Title: Miniature Exercise Device-2 -- Compact Motorized Resistive and Aerobic Rowing Exercise Device

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Topic: Human Health in Space

Short Abstract (This has to be 50 words or less)

ISS sessions using the Miniature Exercise Device-2 -- a compact, lightweight device that provides aerobic and resistive exercise capabilities – have recently been completed. This new archetype of exercise equipment utilizes an innovative series-elastic actuator and motor controller to deliver a customizable load profile to the user.

Long Abstract

Future human missions beyond Low Earth Orbit (LEO) will require onboard equipment to provide exercise capabilities for the crew to counter the adverse physiological effects of long-duration microgravity. To accomplish this within the physical constraints of a space vehicle or transit module, a single miniature device that provides both resistive and aerobic exercise modalities is required. To meet this need, Johnson Space Center's (JSC) Software, Robotics, and Simulation Division (ER) developed the Miniature Exercise Device-2 (MED-2). MED-2 integrates a torque-controlled servomotor and a series-elastic actuator to provide highly-controllable load profiles and a large magnitude output performance in a very small package. This innovative technology is derived from years of JSC/ER design, development and operational experience with cutting-edge robotics, motor controllers, software and actuator/sensor miniaturization, including Robonaut 2 and MED-1. MED-2 was presented at the 2016 ISS R&D Conference. This is an update now that the last of six crewmembers will have completed planned MED-2 sessions on the International Space Station (ISS) in May 2018.

Current state-of-the-art ISS exercise equipment consists of two treadmills, a resistive exercise device and two cycle ergometers with a total mass of several thousand pounds and a total volume of several cubic yards. This equipment has proven vital to mitigate the musculoskeletal and cardiovascular degradation effects of microgravity. However, due to the large operational volume and mass of these ISS devices, tailoring them for smaller vehicles, such as Orion, is not possible. In addition, each of the current ISS devices targets a single specific modality. Compared to the existing spaceflight (and even terrestrial) exercise equipment, MED-2 is a new archetype altogether. The combined features of compact size, multi-modality and high-performance is attributable to its innovative series elastic actuator and motor controller.

Following its arrival on ISS in 2016, MED-2 was evaluated in two parts. The first and shorter evaluation was an engineering functional checkout of the hardware. As this was a novel exercise device previously never used on ISS, the initial checkout assessed the operation of the hardware and ensured the motion and dynamic range of the crew did not present any collision or other hazards. The second portion of the study collected the heart rates, kinematics and utilized operational volumes of six astronauts to determine the quality of both the resistive and aerobic exercise modalities as delivered by MED-2. Investigators from

JSC Biomedical Research and Environmental Science Division (SK) and Glenn Research Center are currently evaluating the data and preparing preliminary results.

For the resistive exercise modality, MED-2 demonstrated a range of constant resistive loads from 10-150 lbf. With a displacement range of 84 inches, the MED-2 accommodates users from 5th percentile Japanese female through 95th percentile American male for all of its certified exercises. The displacement measurement accuracy has also been verified within 2.5% full range. The crew was able to successfully perform all prescribed resistive exercises, except Goblet Squats which were not feasible with a constant load profile.

For the aerobic exercise modality, MED-2 simulated a rowing motion with prescribed and user-selected resistance levels. It has demonstrated rates up to 60 strokes per minute on the ground. MED-2 loads and displacements performance are the same as those cited for the resistive modality. Although each of the crew was able to perform the prescribed aerobic rowing sets, there was considerable variability in the rowing motion among different crewmembers. Also, as expected, the crew was unable to get the full benefits of a typical terrestrial rowing stroke because the current configuration does not allow the user to reach past their feet. These observations have already informed the requirements for other microgravity rowing devices currently in development.

One of the unique features of the MED-2 device is the intuitive touch-screen control system. This One Portal graphical user interface (GUI) was developed based on JSC/ER's heritage knowledge and experience of developing and sustaining the current ISS exercise equipment. Through this interface, the crew easily performed prepared prescriptions as well as had the ability to adjust exercise modality, load and other exercise details such as number of repetitions and number of sets. This touch-screen and GUI fulfilled the MED-2 project goal to simplify the interaction between the user and the device. Furthermore, the extent to which MED-2 utilizes a touchscreen and GUI to control exercise equipment is unmatched among the existing ISS exercise devices.

