



Development of an Extravehicular Activity Physical Workload Simulation for Use in Ground Validation of Exploration Prebreathe Protocols

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Disclosures



- No conflicts of interest/disclosures



Why Exploration Atmosphere?



- Significantly more frequent EVA expected during planetary ops vs. ISS
 - Up to 24 hrs / person / week
- No validated protocols exist for planetary EVA
 - Shuttle & ISS protocols are applicable to microgravity only
- 4:30 resting prebreathe used for 1-g chamber tests > 2 hours
 - 19.5% estimated Type I (pain only) DCS Risk for 8 hour run
 - Almost immediate access to medical care and hyperbaric treatment

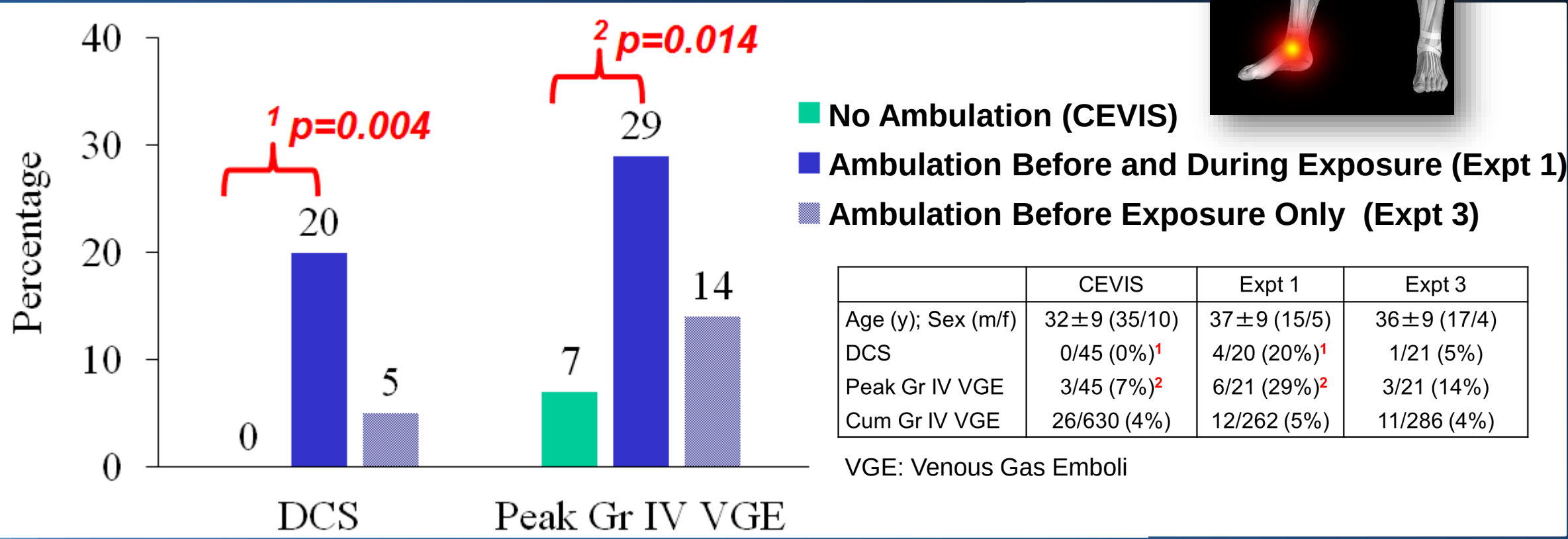


Apollo had 100% O₂
cabin and zero EVA
prebreathe



Planetary vs. Microgravity

- DCS risk is increased by ambulation and physical activity during altitude exposure ^[1]



¹Conkin J, Pollock NW, Natoli MJ, Martina SD, Wessell JH III, Gernhardt ML. Venous gas emboli and ambulation at 4.3 psia. *Aerosp Med Hum Perform.* 2017; 88(4):370–376.



Protocol: EVA Simulations



- Odd Days: EVA Simulations ($N_{EVA} = 5$)
 - Subjects don masks and breathe 85% O_2 during 15 min depress to 4.3 psia.
 - DTs prebreathe 100% O_2 for 30min prior to depress
 - Complete 6 hrs of prescribed simulated EVA activities
 - Rest + noninvasive Doppler and ultrasound bubble monitoring every 15 min during the EVA simulation
 - 15-min repressurization to return all subjects and DTs back to 8.2 psia

Day 1	3hr PB @ 100% O2, 14.7 psia; Depress to 8.2 psia, equilibrate
Day 2	Equilibrate + Hypoxia Characterization
Day 3	Prebreathe; 6hr EVA @ 4.3 psia, 85% O2
Day 4	
Day 5	Prebreathe; 6hr EVA @ 4.3 psia, 85% O2
Day 6	
Day 7	Prebreathe; 6hr EVA @ 4.3 psia, 85% O2
Day 8	
Day 9	Prebreathe; 6hr EVA @ 4.3 psia, 85% O2
Day 10	
Day 11	Prebreathe; 6hr EVA @ 4.3 psia, 85% O2



Requirements/Constraints



1. Does not require use of spacesuits
2. Constraints of the test chamber:
 - Confined space (limited volume)
 - Avoid loud noises
 - Communication and oxygen umbilical lines required for each subject (choreography/umbilical management)
 - Equipment must pass flammability/offgassing criteria
 - Avoid powered equipment for non-research devices
3. Match physical workloads to what is likely for planetary EVAs
 - Accurate representation of planetary EVA activities
 - Validate towards the higher-end of suit and PLSS capabilities
4. Interruptible every 15min (for doppler/ultrasonography)
5. Long, repetitive, high-tempo EVAs
 - Needs to be repetitive enough for a controlled study
 - Sustainable for 6+ hours
 - Find the balance between monotony, complexity, and achievability

