Project Title:
Intelligent Devices/Equipment/Instruments (IDEI) for Enabling Crew Health and Performance on Mars[1]

Recommendations for Enabling Crew EVA Performance and Countermeasures on Mars: A Modified Rowing Machine Design

Project Team:

The Mars Human Health and Performance Monitoring System (M-HHaPS) team, a part of the Bioastronautics and Life Support Systems (BLiSS) team[2]

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1 Introduction

The Moon to Mars eXploration Systems and Habitation (M2M X-Hab) 2024 Academic Innovation Challenge features a project titled "Intelligent Devices/Equipment/Instruments (IDEI) for Enabling Crew Health and Performance on Mars" [1]. The project calls for the development of prototype IDEIs "that could be used for implementing integrated system health management for Crew Health and Performance (CHP) required for crew living on Mars for extended periods of time" [1]. Thus, the deliverable for the project is not only a prototype exercise device, but also an ontology that provides insight into the best ways to exercise on Mars.

To that end, we on the BLiSS team, supported by advisors from industry and academia, set out to ideate an exercise ontology and demonstrate its effectiveness through a functional prototype. To achieve the stakeholders' requests, the device must operate semi-autonomously, must be an analog for an extant exercise device on Earth, and must provide quantitative information about the exercise and the device's own state of health. Here, we define "semi-autonomous" as referring to the fact that while the system should be as autonomous as possible, there are some processes that the system cannot fulfill on its own. These include, but are not limited to, user identification, physical exercise reconfiguration, and wearable sensor placement. The stakeholder objectives were encapsulated in five top-level mission requirements in Table 1.

R1	The exercises shall maintain EVA fitness levels.
R2	The device shall semi-autonomously collect performance metric data.
R3	The device shall semi-autonomously detect system faults.
R4	The device shall interface with the Life Support System, Remote Monitoring System, and Crew Health and Performance Monitoring System in the Martian habitat.
R5	The device shall operate within the Martian habitat.

Table 1: Top-level mission requirements.

R2, R3, and R4 reflect the directly identified stakeholder needs. R5 constrains the device through defining its environment. Since Martian gravity is approximately 38% that of Earth's gravity, normal exercise devices that use weights would be less effective. Additionally, we were advised that while defining Mars mission architectures, planners will trade different atmospheric pressures in order to save on pre-breathe time while not significantly increasing risks associated with flammability [2]. These constraints would also impact devices that rely on air density for resistance and factor into the design chosen for our device that will be discussed in more detail in the Design Deep Dive.

We contend that extravehicular activity (EVA) is the most important and strenuous activity that astronauts will engage in on Mars. Thus, we believe that a Martian exercise ontology should be designed around not only providing normal countermeasures, but also training astronauts to be able to walk around in their spacesuits for extended periods. This goal is reflected in R1 and is specified further in the system-level spec (included in Appendix A). Specifically, L1 R1.1 identifies three analogous activities that are believed to be important for EVA and can be easily translated into exercises, which are stated in Table 2.

These activities require core strength, endurance, leg strength, and arm strength, respectively. To measure the effectiveness of the device at targeting those muscle groups, L1 R1.2 defines which performance metrics would be measured, which are stated in Table 3.

EVA Performance Tasks
Walk with heavy pack
Squat down and pick up item
Manipulate item with hand

Table 2: EVA task exercise analogs

Performance Metrics
Heart rate
VO_2
Reps (note if to failure)
Muscle Strength

Table 3: Performance metrics to measure

It should be noted that we will not measure VO_2 directly, but rather calculate it using heart rate data [3]. Muscle strength will also be measured indirectly by recording force applied during an exercise. In our system, these metrics are measured throughout the exercise and over time to show workout consistency and long-term improvement.

2 Design Concept

The system's overall design is a rowing machine-analog device (herein referred to as "the device") that provides the user with a full-body workout focused on the essential muscle groups for completing crucial EVA tasks. The base rowing machine is a XTERRA Fitness ERG220 Magnetic Foldable Rowing Machine, a commercial off-the-shelf (COTS) product that we modified for this project.

The operational framework of the proposed exercise system mirrors the familiar functionality of a terrestrial rowing machine, featuring a freely sliding seat, adjustable footrests, and a user-selectable resistance cable. To ensure adaptability for astronauts of varying sizes and to facilitate diverse muscle group targeting, our device adds multiple handles and footrest configurations. A user-friendly interface is also integrated into the system via a display screen. The interface serves as a portal for astronauts to access personalized accounts, select workout parameters, and monitor performance metrics. The system's intuitive design is adjustable to the user, fostering a comfortable user experience. The machine is integrated with sensors that allow for real-time monitoring of metrics, enhancing the overall efficiency and providing the crew members with necessary and valuable data. The device generates on-demand reports, contributing valuable insights into astronaut health and system diagnostics. The full rowing machine is shown in Figure 1.

In summary, the BLiSS M-HHaPS Team developed the rowing machine-analog device to address the need for specialized training equipment for astronauts engaged in extravehicular activities. Through meticulous selection of EVA tasks, metrics, and device features, the team aims to provide an effective and versatile solution that contributes to astronauts' physical preparedness for the challenges of space exploration to Mars.

3 Design Deep Dive

In order to produce the M-HHaPS design, the BLiSS team broke up into three subteams and divided the system into five subsystems. Each subteam was responsible for an aspect of the design as follows:

Exercise Capability (EC) took on the role of researching the exercises that would be most useful as countermeasures for reduced muscle and bone loading. Later in the project, EC designed

Figure 1: BLiSS M-HHaPS rowing machine on display during the team's final presentation

and manufactured the physical components of the M-HHaPS device. **Data** was responsible for software, particularly as related to processing data received from the sensors team. The Data team was also responsible for creating the user interface screen and displaying the data they processed. **Sensors** were responsible for all sensor components in the system. They were also responsible for low-level data acquisition code, and power control.

The subsystems of the M-HHaPS project were: Mechanical, Sensors, Software, User Interface, and Power. These were broken up among the three subteams as shown in Figure 2. The **Mechanical** subsystem consists of all moving physical components. EC is responsible for the design and manufacture of those parts, and Sensors may be responsible for their ability to move. The **Sensors** subsystem consists of all physical sensors components. The **Software** subsystem consists of all software written for the M-HHaPS system. This includes low-level data acquisition software written by the Sensors subteam and higher-level data processing software written by the Data subteam. The **User Interface** subsystem consists of all components that interface with the user. This includes physical components such as the seat, which are EC's responsibility, as well as the user interface screen, which is Data's responsibility. The **Power** subsystem consists of all components that receive or provide power to any components of the system that require it. Specifically, this includes Sensors and Data components such as the user interface screen, sensors, and microcontrollers.

3.1 Exercises

Incorporating a diverse range of exercises, our machine offers users a comprehensive workout experience tailored to the unique demands of space conditions. Leveraging a sophisticated magnetic resistance system, the equipment provides a dynamic platform for both cardio and resistance training, surpassing the capabilities of traditional exercise machines. Anecdotal evidence underscores the effectiveness of the magnetic system, highlighting its ability to simulate the feel of traditional weightlifting while offering distinct advantages. The system's reliance on magnets interacting with the flywheel in close proximity enables sufficient control over resistance, ensuring a challenging yet safe workout environment.

