National Aeronautics and Space Administration



Development of Weigh Out Process and Evaluations for Underwater Partial Gravity Simulations (ICES-2024-344)

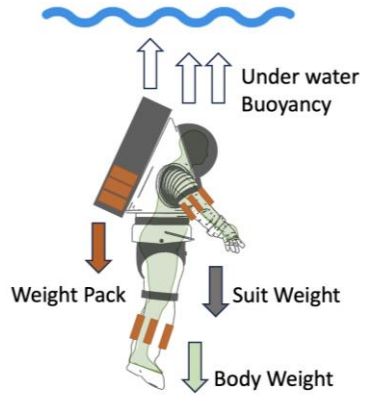
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Pouyan Sabahi, Joseph Yao, KBR Inc., Houston, TX 77058
Linh Vu, Aegis Aerospace, Houston, TX 77058
Han Kim, Leidos Technology, Houston, TX 77058
Christine Jerome, Zach Tejral, Jacobs Technology, Houston, TX 77058
Nate Newby, KBR Inc., Houston, TX 77058

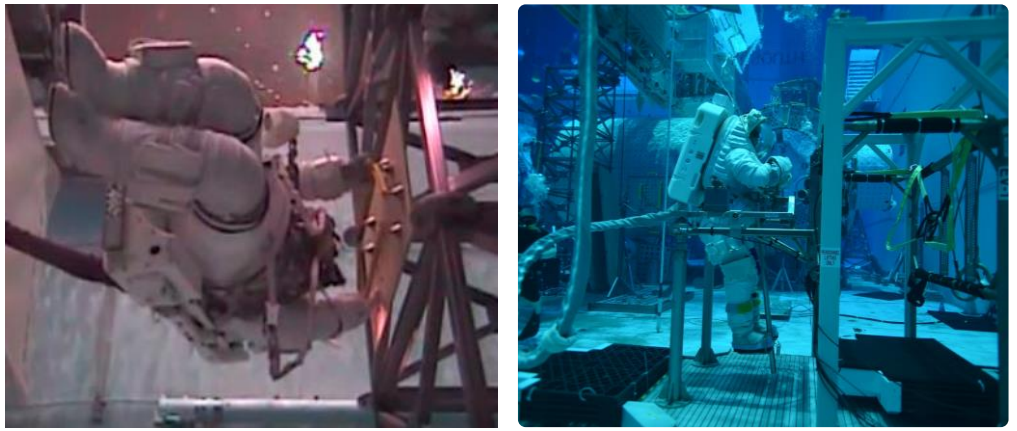
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Background

- Traditionally, weigh outs have been done at the Neutral Buoyancy Laboratory (NBL) for ISS and Shuttle microgravity operations
- With the Artemis Program aiming towards partial gravity human exploration, there is an increased need for partial gravity training facilities that provide good simulation quality
- Partial gravity weigh out: The process of manipulating the center of gravity (CG) and center of buoyancy (CB) to simulate a lunar-like environment:
  - Reduce the overall weight to 1/6 of the total weight
  - Maintain lunar-like balance and inertia



Considerations for NBL weigh out



Microgravity weigh out process (Left) and Partial gravity weigh out process (Right)

Initial NBL xEMU Testing

- During the initial 2022 xEMU NBL test events (NBL 1.0), weight distributions were "**guestimated"** using the Partial Gravity Weigh Out Stand (PGWS) resultant readings
  - While under water, the PGWS measures the resultant force between CB and CG
- This test series indicated that more weigh out development was needed:
  - CB had to be shifted higher using more foam
  - New weight locations were needed to create more stable weigh out configurations without compromising suit mobility
- As a result, a suited CG and CB estimation model was developed to quantify changes to CB and CG during weigh out evaluations
- Inputs from the model were used to support suit PLSS buoyancy redesigns and weight pocket locations on the suit environmental protection garment (EPG)



Suboptimal Weigh out during xEMU 1.0 Test Series

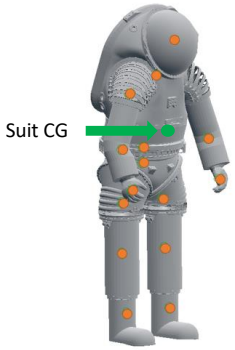


Left, 2022 NBL series foam locations (red highlighted boxes). Right, 2023 NBL series foam locations

