Modeling and Simulation for Exercise Vibration Isolation and Stabilization System Design

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Abstract— **The microgravity environment that crew members experience on orbit presents a well-known health challenge, particularly when it comes to loss of muscle and bone mass. To counteract these negative effects, exercise countermeasures play a critical role in the daily routine of the crew on the International Space Station (ISS). To help inform requirements for upcoming exploration missions such as the Gateway Program, a new device, called the European Enhanced Exploration Exercise Device (E4D), is being built by the European Space Agency through their contractor, the Danish Aerospace Company. The E4D is being demonstrated on the ISS and is unique from other current exercise devices in that it provides four separate modalities in a single device: resistive, cycle ergometry, seated aerobic rowing, and rope pulling. To support the integration of E4D on ISS, a passive Vibration Isolation and Stabilization (VIS) system was required by NASA, and this responsibility was given to the Johnson Space Center.**

This paper describes the end-to-end process of modeling, simulation, and analysis used to inform the mechanical design of the VIS system. The process begins with the collection of representative exerciser motion capture (MoCap) through ground-based testing with the developmental E4D in both the Prototype Immersive Technology (PIT) Laboratory and the Active Response Gravity Offload System (ARGOS) facility at the Johnson Space Center. These collected MoCap data are processed through human biomechanics modeling to create forcing functions as input to a multibody dynamics simulation of the combined E4D/VIS system, with numerous resulting outputs. These outputs include microgravity accelerations, overall system displacements, internal and transmitted loads, as well as collisions. Microgravity accelerations are compared for compliance against ISS requirements while displacements are used for sway space determinations on the design and volumetric constraints within the targeted module. Internal loads are supplied to the supporting stress analysis teams and external loads for structural loads and dynamics teams, both at NASA and ESA. Finally, contact and clearance analysis is performed using the simulation to eliminate potential design issues. To ensure that the elements of the multibody simulation were verified and validated, correlation against multiple VIS related ground hardware testbeds was performed and characterized.

In addition to the isolation part of the VIS problem, stabilization is also key to the integrated performance and evaluation. Due to the difficulty in defining ISS requirements in this area, the stability of the exerciser was inspected via analysis. Loss of balance was defined analytically as occurring when the resultant force vector acting on the exerciser lies outside the base of support of the feet.

Both the VIS and E4D teams have recently gone through their Critical Design Reviews (CDRs) and the iterative model-based approach has been integral to inform mechanical design, particularly in the case of the VIS. This same end-to-end approach is now being applied for the Gateway Program, where an Exploration Exercise Device (EED) derived from the E4D and notional VIS for the device are under concept development.

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1. INTRODUCTION

Exercise countermeasures are critical to counteract the negative effects of the muscle and bone loss in the microgravity environment, as well as protect multiple other physiological systems (e.g., cardiovascular). Exercise devices serve as the primary means used for these countermeasures [1], and most often include corresponding Vibration Isolation and Stabilization (VIS) systems [2, 3]. The purpose of a VIS system is to protect the on-orbit spacecraft from crew-imparted exercise loads through attenuation, and to provide sufficient platform stability for a crewmember to exercise safely and effectively. A new exploration exercise device is under development by the European Space Agency (ESA) through their prime contractor, the Danish Aerospace Company (DAC), called the European Enhanced Exploration Exercise Device (E4D) [4, 5], and the VIS, developed by the National Aeronautics and Space Administration (NASA) Software, Robotics, and Simulation Division (ER) at the Johnson Space Center (JSC), is required to support integrated E4D operations on the International Space Station (ISS) [6]. The integrated E4D/VIS system, which is slated for the ISS Columbus Orbital Facility (COF), will operate as a demonstration device to help develop requirements and evaluate efficacy for similar systems in upcoming exploration missions such as the Gateway Program [7, 8].

The primary purpose of this paper is to describe the iterative end-to-end process of modeling, simulation, and analysis used to inform the mechanical design of the VIS system. It begins with laboratory data collection with the prototype E4D through the generation of exercise forcing functions using biomechanical simulation tools. From there, it proceeds with the generation of VIS physical characteristics to attenuate the transmitted loads and a multibody dynamics representation of the combined E4D/VIS system, along with the exercising crew member. Specific topics of flexibility, friction, and power/data cable nonlinear behavior are addressed. Efforts to characterize, verify, and validate contributing subsystem elements of the models and overall analytical simulation are discussed through ground-based testbeds and analogues.

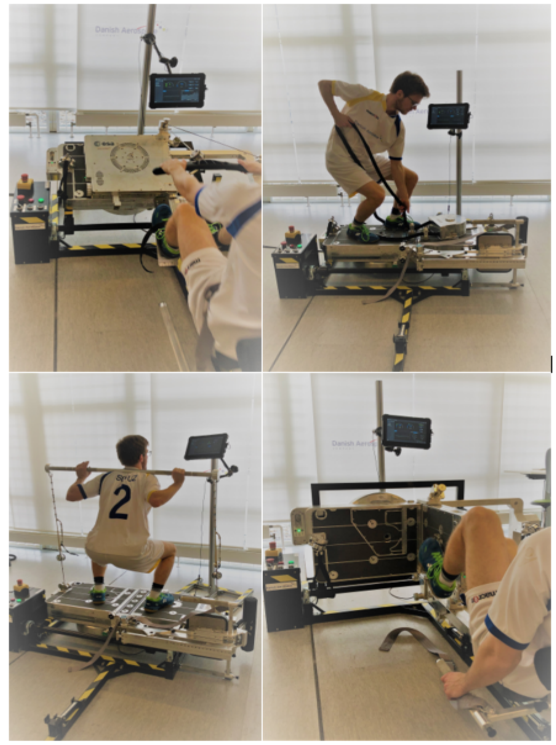


Figure 1. European Enhanced Exploration Device (Photo Courtesy of DAC)

Once the modeling and simulation methodologies are introduced, analysis results in terms of microgravity accelerations, combined E4D/VIS displacements, internal and transmitted loads, contact and clearance, and stability are presented. Qualifying requirements for these results are covered. Since the units associated with the flight project requirements vary between the ISS Program and ESA, a mixture of English and SI units are used here throughout the paper. Finally, specific observations are made based on the outcomes from this iterative model-based design approach to the integrated E4D/VIS flight hardware project.

2. METHODS

The overall methodology used for this extensive effort consists of three primary steps: (1) data collection, (2) biomechanics modeling and simulation to generate forcing functions, and (3) multibody dynamics to perform the actual analyses.

Data Collection

Historically, exercise forcing functions for informing VIS design have been generated with a human model moving at an idealized sinusoidal profile or with stroke profiles representative of human-in-the-loop testing with an exercise device [9]. While sinusoidal synthetic trajectories may be adequate to capture basic exercise modalities (e.g., resistive), a more comprehensive and accurate approach was needed for E4D. A new approach to further capture variability in human exercise and expected worse case conditions was developed and adopted for this flight project and corresponding analyses: recording full-body motion capture data in a human-in-the-loop data collection with the E4D prototype unit [10] and processing through the biomechanics software OpenSim [11, 12] to obtain dynamic terms of interest as inputs to the VIS simulation.

Six test subjects of varied anthropometry with prior exercise experience participated in the Prototype Immersive Technology (PIT) laboratory [13] (Figure 2) testing, and a subset of 4 subjects also participated in the Active Response Gravity Offload System (ARGOS) testing [14, 15] (Figure 3) at the NASA JSC. These 6 subjects included 3 male and 3 female, with weight ranging from 136.5 – 201 lbs (an additional ~25 lbs in ARGOS), and height ranging from 66 – 71.375 inches (while shoes were worn). All subjects had prior usage of the same or similar exercise device and/or athletic experience (e.g., frequent exercise in gym or trained sports), and a subset had prior experience working in ARGOS. Supporting equipment included the PIT OptiTrack [16] and ARGOS Vicon [17] motion capture systems, full body motion capture suits to which passive retroreflective markers were placed according to the Plug-In Gait marker set [18] (markers also placed on E4D hardware for reference), a balance-beam scale for measuring subject body weight, as well as video recording and photography for reference during data processing and analysis.

