Verification, Validation, and Credibility Assessment of a Computational Model of the Advanced Resistive Exercise Device (ARED)

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BACKGROUND

NASA's Digital Astronaut Project Vision

The Digital Astronaut Project (DAP) implements well-vetted computational models to predict and assess spaceflight health and performance risks, and enhance countermeasure development.

HRP Risks/Gaps Addressed by This Effort

Risk of Muscle Atrophy: impaired performance due to reduced muscle mass, strength and endurance

To specifically inform research questions aimed at addressing gaps M7, M8 and M9.

Risk of Loss of Bone Mineral Density: early onset of osteoporosis and bone fracture

To specifically inform research questions aimed at addressing gaps Osteo 7 and Osteo 6 (*formerly Gap B15 and B1 respectively*)

OBJECTIVES

Model and Simulation Description

- The Advanced Resistive Exercise Device (ARED) is the main exercise device used by astronauts for resistance training on the International Space Station (ISS) as shown in Figure 1.
- DAP has created a multi-body dynamics model of the ARED using Adams^{TM} for integration with exercise biomechanics models (Figure 2) for use in exercise physiology research and operations [1- 3]
- In an effort to advance model maturity and credibility of the ARED model, the DAP performed verification, validation and credibility (VV&C) assessment of the ARED model and simulations (M&S) in accordance to NASA-STD-7009 'Standards for Models and Simulations [4-5]

Objective

- The goal of VV&C for the ARED is to quantify the current value of the simulation
- This allows other groups to use the model to make future decisions with a certain level of confidence that the ARED simulation will behave exactly like the ARED onboard the ISS
- VV&C is an open ended cycle where the model is constantly validated with each set of data that is required

Figure 1

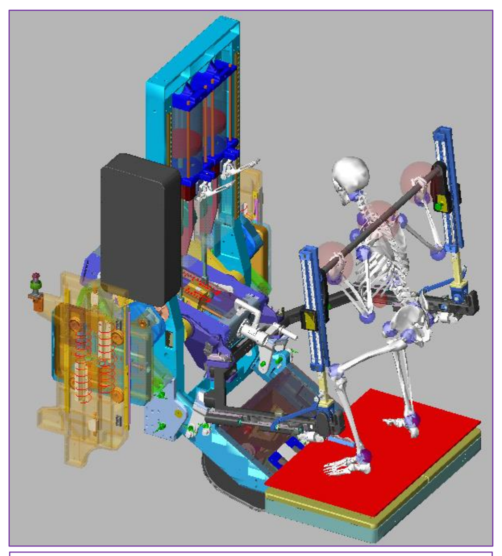
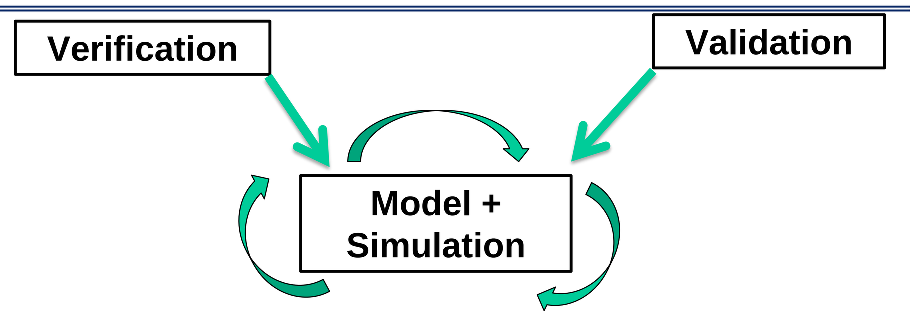


Figure 2



METHODS

Overview: Verification

- Vacuum Cylinders forces are calculated using the Ideal Gas Law
- Springs, dampers, and bearing friction are modeled using manufacturer-specific values

Ideal Gas Law

Vacuum Force explicitly modeled in the simulation

$$PV^n = k \rightarrow PV^n = P_0 V_0^{\,n} \rightarrow F_V = A * P_0 \left(\frac{l_0}{l + l_0}\right)^n - AP_a$$