NBL Weigh Out Modeling Process Overview



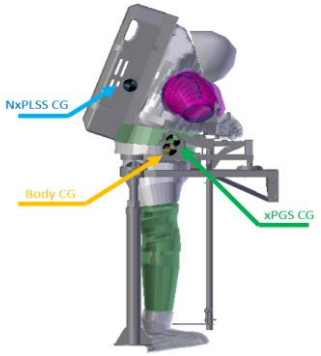
Step 1:
CG Estimation from 3D Body Scan



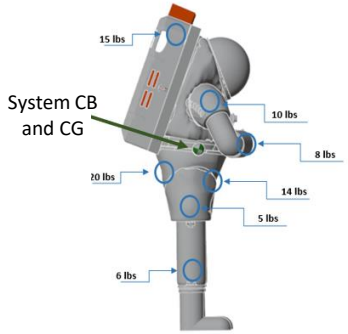
Step 2:
CG Estimation from xEMU Suit Model



Step 3:
Integrate NxPLSS Components, Including Foam



Step 4:
Estimate System CB and CG



Step 5:
Identify Potential Weigh out Configurations

Step 6:
Perform Weigh out Evaluation Tasks on Test Day

$$Resultant\ CG\ location = \frac{CG_1 * m_1 + CG_2 * m_2 \ldots + CG_{\mathrm{n}} * m_{\mathrm{n}}}{\sum_{i=0}^{n} m_n}$$

$$Buoyant\ \mathrm{Force} = V \times \rho \times g$$

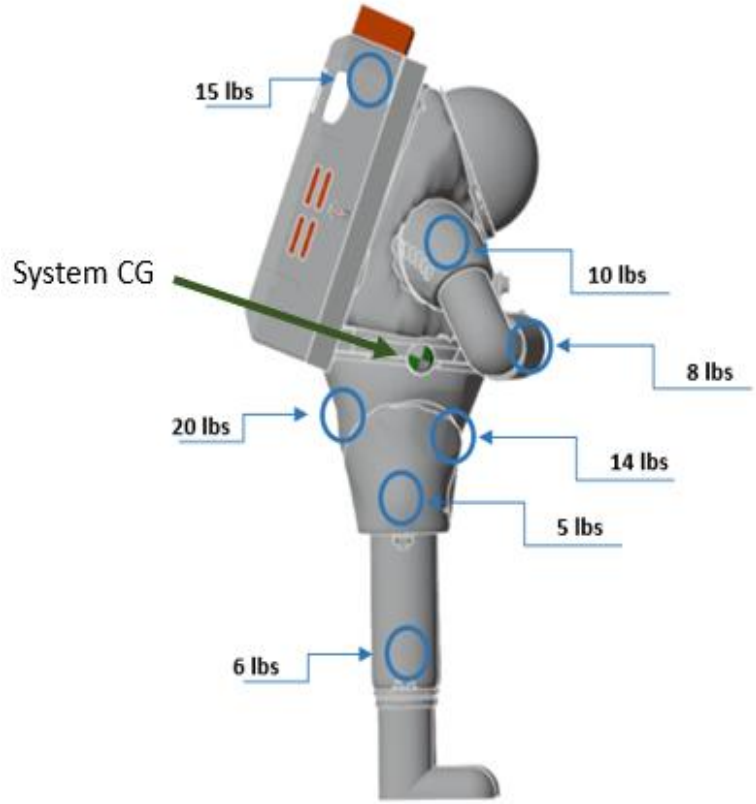
Modeling Subject Specific Weigh Out Configuration

1. Foam amounts are identified and adjusted in model based on test objectives and subject anthropometry

2. Suit is resized in model based on subject suit sizing, and system CB and CG are updated

3. Neutral weigh out: Weights needed to achieve a 3-axis neutral are adjusted iteratively in model until CB and CG are collocated

4. Lunar weigh out: Additional lunar weights are added in the model to achieve the expected 1/6G net downward force while keeping CB and CG collocated



Example of weights added to virtual weight locations in the model

Evaluation Tasks

- Evaluation tasks focused on analyzing functional capabilities, such as object pickup, prone to recover, and single knee kneel
- Weigh out configurations can be modified based on task results
- Evaluation tasks help verify that the subject-specific weigh out is acceptable
  - A universal weigh out configuration does not produce consistent subject performance
  - Suit size, body proportions, and the interplay among dynamic postures are difficult to model and all contribute to variations in subject performance