As a motorized device, MED-2 technology can provide a customizable force profile that can be varied as a function of strap displacement, strap velocity or a combination of these and other variables. During 2017, JSC/ER developed and flight-certified a resistive exercise algorithm that mimics the 1-G inertial effects of free-weights and enables adjustable eccentric-to-concentric loading ratios. Subsequent development will explore varying the load profiles and incorporating additional exercises beyond the current list of certified movements.

Miniature Exercise Device-2 (MED-2)

Preliminary ISS Evaluation Results for a Compact Motorized Resistive and Aerobic Rowing Exercise Device

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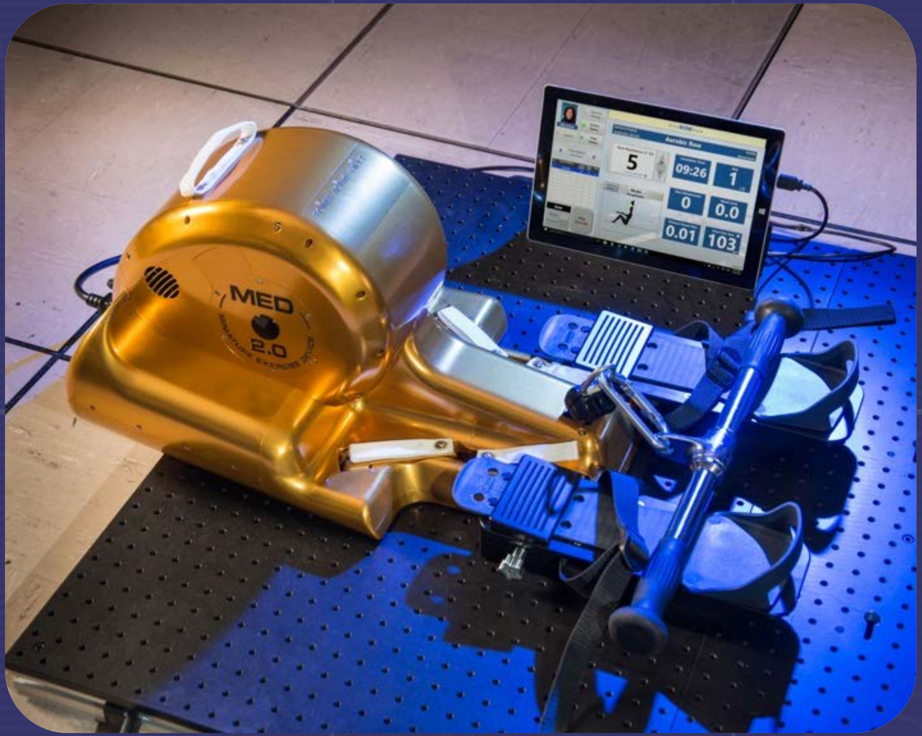
Miniature Exercise Device -2 (MED-2) - Overview

- ISS science payload evaluating usefulness and effectiveness of a small, lightweight resistive exercise device for exploration missions
  - Weighs 65 lbs
- Developed on compressed 9-month schedule to demonstrate the new Class-1E processes
- Launched in March 2016
- Series elastic motor controlling a pulley, which tensions an exercise cable, to provide resistance as the user pulls against the exercise cable



