Development of Weigh-out Process and Evaluations for Underwater Partial Gravity Simulations

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For the upcoming Artemis lunar missions, astronauts will need to train in a spacesuit where partial gravity can be simulated such as the NASA Neutral Buoyancy Lab (NBL). At the NBL, dive weights and foam can be added around the spacesuit to attain a satisfactory center of buoyancy (CB) and center of gravity (CG) location to simulate the lunar gravity (1/6th-g) effects. If CG and CB are not co-located properly, incorrect righting moments can be introduced, and both simulation quality and EVA task performance can be impaired. Based on the findings from the initial testing using xEMU spacesuits, it was observed that the weigh-out method (i.e., determination of the weights and foam quantities and position) needed further development to improve the simulation quality, especially for the subjects who experienced excessive instability. This paper aims to present the on-going effort to improve the weigh-out process for enabling NBL lunar EVA simulations. For this effort, a human-suit model was created to use suit computer-aided design (CAD) and 3D human body scans to estimate both CB and CG location for each suited subject. NBL weigh-out testing was performed to characterize the effects of CG and CB positioning, in which the 3D human-suit model was used to determine optimal weigh-out combinations of weights and foam. Postural, balance, and subjective feedback were gathered for each weigh-out configuration. The results indicated that, as the CB was shifted higher and the CB and CG were located closer to each other, the subject tended to be more stable and their EVA performance improved. A high CB location was then prioritized across 4 additional subjects in both small and large size spacesuits. When compared to the initial xEMU test series, improved performance was observed across all subjects as the CB moved higher and aligned closer to the system CG.

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Nomenclature

CAD = *Computer-aided Design*
CB = Center of Buoyancy
CG = Center of Gravity
CoP = Center of Pressure
EPG = Environmental Protection Garment
EVA = Extravehicular Activity
HUT = Hard Upper Torso
ILBA = Integrated Lighting Band Assembly
ISS = International Space Station
NASA = National Aeronautics and Space Administration
NBL = Neutral Buoyancy Lab
NxPLSS = NBL Exploration Portable Life Support System
PGS = Pressure Garment System
PGWS = Partial Gravity Weigh-out Stand
PLSS = Portable Life Support System
xEMU = Exploration Extravehicular Mobility Unit
1/6th-g = 1/6th gravity

I. Introduction

With NASA's Artemis Program focusing on lunar exploration, training the astronauts for lunar Extravehicular Activities (EVAs) is critical to ensure safety and efficiency of performing scientific tasks. To provide realistic training to the crew members, the Neutral Buoyancy Lab (NBL) is used to create a simulated reduced gravity environment. However, as gas-filled spacesuits need to move and function in a naturalistic manner under the water, simulating lunar gravity for spacesuits in the NBL requires balancing the center of buoyancy and center of mass of the system. This is achieved by adding weights and foam to the spacesuit in various ways to counteract buoyancy and get the suit/subject system in a 1/6th-gravity (1/6th-g) weight simulation[1].

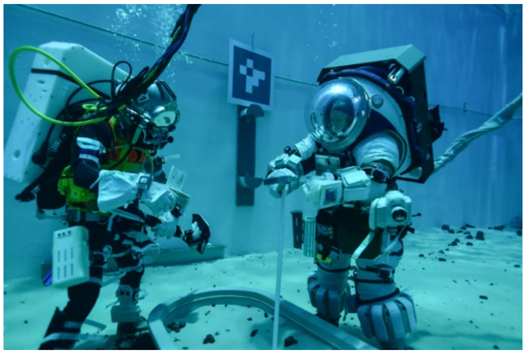

Figure 1. Z-2 Suited Partial Gravity Test in the NBL

Partial gravity simulations had been performed underwater during Apollo mission training prior to the Artemis Program. However, more recently at the NBL using the NASA Z-2 spacesuit (Figure 1), a new model-based weigh-out approach was proposed and deployed, with a focus on system-wise estimation for the center of gravity, incorporating not only the suit and mockup PLSS, but also the wearer's body inside of the suit[2]. This effort highlighted the challenges of achieving a consistently repeatable weigh-out across subjects of different anthropometry, especially when performing dynamic tasks underwater. An underwater forceplate was used to accurately analyze differences in weigh-outs across subjects during the Z-2 test series, demonstrating visible changes across attempted weigh-outs.

The initial lunar simulation test series using the Exploration Extravehicular Mobility Unit (xEMU) spacesuit showed that subjects experienced instabilities when performing tasks, primarily due to their weigh-out. Hence, further investigation was needed to create a stable and repeatable 1/6th-g weigh-out process based on structured metrics and procedures. For this work, a human-suit model was created to calculate the center of buoyancy (CB) and center of gravity (CG) of the system to assess the human/suit to environment interactions as a function of different parameters of lunar weigh-out in water. To evaluate model-based weigh-out configurations, a series of suited tests were performed at the NBL using the xEMU to assess the experience of subjects when performing tasks in different configurations of weigh-out.In the past, the lunar weigh-out process at the NBL began with the divers adding weights to the spacesuit environmental protection garment (EPG) pockets to achieve a neutral weigh-out, similar to the process used for the International Space Station (ISS) training in the NBL. This is done to ensure a safe extraction from the pool in case of an emergency. Once the suit is in a neutral weigh-out configuration, more weights are added to the suit to reach 1/6th-g weight. In the initial test series, the 1/6th-g weight placements were decided based on a guess-and-check method.