Users can transition between various exercises, including rowing, leg press, chest fly, seated row, delt fly, bicep curls, and tricep kickbacks, each targeting specific muscle groups essential for EVAs. For instance, the rowing exercise mimics the motion of rowing a boat, engaging the upper body and

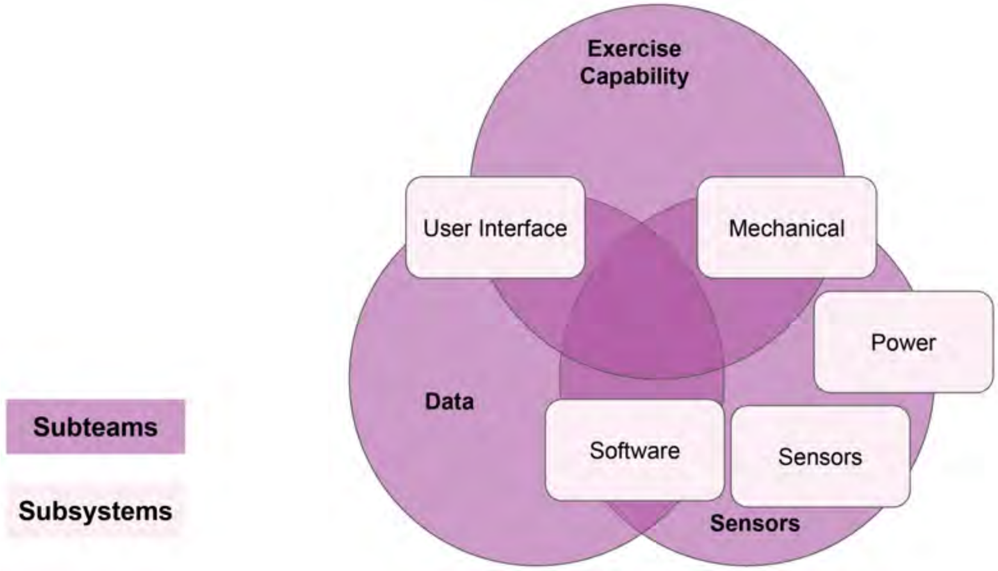


Figure 2: M-HHaPS team work breakdown structure

core muscles, while the leg press exercise targets lower body strength, vital for astronauts' mobility and stability in microgravity environments. Additionally, exercises such as chest fly and seated row focus on strengthening upper body muscles, essential for performing tasks during space missions.

A detailed user guide accompanies the device and is included in Appendix D, providing comprehensive instructions on exercise execution and machine configuration for optimal performance and safety. For instance, the resistance adjustment mechanism allows users to tailor workout intensity by manipulating magnet rack locations, while proper positioning and technique guidelines ensure safe and effective exercise execution. Mitigation strategies are integrated into exercise protocols to address potential risks, such as ensuring proper foot positioning and seat adjustment to mitigate injury risks during leg press and rowing exercises.

The equipment's versatility extends to user-worn sensors for monitoring vital signs, including pulse and blood oxygen levels, enhancing health monitoring capabilities during workouts. Despite the inherent challenges of exercising in space, our machine offers a user-friendly and effective solution, empowering astronauts to maintain physical fitness and overall well-being during prolonged missions. By combining innovative design with ergonomic functionality, our exercise equipment represents a significant advancement in space fitness technology, supporting astronauts' health and performance in the demanding environment of space exploration.

3.2 Mechanical Components

The mechanical subsystem encompasses all device components that undergo physical movement and directly engage with the user. The system is designed to be adaptable to accommodate users with a variety of physical attributes.

After the selection of the rowing baseline design, a comprehensive trade study was performed to identify the features requiring modification to incorporate additional exercises that effectively engage the muscles essential for the selected EVA tasks. The adjustable components under consideration include the rower's seat, handle, and footrest. The trade study encompasses a holistic analysis of the entire system, aligning with the requirements of performing analogous EVA tasks, accommodating a diverse range of users, and facilitating integration with sensors. Evaluation criteria for each alternative involved factors such as the value in simulating EVA tasks, feasibility, and complexity for the BLiSS team, novelty, low power consumption, integration with gamification, added volume, and increased mass. The detailed scoring and rationale for each decision within the trade study are documented in Appendix B. Notably, the alternatives that earned the highest scores were the adjustable handle and footrest. Upon further consideration, modifications to the seat were also deemed necessary to incorporate an attachable backrest and handle for leg press exercises, with the moveable seat requiring locking in place for lateral flies.

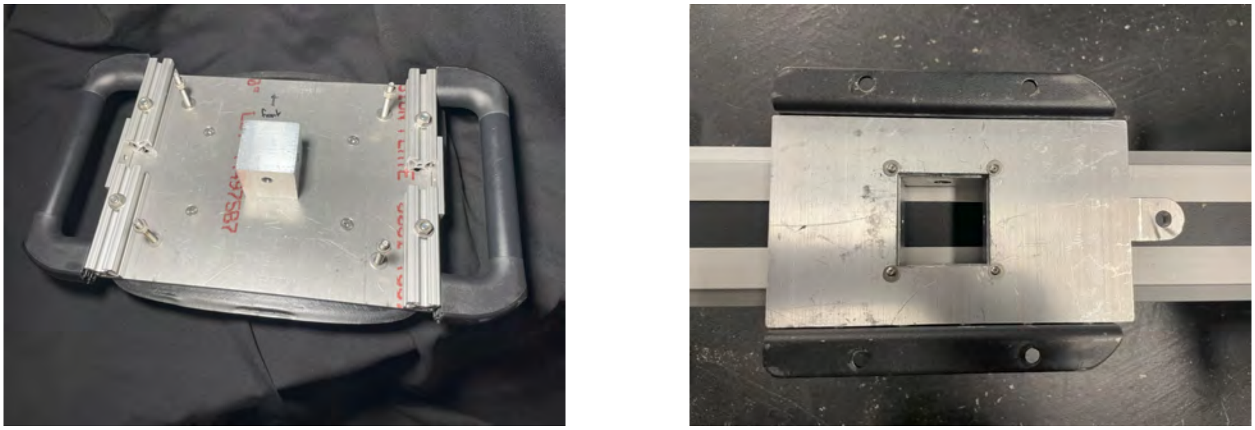
Following the identification of modification areas on the baseline design, supplementary trade studies were undertaken to explore various aspects, including the type of handle attachments, the grip type on the handle, and the design of the footrest. To inform these decisions, we dedicated time to exploring the University of Michigan Intramural Sports Building, where we examined the exercise equipment in their exploration of potential alternatives. By actively engaging with the equipment, we gained practical insights that proved invaluable when assessing and scoring the alternatives in the subsequent trade studies. This hands-on approach enhanced the decision-making process, ensuring informed choices for the incorporation of handle attachments, grip types, and footrest designs into the rowing machine. The following sections will discuss the modifications made to the rowing machine.

3.2.1 Seat

When considering the development of our seat as a crucial element of our final design, we initially outlined the objectives we aimed to achieve with the seat. Through the trade study in Figure 24, we delineated the need for a seat capable of assuming three distinct positions: the default orientation, a ninety-degree counterclockwise rotation, and a ninety-degree clockwise rotation. Although we initially desired to make the seat fully rotatable, the design was eventually changed to support only the forward and 90-degree positions to be locked in. To realize this functionality, the seat is attached to a large square peg that both provides support and facilitates the desired ninety-degree shifts in both clockwise and counterclockwise directions, as shown in Figure 3. The peg fits into a square hole in a base plate attached to the COTS seat roller, and the seat can be reconfigured by lifting it out of the hole, rotating it, and placing it back in the hole. The implementation involves a 0.375-inch diameter pin (Figure 4) that slides through the peg when the seat is positioned as desired, effectively locking it in place to prevent any unintended rotation or lateral movement during use.

The integration of handles onto the seat presented challenges initially, particularly in ensuring their functionality across all seat orientations without obstructing other exercises. The original design consisted of solid aluminum bars that were attached to the handles with two screws per handle about 1 inch apart and attached to the bottom of the bottom plate via nuts and bolts. While they proved beneficial for various exercises like leg presses, chest flies, and deltoid flies, the initial design, featuring solid aluminum bars affixed with screws and nuts, encountered issues with interference with the seat base plate when the seat was rotated sideways. The seat base plate can be seen in Figure 3b, and the main cause of interference was the rounded piece on the right with a hole for a carabiner.