Figure 2. E4D Collection in the PIT

With a total of 292 recorded trials, exercises included Seated Aerobic Rowing (seated), Cycling (varied rates), Rope Pull (up to 12 different techniques per subject), and Resistive exercises performed at self-selected paces (see Table 1). While the E4D currently has additional capabilities, the collection sought to capture the drivers in terms of body center of mass (CM) movement, multi-axis motions, frequency ranges, and variety from those exercises expected in the 2019 timeframe. The E4D load was set such that adequate resistance was provided for engaging in the exercise yet minimized to support subject endurance through a test session. Note that device load does not directly impact the VIS. Human motion is the direct input. Load was provided such that the subject could maintain their targeted exercise form at their nominal pace. Increased loads, as well as other causes, could have an impact on crew member exercise cadence, and so data undergoes frequency sweeps in relevant analyses, such as exploration structural fatigue assessments performed by Loads and Dynamics (L&D) teams.

Figure 3. E4D Data Collection in the ARGOS Facility

Table 1. PIT/ARGOS Subject Exercises

Exercises	PIT	ARGOS
Back Squat	X	---
Bent Over Row	X	X
Cross Body Pull	X	X
Cycle	X	X
Deadlift	X	X
Front Squat	X	X
Hang Clean	X	X
Hang Clean & Press	X	X
Heel Raise	X	X
High Pull	X	X
Kettlebell Swing	X	X
Modified Get Up	X	X
Overhead Press	X	X
Rope Pull	X	X
Seated Aerobic Row	X	---
Thruster	X	X

Driving VIS Simulation with Human Exercise Motion

To sidestep the formidable challenges of modeling the human control system, be it in 1g or 0g, an assumption was made that the body trajectory of the exercising human relative to the moving E4D/VIS platform is the same as the trajectory recorded for that exercise in the terrestrial lab on a stationary exercise device.

It is not enough to record the force and moment applied by the human to a stationary device while exercising in the terrestrial lab, and then simply apply these loads to the moving platform in the simulation. The force and moment on a moving platform will differ from those on the stationary device due to inertial effects involving the motion of distributed masses comprising the human body. For example, standing up on a platform as it gives under the subject's feet reduces the foot force on it, and rotational inertial effects are especially complex. One way to account for all such effects would be to include the full articulated human body in the dynamic VIS simulation, drive the body kinematically on a prescribed recorded trajectory relative to the E4D/VIS platform, and obtain VIS motion and the transmitted loads from time-domain state integration of the non-prescribed VIS degrees of freedom (DOFs).

However, different simulation tools are commonly used for mechanism design analysis (e.g., ADAMS [19], SIMULIA [20], etc.) and human biomechanics (e.g., OpenSim, AnyBody [21], Visual3D [22], etc.). For that reason, an approach was developed that allowed the preferred tools to be used in their respective domains [23]. In the VIS simulation, the human body was represented in the dynamics tree topology by a special single body with allowed internal mass motions. To account for its changing shape due to moving body segments, the CM of this body relative to the platform was continuously updated, as was the moment of inertia. Following a rigorous mathematical formulation [23, 24], the additional inertial effects of the body motion relative to the platform were captured by force and moment terms depending on the time-varying linear and angular momenta and their time derivatives as well as the moment of inertia time derivative. Thus, a limited number of composite dynamic quantities were sufficient, obviating the need for a fully articulated human body in the VIS simulation itself, while at the same time representing the same dynamics fidelity of the whole body.

To obtain the time histories of these dynamic quantities, the human was modeled using OpenSim, with a modified Full Body Rajagopal Model [25, 26] which was scaled to each individual subject based on a static pose and body weight measurement. Using the exercise motion capture data collected, inverse kinematics was performed to obtain trajectories for the body segments. A custom OpenSim plugin was developed to output quantities of interest: body mass, the human CM location relative to the platform, the linear momentum, and its time derivative, as well as the angular momentum and moment of inertia of the subject with their time derivatives [23]. These quantities were then available as inputs to a multibody VIS simulation to drive the modeled VIS response for all analytical assessments. This simulation was developed using MBDyn [27, 28, 29], an in-house software package used extensively at the NASA JSC for formulating and integrating the equations of motion of rigid and flexible articulated multibody systems.

Exercise Data Extrapolation/Exercise Duration

Recorded data were extrapolated to represent exercise for required anthropometry (i.e., percentile mass requirements) and longer duration exercise trials, with a few trials omitted [see Appendix A]. Combined with multiple orientations of E4D/crew member (see E4D Configuration section), a total of 469 simulation runs were used for analysis.

The test subject models and data were extrapolated to represent a 5th percentile female and 95th percentile male in terms of height and body mass in accordance with NASA-STD-3000 [30] and as set by the VIS project requirements.

Trials providing less than 15 seconds of exercise data, e.g., due to faster exercise cadence, were not sufficient in duration to perform certain analytical assessments, such as internal loads for stress analysis. Exercise data duration was extended by selecting a segment of the exercise that started and ended in a similar part of the repetitive exercise cycles (Figure 4, top) and placing several copies one after another (Figure 4, middle). The highest priority in selecting starting and ending points of the interval to be replicated was for these points to occur in the same parts of the exercise cycle. The second priority was to select the interval such that the differences between starting and ending human center of gravity (CG) positions on all three axes were minimized.

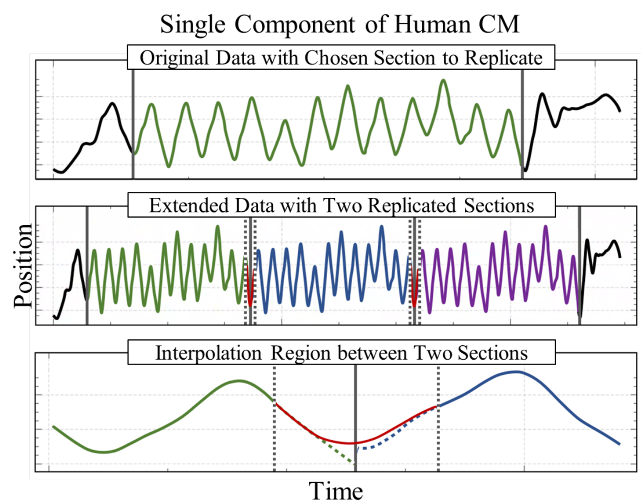


Figure 4. Exercise Data Extension Illustration

The dynamical quantities driving the simulation needed to be continuous and, to assure linear and angular momentum conservation, consistent. It was not possible to simply repeat segments of data while maintaining continuity on all axes of the human CM, angular momentum, and inertia terms as well as their necessary derivatives. Instead, a relatively narrow interval of data around each junction was excised. Then, each quantity was interpolated across the excised interval with the lowest-order polynomial necessary to fit the quantity and the requisite number of its derivatives on both sides to the retained data (Figure 4, bottom). For the CM location, this resulted in the 7th order polynomial, which has eight coefficients, accounting for the CM location and its first three derivatives on both sides of the excised interval. The angular momentum and the moment of inertia components required only 5th order polynomials with their six coefficients to fit the quantities and their first two derivatives on both sides. Overall, it was found that implementing this approach is as much an art as a science, since human motion does not repeat exactly. Nevertheless, satisfactory results were achieved for all the trials requiring this procedure.

Model Description

The mechanical design of the VIS was developed over the course of four years, with MBDyn simulations playing an integral role in the course of its evolution. Simulations provided relevant information in several key areas which allowed the design to develop such that system requirements/criteria were met. These areas included: (1) the choice of the DOFs to isolate, (2) the order and placement of the DOFs, (3) the spring/damper design, (4) snubber (or miniature shock absorber) choice and placement within the system, and (5) the geometry of several VIS related structures.

VIS Configuration

Beginning with System Requirement Review (SRR) in June 2020, the ER VIS design has been under active development moving from the Preliminary Design Review (PDR) in October 2020 through Critical Design Review (CDR) in May 2021 to Delta CDR in December 2021. The stabilized designs of VIS and E4D are shown in Figure 5, along with the topology of the simulation model. As shown in the sketch, counter mass, E4D and crew member are at one end of the series topology isolated from the rack in five DOFs by means of linear springs and dampers. Any moment applied about the axis perpendicular to the y-rotation axis and instantaneous x-rotation axis, the sixth or Yaw DOF, is not isolated and therefore directly transferred to the rack. A visualization of the configuration in the Columbus module, with representation of the E4D and the crew member operating the device, is shown in Figure 6.