This method relied on measurements through the Partial Gravity Weigh-out Stand (PGWS)[1]. The PGWS is an underwater force transducer system[2] which only outputs the resultant moment between the CB and CG of the suit underwater in a standing posture. More information, such as an estimated system CB and system CG, are needed to understand the resultant moment and its magnitude when achieving a stable weigh-out. Therefore, the guess-and-check method did not provide a repeatable process and subjects often reported instability while performing tasks, especially when switching postures between standing and kneeling, for example. During the first xEMU test series, subjects were observed to have difficulty with performing simple tasks in a stable manner, such as steadily holding a single knee kneel (Figure 2). In these cases, divers helped subjects in performing such dynamic tasks to gain more stability.

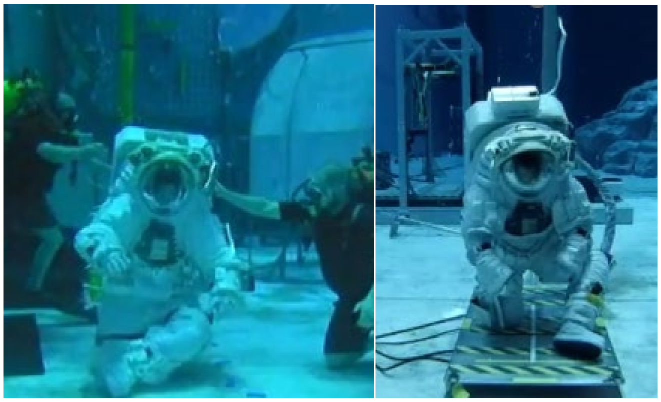

Figure 2. Effects of poor weigh-out requiring diver support (left) compared to an improved weigh-out (right) while holding a single knee kneel in the xEMU.

The initial xEMU NBL testing indicated that the CB should be adjusted to a higher position by attaching more foam to the suit. Additionally, improved weight locations were needed to create more stable weigh-out configurations without compromising suit mobility across subjects. As a result, new foam placements were created inside the NBL Exploration PLSS (NxPLSS), and additional weight pockets were created on the EPG. The previous NxPLSS only allowed for foam at the bottom of the PLSS, so new locations were added towards the top of the PLSS to assist in shifting the system CB higher (Figure 3). The addition of weight locations also allowed for a more distributed weight allocation to assist with a more stable center of gravity when changing postures and performing dynamic tasks.

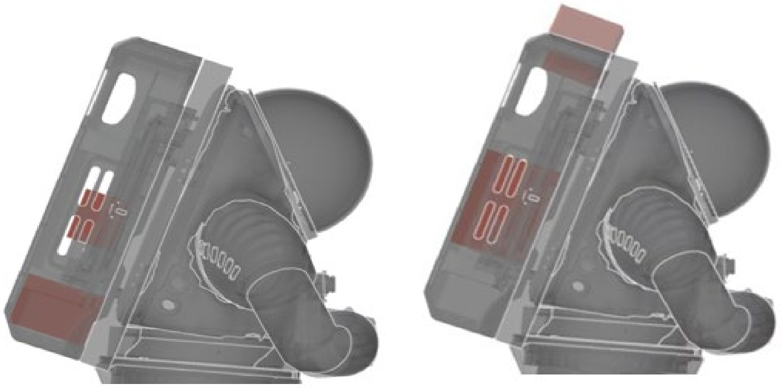

Figure 3. Left: 2022 NBL series foam locations (red 3ighlighted boxes). Right: 2023 NBL series foam locations.

With the hardware upgrades made, the limitations of the guess-and-check weigh-out method needed to be addressed. The guess-and-check method was dependent on subjective measurements done by the divers to achieve a neutral weigh-out. Without understanding where the system CB was located for each subject, the target CG location was subjective and inaccurate. Additionally, considering the PGWS only measures the moment created by system CB and CG, the weigh-out process was not repeatable across different subjects since the CB and CG locations vary based on subject anthropometry. This meant that for each subject, the team had to come up with places to mount lunar weights in real time. This process was very time consuming and, at times, an acceptable weigh-out for subjects could not be achieved. Therefore, with a goal of increasing efficiency and weigh-out quality, creation of a suit model was proposed to estimate system CB and CG for each subject and predict weight locations ahead of each run.

II. Methods

A. Human-Suit Model Development

To assist with creating a more stable and repeatable lunar weigh-out in the NBL, a center of buoyancy model was created for the suit wearer. This model was incorporated with a suit CG model, to quantitatively identify the interactions between CG and CB. The xEMU CG and CB model was developed using CAD and mass properties from NBL mockup and suit hardware specifications and measurements.