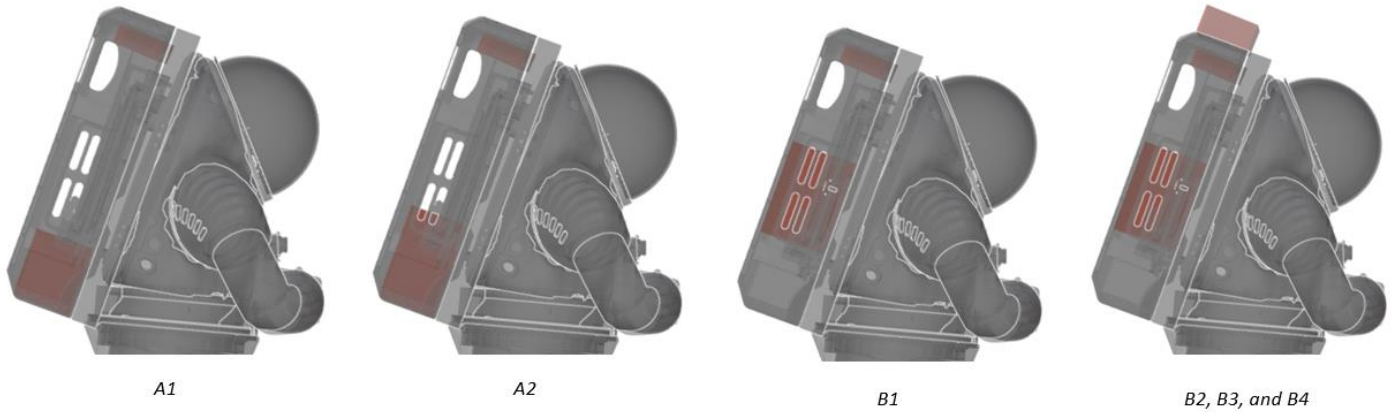
NBL Functional Changes with Weighout

xEMU NBL 2.0 Series Objectives

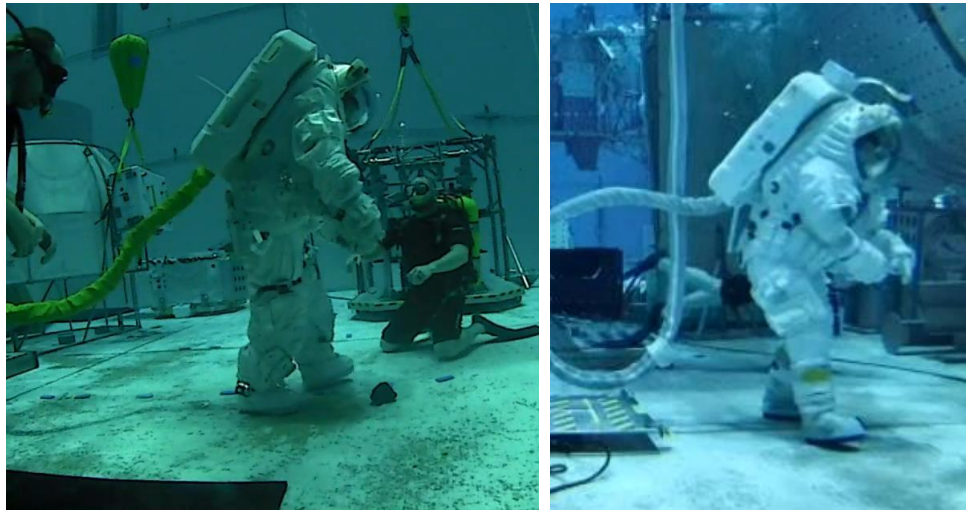
- Phase 1
  - Evaluate initial model capabilities
  - Improve understanding of under water partial gravity weigh out while shifting CB higher
  - 1-g measurements taken after 3-axis neutral are done to help improve CB model
- Phase 2
  - Evaluate updated model accuracy to PGWS readings
  - Improve understanding of under water partial gravity weigh out for a wider range of anthropometry
  - 1-g measurements taken after 3-axis neutral are done to help improve CB model
- Phase 3
  - Evaluate partial gravity weigh out capabilities across a simulated EVA training through a dual suit run