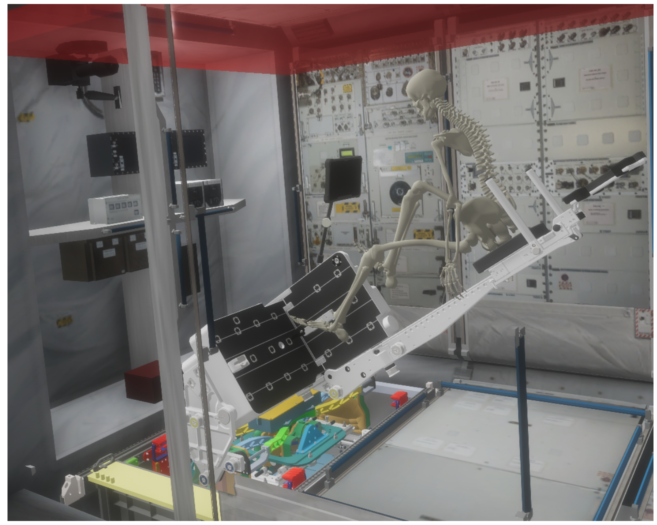
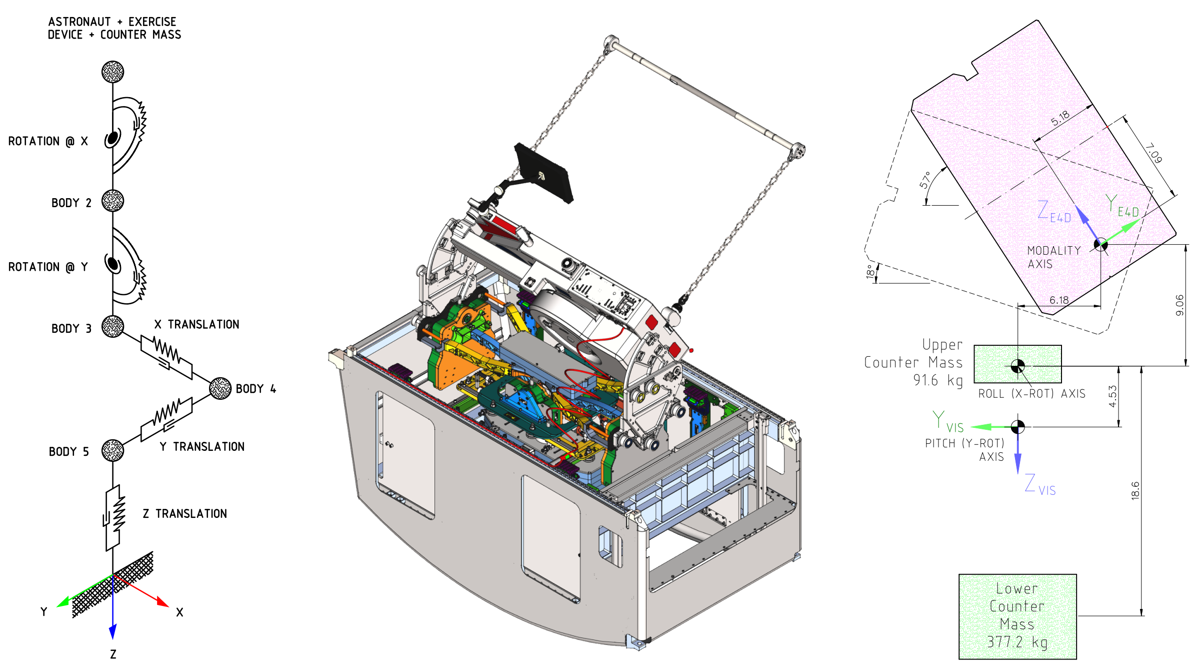


Figure 6. E4D Device Depicting Cycling Configuration and VIS Inside Rack within Columbus



(a) (b) (c)

Figure 5. VIS - Schematic Diagram, 3D Model, and Placement of Parts

E4D Configuration

The E4D simulation model has four distinct geometric configurations and associated mass properties. The range of E4D mass varies from about 175 kg to 215 kg. E4D has been tilted through 57 degrees for different modalities, (i.e., resistive, cycling and standing rope pull) because the interior dimension of the Columbus module is not enough to accommodate VIS, E4D, and a standing crew member. To account for rowing and seated rope pull modalities, the E4D is canted to 18 degrees. Again, the amount of this tilt is chosen by volumetric considerations. In deciding the angled configurations, one of the considerations was to align significant exerciser motion along any one axis. The y-axis is chosen as that axis.

Spring/Damper Characteristics

Table 2. VIS Properties

Property	Translational DOF			Rotational DOF	
	X	Y	Z	@ X	@ Y
Nat. Freq. (Hz)	0.04	0.03	0.035	0.08	0.15
Damp. Ratios	0.03	0.03	0.03	0.20	0.60
Stiffness (N/m, N-m/rad)	49.13	28.06	39.55	62.85	207.7
Damping (N-s/m, N-m-s/rad)	11.73	8.932	10.79	50.01	264.5

The constants of the linear springs and dampers for the unclamped DOFs have been part of the iterative design process with the VIS Mechanical Design Team. Their values have been decided by considering structural sensitivity of the Columbus module, direction of exercise activity, E4D tilt, and availability of internal sway space.

In an ideal VIS, all six DOFs would be isolated in order to attenuate exercise loads from all six directions. However, when one has a long box-shaped exercise device in a rectangular rack, it is necessary to prevent rotation in the 'horizontal' plane to avoid collisions. Examination of exercise forces reveals that, barring a few exceptions such as cross body pull, the moment about the vertical axis is small. During the initial stages of design, the E4D was not tilted and therefore, clamping the vertical axis did not transfer significant yaw moment to the base. The remaining five DOFs were isolated.

Exercise forces exerted on VIS depend on the acceleration of the overall CM and mass of the crew member. E4D tilt angles have been decided such that this exercise action aligns roughly along the y-axis. Since, y-axis translation requires the most isolation, these springs are the most flexible and damping is also very low. The x-axis of the mechanism experiences the least force and therefore has the least isolation.

As for rotations, the x-axis experiences a significant amount of moment compared to the y-axis. Over the multiple design cycles, it was observed that y-axis rotation created many contact issues because of the long E4D. To avoid these complications, this axis has been stiffened and damped significantly. Current values for the VIS are shown in Table 2.

Flexibility

In the multibody dynamics model of the VIS, almost all the components have been modeled as rigid bodies except the thin, foot-long, drop rod that connects the lower counter mass to the roll rotating assembly. Natural vibration analysis of the rod with the upper end clamped and the lower counter mass connected at the lower end revealed that the fundamental natural frequency of the rod is 4.9 Hz. The mode is shown in Figure 7. Since this frequency is close to that of the primary exercise frequencies, it was decided to model the rod as flexible. Four modes with the highest natural frequency of 22.3 Hz have been considered in the analysis.

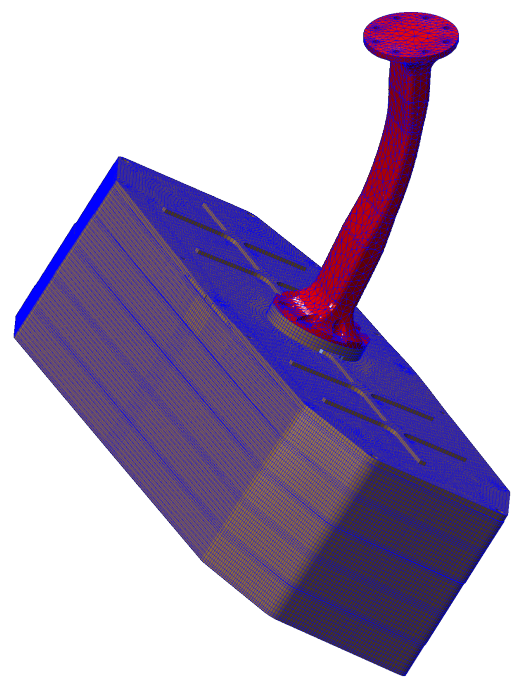


Figure 7. Fundamental Mode of Counter Mass

Friction

VIS linear and angular bearing friction is modeled as Coulomb friction using a reset-integrator friction model sometimes referred to as a “bristle friction model” [31]. The latest VIS design uses commercial-off-the-shelf DualVee bearings similar to those used on the Advanced Resistive Exercise Device (ARED) [32, 33]. For this analysis, 0.3 lbf friction force based on testbed characterization has been used for translational degrees of freedom [34]. For rotational degrees of freedom, 2.0 lbf-in frictional torque is used which is based on the vendor supplied calculation procedure.