Simple Spring

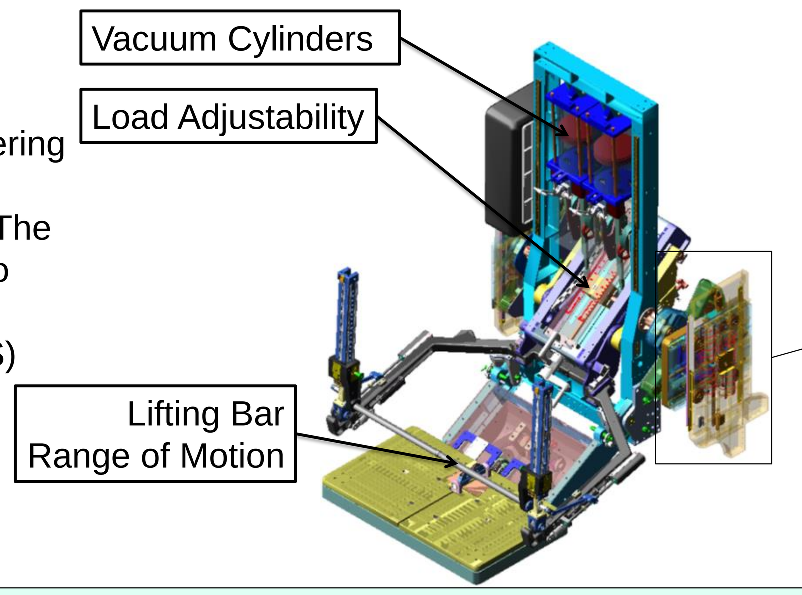
$$F_s = k * x$$

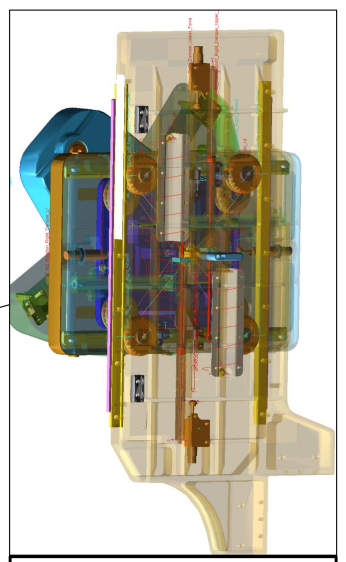
Spring Force

Overview: Validation

The Johnson Space Center (JSC) engineering team provided performance data from the actual ARED currently on board the ISS. The performance data was broken down to into seven categories and focused on both the ARED and Vibration Isolation System (VIS)

- Load Adjustability of the lifting bar
- Leak Testing on the Vacuum Cylinders
- Lifting Bar Range of Motion
- VIS Range of Motion
- VIS Spring performance
- VIS Damper performance
- VIS Mass Properties





VIS:
- Range of Motion
- Mass Properties
- Springs
- Dampers

The validation data is NOT used to update the model so it matches the data. Rather, the validation data is used to assess how well the simulation matches within a specified range of tolerance. If the results from the simulation, don't fall within the range, more investigation and understanding in the model is required.

RESULTS: VERIFICATION

Spring Force

- VIS Z Spring showed linear increase in force as the spring was displaced in the model (Figure 3) matching theory.

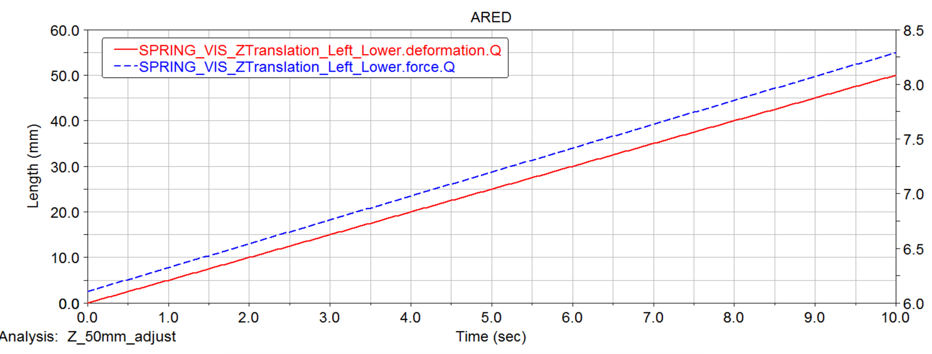


Figure 3

Vacuum Cylinder Force

- The plot of force versus cylinder position is shown in the Figure 4 (note x axis is in log scale).
- Force remains fairly constant after the position exceeds 1mm of travel

