a CTB, side mounted ladders may be used. These two scenarios are illustrated in Figure 15[†]and Fig. 16[†] .

Fig. 15 Centrally mounted ladder

Fig. 16 Wall mounted ladder

This was evaluated in a preliminary scenario using the fixed ladder on the wall of the NBRF and a cylindrical mock-up composed of aluminum strips and plastic sheeting. As shown in Figure 17, test subjects climbed the vertical ladder within the 1.5m diameter tunnel, with and without an appropriately-ballasted CTB. This test verified the basic protocols for future testing of vertical ladder translation with external volumetric constraints.

Another planned test in this series is the study of how varying gravity levels affects internal habitat systems servicing, which is one of the highest demands on crew time in the International Space Station. As shown in Figure /refOGA, a sliding module was fabricated within a simulated habitat equipment rack. A sphere in the center of the sliding module can be adjusted to provide any required level of overall buoyancy for the removable module. Test subjects ballasted for varying gravity conditions will be required to remove and reinsert the module to better understand the interactions between weight on the subject's feet and ability to perform both gross and fine motor functions in support of a generic servicing task. It is also planned to repeat these tests on floors at various inclinations up to 10^o, to replicate the effect of gravity vector angles for locations in artificial gravity habitats offset from the spin radius.

VII. Conclusions and Future Testing Plans

Data analysis to date has highlighted the importance of knowing exact tread placement in order to predict and understand the recorded joint locations. Future iterations will attach marker sets to each tread to allow for direct comparisons from expected/ideal tread locations to actual locations in the experiment, instead of inferring locations from set reference points.

Work to date has only "scratched the surface" of the potential research in this area. Immediate plans are to fully populate the test matrix (staircase angles from 30^o to 90^o in 10^o increments, tread spacings from 30 cm to 60 cm in

[†]Image generated using Siemens NX tools and courtesy of Bianca Foltan

Fig. 17 Ladder testing with cylindrical constraints

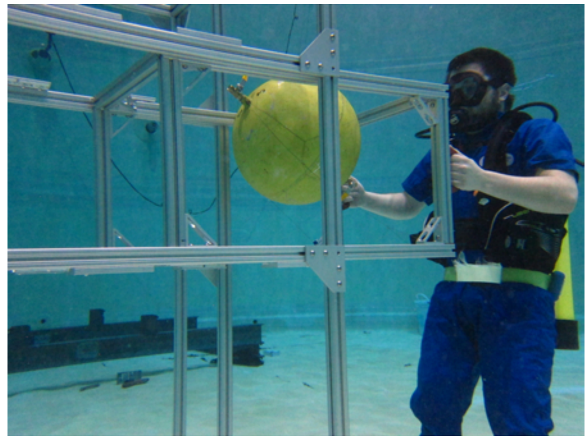

Fig. 18 Prototype servicing test with variable-ballast rack

10cm spacing, with and without hand-carried cargo, and testing in both lunar and Mars simulated gravity and associated laboratory testing) with a statistically significant number of diverse test subjects. Data collection will still include time and error tracking and subjective evaluations, but will also focus on motion capture including gait analysis.

Perhaps the largest single lesson learned to date is that the process of sequring the desired data is much more complicated and time-consuming than expected. Based on testing to date, to test a single subject at 30^{o} - 70^{o} angles, with 3 tread spacings, and two tread depths at all three gravity levels will take an estimated 81 hours of dive time. For the same subject an estimated 27 hours of test time will be needed to complete the laboratory testing with the Vicon system. If 6 subjects are to be evaluated, a total of 648 hours of testing will have to be completed. Counting the support staff required for safety and data collection on dives and surface tests, over 2400 person-hours will need to be spent to complete this project as outlined. In order to continue moving forward, significant effort will have to be put into streamlining the process. Plans exist for modifying the modular staircase to reduce time required for reconfiguration. The SSL has also procured sufficient equipment to support two test subjects simultaneously, allowing twice as many data points to be collected at each hardware configuration.

The existence of this test rig provides opportunities for associated studies. For example, it was mentioned earlier that the test apparatus was designed to study two test subjects passing on the staircase as an alternative to simple ascents and descents. We have been requested by NASA sponsors to investigate the issue of cargo transport more thoroughly, including larger standard stowage bags (e.g., M01 bags) with both single person and two-person transports. The current ENAE 484 capstone course in spacecraft design at the University of Maryland is currently working on the design of an artificial gravity space station, and is interested in working with the test hardware in the 90^{o} orientation to investigate locomotion along radial transfer tubes from the center of a rotating station to the habitats. Planning for this study has already developed a technique for changing flotation as a function of depth, allowing test hardware to simulate changing gravity levels along the changing radius of the modeled habitat as a function of depth in the neutral buoyancy tank.

Although this paper has focused on accessibility between floors of habitats in different gravity levels, the UMd research team is also developing other approaches to understanding the effect of gravitation on habitat design. We have developed a neutral buoyancy version of a generic life support rack with various tasks that have to be performed for system repair and maintenance, including the removal and replacement of parts of varying masses. Each component can be ballasted to represent the appropriate apparent weight in different gravity conditions, and the same repair tasks repeated to find the differences in performance and best repair practices as a function of gravitation. Another research initiative from the ENAE 484 design effort is the realization that rotating habitats with flat floors actually have noticeable divergence of the sensed gravitation vector from the local perpendicular to the floor as the position varies in the positive or negative spin direction. Current plans include additional testing of the rack repair tasks on an inclined platform, to represent the effect of this gravitational vector shift with position in the habitat.

While there are definitely complexities in dealing with underwater simulation of human factors and habitat design, it does represent one of the few economical means of simulating the gravity of the moon or Mars, or any other gravitation level of interest. Although it will never be practical to just have people go about extended "missions" in the underwater environment, a closer examination of those aspects of habitat design which can be effectively studied underwater will provide valuable design data that we do not have from flight experience and are not likely to obtain in the foreseeable future.

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