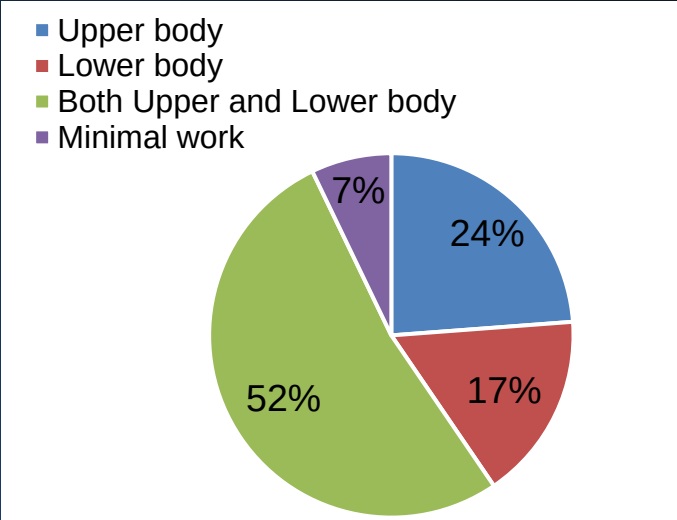




EVA Simulation – Rationale for Tasks



- 61 exploration EVA tasks^[2] were decomposed into 126 subtasks and then characterized by functional requirements of each subtask
- Categories:
 - **Body Positioning:** Seated, Kneeling, Standing, Mobile, etc.
 - **Muscle Groups:** Whole/Both, Upper, Lower
 - **Ambulation:** None, Walking, Walking (terrain), Walking (slopes), Crawling, Climbing
 - **Loading Bearing:** None, Carrying, Pushing/Pulling, Attached to Suit
 - **Loads:** None, Minimal (<5 lbs), Variable, Heavy (>30 lbs)
 - **Upper Body Reach (Workspace):** None, Standard, Extended
 - **Hand Usage:** None, Fine Motor Skills, Grip Strength, Vibration, Shock, Other/Combination
 - **Task Occurrence:** Rare (<10% of EVAs), Some (~30%), Many (~50%), Most (~75%), Nearly All (>90%)
 - **Task Duration (expected)**
 - **Task Frequency:** 1-2 times per EVA, Every 2 hours during EVA, Every hour during EVA, 1-30 minutes during EVA



Parent Task Title	Children of the Parent Task	Load Bearing Type	Upper Body Loads	Upper Body Reach	Fine Motor / Grip	Task Occurrence	Task Duration	Task Frequency
Offload Equipment from Landers	mobile, upper and lower body work	Carrying Load	Variable Load (minimal to heavy)	Extended Workspace	Grip Strength	Rarely Occurs in any EVA (<10%)	5-15 minutes	Every 1-30 minutes during EVA
Offload Equipment from Landers	mobile, upper and lower body work	Pushing / Pulling Load	Heavy Load (> 30 lbs.)	Extended Workspace	Grip Strength	Rarely Occurs in any EVA (<10%)	5-15 minutes	Every 1-30 minutes during EVA
Load Equipment onto Rovers	mobile, upper and lower body work	Carrying Load	Variable Load (minimal to heavy)	Extended Workspace	Grip Strength	Occurs in many EVAs (~50%)	5-15 minutes	Every ~1 hr during EVA
Clean Equipment	stationary, upper body work while kneeling	No Load	No Significant Loading	Extended Workspace	Fine Motor	Occurs in some EVAs (~30%)	15-60 minutes	Total of 1-2 times during EVA
Clean Equipment	stationary, upper body work while standing	No Load	No Significant Loading	Extended Workspace	Fine Motor	Occurs in most EVAs (~75%)	15-60 minutes	Total of 1-2 times during EVA
Conduct Visual Inspection / Examine Surroundings	mobile, ambulation	No Load	No Significant Loading	None	Fine Motor	Occurs in nearly all EVAs (90-100%)	1-5 minutes	Every 1-30 minutes during EVA
Conduct Visual Inspection / Examine Surroundings	seated	No Load	No Significant Loading	None	Fine Motor	Occurs in nearly all EVAs (90-100%)	1-5 minutes	Every ~1 hr during EVA
Conduct Photo Documentation	stationary, upper body work while kneeling	Other / Unknown	Minimal Load (less than 5 lbs.)	Standard Workspace	Fine Motor	Occurs in nearly all EVAs (90-100%)	1-5 minutes	Every 1-30 minutes during EVA
Conduct Photo Documentation	stationary, upper body work while standing	Other / Unknown	Minimal Load (less than 5 lbs.)	Standard Workspace	Fine Motor	Occurs in nearly all EVAs (90-100%)	1-5 minutes	Every 1-30 minutes during EVA