Cable

As mentioned previously, the VIS provides isolation to E4D in its five DOFs. However, the E4D power/data cable (depicted in Figure 8) circumvents that isolation and provides direct mechanical connection between the exercise device and the Muscle Atrophy Research and Exercise System (MARES) [35] rack. A Kelvin-Voigt (K-V) model [36] has been chosen to represent the cable connection in the simulation and a series of hardware tests, to obtain cable parameters, have been performed to increase the accuracy of the simulation model [37].

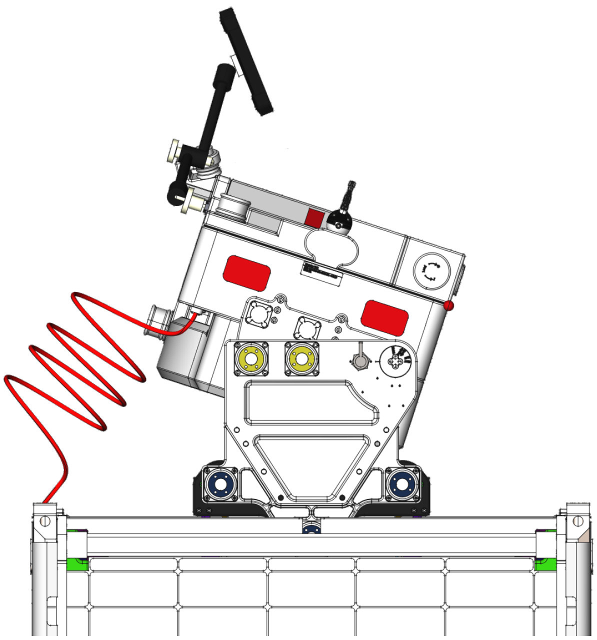


Figure 8. E4D Power/Data Cable Model

Characterization Testing

Two-DOF Testbed—A 2 degree of freedom (2DOF) hardware prototype testbed that included x and y translational DOFS was used to investigate the VIS performance in response to planar forces and is shown in Figure 9 and Figure 10. The heavy counter mass was also reduced to a manageable level in this testbed. The objective was to validate simulation capabilities and obtain the amount of friction between the DualVee bearing and the rail. The testbed response to release and prescribed motion tests in a single axis were measured by load cells and compared to our VIS model response. Tests with springs only as well as spring and dashpots were used to analyze quantities of interest including the spring constant, damping and friction. The translational friction value of 0.3 lbf mentioned previously was determined from 2DOF release tests. Based on the comparative analysis of the release tests, the E4D VIS 2DOF testbed behaved as intended, producing dynamic response profiles consistent with the ideal mathematical models [38].

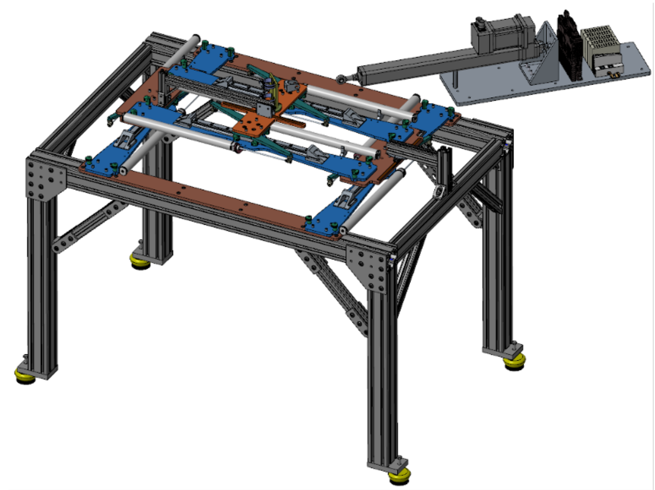


Figure 9. VIS Two-DOF Testbed

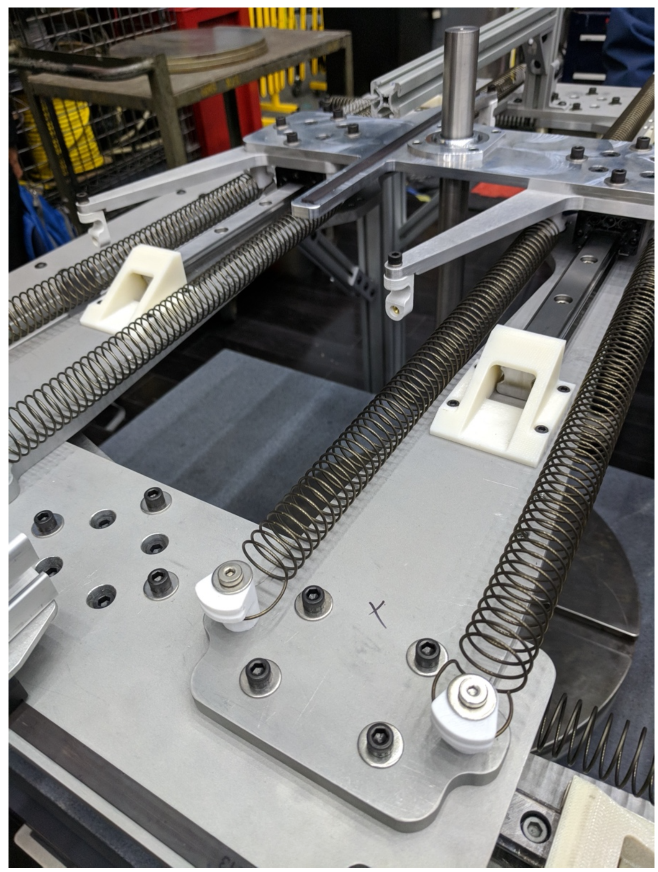


Figure 10. VIS Two-DOF Testbed

Snubber Testbed—Since the manufacturer provided data on the snubber performance, testing of the device was done to verify this data. The testbed used during the characterization testing was a pendulum, where a weight was attached to a pendulum arm and released at different angles (see Figure 11 and Figure 12). The swinging pendulum arm would then impact the snubber. Three quantities were measured: the angle of pendulum arm, snubber displacement, and force being exerted on the snubber. A good agreement was found between vendor supplied simulations and the collected pendulum test data, therefore meeting the objective of the snubber characterization [39].