1. System CG Calculation

The model relies on the wearer's body mass, component-wise suit mass, and the NxPLSS mass to calculate the system CG. Specifically, point masses of both suit components and human body segments were extracted and used to calculate the system CG. The subject-specific CG relies on a 3D scan of the subject in a neutral standing posture, with arms slightly away from the sides and in minimal scanwear clothing. The segment-wise mass and CG were estimated through volumetrically proportional mass distributions with an assumption of homogeneous density distribution across the body. The suit was resized by adjusting the sizing rings and soft goods in the model based on subject specific fit check data, and a resultant system CG was calculated using equation (1), where CG_n denotes the CG location of the n-th suit component or body semgnet, and m_n denotes the corresponding component mass. To validate the model prediction to the PGWS measurements during the test phase, the human-suit model was posed similar to the posture observed from the suited subject when standing in the PGWS (Figure 4).

$$(1)\quad Resultant\ CG\ location = \frac{CG_1 * m_1 + CG_2 * m_2 \ldots + CG_n * m_n}{\sum_{i=0}^{n} m_n}$$

2. System CB Calculation

The center of buoyancy is dependent on volumetric measurement of the suit system. The suit component 3D scans and CAD as described in the previous step were used to estimate the component-wise volume, which determined the CB location of the system. Once the buoyancy of the suit was calculated, the pre-measured buoyancy data from the NxPLSS and added foam was integrated into the calculation to output an entire suit system CB using equation (2), in which F_B, V, ρ and g denote buoyant force,volume of the displaced liquid, density of the liquid the object is immersed in, and gravitational acceleration, respectively. EPG estimates were used to account for the complete suit volume.

$$(2)\quad F_B = V \times \rho \times g$$

3. Modeling Subject-specific Weigh-out Configuration

Mass and buoyancy properties of dive weights and foam blocks were incorporated into the suit model to create a more accurate calculation of the final system CB. Foam amounts, fixed during the test event, were identified prior to each NBL run based on previous weigh-out data, the subject specific body geometry information, and test objectives. To create a model for each subject, the weights needed to achieve a neutral weigh-out were iteratively adjusted within the model, until the CG and CB were collocated in all 3 axes (right-left, fore-aft and up-down).This process was similar to the process used by divers at the actual NBL runs. These "virtual" weight placements were provided to the divers as a starting plan for neutral weigh-out on the day of the NBL test run. Once a neutral weigh-out was achieved in the model, virtual lunar weights were added to the model by increasing the mass for the pre-allocated locations to collocate CB and CG of the suit and subject's body. The specific magnitude of the mass corresponded to the total lunar weight of the human-suit system. During the actual NBL run, the divers first achieved a neutral weigh-out, then mounted the 1/6th-g weights across the suit as specified by the model predictions

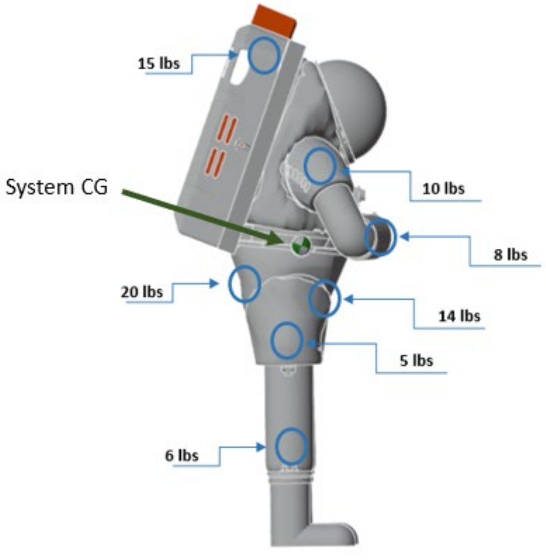

Figure 4: xEMU CB/CG weigh-out model. Sample weights are added at multiple locations across the suit.

B. Model Test & Validation

To assess the performance and limitations of the model, a total of 5 tests were performed across 3 phases in the NBL using the xEMU spacesuit. Phase 1 consisted of two runs with one male subject performing a set of weigh-out evaluation tasks (detailed in the following section) across 6 different weigh-out configurations (Table 1). Additionally, 2 CG measurements were taken on the PGWS out of the water once the subject had achieved a neutral weigh-out, with the assumption that CB and CG were collocated once divers approved the neutral weigh-out. These two measurements assisted in improving the model accuracy ahead of Phase 2. The model was then updated by modifying buoyancy estimations of suit components to match the system buoyancy to the actual measured data.

Table 1:Description of weigh-out configurations attempted across the 3 phases of testing

Phase	Weigh-out Configuration Type	Configuration Description
1	A1	20 lb. foam at bottom, 3.5 lb. foam in top portion of NxPLSS
	A2	27 lb. foam at bottom, 3.5 lb. foam in top portion of NxPLSS
	B1	Similar foam to A2, with bottom foam shifted up 6 in.
	B2	Similar to B1, with 4.9 lb. foam added over NxPLSS
	B4	Similar foam to B2, with modified lunar weights to better collocate CB and CG
2	C1	32 lb. foam at bottom shifted up 6 in., 3.5 lb. foam in top portion of NxPLSS, and 10.5 lb. foam over PLSS
	C2	25 lb. foam at bottom shifted up 6 in., 3.5 lb. foam in top portion of NxPLSS
3	C3	20lb. foam at bottom shifted up 6 in., 3.5 lb. foam in top portion of NxPLSS, and 10.5 lb. foam over PLSS

Once the model was updated, two runs were performed in Phase 2, one with a female subject in a small HUT and one with male subject in a large HUT, to assess the weigh-out configurations across a broader range of anthropometry. Phase 2 included two single-suited runs to evaluate 1/6th-g weigh-outs. For these runs, each subject assessed three neutral weigh-out configurations with different foam setups, in an attempt to adjust the CB location. For each configuration, a 3-axis neutral weigh-out was performed, followed by a poolside 1-g measurement of system CG using the PGWS, which was assumed to be collocated with the system CB after being neutrally weighed out. If an acceptable 3-axis neutral weigh-out had been achieved, subjects would have proceeded into a 1/6th-g weigh-out and functional evaluation, as described in the following section.