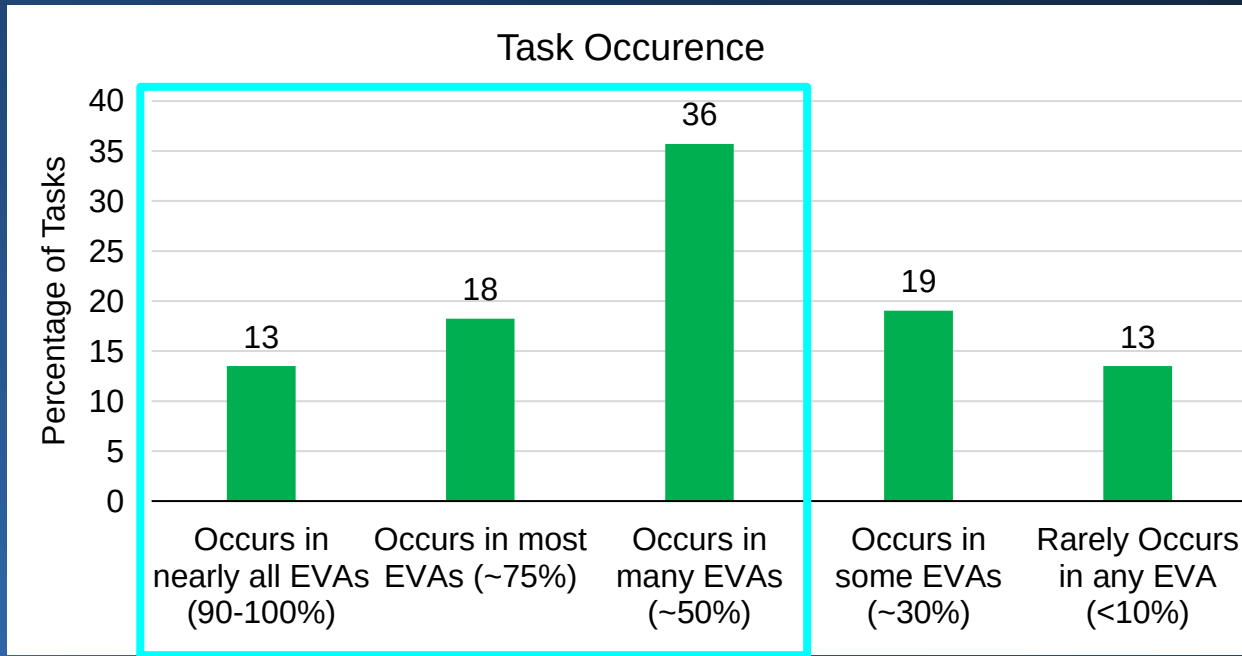
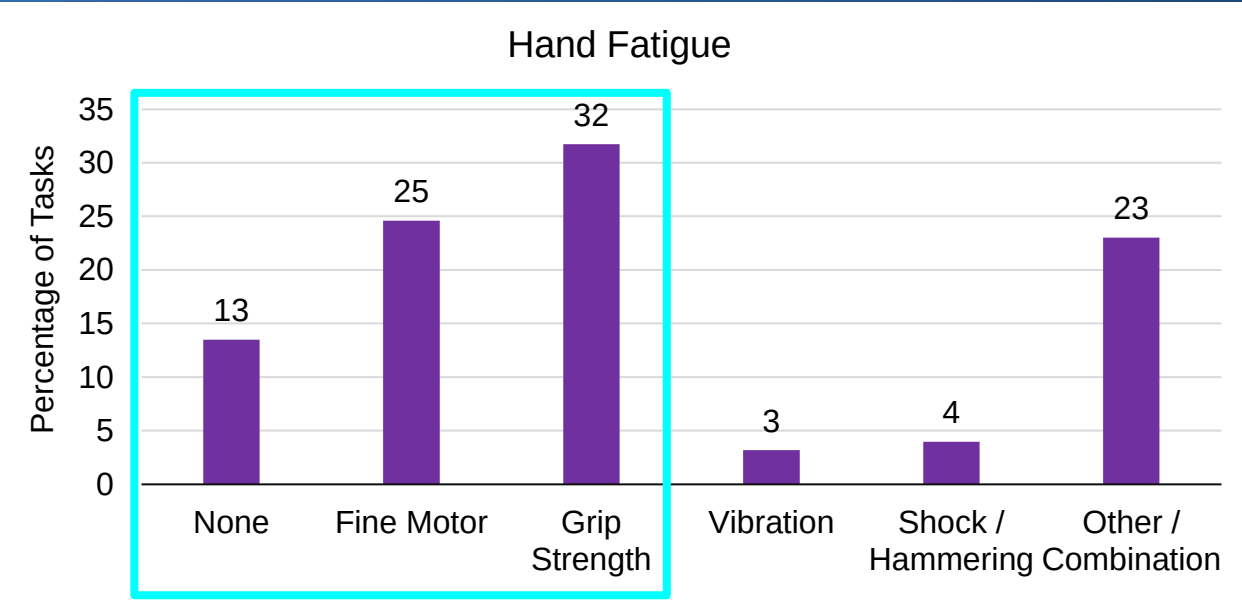
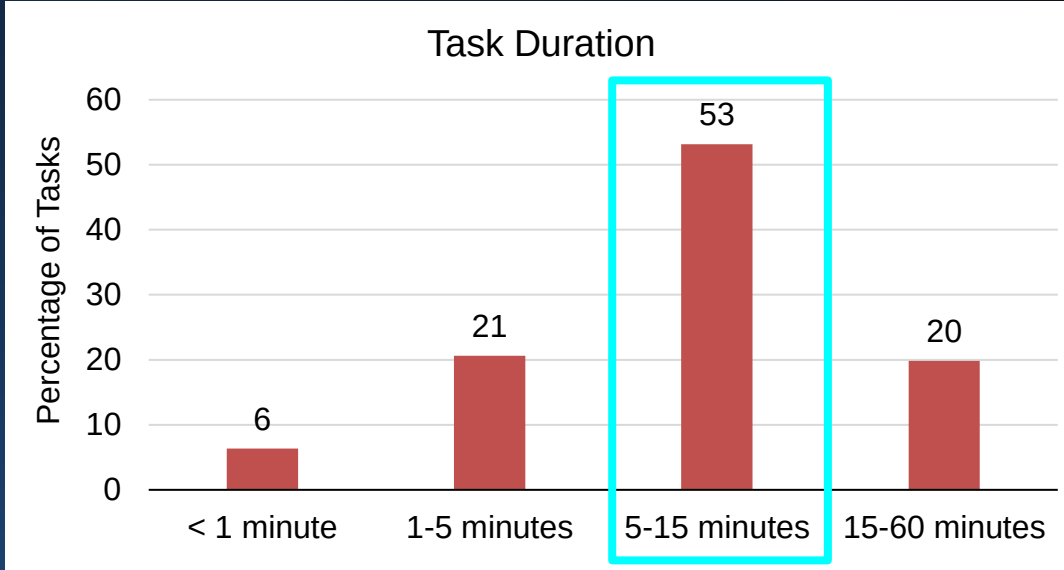
²Coan D. Exploration EVA System Concept of Operations. NASA TR, EVA-EXP-0042 RevB. 2020



EVA Simulation – Rationale for Tasks



- Most defined EVA tasks were expected to have 5-15minute durations, and occur across at least 50% of EVAs
- Hand-focused tasks are more geared towards grip strength and fine motor movements

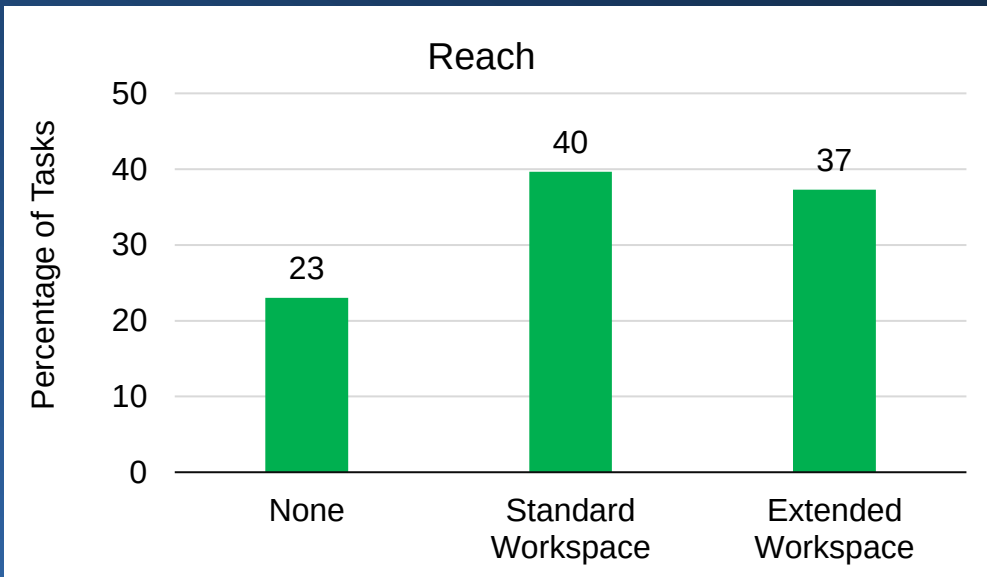
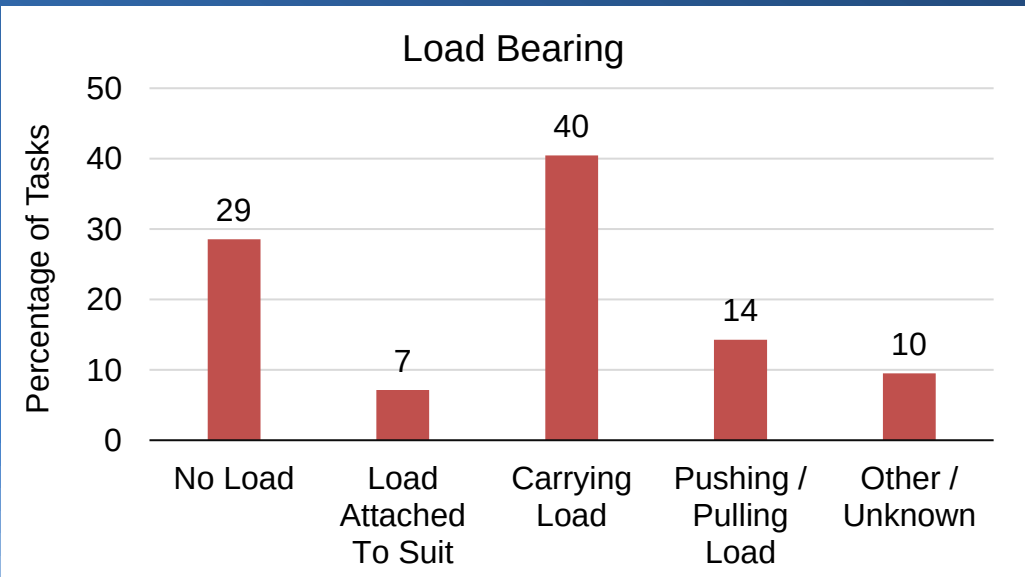
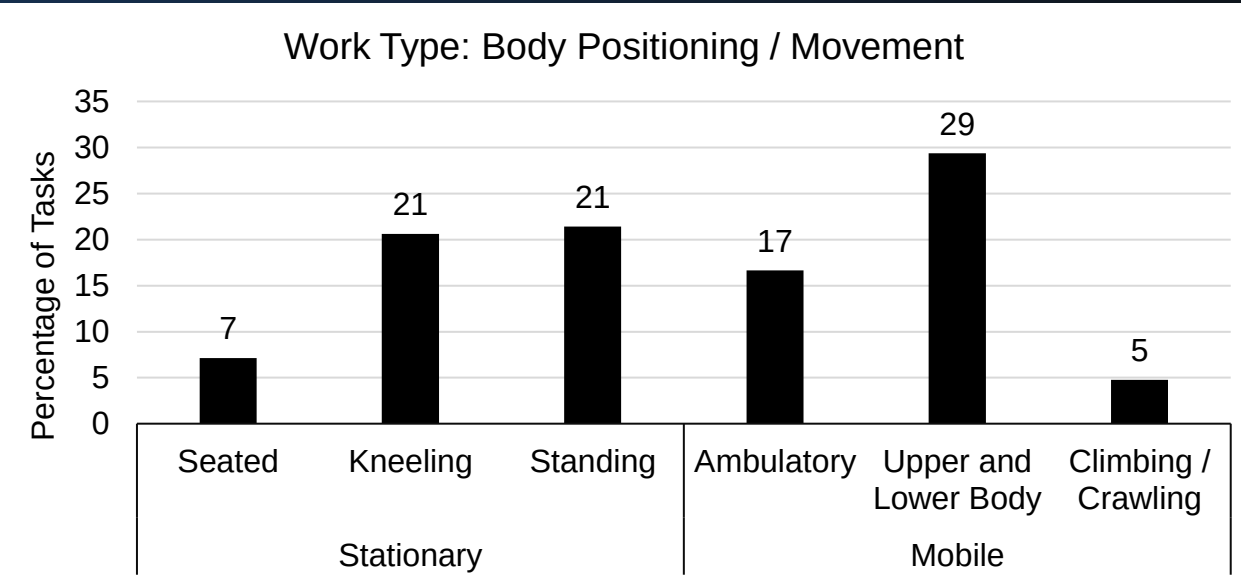