In response to this limitation, a redesign of the seat handles was undertaken. The revised design utilizes 80-20 material, allowing for the creation of two separate bars with a gap in the middle to accommodate the base plate. The 80-20 with the gap can be seen in Figure 3a. This adjustment not only addressed the interference issue but also simplified the manufacturing process, as 80-20 facilitated easy attachment using brackets and eliminated the need for drilling and tapping holes. This refined approach resulted in a more lightweight and easily manufactured design that effectively met the requirement of not obstructing the base plate in any seat orientation.



(a) (b)

Figure 3: Seat square peg medication to enable three locked positions. The square peg (a) slides into the square hole in (b)

(a) (b)

Figure 4: 0.375-inch seat pin shown in (a). The pin slides through the holes in the roller (b) and through the holes in the square peg in Figure 3a

To accommodate movements such as the leg press, the design features a backrest that can be attached to the seat (Figure 5b). If a user were to attempt a leg press or calf raise on the seat without a backrest, they could slide off the seat and risk injury from poor posture support. The backrest consists of an approximately 1-foot by 3-foot cushion mounted to an aluminum plate. The aluminum plate is attached to two L-shaped pieces made with 1010 series 80-20 that allow it to be integrated with the seat (Figure 5a). Originally, these L-shaped pieces were made from steel tubes that were bent to 90-degrees to provide a monolithic piece that would, theoretically, support loads better. However, it proved difficult to machine those pieces and drill holes where needed, so the design was changed to take advantage of 80-20's flexibility. The backrest also features a support that attaches behind it and sits on the rowing machine track to help support loads during a leg press exercise (Figure 5c).

(a) (b) (c)

Figure 5: Backrest with L-shaped pieces (a). The backrest can be attached to the seat, as shown in (b). The backrest support (c) attaches to the back of the backrest

3.2.2 Footrest

The development of the footrest posed numerous challenges and design constraints for the team, particularly in terms of its implementation separate from the rowing machine itself. A primary difficulty arose in securely attaching the footrest to the rower, as conventional methods like drilling and direct attachment proved infeasible due to limited access to necessary equipment and materials in the lab setting. Although we did have access to machine shops at the University of Michigan, we were unable to use their tools on the rowing machine's frame itself due to its size and awkward shape. This realization led to the acknowledgment that alternative solutions needed to be explored to ensure the footrest's integration into the design.

The concept of the footrest emerged alongside the decision to incorporate a leg press function into the rower, driven by the team's focus on targeting weight-bearing muscles, such as the quadriceps, hamstrings, and calf muscles, to address potential issues like muscular dystrophy. We conducted a trade study to determine the most suitable type of footrest for performing exercises on the rowing machine, as outlined in Figure 23. The requirements for this trade include ensuring that the footrest does not interfere with the cable during rowing, providing accommodations for resting the feet during both upper and lower body exercises, allowing for a wide range of motion in the transverse direction, withstanding forces exerted by the crew member, and being compatible with all members of the crew. The considered alternatives comprised a typical rowing footrest, removable footrest, expandable footrest, footplate, and a platform. Evaluation criteria included the ease of transition between exercises, a slight angle for lower mobility during leg press and calf raises, the comfort of the footrest, simplicity in design, effectiveness in targeting desired muscles, and overall durability. Detailed scoring and rationales for each alternative are available in Appendix B. While the typical rowing footrest emerged as the initial winner, upon further consideration, it was decided to combine it with a stationary footplate to enhance the machine's capability for performing leg press exercises.

Drawing inspiration from leg press machines, the team devised a design featuring an aluminum skeleton forming the core of the leg press structure, extending behind the rower to create a robust framework. Positioned at the rear base, the footrests comprised aluminum sheets angled slightly upwards on either side of the cable housing, facilitating comfortable foot placement during exercise. The footrest and support structure can be seen in Figure 1 on the left.

In the initial design iteration, the team utilized aluminum sheets and bars arranged in a "sandwich" configuration to achieve a balance of structural strength and lightweight construction. However, challenges arose in ensuring compatibility with the rower's existing mechanisms, prompting modifications such as cutting a hole in the center of the footrest to accommodate the carabiner and tether. A subsequent redesign of the footrest involved the adoption of 80-20 aluminum bars, offering improved ease of assembly and modification while maintaining the desired mechanical properties. This approach streamlined the design process, allowing for swift adjustments without the need for extensive rework. Additionally, the footrests are equipped with Velcro straps, providing secure foot placement while astronauts perform rowing motions and leg presses. Further reinforcement using additional 80-20 is included in areas prone to flexion.

The decision to utilize two separate plates for the footrest in the redesign not only addressed clearance issues, but also facilitated easier adjustment of the plate span if required, enhancing the overall versatility and functionality of the design. Ultimately, the strategic use of materials like 80-20 and thoughtful design refinements resulted in a more robust and adaptable footrest solution for the rowing machine.

3.2.3 Handle Attachments

In the initial phases of the design process, discussion centered around the optimal attachment method for the handles to the machine, a pivotal decision shaping user experience and functionality. The consensus emerged, after conducting two trade studies (Figures 21 and 22), that versatility and user comfort were paramount, leading to the adoption of multiple handles instead of a singular one. This choice not only diversified the range of exercises achievable, but also catered to varying grip preferences and exercise goals. To ensure secure yet adaptable attachment, the implementation of carabiners emerged as the preferred solution. This approach not only facilitated swift interchangeability but also upheld safety standards during intense workout sessions. Five handle types were selected: narrow grip bar, v handle, single neutral grip handle, rope, and wide neutral grip bar. Four of these handles are shown in Figure 6. The narrow grip bar can be used for rowing exercises. The v handle or triangle bar, the rope, and the wide neutral grip bar can be used to perform seated stationary rows as well as standing rows. The single neutral grip handle can be used to perform individual chest and deltoid flies. With a meticulously curated selection comprising handles, the design aimed to provide a comprehensive workout experience, catering to the diverse needs of users while maintaining an emphasis on safety and functionality.

The first handle attachment trade study focused on assessing the types of handle attachments suitable for integration with the rowing machine (Figure 21). The evaluation criteria for this trade included the ability to simulate specified EVA tasks, accommodation of a diverse user range, resilience to crew load, attachment capability to a metal carabiner, and the versatility to switch out handle types. The considered alternatives comprised a straight bar, triangle bar, neutral grip, lat pull-down bar, and ropes. Evaluation parameters involved stability with a metal carabiner attachment, effectiveness in engaging muscle groups relevant to EVA tasks, considerations for added

(a)

(b)

(c)

(d)

Figure 6: Wide neutral grip bar (a), v handle (b), narrow grip bar (c), and single neutral grip handle (d). The narrow grip bar came with the COTS rowing machine

mass, and the compatibility of rowing attachments for storage purposes. Detailed scoring and rationale for each alternative can be found in Appendix B. The winning alternative, determined through the trade study, was the triangle bar, complemented by plans to integrate a soft single handle for lateral flies and the standard rowing handle. Following this decision, we decided it would still be best to have multiple handle attachments such as a triangle bar, straight bar, rope handle, and a single hand attachment, to provide the greatest variety in exercises.

The second handle attachment trade study focused on evaluating the type of hand grip suitable for integration with the selected handle attachment (Figure 22). The requirements for this trade encompassed a grip length accommodating multiple hand sizes comfortably, compatibility with the chosen handle attachment, and the capability to remain securely in the same location on the bar. The considered alternatives included a knurled bar, leather, rubber, polished metal, and polyethylene foam. Assessment criteria involved an increase in grip diameter, a comfortable grip texture, integration potential with a bike brake mechanism, compatibility with a wrist strap attachment, and the durability of the grip material. Comprehensive scoring and rationale for each alternative are available in Appendix B. Following the trade study, the winning alternative emerged as the rubber grip, deemed the most suitable for meeting the specified requirements.