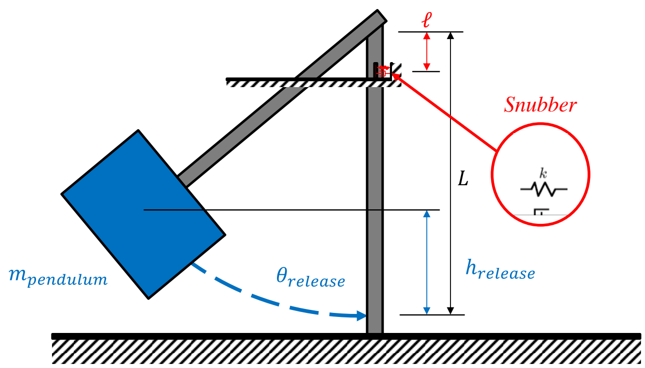


Figure 11. Snubber Pendulum Test Schematic

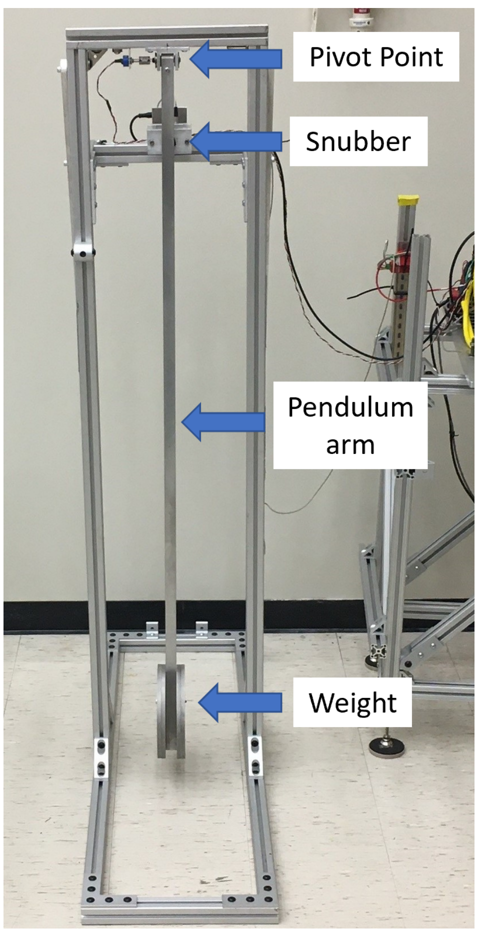


Figure 12. Snubber Pendulum Testbed

Cable Characterization Testbed—After reviewing photos of the cable taken on orbit and then handling a piece of a similar cable, it was realized that the cable can be modeled using a suitable beam theory. Therefore, during initial tests conducted on a piece of the cable; the objective was to determine basic properties of the cable cross-section. Stiffness properties of the cable were determined by measuring the natural periods of vibration in bending as well as torsional modes. Similarly damping was estimated by measuring the decay of free vibrations. Enough information was now available to model any cable shape using a beam finite element model. The next step was to propose a suitable shape of the cable coil. After many trials using finite element analysis in which different diameters and number of loops were tried, it was decided to use four loops of 8-inch diameter. Numerical analysis performed on the proposed shape of the cable gave stiffness of around 10 N/m and damping of 2 N-s/m. This was a conservative estimate for the range of exercise frequencies and amplitudes. These values have been verified by the last round of tests conducted on a longer cable helix as shown in Figure 13. In this test, the coiled cable was subject to cyclic axial deformation and its axial resistance was measured. Force-displacement response of a K-V model to cyclic deformation is of elliptical shape, and test data was post-processed to find equivalent parameters needed by the model using a least square approach. It was found that the numerically evaluated values of the K-V model parameters were indeed conservative.

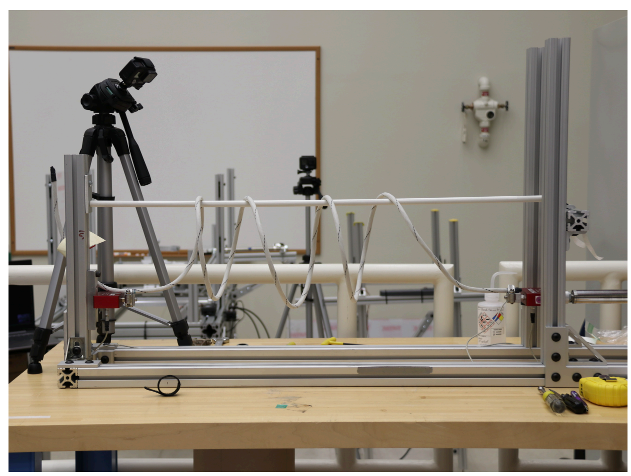


Figure 13. Helical Cable Testbed

3. RESULTS

Analysis Approach

The step-by-step approach used for analysis of the VIS is shown in Figure 14. The multibody dynamics model of the integrated system is driven by the previously described dynamical properties of the exercising subject. The resulting isolated base forces transferred to ISS structure are processed using the methodology in accordance with ISS requirements [40] based on wide-band transfer functions defined in Thampi et al. [41]. This transformation yields microgravity accelerations at a given location on ISS. Vibration limits are assessed based on the microgravity allocation provided by the ISS Boeing L&D team and implemented at the VIS project level in terms of specific verification requirements [42].

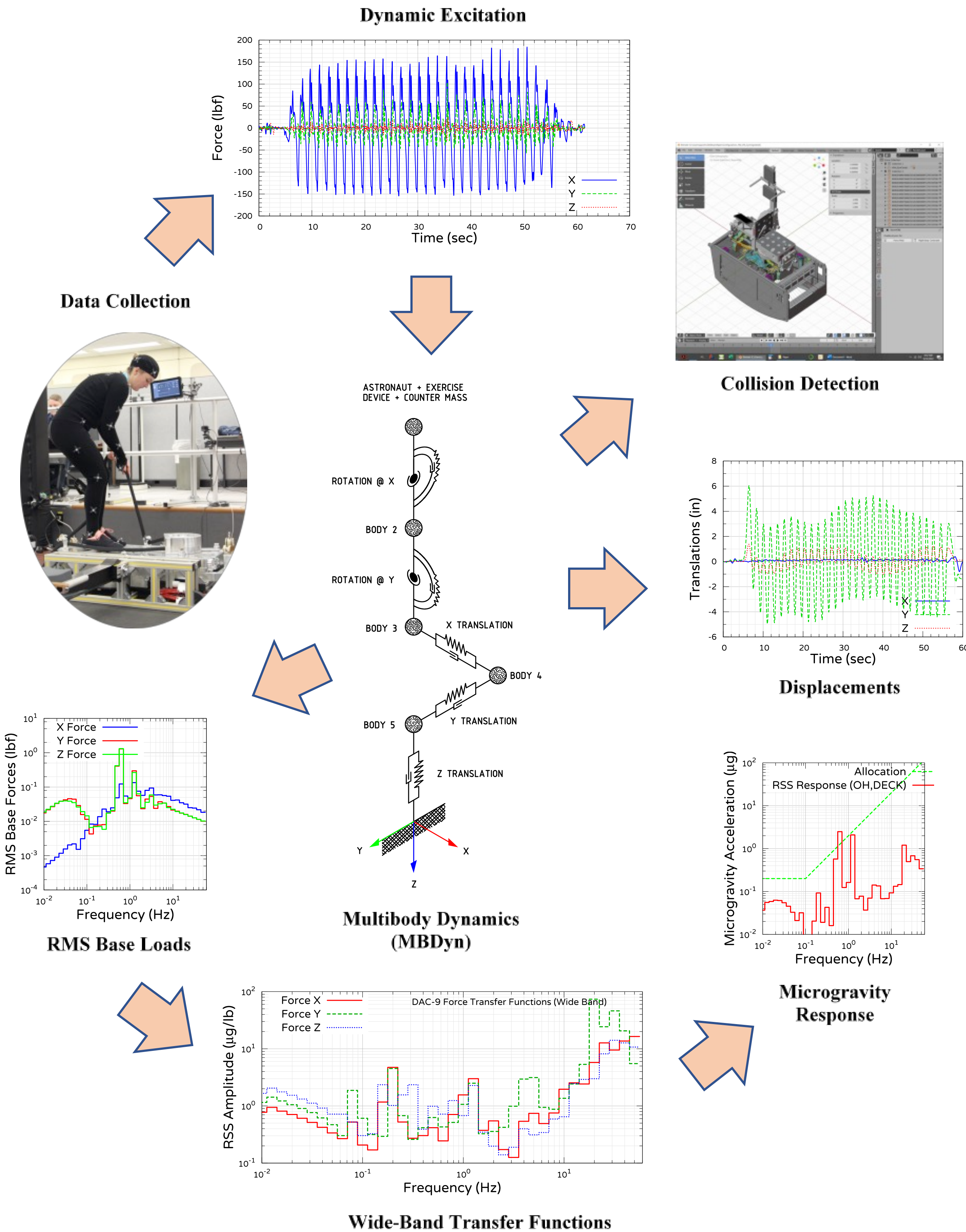


Figure 14. VIS Analysis Procedure

Transfer functions mapping loads to microgravity acceleration are direction dependent, so the microgravity acceleration response varies depending on how the supporting VIS rack is oriented within the Columbus module (or any other location) on ISS. In addition to the microgravity acceleration response, other outputs from the VIS multibody dynamic simulation also include displacements for volumetric assessments and collision detection for contact and clearance analyses.

Qualifying Requirements

There are many qualifying requirements for the VIS. A subset relevant to this effort are presented below:

- Accelerations at microgravity experiments should stay under the provided allocation.
- Microvibrations at the Atomic Clock Ensemble in Space (ACES) location are below the given allocation for this experiment.
- VIS displacements during dynamic exercise runs should stay within limits without engaging the snubbers.
- VIS displacement within snubber hard stop limits is free from any contact other than snubbers themselves. A positive gap of at least 0.1" is desirable to account for manufacturing tolerances and flexibility of the parts.
- Volumetric assessments considering movement of VIS operating crew member in Columbus module should remain within the available space.
- VIS displacement during dynamic events such as ISS attitude reboosts, docking, undocking, and robotic arm movements are within acceptable ranges.