EVA Simulation – Rationale for Tasks



- Tasks were pretty evenly split between:
 - Upper- and lower-body usage
 - Standing and kneeling
 - Standard and extended workspaces
- Many tasks involved interaction with some load





EVA Simulation – Final Task Circuit



- Navigate, ascend/descend, and traverse terrain
 - **Step-ups (low and high)**: lower/full body task, no powered equipment required, can alter workload with step size and cadence
- Retrieve, transport, and stow equipment/tools
 - **Weight transfer**: mobile whole body task
- Collect samples, conduct repairs, or install connectors
 - **Kneeling task board**: stationary task, mild cognitive engagement
 - **Standing task board**: stationary task, mild cognitive engagement
- Deploy/operate experimental package
 - **Arm ergometer**: stationary upper body task, can standardize workload with rpm and resistance
- Target: Maintain an average of 30-40% VO₂max^[3-5]
 - High-step included a fast 2-min period (70%), as high levels of activity have been shown to highly correlate with DCS risk^[6]

	Task	ConOps	Workload Rx
1	High Steps	Ambulation on Uneven Terrain	Step Height at 12 inch Cadence to target 50-70% VO2peak
2	Standing Task Board	Maintenance R&R and Procedures	---
3	Weight Transfer	Transport Equipment/Tools	Number of transfers (15 or 25lb weights)
DOP	Doppler / Rest	Rest	---
4	Low Steps	Ambulation on Flat Terrain	Step Height at 6 inch Cadence to target 50% VO2peak
5	Arm Ergometer	Deploy Experiments, and Use Sampling Tools	Resistance at 30W Cadence to target 30%VO2peak
6	Kneeling Task Board	Kneeling, Fine Motor, Upper Body	---
DOP	Doppler / Rest	Rest	---

³Astrand I. Degree of strain during building work as related to individual aerobic work capacity. Ergonomics. 1967;10(3):293-303.

⁴Jørgensen K. Permissible loads based on energy expenditure measurements. Ergonomics. 1985;28(1):365-9.

⁵Epstein Y, Rosenblum J, Burstein R, Sawka MN. External load can alter the energy cost of prolonged exercise. Eur J Appl Physiol Occup Physiol. 1988;57(2):243-7.

⁶Webb J, Krock L, Gernhardt M. Oxygen consumption at altitude as a risk factor for altitude decompression sickness. 2010; 81(11): 987-992.



EVA Simulation – Task Decomposition



- The EVA Sim includes approximately 75% of the ConOps functional tasks:
 - Does not include airlock and spacesuit control tasks
 - Also missing some science tasks (e.g. trenching, pushing a cart)
- The EVA Sim aligns with the distribution of workload categories, see below:

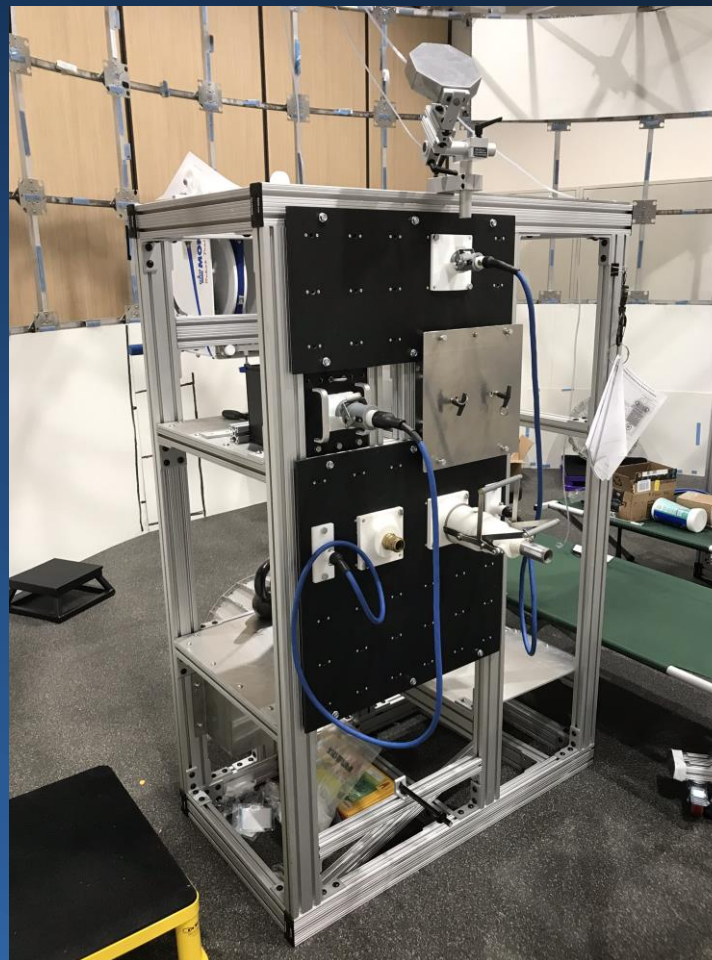
Categories	ConOps	EVA Sim	Step-Ups 1	Standing Task Board	Weight Transfer	Step-Ups 2	Arm Ergometer + Tools	Kneeling Task Board
Mobile	~50%	~50%	Yes		Yes	Yes		
Standing	~20%	~20%		Yes			Partial	
Kneeling	~25%	~20%					Partial	Yes
Upper Body Work	~40%	~45%		Partial	Yes		Yes	Partial
Carrying Load	~30%	~25%		Minimal	Yes		Minimal	Minimal
Extended Workspace	~30%	~30%			Yes			Yes
Grip Strength	~45%	~45%		Yes	Yes		Partial	Minimal
Fine Motor	~30%	~30%		Partial	Minimal		Minimal	Yes



EVA Simulation Station



- A central task station was needed due to the spatial limitations in the chamber.
 - Size: 24" x 44" x 60"
 - Ultem 9085 and metallic components
- Each side of the station has 2 tasks
 - Side A (left): Standing Task Board, Weight Transfer
 - Side B (right): Arm Ergometry, Kneeling Task Board
- Detailed EVA-like procedures
 - Requires procedure document and pre-test training





Taskboard Procedures



- Standing Tasks:

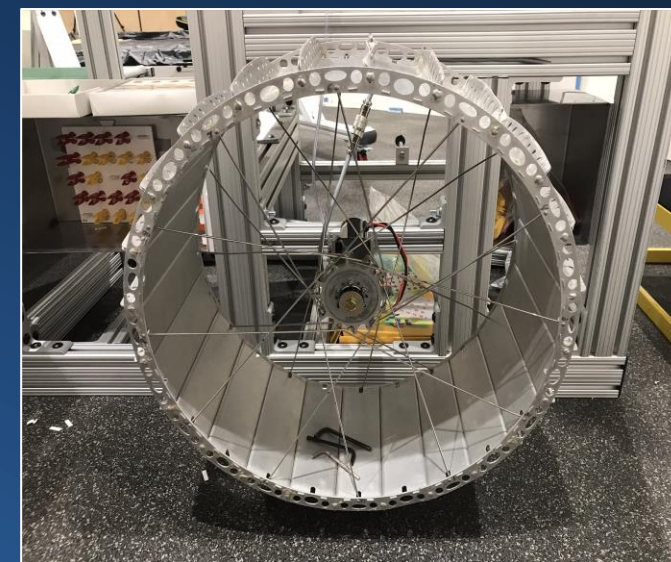
- Small/medium orbital replacement unit (ORU) repair and replace (R&R)
- Antenna Array R&R
- Fluid Disconnect Jumper R&R

- Kneeling Tasks:

- Rover Wheel R&R
- Rover Drive Motor R&R
- “Geology Sampling”

- Simulated flight-like components:

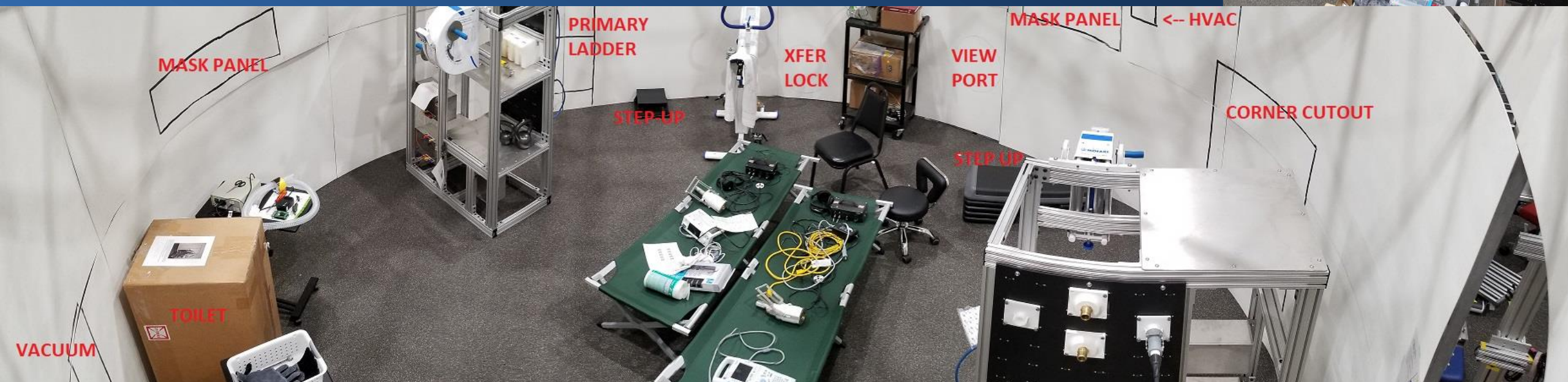
- Bolts, pins, cables, and fasteners
- Wrenches, wire ties, storage
- Electrical and fluid connectors





Choreography - Hippodrome

- H-3PO Design, Research, and Operational Mockup Environment
- Representative 1st floor mockup in B21
 - Functional checkouts
 - Layouts and choreography
 - Procedure refinement and documentation
 - Training and dry runs