Results – Phase 1

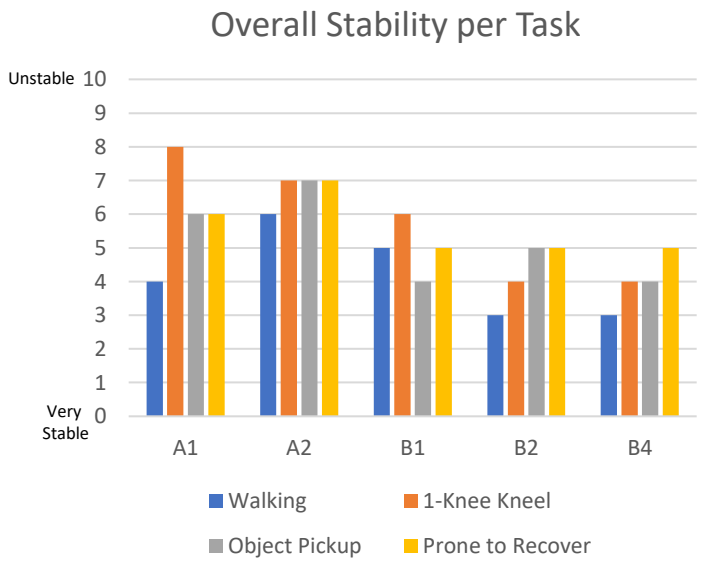
- One test subject tried 6 different weigh out configurations to better understand the effects on suited performance, with only weights changing between B2-B4 configurations
- Shifting CB higher and collocating CB and CG drastically improved subject stability across functional tasks
- Subjective ratings showed an increase in stability as CB was shifted higher

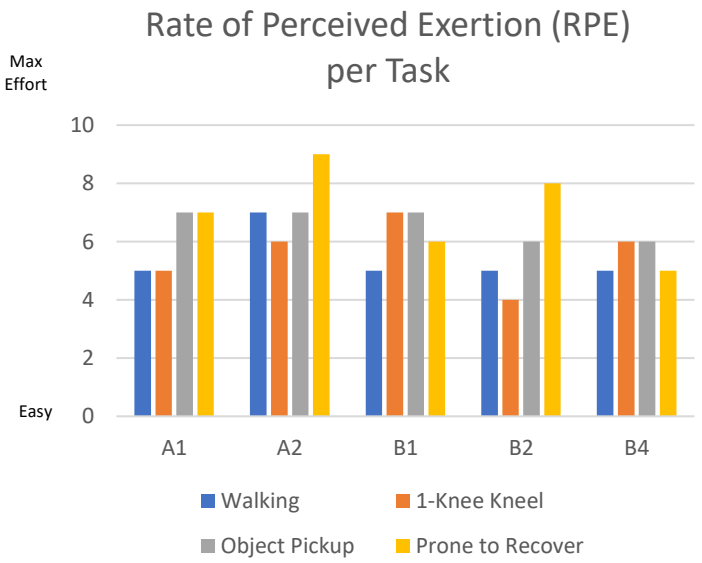


Foam configurations tested during Phase 1



Comparison of Object Pickup in NBL 1.0 (Left) vs. NBL 2 Phase 1 B4 Configuration (Right)