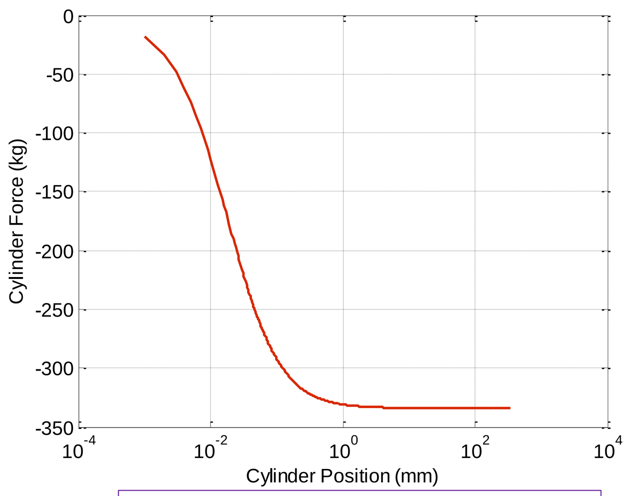


Figure 4

RESULTS: VALIDATION

Load Adjustability

- Error in model force, between load setting and measured load, increased as load increased (Figure 5)
- The force at the lifting bar proved to show a great dependence on the position of the bar which was not clearly defined in the flight data.
- Further investigation uncovered the complexity of load variation from a 4 bar linkage system (Figure 6)

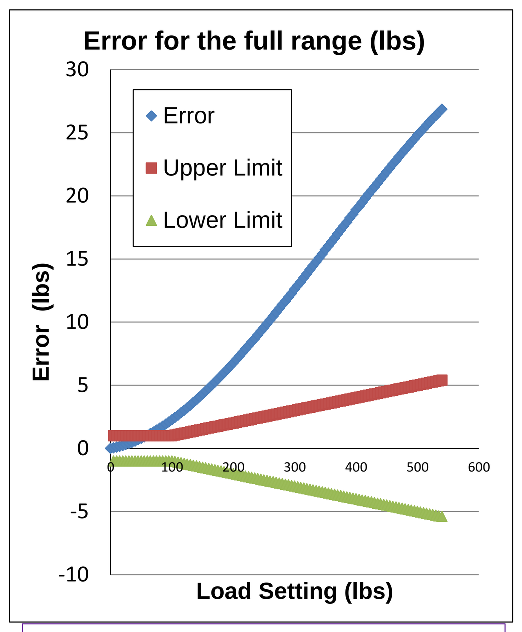


Figure 5

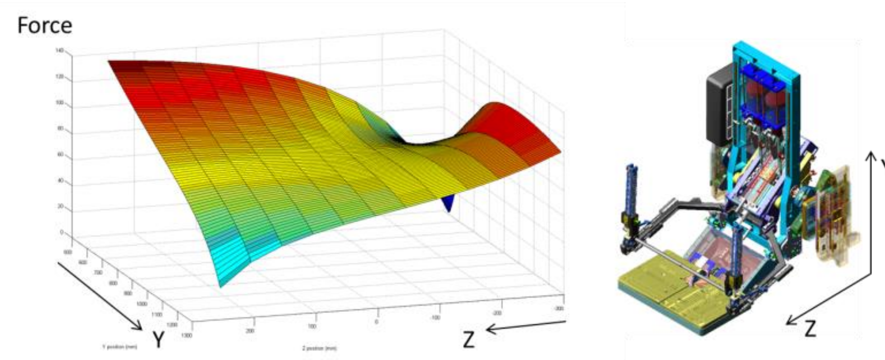
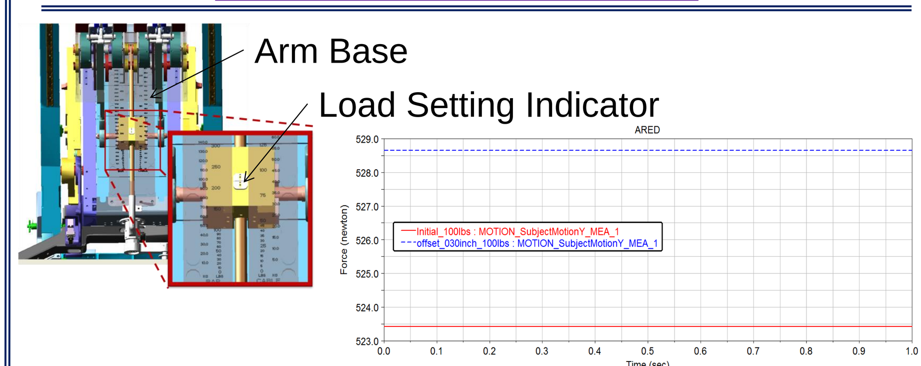