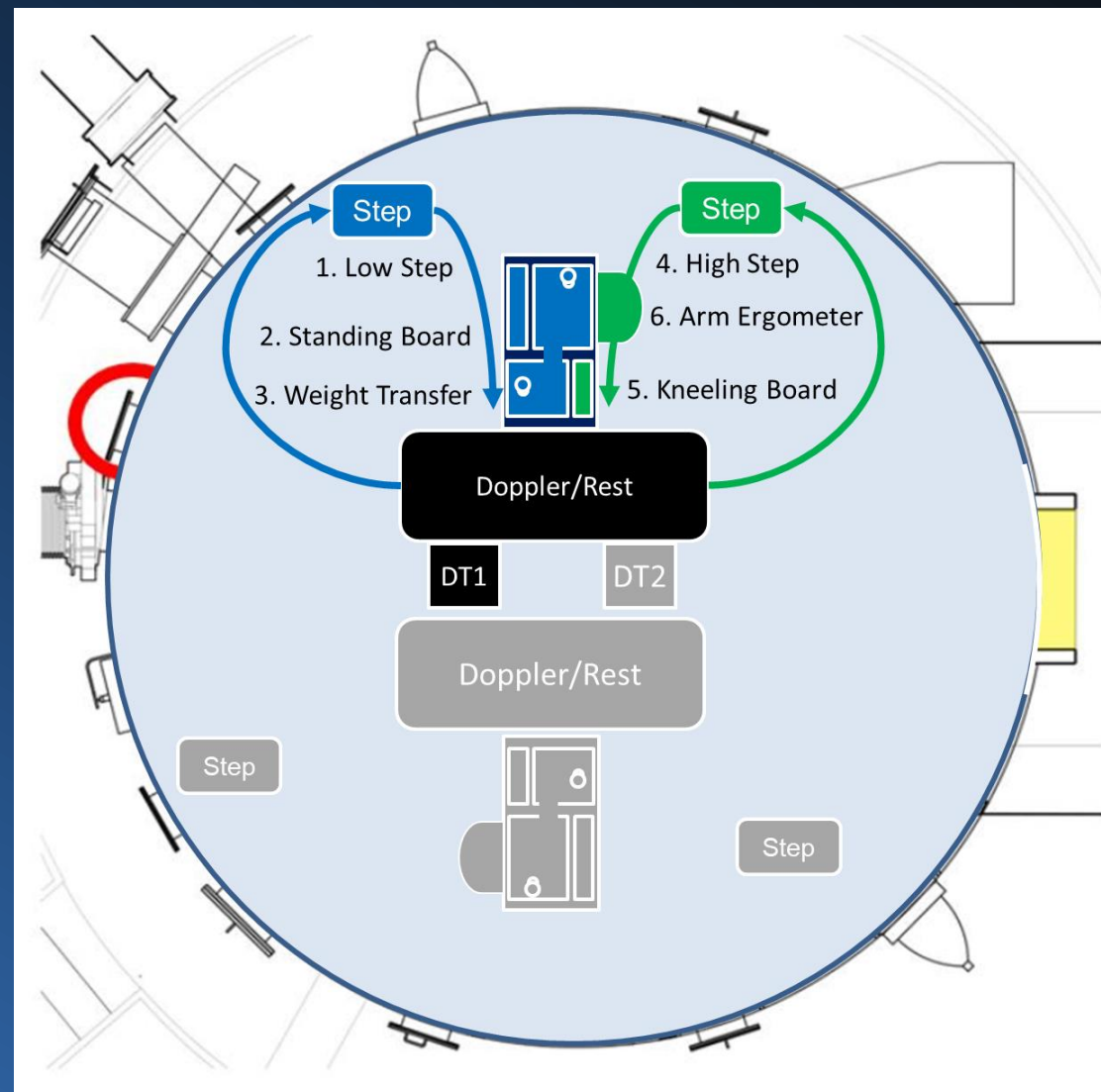


- Layout:

- Divide the Chamber into two halves
- Separate into two teams of 4 people:
- 3 subjects and 1 Doppler Technician (DT)
- Deconflict subject spacing between tasks

- Choreography:

- Doppler/US Monitoring every 15 min
- Perform Tasks 1, 2, and 3 for **5-min each** (total of 15 min), then Doppler / rest.
- Perform Tasks 4, 5, and 6 for **5-min each** (total of 15 min), then Doppler / rest.





EVA Simulation – Pilot Testing



- Assessed the feasibility of performing repeated and timed EVA-simulated tasks in a confined area, while also characterizing the metabolic costs and overall acceptability
 - N = 8
 - Collected VO_2max on all subjects prior to testing, as well as some pilot data for each task
 - Not all subjects completed a full 6-hour runthrough (due to schedule/availability)
 - Captured some subjective responses for pain to distinguish from DCS symptoms
- Subjects were prescribed workloads based on individual VO_2max
 - Workloads based on ACSM Calculator or pre-pilot data
 - Step-up and arm ergometry cadences were tracked using a metronome
- Subjects were pre-trained on each task
- Some subjects wore specialized clothing or flight suits to mimic the thermal conditions of the actual test chamber
- Heart Rate was actively monitored using a Garmin HRM-PRo
- Metabolic Parameters (VO_2 , VCO_2 , RR, metabolic rate) were measured using a Cosmed K5
 - Data reported come from last minute of each 5-minute task segment



Workload Calculator



- Individual work rate prescriptions were based on a combination of existing validated calculations through ACSM and prior data.

SUBJECT											
	ID	Hippo1									
	Female or Male:	male									
	Weight	180 lbs		82 kg							
	Cycling VO2peak (measured)	4 L/min		49 ml/min/kg							
	Treadmill VO2peak (calculated)	4.4 L/min		54 ml/min/kg							
TASKS											
	Reference	Target VO2	Target VO2	Calculated	PILOT	Task VO2	total	Fractional			
	Equivalent	(% of peak)	(ml/min/kg)	BTU/hr	BTU/hr	(L/min)	hours	VO2 (L/min * total hrs)	Task Parameters	Task Rate	
1 Low step	Target VO2	40%	22	2038		1.76	0.75	1.32	Step height (inch) = 10	22 steps/min	--> 45 cadence (compare to PILOT study)
2 Standing Task Board	PILOT DATA: BUSY BOARD				1149	0.97	0.75	0.72			
3 Weight Transfer	PILOT DATA: UNLOAD / LOAD				2144	1.80	0.75	1.35			
4 Rest	PILOT DATA: MOCK DOPPLER / REST				924	0.78	0.75	0.58			
5 High Step	Target VO2	40%	22	2038		1.76	0.60	1.06	Step height (inch) = 12	19 steps/min	--> 39 cadence (compare to PILOT study)
	2 min at 70-80%!	75%	40	3822		3.30	0.15	0.50	Step height (inch) = 12	40 steps/min	--> 79 cadence (compare to PILOT study)
6 Kneeling Task Board	PILOT DATA: FINE MOTOR / KNEELING				1442	1.21	0.75	0.91			
7 Arm Ergometer	Target VO2	30%	16	1529	1496	1.32	0.75	0.99	Monark Power setting (W at 50RPM)= 30	96 rpm	--> 345 kg*m/min (Work Rate)
8 Rest	PILOT DATA: MOCK DOPPLER / REST				924	0.78	0.75	0.58			
				6 hours							
				Avg BTU/hr:	1589	Average VO2:	1.34 L/min				
				30 % <-- Target 30-40% VO2peak							
										red = above target	
										green = within target	
										blue = below target	

⁶Engineering ToolBox, (2004). Met - Metabolic Rate. [online]



Pilot Data – Subject Results



Subject	Sex	VO _{2peak} (mL·kg ⁻¹ ·min ⁻¹)	Rounds completed per Session	%VO _{2peak} per round (mean ± SD)
01	Male	31.4	8.5	40 ± 19
02	Male	40.4	2	36 ± 14
03	Female	37.7	3	41 ± 23
04	Female	36.9	3	30 ± 13
05	Female	37.0	3	33 ± 18
06	Male	46.4	2 rounds	33 ± 18
07	Female	38.1	2 rounds	36 ± 16
08	Male	31.3	8.5 rounds	44 ± 19
The full 6-hour protocol planned for the 11-day chamber study includes 8.5 rounds (lasting 40 minutes each) plus 20 minutes of additional rest.				