Each of the handle attachments can be attached to the rowing cable using a carabiner. We opted for a carabiner because it was strong enough to withstand the force on the cable and most importantly it allowed for the user to swap out the attachments from exercise to exercise with little effort.

3.2.4 Resistance

During the engineering design phase, the team encountered a significant hurdle in devising an effective resistance mechanism for the leg press function of the rower. The factory-installed eddy current system, reliant on manipulating the surface area of a magnet on the flywheel, posed limitations in providing adequate resistance for leg press exercises, which typically require the user to exert nearly double their body weight. An eddy current brake generates a resistive force according to Equation 1 [4], where F is the force, B is the magnetic field strength, A is the surface area of the material over which the magnetic field acts, ρ is the resistivity of the material, and v is the velocity of the material through the magnetic field.

$$F = B^2 A \rho v \tag{1}$$

We can see that the primary ways to increase the resistance would be to increase the magnetic field strength by adding more and stronger magnets or by changing the velocity at which the flywheel rotates. These options were considered in a trade study to explore alternative solutions (Figure 20), including permanent magnets, electromagnets (either as additional brakes or as solenoids), a gear system (to change v), and a motor (to provide countertorque). Each alternative was evaluated based on criteria such as resistance adjustability, mass, resistance granularity (how big the step sizes would be between settings), manufacturing feasibility, and projected maintenance needs, with permanent magnets emerging as the most promising option.

Opting for pairs of permanent magnets, the team devised a robust resistance mechanism capable of delivering up to 300 pounds of force, meeting the desired resistance threshold for leg press exercises. This system features a permanent magnet housing positioned near the flywheel, augmented by removable magnet racks that facilitate precise adjustment of resistance levels. The resistance level is directly proportional to the number of magnets interfacing with the wheel, with higher speeds of rotation correlating to increased resistance, controlled by the speed of the cable being pulled during exercise performance. Figure 7 shows data collected with up to 20 magnet pairs. Since each added pair increased the surface area over which the magnetic field acts, a linear fit was applied to determine the general trend in the resistance. The data were collected using a luggage weight to measure force as a user pulled on the cable. For each addition of a magnet pair, the test was repeated three times and the average was taken and used for Figure 7. Since the resistance depends on the speed of the cable, a more robust testing apparatus would need to be devised for future iterations to avoid deviations caused by the fact that it is harder to consistently pull a heavier load at the same speed as a lighter load.

To enable seamless adjustment of resistance levels, users can follow a straightforward procedure outlined by the team. Increasing resistance involves inserting a magnet rack into the magnet housing as shown in Figure 8, or adjusting an existing one, while decreasing resistance requires the removal or adjustment of the magnet rack already installed. Figure 9 shows CAD drawings of the magnet rack, the magnet housing, and the pins, which were 3D printed in nylon. This material was chosen for its strength and due to the current manufacturing capabilities available to the team. Installation entails carefully positioning the magnet bar with magnetic legs around the flywheel and securing it in place with a pin, while removal and adjustment procedures involve removing the securing pin, sliding the magnet bar in or out of the housing, and reinserting the pin to lock

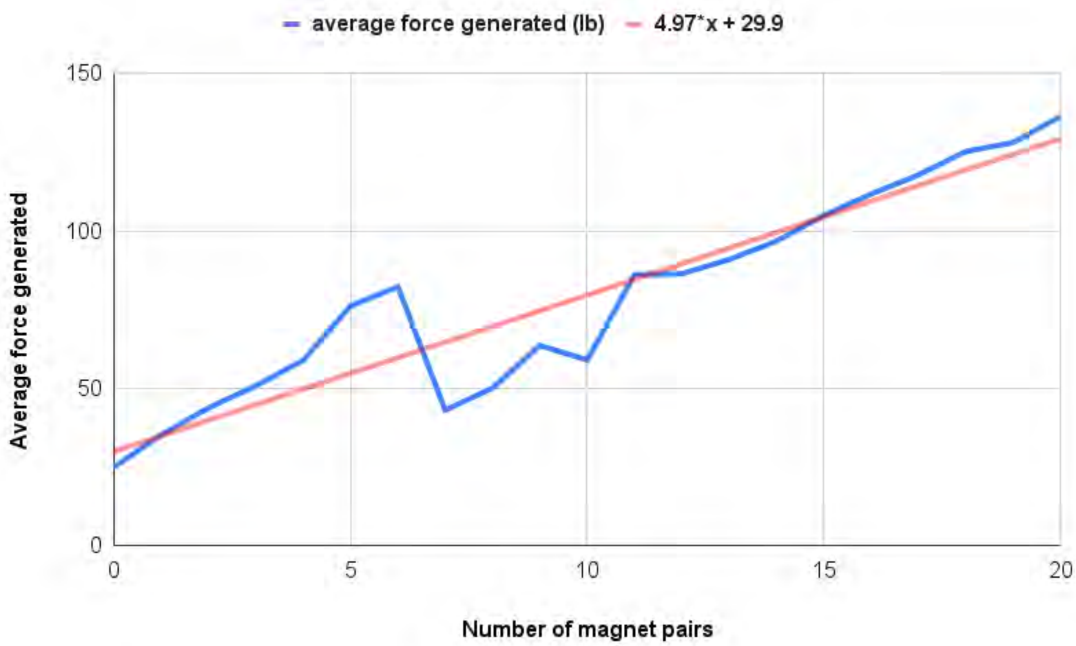
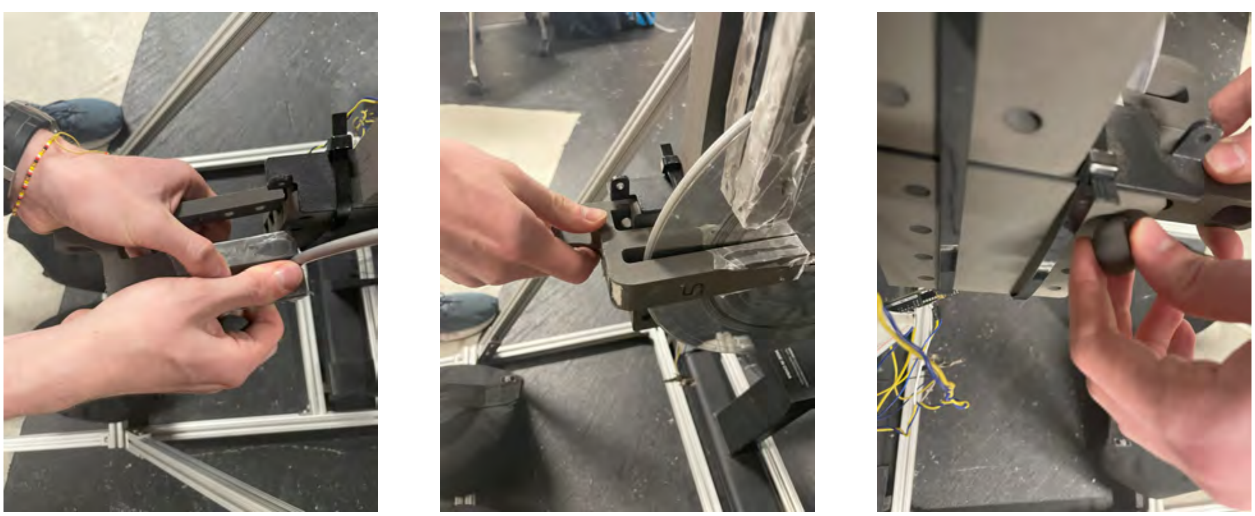


Figure 7: Average force measured per number of magnet pairs on the flywheel

it in the desired position. This process is shown in Figure 8. This meticulous approach ensures precise control over resistance levels, allowing users to tailor their workout intensity to meet their individual needs and fitness goals. The current iteration involves color detection with color strips installed on the magnet racks which are read by the color sensor installed on the magnet housing for the software to recognize what resistance is set for the exercise being performed.