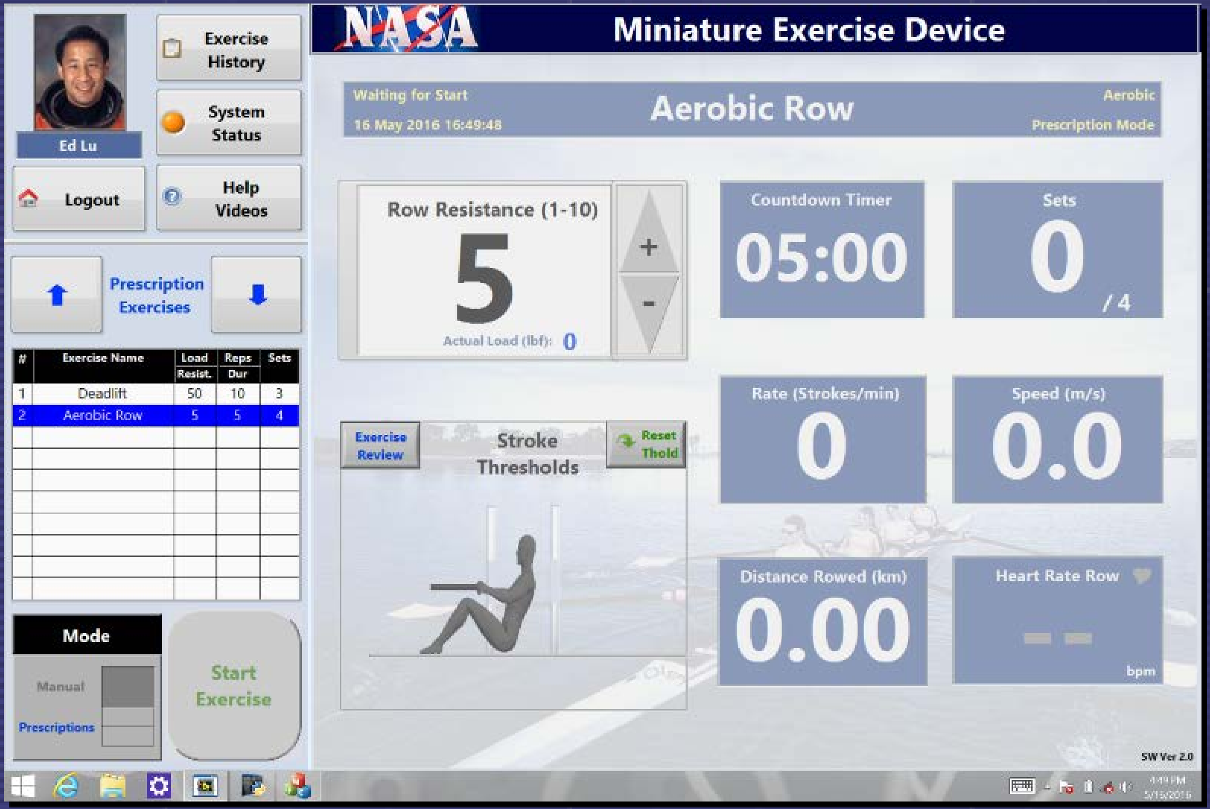
MED-2 with rowing attachments and tablet

MED-2 Exercise Modes

- Resistive
  - Current MED-2 on ISS provides constant force up to 150 lbs
  - Certified software update adds inertial loading and adjustable eccentric-to-concentric loading ratios, but not yet deployed on ISS
  - Enables exercises with grip in front of person and below shoulders
- Aerobic Rowing
  - New modality of aerobic exercise for ISS
  - User can change settings 1 - 10, similar to commercial ground units
  - Software simulates boat drag and weight

MED-2 One Portal Graphical User Interface (GUI)

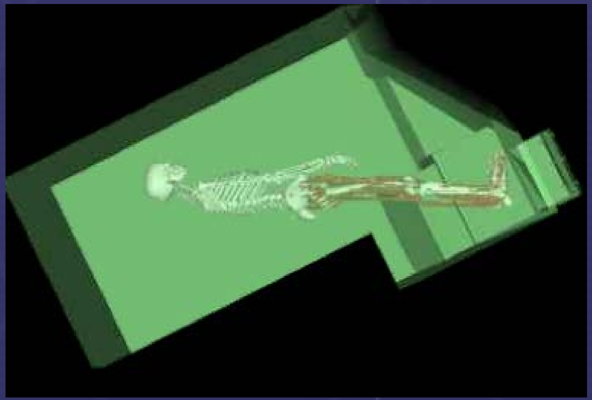
- Optimized for touch screen format on Surface Pro 3 (SP3) tablet
- Enables uplinked exercise prescriptions and data storage/transfer/downlink