Pilot Data – Simulation Results



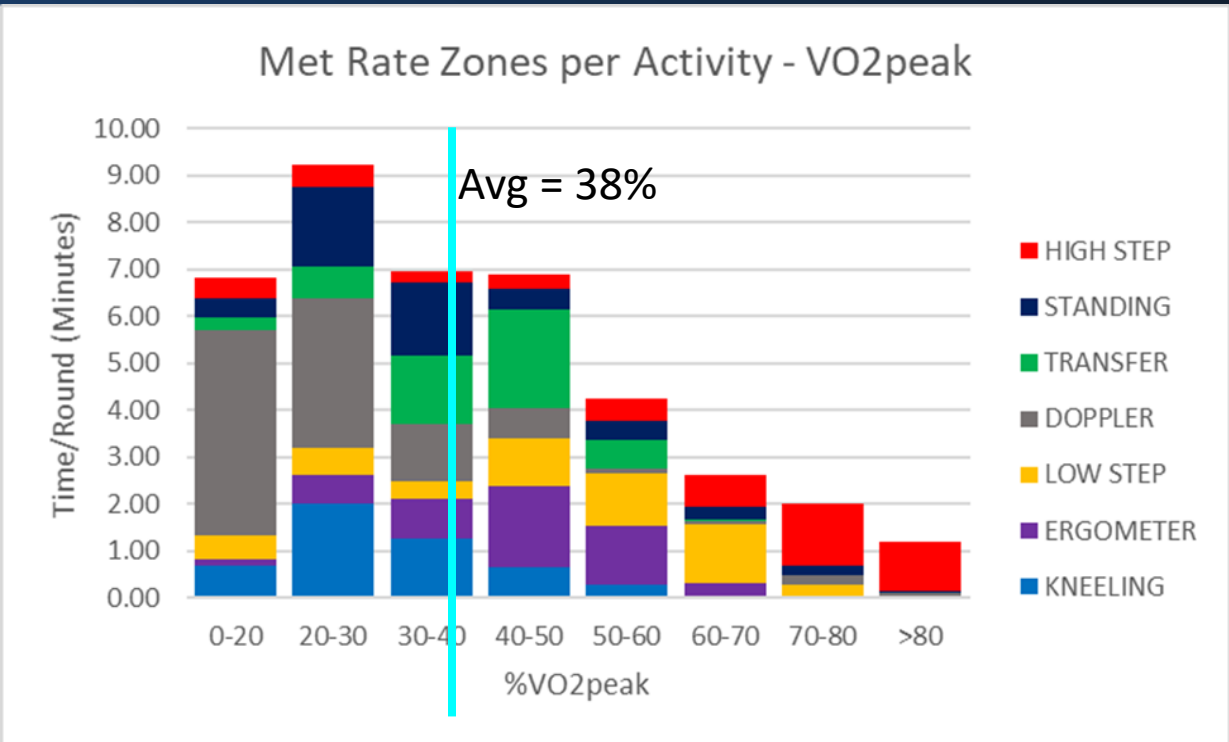
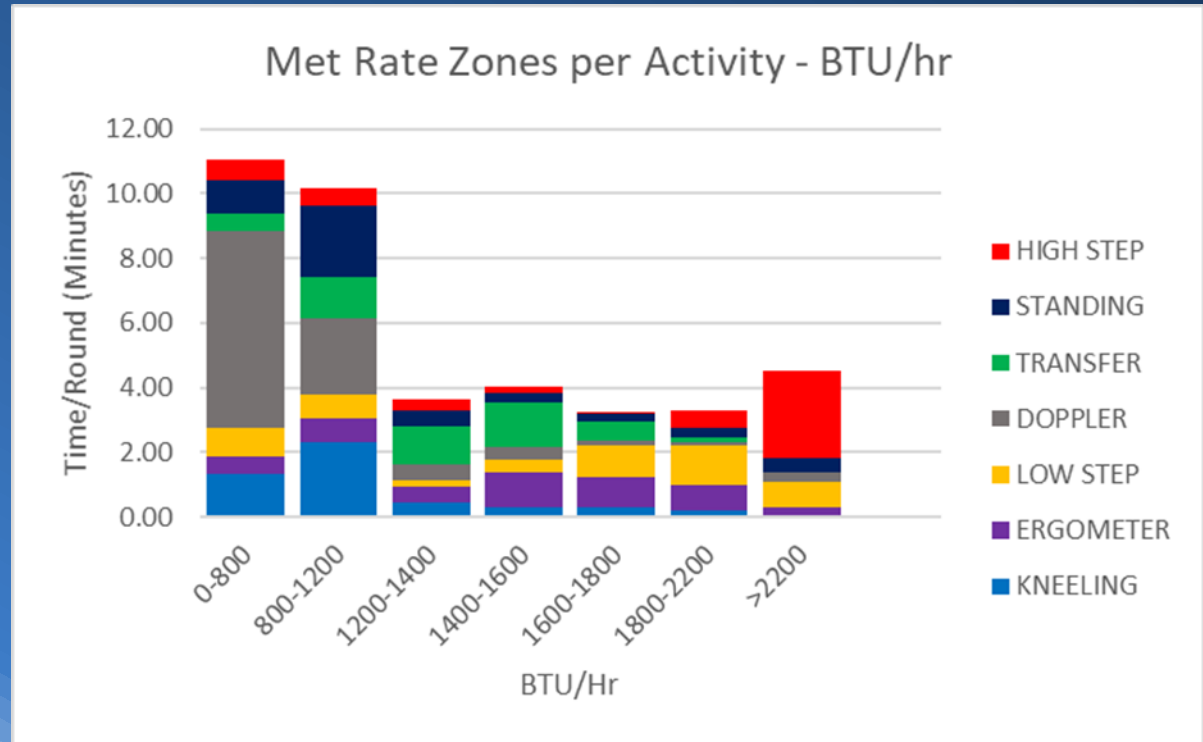
						Observed during Test Development (mean ± SD, n=8)	
TASK	TASK	Predicted BTU/hr	Equivalent	total hrs	Predicted BTU	BTU/hr	%VO _{2peak}
1	Low step	1500	Targeted BTU	0.75	1125	1886 ± 396 [#]	57 ± 10 [#]
2	Standing Task Board	712	Standing Medium Work	0.75	534	914 ± 214 [#]	28 ± 5 [#]
3	Weight Transfer	1688	Building Industry	0.75	1266	1402 ± 270 [#]	43 ± 7 [#]
5	High Step	2500	Targeted BTU	0.75	1875	2223 ± 623 [#]	68 ± 16 [#]
6	Arm Ergometer	1000	Targeted BTU	0.75	750	1588 ± 437 [#]	47 ± 10 [#]
7	Kneeling Task Board	430	Sedentary activity	0.75	323	861 ± 211 [#]	26 ± 6 [#]
4 & 8	Rest	282	Reclining	1.5	423	627 ± 306 [#]	19 ± 9 [#]
6 Hour Total:					6296		
Average (BTU/hr):					1049	1274 ± 653 [*]	39 ± 19 [*]
[#] Average metabolic rate recorded during <u>final minute</u> of 5-minute activity cycles to reduce bleed-over effects from previous activities in the round.							
[*] Average total metabolic rate from 8 subjects completing between 2 - 9 rounds.							