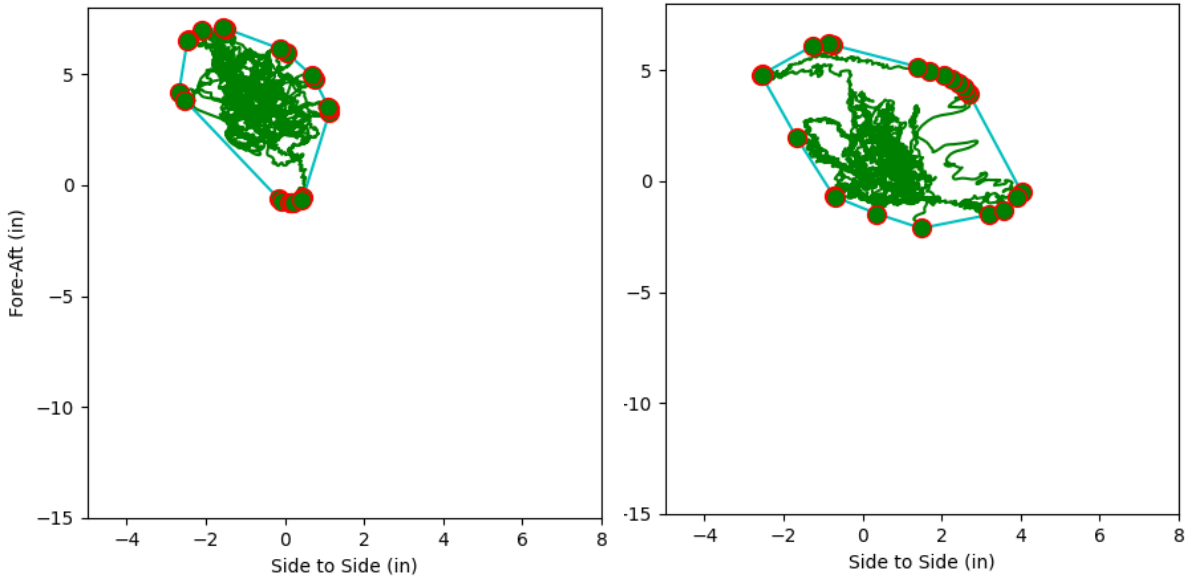




Results – Phase 2

- 2 new foam configurations tested across 2 subjects (1 small and 1 large HUT) that maximized the achievable high CB location
  - C1: maximum foam possible, both inside and over the PLSS
  - C2: maximum foam possible inside PLSS
- Large subject had lowest difficulty ratings in max foam config
- Force plate data across evaluation tasks, such as squatting, showed increase in stability (smaller center of pressure (CoP) excursion ranges) in higher CB configuration C1





Comparison of squat force plate data for large HUT subject in C1 (Left) vs. C2 (Right)

Model Refinement

- Additional model verification and refinement was performed using force plate measurements from the Partial Gravity Weigh out Stand (PGWS)
- Once divers performed a 3-axis ISS neutral weigh out, subject was pulled out of the water and their CG was measured
- A series of PGWS measurements were taken on the pool deck of the suited subject, and the model was adjusted to match the 1-g data after Phase 1 testing
- During Phase 2, model predictions were compared to 1-g data from 2 new subjects, showing the predicted neutral CB location within 0.5 in. in each axis of the PGWS measured point

Subject	Foam Configuration	Model CB – 1-g Measurement Difference
Large HUT	C1	(0.33, 0.03, 0.01)
	C2	(0.03, 0.13, 0.18)
Small HUT	C1	(0.22, 0.07, 0.15)
	C2	(0.25, 0.10, 0.48)

Phase 2 comparison of model CB to 1-g measurements

Results – Phase 3

- Two subjects tested – one average male (Small HUT), one larger male (Large HUT)
- Testing showed that predictive modelling of CB could be implemented successfully
- A functional weigh out was achieved for the subjects but the final weigh out was still likely not representative of a flight CG. The magnitude of impact is indeterminate.
  - Both subjects were successful in performing geology and manual materials handling tasks in model-predicted lunar weigh outs
- Time to achieve initial neutral weigh out was reduced by as much as 50% using model predictions as a baseline
  - compared to the initial xEMU NBL Lunar Test Series
  - Achieving a neutral weigh out is a portion of the full weigh out process



Phase 3 subjects performing EVA geology tasks

Lessons Learned - Simulation Quality

- Familiarization run for new subjects is key to distinguish weigh out related issues and ensure generated data is meaningful
- A shift in system CB, combined with a colocation of system CB and CG, led to subjects achieving improved stability when performing some tasks
- Neutral weigh out is a subjective visual measurement of translational and rotational torques which can introduce deviations in modeling of lunar CB and CG
  - Neutral weigh out has not been demonstrated to be repeatable, leading to challenges achieving an acceptable Lunar weigh out
- Weight placement on the suit can introduce mobility restrictions that influence performance, including RPE, stability, and task difficulty
- Additional weigh out data is necessary to develop a complete understanding of the training facility and its simulation quality

Lessons Learned – Modeling Process

- Outdated body scans and subject mass data can lead to inaccurate modeling
  - Receiving updated body mass prior to runs can reduce uncertainty
- Preloading model predicted weights can reduce neutral weigh out time by up to 50%
- As more weigh out data is gathered across the anthropometric range, new subject models can improve by referencing past weigh out experience as guidance

Forward Work

- The weigh out process maturation involves:
  - Further testing to better understand the effects of various correlations between CB and CG
  - Conduct additional testing with a greater anthropometrically diverse subject pool
  - Demonstrate consistent weigh out performance
  - Model refinement
  - Assess more dynamic postures to understand CG deviations
- Collect and compare standardized metrics from future parabolic flight/lunar missions to fine-tune weigh outs for greater lunar simulation fidelity



Questions?

Pouyan Sabahi
seyedpouyan.sabahi@nasa.gov

Nate Newby
nathaniel.newby@nasa.gov