(a) (b) (c)

Figure 8: Pin mechanism for adjustment of magnet racks

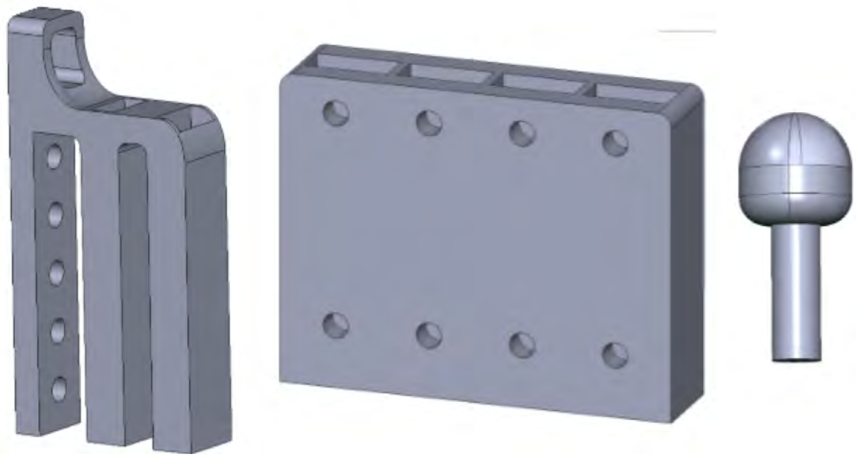


Figure 9: CAD drawings of magnet rack, magnet housing, and pin

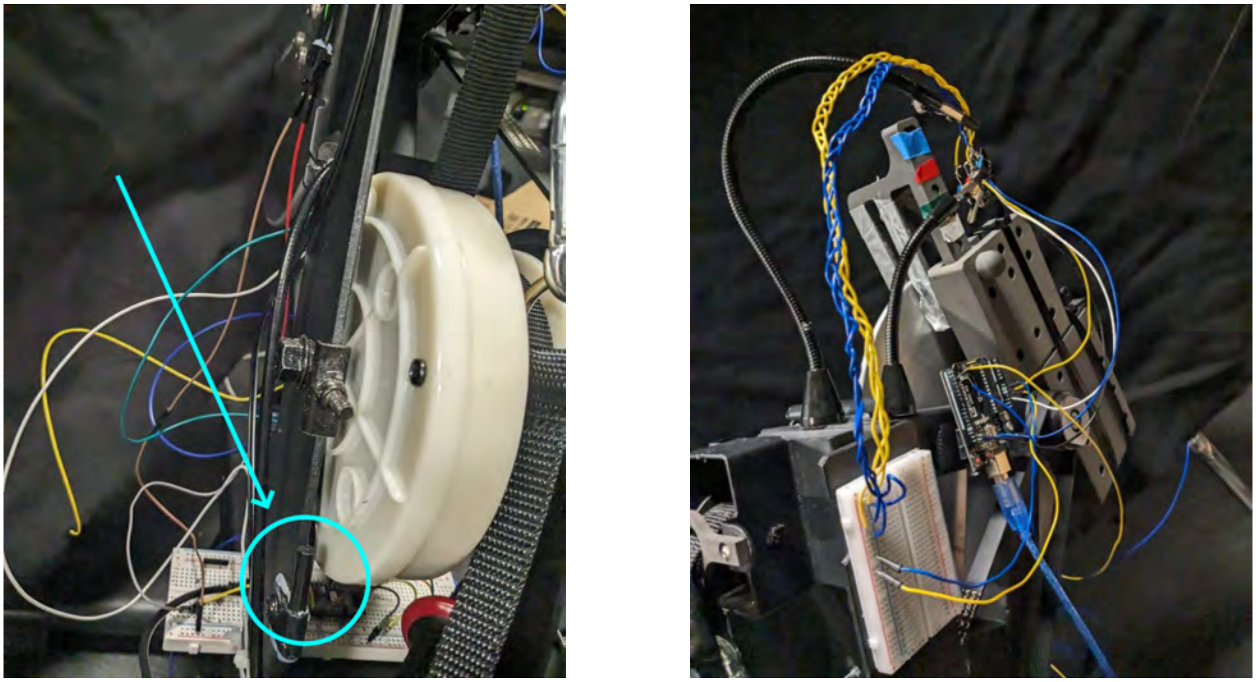
3.3 Sensors

The sensors subsystem was responsible for measuring the performance metrics for each user and transferring this data to the user interface. The performance metrics as stated previously in the document are heart rate, VO_2, muscle strength, and reps. For each of the following metrics, the sensor system used to measure each will be explained.

Firstly, the rep sensor was used to measure the amount of reps done by each user. This was measured using two reed switches, one of which was already internally in the rowing machine as highlighted in Figure 10a. Reed switches allowed the system to detect the magnet on the white, rotating wheel. When the magnet passes by a reed switch, there would be a change in the output voltage that allowed our system to determine if the wheel had made a full revolution, and more importantly, what direction the wheel was going. For the specific case of this device, a rep consists of many revolutions of the wheel, so reps were counted based on the change of direction of the wheel which was caused when the user stopped pulling the rope or finished a rep. The data processing was then done through an Arduino Nano device on the breadboard visible in Figure 10a. The Nano would send the user interface a single number representing the number of reps.

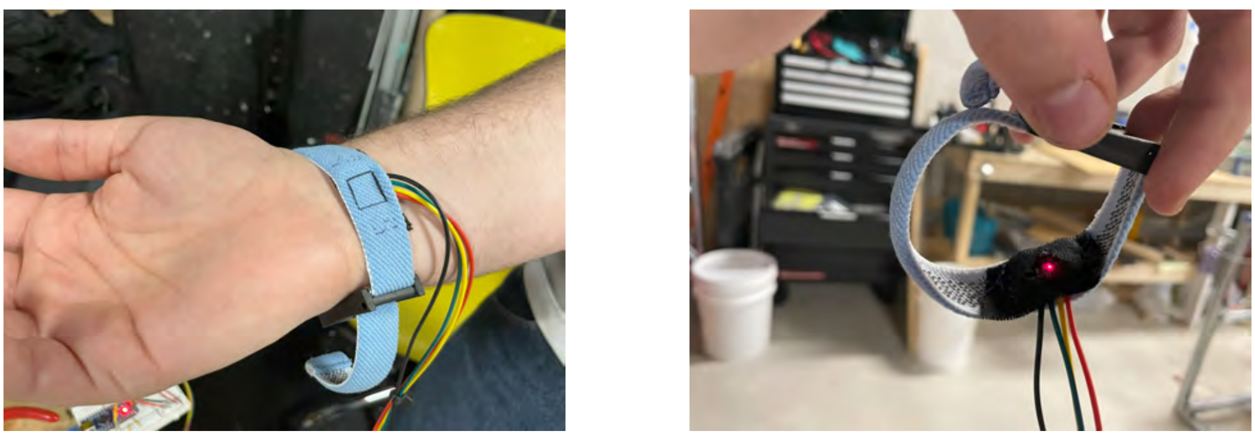
Next, to measure heart rate and VO_2, the team designed a wearable device that would communicate via Bluetooth to the user interface. The wearable contains a pulsometer that sends the heart rate of the wearer. With the heart rate, the VO_2 could be calculated by finding the ratio of the maximum heart rate over the resting heart rate. Unfortunately, the Bluetooth sensor was not stable and provided bad data, so instead the team decided to make a wired connection to get better results. This also made it much easier to power the sensor as opposed to finding a battery to fit onto the wearable. The final wearable is shown in Figure 11. We determined that this workaround was sufficient for our prototype, but we also acknowledge that wires could prove uncomfortable for the astronaut. Given that fitness watches exist, we believe that a wearable device can be designed that would meet all the requirements of the system.