Pilot Data - Results



- The average %VO₂peak across all tasks was ~38% (1274 BTU/hr).

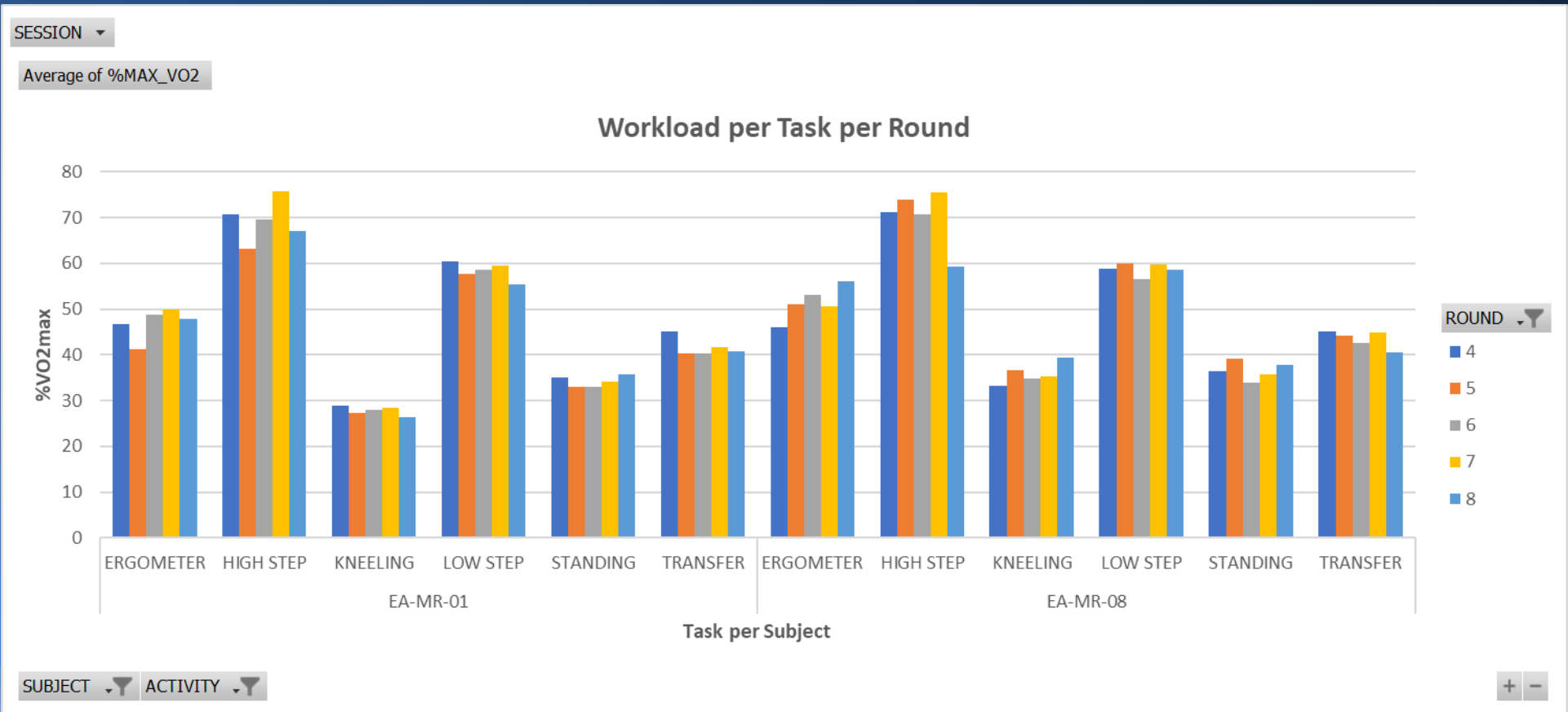




Pilot Data - Results



- No significant change (decrease) in workload observed over time
 - N = 2, used first three rounds to “calibrate” subject to appropriate workload
 - Subjective assessment from other individuals and events indicates that the prescribed workloads are sustainable for 6-hours





Lessons Learned



- Recovery from preceding tasks made it difficult to characterize each task individually.
- Almost all task prescriptions (except for High Step and Weight Transfer) tended to over-estimate the work rates required to maintain %VO₂peak targets.
 - Average work rates ranged from 600 to 2300 BTU/hr.
 - Resulted in higher metabolic rates than predicted (1274 BTU/hr observed vs 1049 BTU/hr predicted).
 - However, the average metabolic rate during the EVA sim remained around 38% VO₂peak, which was within the target range of 30 - 40%.
- Work rate calculations that were used for Arm Ergometry used incorrect assumptions.
 - This resulted in work rates of approximately 47% VO₂max which were considerably higher than the targeted 30%.
 - The formulas have since been corrected and now incorporate adjustment factors to account for expected differences between treadmill vs. cycling vs. arm ergometry VO₂max^(7, 8).
- Mean and SD %VO₂max was comparable for subjects completing 8.5 rounds in comparison to subjects completing 2 - 3 rounds.
 - i.e. Completing the full 6-hour protocol did not appear to result in diminished performance or increased variability

⁷Schrieks IC, Barnes MJ, Hodges LD. Comparison study of treadmill versus arm ergometry. Clin Physiol Funct Imaging. 2011;31(4):326-31.

⁸Larsen RT, et al. A systematic review and meta-analysis comparing cardiopulmonary exercise test values obtained from the arm cycle and the leg cycle respectively in healthy adults. Int J Sports Phys Ther. 2016;11(7):1006-39.

Post-pilot Testing Evaluations

- In Nov 2021, a multi-day operations validation test series was conducted at ambient pressure/O₂ in the test chamber.
- One objective of this series was to fully vet the EVA simulation.
- Subjects were able to successfully navigate the simulation while managing spatial limitations and umbilical cabling.





Summary/Conclusions



- A subset of decomposed tasks that includes ranges of physical movements and intensities can be used to simulate a range of EVA-like procedures within a confined workspace.
- This repeatable, low-fidelity EVA simulation with average individually-prescribed work rates of 30-40%VO₂max was tolerable for up to 6 hours by subjects with varying fitness levels.
- Future work should include further refinement and simulation of tasks matching planned types, durations, and intensities of activities that are anticipated to be included as part of Artemis missions.
 - As task fidelity is improved, forward work should include additional considerations such as suit constraints and gravitational conditions.



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Thank you!