Based on the data gathered across all previous runs, a dual-suit run was performed as Phase 3, where two subjects were weighed out in a stable 1/6th-g configuration based on model predictions and performed EVA-like tasks, such as object pickup, across the pool floor.

During the Phase 2 and Phase 3 test series, some neutral weights were mounted on the suit prior to entering water to evaluate if model predicted weights can assist in reducing overall time taken to perform a lunar weigh-out.

C. Evaluation Tasks and Scoring Metrics

During the Phase 1 runs, a set of evaluation tasks were performed by the subject across the different 1/6th-g weigh-out configurations (Table 2). These tasks focused on extreme cases of posture when performing EVA tasks, such as recovery from prone and single-leg kneel. A forceplate was installed on the underwater floor. Additional tasks were performed on the forceplate to assess stability of subject across tasks, such as standing quiet stance (Table 2). Functional tasks were also assessed via reported subjective feedback, using a structured survey composed of a scale of 1-5 (1 being “easy”, and 5 being “can’t do it”) for task difficulty. Subject was also asked to rate their overall stability for these tasks, using a scale of 0-10 (0 being “very stable”, and 10 being “unstable”). Rating of perceived exertion (RPE) was also gathered for the functional tasks on a scale of 0-10 (0 being “easy”, and 10 being “maximum effort”).

Table 2: Phase 1 and 2 weigh-out evaluation task list

Task	Task Description	Data Collected	Test Phase Used At
Standing Quiet Stance	Stand in a neutral posture with eyes closed and remain still for 30 seconds.	Force Plate Measurements	1, 2
Dual Knee Kneel Reach	Get in a dual kneel position with arms at shoulder height. Reach forward as far as you can without losing stability.		1, 2
Isolated Waist Flexion/Extension	Perform 5 reps of maximum torso flexion and extension.		1
Limit of Stability	Sway back and forth in all cardinal directions, with 10 reps for each direction without losing stability.		1
Prone-Plank position	Get in a prone plank position and hold for 30 seconds.		1, 2
Prone-Buoyancy Check	Start in plank position, slowly shuffle hands toward waist.		1
Kneeling Side Reach	Get in a one knee kneel. Raise arms to shoulder height and reach forward at 45 degrees angle and hold without losing balance.		1
Standing Maximum Forward Reach	Raise arms to shoulder height and reach as far forward as you can while maintaining stability.		1, 2
Squat	Squat with hands at shoulder height and find a position where you can comfortably hold it.		1, 2
One Knee Kneel Quiet Stance	Get in a one knee kneel position and hold for 30 seconds with eyes closed.	Questionnaire	1, 2
Single Kneel Object Pickup	Pick up rock with a repeatable technique.		1, 2
Prone to Recover	Get into a prone position and recover to standing position.		1, 2
Walking	Walk back and forth.		1

Due to time limitations and difference in objectives of Phase 2, a shorter evaluation task list was created for Phase 2. These tasks are similar to ones performed during Phase 1 tests, with a reduction of a few tasks that were performed on the force plate to reduce evaluation duration. Subjective ratings were gathered for functional tasks similar to Phase 1.

The Phase 3 dual suit run was focused on evaluating the weigh-out across a simulated lunar EVA training. Therefore, the weigh-out evaluation task list was further reduced to focus mainly on functional tasks, with each subject only evaluating one weigh-out configuration prior to performing EVA tasks. Subjective ratings were gathered across the tasks (Table 3).

Table 3: Phase 3 weigh-out evaluation task list

Task
Dual Knee Kneel Reach
One Knee Kneel
Standing Maximum Forward Reach
Squat
Single Kneel Object Pickup
Prone to Recover

III. Results

A. Model Refinement

The data gathered during Phase 1 testing indicated a 2-inch difference in accuracy of CB estimation between the model and the as-measured CG location taken by the PGWS on the pool deck. The model was then updated according to the procedure described in the previous section to match the Phase 1 data and the updated version was tested during Phase 2. During the Phase 2 runs, a total of 3 neutral and 2 lunar weigh-outs were tested per subject. When comparing the 1-g measurements of system CB taken across the 2 runs to the model data, the model predicted CB was within ±0.5 inch of the PGWS measurements during Phase 2 tests (Figure 5). However, there is a level of uncertainty to using the PGWS as the basis of comparison. Recall that after a neutral 3-axis weigh-out the CB and CG are assumed to be collocated to within a reasonable, but not measured or verified, level; thus enabling the comparison of the modelled and "measured" CB.

The observed differences between the model prediction and PGWS measurements can be potentially attributed to several factors, such as use of old body scans of subjects, precision of foam and weight attachment locations, and divers' subjective assessment in reaching an acceptable neutral weigh-out. The suit/subject posture is also hypothesized to have affected the PGWS data when compared to the model. For both subjects tested in Phase 2, the C1 configuration had the closest CB-CG locations. The comparison of PGWS data to model during Phase 2 showed accuracy improvements in the model, namely the difference of CB predictions from CB predictions in the previous phase. The updated model's accuracy of ±0.5 inch per axis was deemed as acceptable, considering the precision level of the source data, such as off-nominal foam and weight positions, human body shape and posture variations.