MED-2 Rowing Exercise Screen

MED-2 Resistive Exercise Screen

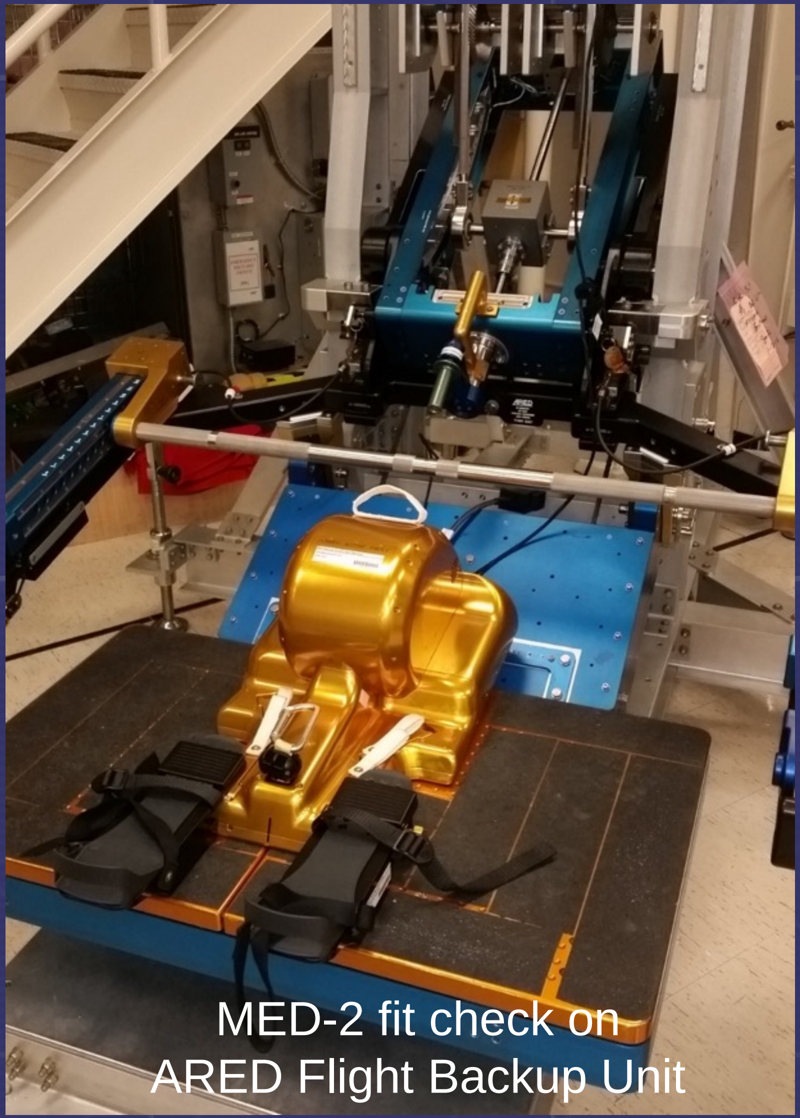
MED-2 Exercise Evaluation Objectives on ISS



- Inform current & future Exploration Exercise Device designs
- Main Objectives
  - Assess operational envelopes for aerobic rowing and deadlift exercises in µG
  - Assess potential training efficacy of aerobic rowing
  - Assess whether multiple resistance exercises can be performed comfortably and with acceptable form with MED-2
- Secondary Assessment Opportunities
  - Calculate joint kinematics by building subject-specific open sim models & estimating joint angles
  - Apply kinematics to a 99th percentile-scaled version of the model to yield maximum operational envelope
  - Compare MED-2 kinematics to Advanced Resistance Exercise Device (ARED) kinematics
  - Gather imparted loads data to generate input forcing functions for Vibration Isolation & Stabilization (VIS) designs and for exploration vehicle dynamic loading assessments

MED-2 Evaluation Configuration on ISS

- Six astronauts recruited to participate in study
  - All data collected (Jun 2017 – Apr 2018), except one MED-2 session remaining for 6th crewmember
- Sessions include: pre-flight familiarization, 2 in-flight MED-2 exercise sessions, 1 in-flight ARED exercise session
- Resistance exercises: deadlift, Romanian deadlift, bent over row, upright row, bicep curl, front squat
- Aerobic exercise: rowing (MED-2 only)
  - Warm-up, nominal and fast cadences at light, medium, and heavy loads
  - 1-2 minute durations, and high velocity 30 second bouts
- Instrumentation
  - Polar Heart Rate Monitor
  - 21 reflective markers
  - 4 HD cameras
  - ARED force plates
  - Load and displacement from MED-2
- Post-exercise survey