Lastly, there was the muscle strength sensor. The goal of this sensor was to best show how much force was being outputted by the user. To do this the team used a color sensor and color-coded each level on the magnet housing, which corresponded to a different amount of resistance, as shown in Figure 10b. The color sensor allows the device to differentiate the different resistances.



(a) (b)

Figure 10: Reps sensor (a) (white wheel rotates) and color sensor (b) on the device



(a) (b)

Figure 11: The wearable heart rate and blood oxygen sensor

3.4 User Interface

The user interface for this device was the 9” Arduino Touch Screen Shield w/SSD1963. It is placed on the system in between the two footrests and above the rowing cable. This screen is powered by an Arduino Due board and held on the machine via an adjustable mounting system, as shown in Figure 12.

The goal of the user interface was to give the user the ability to start and track their workouts as well as for the user to view their workout results both past and present. The user also can look at the system’s health status. For this project, we developed a system where the user is given a

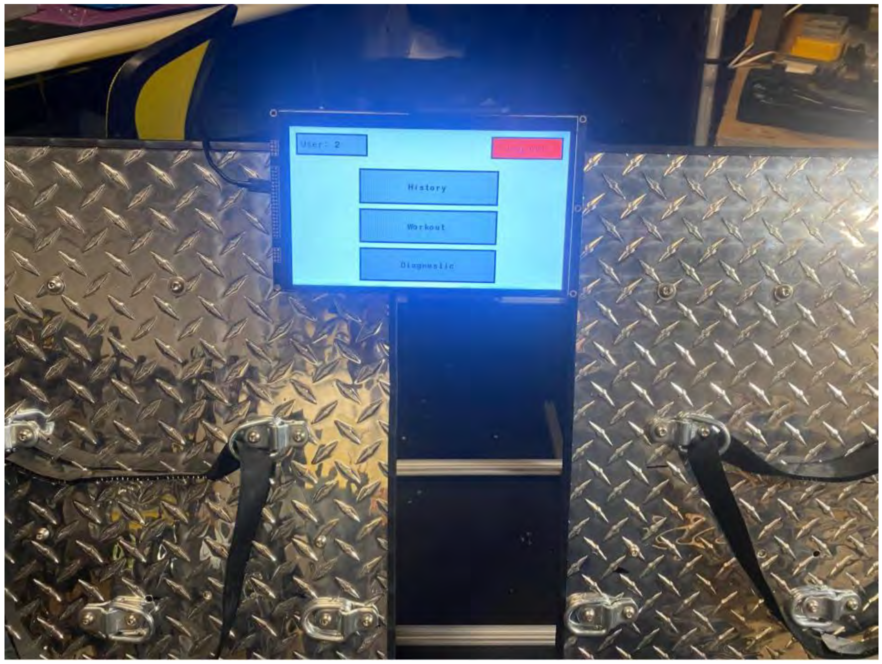


Figure 12: User interface on the device

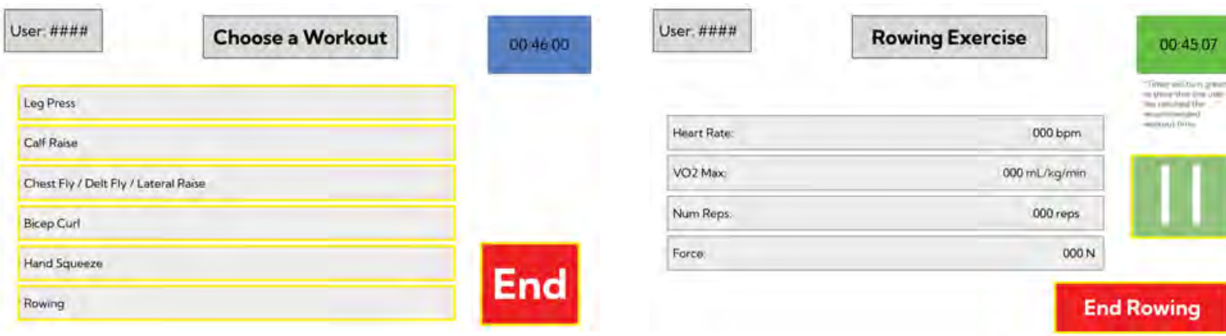
4-digit code which would be used to differentiate their data from other users. The 4-digit code was used for simplicity as opposed to the crew members' names. This is shown in Figure 13. After logging in with their code, the user would be taken to a screen in which they could choose to start a workout, look at previous workout data, or look at the system's health diagnostic, as shown in Figure 14.

(a) (b)

Figure 13: User interface login screen (a) and user code screen (b)

We tried to keep the workout pages as simple as possible. Since the user will be seeing these while working out, we wanted to ensure the user would be able to easily interpret what was on the screen even if exhausted from working out. These screens allow the user to pick the workout they would like as well as monitor their performance metrics during the workout. The pause button also allows the user to stop the workout at any time. These features are shown in Figure 15. These pages also show a time counting down from 2 hours to show the user how much of the workout they have left and another timer for the exercise they pick telling them when to switch exercises.

Figure 14: User interface home screen

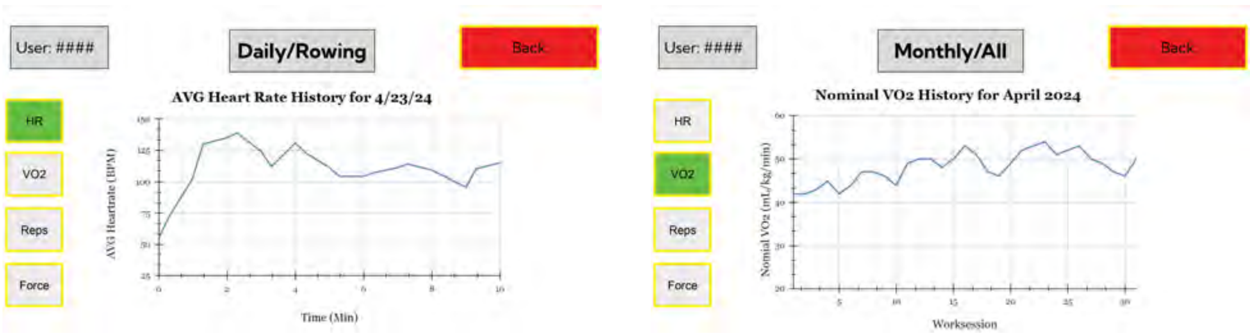


(a) (b)

Figure 15: User interface workout home page (a) and rowing exercise page (b)

Regarding the data history pages, we did not get as far as to develop those, but we had pages mocked up of what they would look like and how we would want to display that data and use it in ways that benefit the user and accurately track their fitness. We mainly wanted to show the trend of the performance metrics over time, which we mocked up as either looking at it over the span of a workout, over the course of a month, or all time depending on the user's needs. Showing these trends over time can be very useful because in the case of heart rate and VO_2, heart rate throughout a workout can show what parts of a workout are causing the user to work harder than other areas. This could inform the user of areas of weakness in a certain muscle group depending on the exercise. It can also be a good sign for the user to increase the speed or weight of their workout if their heart rate is a little lower than usual. VO_2 on the other hand is a measure of a user's max heart rate over their resting heart rate. This means it is more useful to look at it over time to see the trend of the user's fitness. If the user is working hard, over time their resting heart rate should decrease because the heart is becoming more efficient, and the max heart rate should increase because the heart can now perform at a higher maximum level. This would result in a higher VO_2 over time, which would not be observed over the course of a single workout. Example plots are shown in Figure 16.