Additionally, with an aim to evaluate if the model is effective in increasing the efficiency of the weigh-out process, with selected subjects during Phase 2 and Phase 3 runs, model predicted weights were pre-mounted on the suit before NBL testing. This resulted in achieving neutral weigh-outs within 20 minutes, which is a significant reduction in time consumed when compared to the initial NBL xEMU test series, where the average time taken was 45 minutes, proving that the model predictions are helpful in saving under-water time for future NBL lunar testing and training.

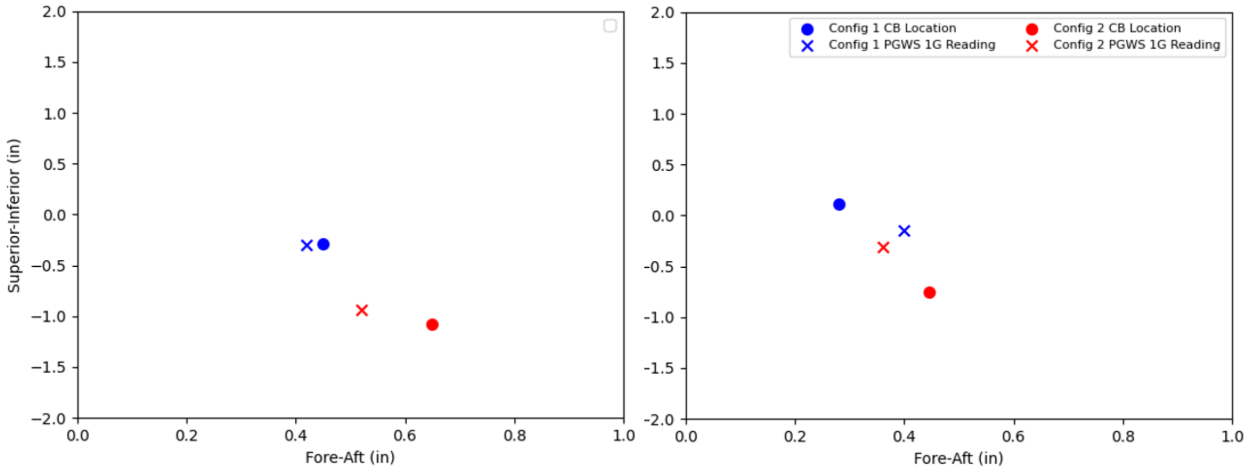

Figure 5: Comparison of Modeled CB and PGWS measurement across Phase 2 subjects weigh-out configurations. *Large HUT subject is shown on the left and small HUT subject data is shown on the right*

B. Evaluation Tasks

1. Forceplate Data

During Phase 1 testing, data from the force plate was analyzed to compare Center of Pressure (CoP: CG locations projected on the floor) for different weigh-outs across the tasks. One metric assessed across all weigh-outs was balance performance measured from standing quiet stance. For this metric, the CoP excursion magnitudes are calculated, and in general, smaller excursion magnitudes are regarded as the improved balance performance and better postural stability. The data showed a decrease in excursion range between day 1 and day 2 configurations (Table 5), as the CB was shifted higher and CB and CG were more closely collocated. This difference is more pronounced when comparing A2 to B2 and B4 configurations, in which the weigh-out configurations are varied by a shift in system CB to a higher location. The subject mentioned they had to perform a higher amount of micro-adjustments within the suit to stabilize the suit-human system in a standing position on day 1 than day 2, which agrees with the force plate data from standing quiet stance (Figure 6).

Table 5: Phase 1 standing quiet stance maximum excursion ranges from force plate. The maximum excursion range was calculated by finding the difference in maximum and minimum value from force plate in each axis. Day 1 configurations are A1 and A2. Day 2 configurations are B1, B2, and B4.

Weigh-out Configuration	Excursion Range Fore-Aft (in)	Excursion Range Left-Right (in)
A1	11.3	11.9
A2	9.6	8.6
B1	7.6	5.7
B2	5.2	5.1
B4	7.1	4.6