MED-2 fit check on ARED Flight Backup Unit

Results – MED-2 Performance

- MED-2 provision of exercise loads and profiles was consistently excellent
- Enabled all intended resistive exercises, except Front Squat
  - Most crew prevented from getting to Front Squat start position in µG due to constant-load profile and inability for single crewmember to easily initiate loading at top position
  - New inertial-load profile is expected to help remedy this
- SP3 Bluetooth connection challenges for Heart Rate Monitoring data collection

Results – Operational Envelope and Joint Kinematics

- Successfully gathered body marker data from video. Currently processing entire collection of videos to determine ops envelope.

Results – Rowing Video & Observational Biomechanics

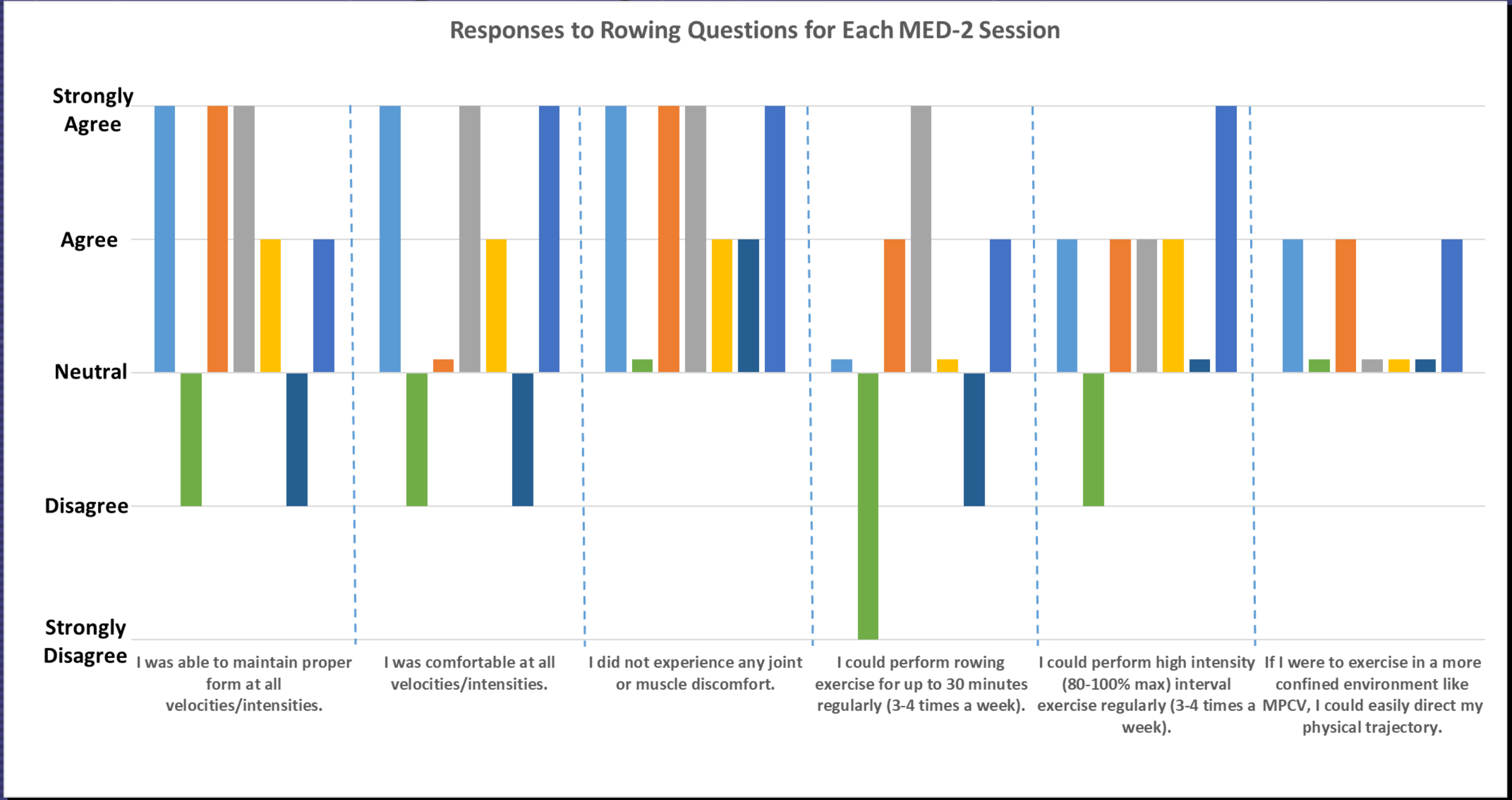
Release Position / Early Drive / Catch Position