The data in Figure 16a is real data we collected from our device, whereas the VO_2 data in



(a) (b)

Figure 16: User interface screen showing heart rate throughout a rowing exercise (a) and nominal VO_2 over a month (b)

Figure 16b is hypothetical data that shows a proof of concept on what the end goal for our device would be. The user can also select other performance metrics to see by clicking on the buttons on the left-hand side of the screen. Another graph we would want to highlight is the ability to show performance metrics plotted against one another. This would be most advantageous for reps vs. force, as shown in Figure 17. Logically, the user should be able to do fewer reps at higher force, but if compared over a period of time, the user should be able to track progress since they should be able to do more reps at higher forces if they are getting stronger. The force's "lvl" unit is because of our sensor's data. We tracked the force output by looking at what height the magnets were on the wheel, which were broken into five levels. The color sensor on the wheel would then send us a color corresponding to levels 1 through 5 to indicate the amount of force the user was exerting.

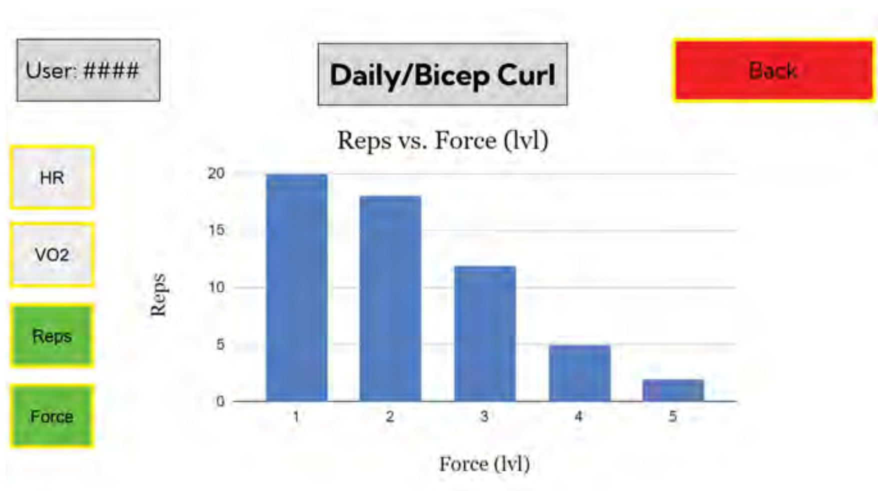


Figure 17: User interface screen showing exercise force vs. reps

Our final use for the user interface was the system diagnostic screen. Unfortunately, we did not get to implement this design because we took priority to the workout and history screens. However, for system health, we were planning to use abnormal data to track this. For specific workouts we could set a range of acceptable data, such as for rowing, any reps lower than 0 could be regarded as abnormal and most likely be a sign of a reps sensor fault. This methodology could be used for all four performance metrics, which would cover all the sensor groups.

4 Risk

Risk management is a critical aspect of any project, particularly in endeavors as complex and multifaceted as ours. A comprehensive risk matrix has been developed to identify and assess potential hazards that could impact the success of our mission. Each risk item has been meticulously analyzed, considering its likelihood of occurrence and the severity of its consequences on a scale of 1-5. Through this process, we have identified various technical, schedule, cost, and safety-related risks that could impede our progress or compromise the functionality and safety of our equipment. Appendix C includes the missions and human risk matrices along with their respective fever charts for detailed documentation of risks. Fever charts are a visual representation of how application of mitigation strategies has a positive impact on the risks associated with the design.

One notable technical risk involves the possibility of magnetic system failure, wherein the fracture or malfunction of the permanent magnet housing could compromise the machine's resistance mechanism during exercises. Similarly, concerns regarding insufficient handle friction and potential damage to the user interface have been flagged, highlighting the importance of addressing user interface issues to ensure optimal performance and user experience.

Mitigation strategies have been proposed for each risk item to minimize their potential impact. For instance, in response to concerns about handling friction and user interface damage, efforts are underway to enhance grip and reinforce components to prevent mechanical damage. Similarly, measures to mitigate risks related to electrical system exposure to liquids and user-worn sensor exposure have been proposed, including the incorporation of waterproof enclosures and selecting sensors with appropriate resistance to liquid exposure.

In addition to technical risks, human-level risks have also been identified and addressed in our risk management approach and evaluated on a logarithmic scale for their likelihoods of occurrences. These include risks such as user injury due to improper form or position during operation, failure to secure the seat properly, sudden tether failure, and wearable component overheating. Mitigation strategies for these risks focus on providing proper training, instructions, and incorporating safety features to minimize the likelihood of accidents or injuries during device operation.

Overall, our risk management strategy is aimed at proactively identifying and mitigating potential hazards to ensure the successful and safe execution of our mission. By implementing robust mitigation measures and continuously monitoring and reassessing risks throughout the project lifecycle, we aim to minimize disruptions and maximize the effectiveness of our equipment in supporting the health and well-being of astronauts during space missions.

5 Verification & Validation

Verification and validation (V&V) procedures play a pivotal role in ensuring the robustness, functionality, and safety of hardware systems across diverse engineering domains. Verification methodologies encompass several approaches to ascertain the conformity of the hardware design with specified requirements and standards. Verification by Inspection involves a comprehensive examination of hardware designs, documentation, and specifications to identify and rectify errors or inconsistencies. This static analysis ensures adherence to prescribed requirements. Verification by Analysis employs mathematical models, simulations, and computational tools to evaluate hardware behavior and performance, aiding in the identification of potential design flaws. Meanwhile, Verification by Demonstration entails physical testing of hardware prototypes to validate functionality under real-world conditions. Lastly, Verification by Test involves executing hardware systems under controlled conditions to verify functionality and compliance with requirements.

Similarly, validation procedures encompass a range of methods to confirm the effectiveness, usability, and suitability of the hardware for its intended purpose. Validation by Inspection involves direct observation and stakeholder feedback to ensure alignment with user requirements. Validation by Analysis utilizes modeling and simulation to verify system objectives and performance criteria. Validation by Demonstration conducts real-world tests to assess hardware performance in operational environments, while Validation by Test conducts comprehensive testing under realistic conditions.

The BLiSS V&V procedural documentation, as detailed in Appendix E, includes the requirements earmarked for validation along with their associated validation tests and results. The validation process confirmed that the device meets project objectives and performs as intended. Notably, testing was conducted in an Earth environment due to resource constraints; however, future iterations should undergo validation in simulated Martian habitats to ensure comprehensive validation of the IDEI.

6 Team Dynamics & Schedule

As a general schedule, the M-HHaPS team met twice per week, in addition to some subteam meetings during the fall semester. During the fall semester, these meetings took place in a classroom and were more dedicated to information sharing among subteams and presentations from the leads on information that general members would need to do the work they planned to do that week. This meeting format worked but did not provide the urgency and interdisciplinary work time required for the progress that had to be made during the winter semester. Therefore, the team transitioned the two meetings per week to work sessions in the BLiSS lab where all of the subteams were present and could ask one another questions as they worked on their tasks. In the future, we believe that this type of meeting is far more valuable and wish we had started such meetings earlier in the process. However, the team did lose some of the benefits of the information-sharing meetings, so it might be better in the future to create a more hybrid system between the two meeting types, with an emphasis on the work session meeting.

The team dedicated most of the fall semester to literature review work. Based on this literature review, the team also developed requirements and investigated design options during that first semester. Some initial trade studies were conducted to determine the overall design of the device, and planning for the work to be done in the next semester was started. The team selected a baseline rowing machine in late November but did not receive it until mid-December, right before winter break started.

The team accelerated its work in the winter semester, designing and building physical components and starting to work with real sensors. The initial aim was to finish building the device by the start of April, in order to spend the entire month of April on testing and iteration. Unfortunately, midterm season during March made this plan infeasible, since many team members were not available for all of the work sessions that would have been necessary for such rapid progress. The team did finish the whole device a little while before the April 24 final presentation and had sufficient time to conduct testing after that point.