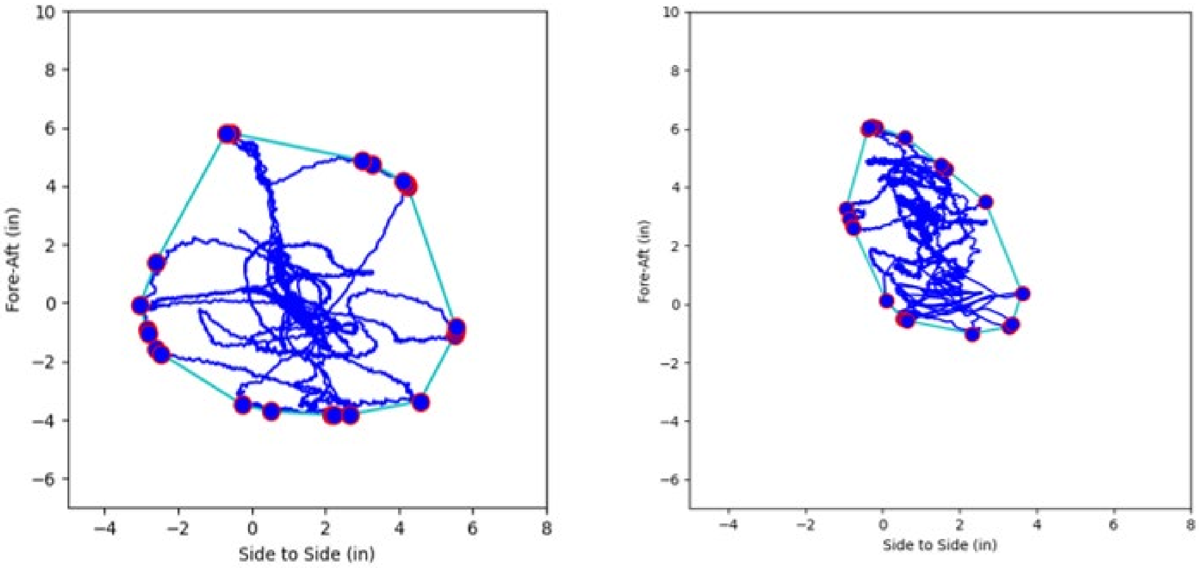

Figure 6: Standing quiet stance force plate data for day 1 (left; A2) and day 2 (right; B4) weigh-out configurations

Similarly, data from Phase 2 force plate analysis notably demonstrated the unique CoP patterns in standing quiet stance and squat. A comparison of standing quiet stance across the two subjects suggested that the weigh-out configuration with higher CB location (Figure 7 left panel) of configuration C1 provided more stability and lower excursion range than a lower CB with more distant CG (Figure 7 right panel) in configuration C2.

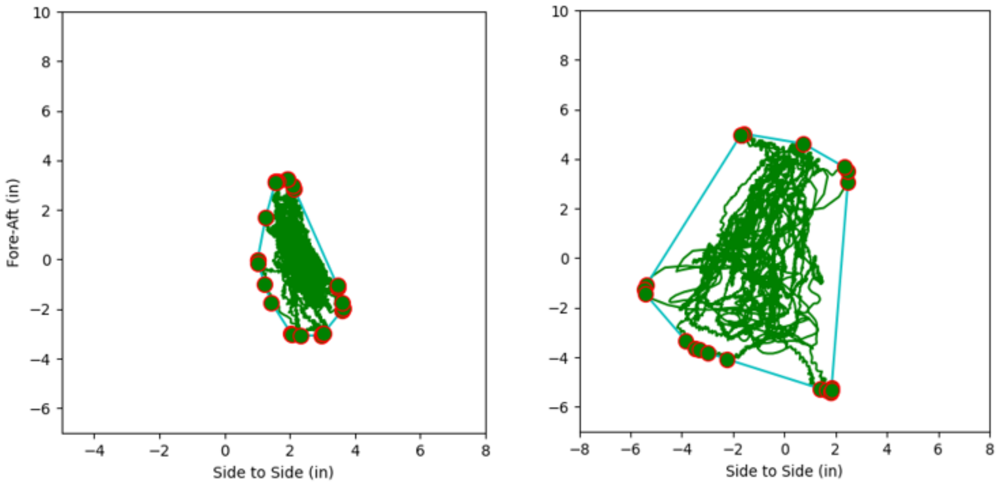

Figure 7: Standing quiet stance force plate data of large HUT higher CB location (left; configuration C1) and small HUT configuration (right; configuration C2)

A comparison of squat data was performed for each subject across their different weigh-out configurations. The shift in CB to a higher location led to more stability (i.e., smaller CoP excursion ranges) for subjects throughout the squatting task. The subject also had the ability to get into a squat position and hold it more quickly in the higher CB configuration, while in the C2 configuration they required multiple attempts to reach a stable squat stance.

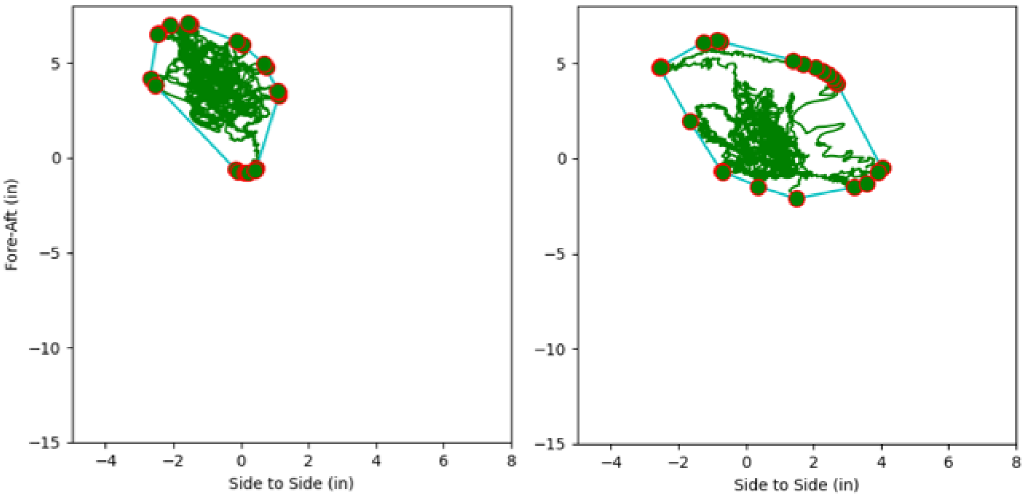

Figure 8: Phase 2 squat force place data from large HUT subject's C1 (left; higher CB) and C2 (right; lower CB) configurations

2. *Subjective Ratings*

The Phase 1 subjective feedback indicated a decrease in task difficulty, exertion ratings, and improved stabilty as the CB was shifted higher. Figure 10 shows that the subject felt less stable in the A1 configuration. The improved stability was observed from stability ratings across the tested configurations with higher CB, with B4 identified as the most stable. Prone to recover and object pickup also had the lowest level of perceived exertion in RPE in B4 and the highest in A2, indicating the higher CB and more closely aligned CB and CG setting led to a lower amount of effort exerted by the subject to perform tasks. The configurations evaluated during day 1 had the highest RPE scores overall with an average of 7 for A2, while B2 and B4 configurations on day 2 had the lowest scores, averaging at 5.5.