Peak Displacements

Snubbers, as depicted in Figure 15, have been placed at the extremes of each DOF. During the simulation of recorded forcing functions, the displacements are expected to stay within the limits defined by first contact with these snubbers. Peak displacements of the E4D obtained from dynamic simulation runs are also used to determine any excursions of crew members inside the Columbus module to check for potential geometric interference with nearby objects in the module. For the latest design iteration, based on the aggregate of all runs, it was found that the maximum translations at E4D along x, y, and z-axes all fell within acceptable displacements, as did the maximum pitch and roll angles [refer to Appendix B].

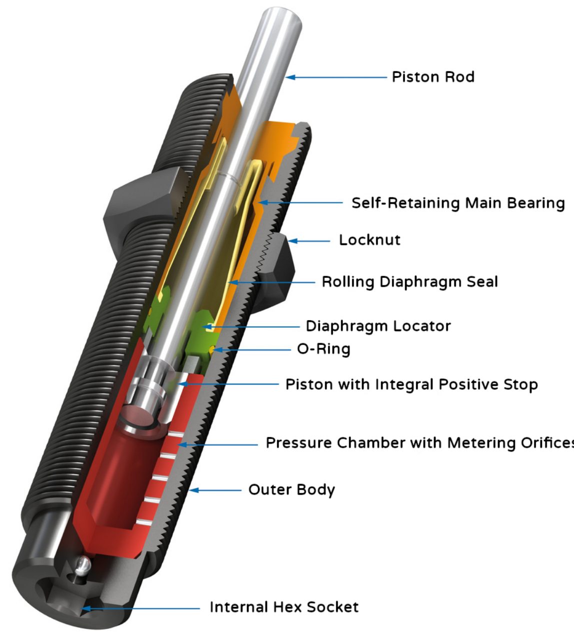


Figure 15. Miniature Shock Absorber MC225H2

Microgravity Accelerations

One of the objectives of the VIS system is to minimize vibrations that might affect microgravity experiments being conducted in the Columbus module and elsewhere on the ISS [43]. Base forces obtained from the dynamic simulation runs are processed to obtain microgravity accelerations at target locations. The procedure is equivalent to what has been followed for earlier exercise devices vis-à-vis the ARED and Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS).

Steady state portions of the recorded base force and torque components are selected for processing. The Hann window function is applied to the time history of each component to reduce spectral leakage. The components are then processed by a fast Fourier Transform (FFT) to obtain the Power Spectral Density (PSD) functions. The PSD functions are used to calculate the root mean square (RMS) values within each one-third octave division of the frequency spectrum. These one-third octave RMS values of each of the six components are then multiplied by frequency dependent transfer function gains provided through the ISS Program requirements that map force and torque components at the VIS location to RMS microgravity accelerations. The resulting RMS acceleration values for each one-third octave division are then combined to produce a root sum of squares (RSS) microgravity acceleration for each one-third octave of the frequency spectrum. Finally, this microgravity acceleration is compared with microgravity allocations provided by the ISS Program as implemented on this VIS project. Figure 16 shows the microgravity response for the current revision [44] along with the allocation.

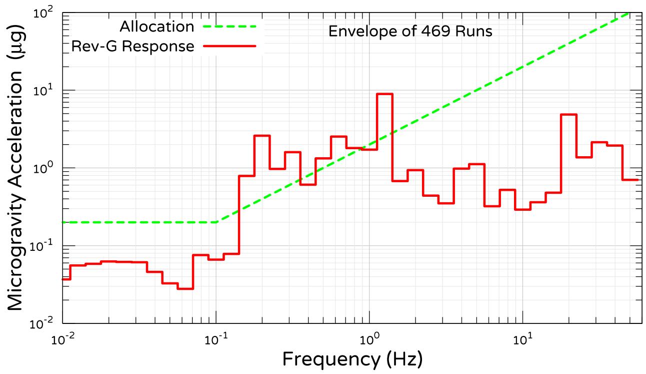


Figure 16. Microgravity Response

In addition to the above frequency domain transfer function approach, the Boeing L&D team is responsible to perform their own transient dynamic analysis of the Finite Element Model (FEM) of the entire ISS for the base forces coming out of this integrated E4D/VIS simulation. The acceleration time histories at target locations are then Fourier transformed to obtain one-third octave band microgravity accelerations.

Accelerations at ACES Location

France's CNES (National Center for Space Studies) has been planning to install a new generation of atomic clocks outside the end cone of the Columbus module [45, 46, 47]. As one might expect, the ACES is sensitive to structural vibrations. The base forces obtained by computer simulation of the E4D/VIS are used to evaluate acceleration levels at the ACES location. The procedure is similar to the one followed above for microgravity acceleration. The only difference is that the frequency dependent transfer functions now map the force and torque components at the VIS location to RMS accelerations at the ACES location. This acceleration is then compared with allocations provided by ESA. Using the above-mentioned frequency domain procedure, the current design exceeds the given allocation [43]. A more detailed FEM analysis is needed in which VIS load time histories are fed at the rack location to evaluate potential effects of VIS exercise impacts on ACES.

Internal Loads

During the operation of E4D/VIS, each part of the VIS is under a constantly varying state of stress. The applied load is partially nullified by the counter mass before it reaches the springs and dampers and consequently, during VIS operation, the parts that lie between crew member and counter mass carry the most stress. D'Alembert's principle is invoked to generate, at each instant, a self-balancing static system of forces and moments acting on a part. This information is then readily used by the VIS Stress Analysis team to carry out strength and fatigue checks on VIS as designed parts. Internal forces on the interface between E4D and VIS are also tracked and logged, as this is important for informing the design of structural attachments [48].

Transmitted Loads

As discussed previously, simulation runs for two tilt angles and four modalities of E4D, totaling 469 cases, were conducted as part of the study. For each simulation, the forces and moments applied by the ISS structure to the VIS are logged in an output file [49]. Flexibility of the rack is not modeled. This set of 469 forcing functions is shared with the Boeing L&D and ESA Columbus Structures teams. The same forcing functions are used for calculations of microgravity accelerations and explained in [50].

Snubber Design

Snubbers are provided to arrest the motion of the VIS at the end of travel on each DOF while safely dissipating the energy of the moving parts without causing damage. Figure 17 graphically depicts a set of snubbers when fully depressed. Kick load criterion, which is based on Skylab exercise requirements, has been used for the design of snubbers, though its applicability to such a flexible system is most likely over conservative. The kick load is defined as 125 lbf acting over a 0.5 second half-sine wave. Numerical simulations of the VIS reacting to kick loads at different locations provided data necessary for snubber design. The vendor-provided software was used for actual selection of the snubbers; the vendor also performed simulations of snubbers for kick load impacts to ensure that the chosen elements met the specifications.

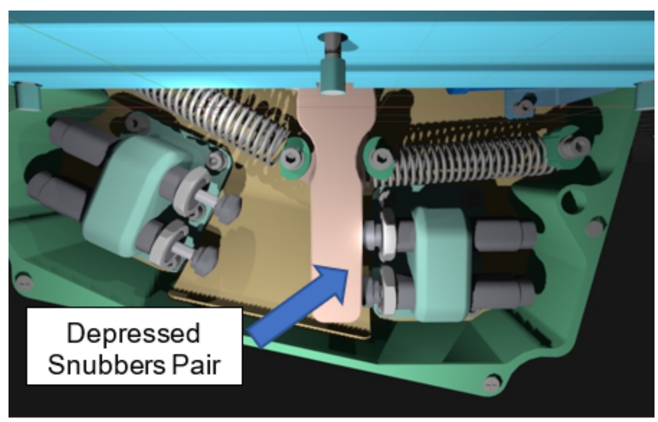


Figure 17. Rotational Snubber Modeling

In addition to kick load analysis, a linearized model of the VIS was shared with the Boeing L&D team which was incorporated within their FEM of the entire ISS [51]. They performed a series of transient analyses for various dynamic events to determine whether snubbers would be engaged during the dynamic events discussed previously.