Figure 6



- The sensitivity of the alignment of the load setting indicator also provided insight into potential sources of error at the load (Figure 7). With an adjustment equivalent to the width of the indicator line (.030"), the load can change by 5N.

Figure 7

Vacuum Cylinder Force

- The measured force on the vacuum cylinders was compared to the force generated in the model
- Ambient pressure was adjusted for apples -to- apples comparison
- Initial length of piston, and thus volume, impacted the generated force (Figure 8). More description is required on the amount of trapped air in the cylinder when the piston is at the top and the valve is closed

	force (lbf)	Error (lbs)
ARED Model	738.42	-
S/N 1004	712.69	25.73
S/N 1005	713.60	24.82
Mean	713.14	25.28
Flight S/N Std deviation	0.64	

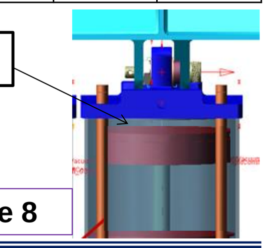


Figure 8

Lifting Bar Range of Motion

- The range of motion on the lifting bar was a discrete assessment of bar settings
- The model matched the data exactly

Minimum Height from Platform to Bar (in)	9.25
Maximum Height from Platform to Bar (in)	43.25
Difference (in)	34

VIS Mass Properties

- The range of motion on the lifting bar was a discrete assessment of bar settings
- The model matched the data exactly

TPS 7Y0720164 vs Model — SEG52100658-301 s/n 1001 Left VIS Assembly

ΔX (cm)	ΔY (cm)	ΔZ (cm)	Difference in Mass (kg)
0.505	0.055	N/A	-5.319

TPS 7Y0720165 vs Model — SEG52100659-301 s/n 1001 Right VIS Assembly

ΔX (cm)	ΔY (cm)	ΔZ (cm)	Difference in Mass (kg)
0.225	0.175	N/A	-5.331

VIS Springs

- X, Y, and Z spring force data was compared to the model forces stretched to the same length
- Model springs matched data at the spring and globally at the lifting bar through the ARED model

Spring Stretched to 9.8"	force (lbf)	Range (lbf)
Measured Flight VIS Z Springs	1.55	σ=.022
Analytical Drawing VIS Z Springs	1.43	+/- 0.223
Model VIS Z Springs Result	1.43	-

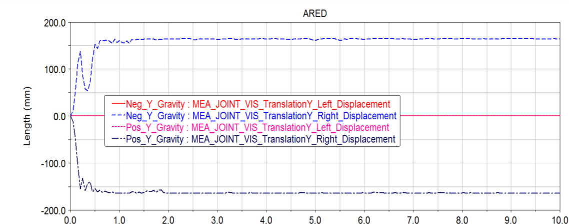
VIS Dampers

- X, Y, and Z Damping rate data was compared to the model damping rates by dividing the resultant force by the velocity
- Model Dampers matched the data damping rates within the measured standard deviation

Z Direction	Damping (N-s/mm)
Pull Direction Error	0
Push Direction Error	0
Measured Std. Dev.	.001
Drawing Tolerance	.003

VIS Range of Motion

- Model range of motion was determined by moving model to the hard stop using the gravity vector
- Hard stops are modeled as reaction forces so the range of motion is determined after the oscillations between gravity and the hard stop force is reduced
- Discrepancy between model and test data will be investigated in future work