- μG knee and ankle angles at the catch are similar to the early drive position in traditional rowing
    - May be a product of trying to lengthen the stroke
    - Effective pitching moment in μG that likely can't be reacted just at the feet
- μG load path remains parallel to the shins throughout entire stroke
- Unlike traditional row, μG config doesn't allow hands to reach beyond the feet
    - More akin to the late drive position in traditional rowing
    - Reduces the amount of ankle and knee flexion
    - Shortened stroke reduces work done by the lower body
- Can resolve both issues by reconfiguring with a kinematic constraint (e.g. seat rail with belt)

Results – Aerobic Heart Rate Data

- The ability to achieve a high percentage of maximum heart rate is critical for an effective aerobic exercise device
- All crewmembers were able to row at >80% max HR for at least 30 sec
- 1 crewmember reached 93% of max HR

Results – Rowing Survey



Conclusions So Far

- Proof of concept that a compact lightweight motorized device, such as MED-2, can provide both resistive and aerobic exercise modalities.
  - Inertial loading profile is expected to improve user experience and help enable Front Squat.
  - For µG environment a kinematic constraint on astronaut (such as seat rail with belt) and reconfiguration is needed to replicate exercise motion of traditional rowing.
  - Rowing has potential to be an effective aerobic exercise countermeasure in µG, though feasibility of longer duration sessions and injury risks needs to be evaluated.
  - One Portal touchscreen GUI was effective and is now intended to be used for forthcoming exploration exercise devices.
- Body marker data collection was successful, enabling kinematic and operational envelope analyses (in work).
- These results have already informed requirements development for forthcoming exploration exercise devices.

MED-2 Forward Plan on ISS

- Current study
  - Perform final remaining MED-2 session for final crewmember to complete data collection
  - Complete video data analysis of operational envelopes for 6 crewmembers
  - Use modeling of kinematic joint angles to determine max operational envelope for 99th percentile
  - Compare resistive exercise kinematics between MED-2 and ARED
- Follow-on studies
  - Submitting request for crew time to assess feasibility of longer duration aerobic rowing sessions (e.g. 30 minutes)
  - Submitting request to deploy and evaluate existing certified software update
    - Inertial loading profile: Confirm it enables Front Squat and get crew qualitative feedback
    - Adjustable eccentric-to-concentric loading ratios: Get crew qualitative feedback

Forward Plan on Technology Development

- MED-2
  - Improve motor controller board to enable higher resistive exercise loads
  - Evaluate multi-motor configurations
- Integration of commercial technology/devices to create an intelligent biofeedback exercise system
  - Wearable sensors
  - Artificial intelligence
  - Virtual reality and haptic feedback
- Collaborative partnerships with commercial, academic, government entities

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INTELLIGENT BIOFEEDBACK EXERCISE SYSTEM
THE FUTURE OF EXERCISE
SOCIAL INTERACTION
1
2
3
VIRTUAL AI BASED TRAINER
LARGE DATA HANDLING CAPACITY
SENSOR FUSION OF HUMAN & MACHINE DATA
HR
SpO2
ALPHA
BETA
GAMMA
TRAINING LOAD
38 %
62 %
3.6
MUSCLE FATIGUE
EXERTION
REALTIME BIOMECHANICAL MODELING
AEROBIC CONDITIONING
ANAEROBIC INTERVALS
AUGMENTED REALITY
ECCENTRIC OVERLOAD
ACTIVE RECOVERY
STATIC LOADING
FREE TRAIN
MANUAL
INTEGRATED TRAINER
OPTIMIZATION PROTOCOL
REHABILITATION
BLUETOOTH COMMUNICATION
OPTIMIZED TRAINING SESSIONS