Contact and Clearance

Two distinct Contact and Clearance (C&C) analyses were performed to assess if the VIS design could encounter unintended contacts. First, to determine if collisions would occur while the crew performs exercises, potential collisions were determined at each timestep in the set of 469 exercise-based suite of runs. This phase is referred to as the dynamic run suite analysis. Second, to account for transitory motion, the system was kinematically stepped through the allowable joint space range, defined by snubbers at their fully depressed locations and potential collisions were calculated. This step is referred to as the kinematic or joint vector space analysis. In both analyses, no contact forces were fed back through the system; the geometric relationships of the VIS, E4D, and Columbus MARES Rack structures were the sole interest.

Several iterations of the VIS design were completed over the course of development, each with a corresponding C&C analysis. The insights discovered during each of these analyses influenced the development of the system either through geometric updates of structure or through limiting the range of the system by modifying spring/damper properties. The final VIS design post Delta CDR shows no likelihood for on-orbit collisions.

Contact Model Setup—Pong [52], an in-house developed contact dynamics engine, was utilized for these analyses. Like MBDyn, Pong is a mature product that has been used in many ISS models and simulations, including the Latching End Effector, Special Purpose Dexterous Manipulator, and Common Berthing Mechanism models.

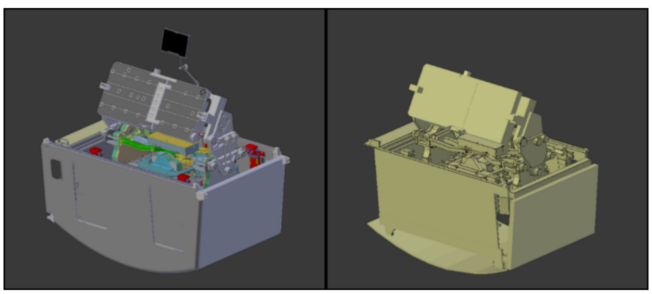
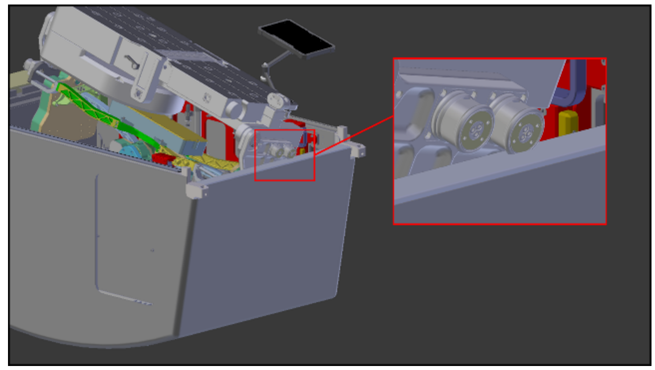


Figure 18. E4D/VIS/MARES Rack Contact Models

To build the contact model, depicted in Figure 18, geometries were first created in Blender [53], an open-source 3D graphics software package, by creating envelopes based upon delivered NASA and DAC 3D models. A geometric data file was then exported and used at runtime where the contact geometries were mapped to the simulation's dynamic bodies.

Clearance Calculations—Since the contact geometries were mapped to the simulation's dynamic bodies, certain assumptions included in the multibody dynamics model may have limited the simulation's capability to detect all collisions which could possibly occur in the on-orbit system. First, aside from the lower counter mass drop rod previously discussed, no flexibility was accounted for in the remaining elements for VIS system response. Second, as-designed versus as-built tolerances and on-orbit adjustments related to attachments between separate DOF structures have not yet been considered. To account for these assumptions, an additional capability was developed within the contact engine to calculate minimum distances between all non-colliding structural pairs. If these distances were calculated to be below a defined tolerance, they were then logged for further investigation.

Contact Case Example—Several previously unknown potential collisions were determined in the joint vector space portion of the analysis. One interesting case occurred between the DAC-designed VIS/E4D interface and the MARES rack, where multiple joints were near their maximum displacements. After pertinent information was provided to the E4D mechanical designers, the VIS/E4D interface design was updated to eliminate the issue (refer to Figure 19).



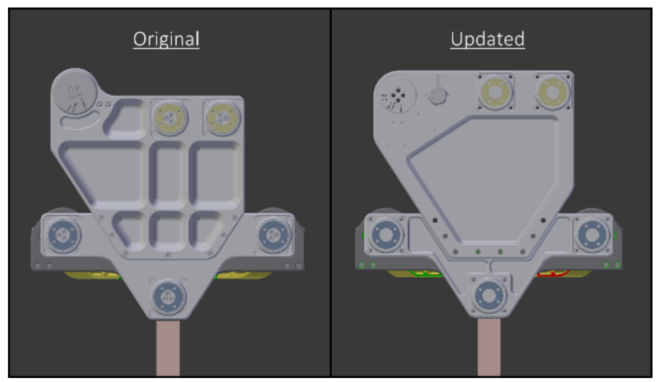
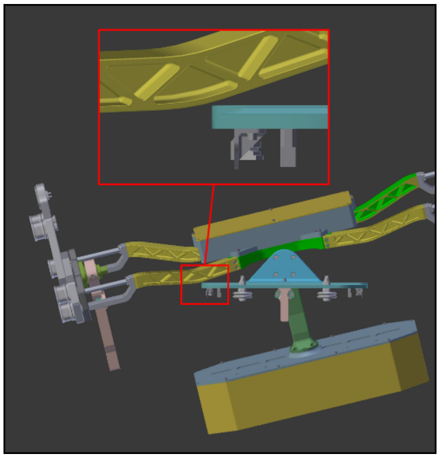


Figure 19. Example of Contact Analysis Changing Design

The joint vector space analysis also uncovered several cases of close clearance. One instance occurred between the rotational (about x) and translational (along x) VIS structures when multiple DOFs were at their maximum range. Instead of changing the geometry of either structure to add clearance space, the snubbers were relocated to reduce the maximum rotational range of the system (example shown in Figure 20). This option was available as little consequence was seen in microgravity exceedances upon increasing rotational spring stiffnesses such that snubber contact was avoided in the exercise-based dynamic run suite.



	Joint	Roll (deg)	Pitch (deg)
Undepressed Snubber Range	Initial	±11.26	±7.97
	Updated	±10.98	±6.54
Fully Depressed Snubber Range	Initial	±13.97	±13.56
	Updated	±13.76	±12.42

Figure 20. Example of Close Clearance Driving Snubber Ranges

Stability

In addition to isolation, a stability requirement is in effect for the VIS for the purposes of safety and exercise efficacy in crew interaction with the integrated E4D-VIS system. Developing and verifying stability requirements for a spaceflight exercise VIS is a long-standing challenge with no established methodology. Prior work investigating VIS stability for this project focused on validating use of exercise data collected on a stable surface by comparing with an unstable surface [54] and preliminary study of human response to exercise on a moving platform in 1g [55]. In the effort to then formulate and address VIS stability requirements, a first-look assessment explored a static, standing human on a moving platform to determine VIS acceleration limits. However, VIS accelerations exceeded these results, driving analysis of the coupled human and VIS motion instead to reduce over-conservatism.

While neurovestibular factors and crew reaction in microgravity remain less straightforward to predict, analytical investigation of the dynamic feasibility of the exercise was pursued [56]. This approach was a novel, first step in assessing if exercise would be possible on the VIS. With the addition of modeled, idealized inertial cable force (a load profile to represent free weights), the dynamic loads between human, VIS, and E4D in microgravity are estimated. The Center of Pressure (COP), i.e., the trajectory of the point of application of the resultant ground reaction force, must always remain within the Base of Support (BOS) which is the contact area of the user's feet with a surface (see Figure 21). This provides a criterion by which to inspect the ground-based exercise motion in a microgravity setting with E4D cable force and VIS motion.

If the location for the COP is calculated to lie outside the BOS on the E4D platform, this indicates that the combination of pre-recorded exercise form, E4D cable loading, and the resulting VIS motion would not be dynamically feasible, and a need for modification among these would be needed for feasibility in flight. Reasonable modifications to foot placement on the E4D and cable load were varied in the analysis while target, pre-recorded exercise trajectories were maintained.