	TPS Data	Model Data
Left VIS Assembly Y Axis Length	12.0 inch	12.86 inch
Right VIS Assembly Y Axis Length	12.0 inch	12.86 inch

OVERALL VV&C RESULTS

- The model's credibility to simulate each of the above cases was assessed independently
- A final credibility assessment was performed by consolidating all individual assessments which is the current level of overall credibility for the ARED model

	CAS Score	Tech. Review Score	Overall Weight	Overall Credibility	Thresholds CAS	Thresholds Tech Review	Weighted Score	Overall Credibility Threshold
Verification	2	2	0.4	2.29	3	3	0.75	3.07
Validation	2.7	2	0.675		3	3	0.6	
Input Pedigree	3.4	2	0.34		4	3	0.37	
Results Uncertainty	2	2	0.2		3	3	0.3	
Results Robustness	2.7	2	0.27		3	3	0.3	
Use History	1		0.15		3		0.45	
M&S Management	2		0.1		3		0.15	
People Qualifications	3		0.15		3		0.15	

Legend
CAS Score > Threshold
Threshold ≥ CAS Score ≥ (Threshold-0.5)
(Threshold-0.5) > CAS Score ≥ (Threshold-1.0)
CAS Score < (Threshold-1.0)

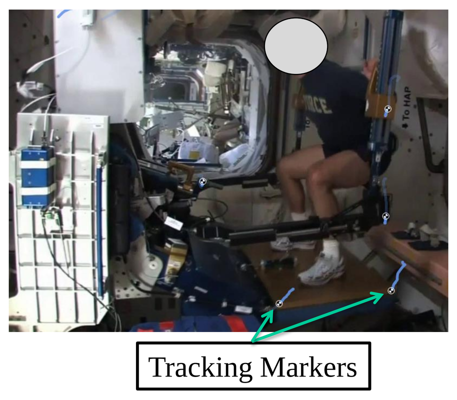
Rationale for Scoring of the six remaining Credibility Assessment Factors

Input Pedigree	Used highest quality data possible. (e.g. engineering specification for manufacturing of ARED parts).
Results Uncertainty	Uncertainty estimates were quantitative and based upon deterministic analysis.
Results Robustness	Sensitivity of the M&S results for the RWS is quantitatively known for <20% of the variables and parameters.
Use History	Specific scenarios were created to test application of the M&S Documented the successful completion of development (including V&V) of the M&S M&S has been used for flywheel inertial component analysis, and ISS exercise envelope evaluation under microgravity conditions.
M&S Management	M&S was developed and implemented in accordance to DAP's Project, Science and V&V plans under configuration control
People Qualifications	M&S developed and implemented by technical staff with advanced degree & advanced M&S training relevant to the specific technical M&S discipline

FUTURE WORK

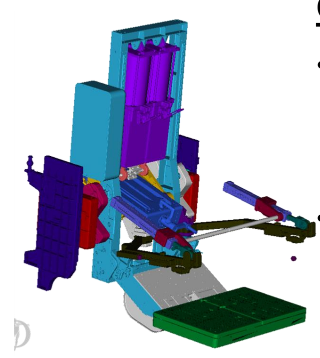
ISS Video Data

- Future work will involve using video data from exercise by the astronauts while on-orbit
- Dynamic motion of the ARED device will be quantified with video tracking tools that capture the motion with markers
- Model and simulation will be run to match impulses and track displacement of the ARED for comparison with video



OpenSim® Model

- Perform VV&C on the newly developed ARED in OpenSim® using the same data sets
- Include the video data captured from on-orbit workouts



ACKNOWLEDGEMENTS

This work is funded by the NASA Human Research Program, managed by the NASA Johnson Space Center. Specifically, this work is part of the Digital Astronaut Project (DAP), which directly supports the Human Health and Countermeasures (HHC) Element. The DAP project is managed out of NASA/Glenn Research Center (GRC) by DeVon W. Griffin, Ph.D., and Lealem Mulugeta of USRA Houston serves as the DAP Project Scientist.

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PARTNERS

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