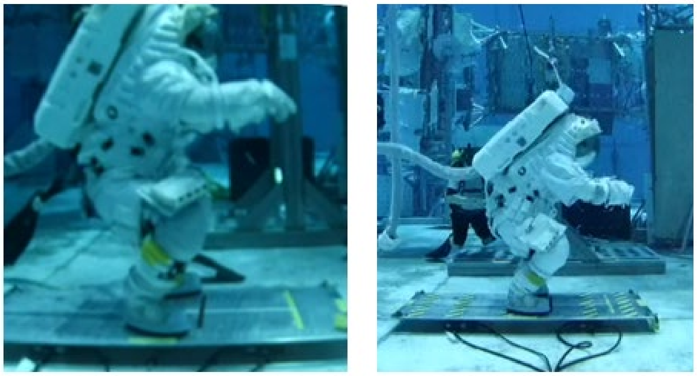

Figure 9: Comparison of a squat performed in A2 (left) and B4 (right). *Subject has a more natural squat posture in B4 when compared to A2.*

An analysis of video footage (Figure 9) and the subject's subjective comments matched the structured survey scores across the two days, highlighting the improvements in the weigh-out stability through a combination of more closely alinged CB and CG colocation and a higher shift in CB.

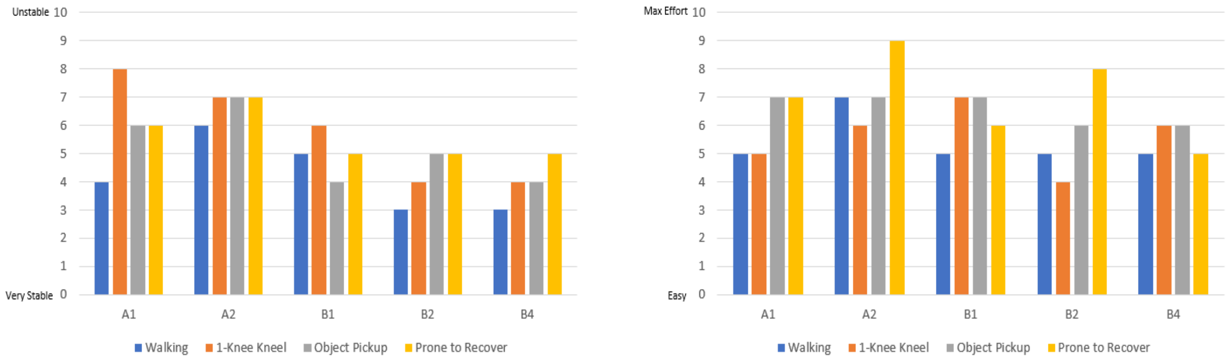

Figure 10: Phase 1 overall stability ratings per task (left) and RPE ratings per task (right)

The subjective feedback from Phase 2 (small HUT subject case) demonstrated minimal differences in task difficulty, overall stability and RPE across the two attempted lunar weigh-outs (Table 6). This data agreed with the subject's general comments, mentioning that they felt minimal changes when performing tasks in the C1 and C2 configurations, in which maximum and minimum foam was mounted, respectively. However, the subject was unable to successfully perform a prone to recover task in the C1 configuration. This may have been due to a reduction on leg weights in an attempt to reach a better system level CB and CG colocation, causing the legs to become buoyant and less stable in a prone position. The subject was able to perform prone recovery in the C2 configuration as the legs were weighted during this weigh-out. This was an improvement from the previous NBL xEMU test series, where smaller subjects were unable to recover from prone in a stable manner. The performance of the prone to recovery task is also affected by water drag, requiring changes in technique to overcome the simulation environment effects.

Table 6: Phase 2 Small HUT subject's functional task scores

	Task Difficulty (1-5)		**Overall Stability (1-10)**		**RPE (1-10)**	
Task	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Prone to recover	5	4	10	9	10	9
Object Pickup	4	3	8	7	7	7
Squat	3	3	7	7	4	6
One Knee Kneel	3	3	6	8	6	7

The functional assessment scores from the Phase 2 (large HUT subject) indicated that the subject had a lower task difficulty in the C1 configuration with a higher CB, signifying an improved stability. This agreed with the subject preferring the higher CB configuration when comparing their two attempted lunar weigh-outs. The subject also had lower overall stability and perceived exertion ratings in C1. This data also agreed with the subject's force plate data.