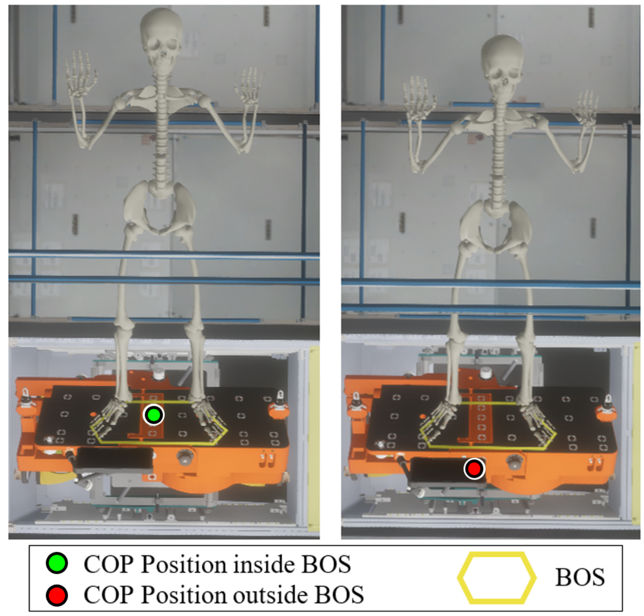


Figure 21. Visualization of COP with respect to BOS

The scope of the analysis included two critical exercises, back squat and deadlift, and focused on the 95th percentile modeled subject whose center of mass would be furthest from the platform. The dynamic feasibility criterion was not always met, but the number of dynamically feasible exercise cycles increased with set point of the cable loads (100-500 lbf) as shown in Figure 22. The overall outcome showed no red flags for VIS motion causing inability to perform these exercises in flight, especially as a "locked VIS" assessment showed similar results. It is expected that adaptation to the system will occur in early crew use in flight. Foot restraints may provide an additional aid for stability as well, though ability to adjust stance and injury prevention are considerations that could potentially influence design and usage of the device. In-flight observations and prospective data collection would inform future countermeasure system stability requirements development and aid validation or improvement of the analytical approach applied herein. Future work could also include investigating other modifications to exerciser cadence and form which achieve dynamic feasibility while maintaining exercise efficacy and avoiding injury.

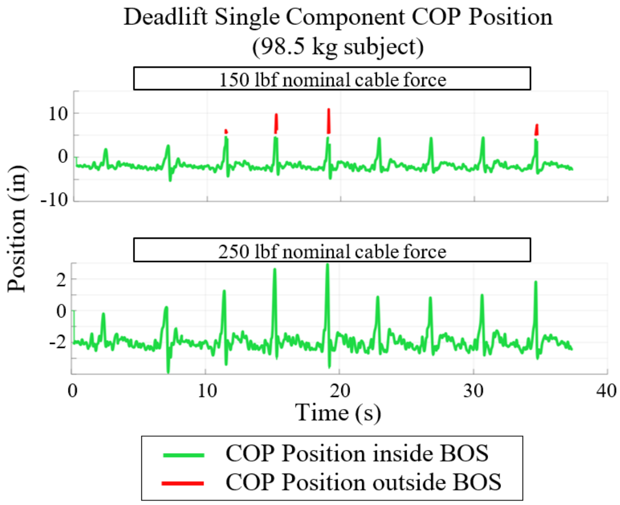


Figure 22. Dynamic Feasibility Increased with Cable Force

4. DISCUSSION

The following observations can be made as a result of this work:

1. Gradual onset of exercise (i.e., slowly increasing to a target range of motion over initial repetitions) minimizes transient response and results in reduced peak displacements. This has been shown using modified exercise data, and suggests that individuals overseeing exercise activity and training could potentially encourage gradual onset of exercise to reduce maximum displacements in order to avoid snubber impacts.

2. As mentioned earlier, the VIS has isolation in its five DOFs. Any moment applied about the axis perpendicular to the y-rotation axis and instantaneous x-rotation axis is not isolated and therefore directly transferred to the rack. This loads transmission combined with the tilt of E4D increases the unisolated base moments and worsens microgravity response against the requirements.

3. By and large, friction adds to the transmitted base loads and worsens microgravity response.

4. The E4D power/data cable is another source of uncertainty in response evaluation of VIS performance. In general, conservative assumptions of stiffness and damping of the cable model were found to increase the microgravity acceleration response, yet currently remains within a range that will be pursued for ISS Program acceptance. Further cable modeling and characterization may be required.

The following are key assumptions and limitations of this work:

1. It is assumed that a prescribed trajectory of the subject relative to the VIS platform remains the same no matter how the platform moves. Since the human control system is not explicitly modeled, as mentioned previously, it is not known how much the exercise trajectory might be altered in 0g on a moving platform when compared to a stationary platform in 1g.

2. Exercise kinematics collected on the ground in the PIT and ARGOS were maintained for the analyses. Variability in exercise motion is limited to that which occurred across 8 exercise repetitions, on average, or fewer (such as in some of the generated exercise duration extension cases where a subset was duplicated). It should be noted, however, that these data sets increase fidelity beyond data used historically for CMS VIS design to encompass an expanded range of inputs needed to inform the E4D VIS design.

3. Since exercise forces applied to the VIS depend on the acceleration of the overall CM of the system as well as the crew member mass, significant changes to these parameters could impact the outcomes of the various analyses (e.g., generation of VIS natural frequencies, microgravity responses, C&C close clearances, etc.). These types of differences would require further evaluation.

5. CONCLUSION

This paper has described the end-to-end process used to drive the mechanical design of the VIS flight hardware system through detailed model-based simulation and analyses, starting with the pre-SRR conceptual design and carrying through well beyond CDR. Correlation to ground based testbeds were used throughout to verify models used within the approach. These efforts were critical as they serve as the basis prior to flight of the integrated system of both the VIS and E4D. This same end-to-end technique described within is now being applied for the Gateway Program, where an E4D-like exercise device and notional VIS are under concept development. Although those program requirements will vary from the ISS, with more of an emphasis on L&D and volumetric concerns, the lessons learned here are still directly applicable.

APPENDICES

A. SUBJECT EXERCISE TRIALS

Progression of Number of Runs

Facility	Subject	Recorded	Generated	Dropped	Additional Cases#	Total
PIT	S01	24			6	30
	S02	27			7	34
	S03	33			12	45
	S04	28		-1	7	34
	S06	24		-1	6	29
	S07	30		-4	11	37
	S05P (S02)		27		7	34
	S95P (S03+S04)		61	-1	19	79
ARGOS	S01	34			10	44
	S02	33		-3	9	39
	S04	26			0	26
	S06	34		-3	7	38
Total		**293**	88	-13	101	**469**

Rope Pull cases were run with two tilt angles of E4D

B. OVERALL VIS MOTION

Peak Displacements

Exercise	Translations (in)						Rotations (°)	
	Pivot Points			E4D Top				
	x	y	z	x	y	z	@y	@x
Back Squat	0.3	2.6	1.7	0.7	3.6	1.6	1.4	5.7
Bent Over Row	0.5	1.8	1.3	1.1	2.9	1.0	2.0	4.4
Cross Body Pull	1.4	2.7	1.7	**2.8**	3.7	1.6	**5.6**	5.1
Cycle	0.2	0.4	0.6	0.3	0.7	0.5	0.6	1.3
Deadlift	0.5	2.0	1.4	1.0	3.4	1.2	1.6	6.3
Front Squat	0.4	2.4	1.6	0.9	3.2	1.3	1.8	6.4
Hang Clean	0.3	2.8	1.4	0.6	3.8	1.2	1.0	5.7
Hang Clean Press	0.3	2.6	1.5	0.6	3.3	1.4	0.9	5.4
Heel Raise	0.4	2.0	1.5	0.6	3.0	1.2	0.9	4.1
High Pull	0.6	2.6	1.4	1.3	3.4	1.2	2.2	5.2
Kettlebell Swing	0.9	2.1	1.4	1.8	2.7	1.2	3.1	3.6
Modified Get Up	**1.5**	2.4	1.7	2.1	3.8	1.4	3.0	7.2
Overhead Press	0.3	2.3	1.5	0.5	3.2	1.3	0.9	4.1
Rope Pull (E4D @ 18°)	1.0	1.2	1.6	1.8	1.6	1.6	3.5	3.2
Rope Pull (E4D @ 57°)	1.0	1.7	1.3	1.7	2.2	1.5	3.0	3.2
Seated Aerobic Row	0.4	**4.3**	**2.0**	0.8	**6.6**	**2.0**	1.7	**10.9**
Seated Aerobic Row (ramp)	0.4	3.1	1.6	0.8	5.5	1.6	1.7	8.6
Thruster	0.5	2.8	1.8	0.9	3.9	1.6	1.4	7.1

Note: Red denotes the maximum displacements for each DOF.

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