Table 7: Phase 2 Large HUT subject's functional task scores

	Task Difficulty (1-5)		**Overall Stability (1-10)**		**RPE (1-10)**	
Task	**C1**	**C2**	**C1**	**C2**	**C1**	**C2**
Prone to recover	3	4	4	5	4	5
Object Pickup	3	4	6	7	5	6
Squat	2	3	6	6	1	4
One Knee Kneel	N/A	2	N/A	3	N/A	3

To evaluate weigh-out efficiency during the Phase 3 dual suited run, a set of weigh-out evaluation tasks were assessed with a focus on EVA-like task performance (Table 8). The subjective data from the subject in the small HUT indicated that their arms were too buoyant, so additional weights were added to the subject's arms. Minor adjustments also had to be made to the subject's waist weights, which was later connected to an error in switching the front and back waist weight packs at the time of lunar weight installations. The subject was then asked to perform object pickup and prone to recover tasks again to ensure the newly added weights did not interfere with their performance. Overall, both subjects provided satisfactory ratings for their functional tasks. This was an improvement from the previous NBL xEMU test series, performed in the summer of 2022, where subjects reported a lack of stability while performing EVA tasks due to poor weigh-outs.

Table 8: Dual suited run functional tasks assessment ratings

	Small HUT Subject Functional Scores			Large HUT Subject Functional Scores		
Task	**Task Difficulty**	**RPE**	**Overall Stability**	**Task Difficulty**	**RPE**	**OverallStability**
Prone to recover	3	6	5	2	3	3
Object Pickup	3	5	3	3	4	2
Squat	2	3	7	2	2	3
One Knee Kneel	2	3	3	3	3	3

C. Lessons Learned

A systematic approach to 1/6th-g weigh-out process using a computational model increased efficiency. As described in the Results section, neutral weigh-out time was reduced to 20 minutes using the new method, compared to 45 minutes on the previous method. The new method also created consistently improved results across subjects of different anthropometry. The weight predictions made by the model are subject and suit specific and can be limited if outdated subject body or suit geometry data is used in the model, or dependent on subject suit fit and posture. However, the predictions have shown to be key to creating acceptable weigh-outs based on current hardware limitations, such as limited weight pockets and foam locations, measurement limitations, and the inherent challenges of weighing out a spacesuit in an underwater environment.

A shift in system CB, combined with a colocation of system CB and CG, led to subjects achieving improved stability when performing some tasks, such as prone to recover and geology tasks, in the NBL simulation environment, when compared to the previous NBL xEMU test series.

Combination of static tasks using force plate data and dynamic tasks to assess extreme EVA tasks and postures, such as one knee kneel and prone to recover, are effective in assessing 1/6th-g weigh-outs underwater. However, there are caveats to what the functional performance data may indicate about the weigh-out. For example, feedback from dynamic tasks may contain artifacts data due to water drag and dampened movement. Weight placement on the suit can introduce mobility restrictions that influence performance, including RPE, stability, and task difficulty. Changes in weight placement between runs and weigh-out configurations can result in varying impacts, considering subjects get weighed out to neutral 3-axis each time they start a run. Accuracy in neutral weigh-out as a subjective visual measurement of magnitude of translational and rotational torques can also introduce errors in modeling of lunar CB and CG.

IV. Forward Work

There are some limitations that exist within the modeling approach. A combination of poor suit fit, outdated 3D body scan and mass data, and inadequate suit model information may result in inaccuracies in the model predictions. The modeling methodology requires continuous improvements as data is gathered at each test event.

Further investigations are recommended to better understand acceptable CB locations and an acceptable magnitude of resultant moment created between CB and CG. The system CG location for an expected flight xEMU model is higher and more aft than the NBL xEMU suit system's system CG, due to foam and weight placement limitations for the NBL suit. The definition of an acceptable weigh-out is currently based on community concurrence and assumptions. An acceptable weigh-out enables subjects to perform EVA-like tasks in a simulated lunar gravity environment, such as kneeling, squats, and walking. An understanding of how the xEMU suit would perform in true lunar gravity would require reduced gravity flight testing. The impacts from different anthropometric range should be also investigated, especially for smaller subjects. Based on initial NBL xEMU results[1], it is hypothesized that performing a weigh-out for small female subjects is more challenging than large male subjects. Additionally, improvements to distribution of weight across the suit can assist with mobility and stability. It is important to ensure arms and legs are weighted and are not buoyant once a subject is being weighed to 1/6th-g. Additional testing to understand the changes in system and component level CB and CG with changes in suit posture is necessary to gain a better understanding of its impact to the simulation environment and any righting moments that may be introduced. Improvements can be made to the EPG design to more optimally distribute the weight pocket locations and foam location within the PLSS to increase stability and realism. The modeling methodology will be applied to future spacesuits and training events to assist in preparing for crew training and applying the present lessons learned.

V. Conclusion

The application of the xEMU computerized weigh-out model appeared to be effective in reducing time taken to weigh-out subjects by as much as 50%, achieving an acceptable 1/6th-g weigh-out for performing EVA tasks in NBL, and providing a repeatable process across a wide range of subjects. Additionally, a combination of higher shift in system CB location and collocation of the system CB and CG proved to improve subjects' stability across the anthropometry range. Further investigations are needed to assess 1/6th-g weigh-out of subjects of more extreme anthropometry.

References

[1] Davis, K., Tejral, Z., Keomany, T., and Vu, L., "Initial Testing of the Exploration Extravehicular Mobility Unit (xEMU) in Lunar Environment Simulation at the Neutral Buoyancy Lab (NBL) in 2022" *52nd International Conference on Environmental Systems*, 2023.

[2] Vu, L., Shaw, J., Kim, H., Benson, E., and Rajulu, S., "Spacesuit Center of Gravity Assessments for Partial Gravity EVA Simulation in an Underwater Environment" *Human Factors Ergonomic Society, 65(6), 1029-1045, 2023.*