As a lesson learned, it would be beneficial to start working with physical components much earlier and integrate the use of physical components into the trade studies and design work that was done in the first semester. Such integration would keep team members more engaged and allow them to make more informed decisions in that first stage. Another related lesson learned would be that it is important to consider dependencies when scheduling, or find a way to control interfaces in order to develop dependent subsystems in parallel. For example, the data subteam required sensors to exist and send data, while the sensors subteam needed a physical system to integrate the sensors into. Finding a better way to build each of these systems in parallel would have eliminated some wasted time during the development cycle when one subteam was blocked from a task until another subteam completed its own task.

7 Future Improvements

The nature of the X-Hab projects as an academic year student challenge means that many good ideas are contributed which cannot necessarily be implemented within the scope of the project. This was certainly true for M-HHaPS. For anyone taking on this project after us, we recommend the following improvements be considered for the next iteration of the M-HHaPS design.

7.1 Non-Concentric Loading

The existing iteration of the device is constrained to providing concentric muscle loading, characterized by muscle shortening, owing to its current resistance system. However, recognizing the additional benefits offered by eccentric (muscle lengthening) and isometric (no movement) loading in muscle development, future iterations of this design will necessitate the integration of negative resistance capabilities into the resistance mechanism.

Presently, the device only permits outward pulling of the cable for concentric loading. To address this limitation and enhance the versatility of the device, modifications will be made to enable the retraction of the cable with equivalent resistance, thereby facilitating resistance training akin to conventional methods with weights and cable systems. This modification will enable users to engage in exercises that involve muscle lengthening and static muscle contraction, thereby promoting comprehensive muscle development. By incorporating the capability for negative resistance, the device will offer users a more comprehensive and effective workout experience, potentially leading to enhanced muscle retention and growth within the same exercise duration. This design change will align the device more closely with conventional resistance training methods, thereby catering to a broader range of fitness objectives and preferences.

7.2 Power Regeneration

The current design operates under the assumption of a power supply within the Martian habitat to support the system's power requirements. However, to enhance power efficiency and promote energy sustainability, considerations for integrating a power generator onto the rotating flywheel have been proposed. This modification aims to transform the system into a power-generating asset for the habitat, shifting its role from being solely power-consuming during exercise sessions.

Integrating a power generator onto the rotating flywheel presents an opportunity to harness kinetic energy and convert it into electrical power for use within the habitat. This adaptation not only contributes to reducing power consumption but also adds to the overall energy autonomy of the habitat. However, it is essential to acknowledge that this addition would necessitate adjustments in how force correlates with the rotation of the flywheel. Therefore, careful consideration and thorough testing will be required to ensure that the system maintains its intended functionality and provides accurate feedback to users while also serving as a viable power source for the habitat.

7.3 Launch Loads

The current iteration of this device encompasses modifications applied to an off-the-shelf (COTS) cardio rowing machine, tailored to accommodate the operational demands both on Earth and in environments characterized by Martian gravity. In its design phase, considerations were made regarding ease of assembly, particularly emphasizing adaptability to Martian conditions. However, for future iterations, additional factors such as launch loads warrant thorough consideration during the preliminary design stage.

Integrating insights from research into payload adapter methods becomes imperative to ensure the safe transport of the machine to Martian habitats. This entails a holistic approach to design, encompassing not only operational requirements but also the structural integrity necessary to withstand the dynamic forces encountered during launch operations. Launch loads, comprising vibrational, inertial, and gravitational forces, exert significant stresses on payloads, especially those with complex mechanical assemblies.

Mitigating potential damage necessitates meticulous attention to detail in the design and assembly processes. Components must be securely fastened and adequately cushioned to withstand the harsh conditions encountered during launch. Moreover, modularity and ease of disassembly become pivotal considerations, facilitating the efficient transport and reassembly of the machine between launches. By prioritizing these aspects, the device can minimize the risk of damage during transit and ensure its operational readiness upon arrival at its destination, thus optimizing its overall functionality and longevity in extraterrestrial environments.

7.4 Additional Autonomy

As discussed in the User Interface section, there were plans to include system self-health monitoring that, due to time constraints, were not fully realized. The general strategy would be to compare the measured sensor readings to readings that are expected for a given workout. For one example, different exercises would have different ranges of resistance. If the measured force level is outside the expected range, the device could notify the user that either the sensor has an anomalous reading or the device was not configured properly. For another example, comparing measured heart rate and VO_2 values to expected ranges could reveal sensor faults. This method was used during the system integration process to troubleshoot sensor issues but was not built into the code. A similar method could be applied to the rep counter as well.

In terms of user identification, currently the system requires the user to enter an identification pin. This could be replaced with biometric identification or an RFID chip unique to each user. This would simplify the login process. User-specific measurements could also be used to diagnose sensor faults. The device could learn where each user tends to perform and then compare measured sensor outputs to those values (within some range to account for performance improvement or degradation).

7.5 Backrest Installation Process

The current M-HHaPS design requires overly lengthy procedures for the installation and uninstallation of the backrest. It and the accompanying stabilizer bar take nearly seven minutes to install and uninstall. During our verification testing, we determined that removal of the stabilizer bar would cut nearly four minutes off of the installation and uninstallation time, so we recommend that additional testing be conducted to determine whether the stabilizer bar is necessary in order for the backrest to support the force it undergoes when a user conducts the leg press exercise.

To further improve the installation time of the backrest, we recommend moving away from the current design requiring four screws to pass from the bottom of the seat through the backrest bars and be secured with nuts. Instead, it would be more convenient and possibly more secure to install the backrest if another attachment mechanism is implemented. One such design could include a clamp under the seat into which the backrest bars slide and can be secured. This design was too complex for the student team to develop during the assigned time frame, but such a design would certainly be an improvement on the prototype design manufactured by the team.

7.6 Magnet Housing

The current implementation of the magnet housing relies on predetermined values derived from testing to ascertain the impact of each magnet configuration on resistance levels. However, this approach presents challenges in terms of scalability and precision manufacturing, particularly in the context of large-scale production. Even minor variations in magnet placement or distance from the flywheel can significantly influence resistance generation, a phenomenon exacerbated by fluctuations in flywheel rotation speed induced by cable tension during device operation.

Enhancing the sophistication of the device entails transitioning from hardcoded values to real-time force measurements facilitated by the integration of force sensors. This advancement would enable precise monitoring of resistance levels during exercise, eliminating inaccuracies inherent in predetermined values and ensuring the provision of reliable performance metrics. Moreover, the incorporation of force sensors enhances the adaptability of the device to varying user profiles and workout intensities, thereby optimizing user experience and fitness outcomes.

Further refinements to the device involve material selection for the magnet housing, with a focus on durability and suitability for extraterrestrial environments such as Martian habitats. While the current iteration utilizes nylon for the housing, future iterations necessitate the exploration of materials better suited to withstand the unique challenges posed by Martian conditions, including limited maintenance capabilities and exposure to harsh environmental factors. By prioritizing material resilience and compatibility with Martian habitats, future iterations of the resistance system can enhance operational reliability and longevity.

7.7 Electromagnetic Interference Risk

One disadvantage to the resistance mechanism selected for the device is that the magnetic resistance mechanism could present an electromagnetic interference risk with both the electronic components of the device and any other electronic components in the surrounding Martian habitat. Depending on the strength and configuration of magnets used in the final design, this risk may be minimal enough not to require mitigation, but the M-HHaPS team recommends mitigation of the electromagnetic interference be put into place.

One way to mitigate this risk would be to select a different resistance mechanism, but we believe that the advantages of this resistance mechanism are sufficient to justify its use. The magnetic eddy current resistance mechanism has no friction component, so the magnets and flywheel will not wear down over time. Thus, the components will not need to be replaced, and there will be no flammability hazard from heat and particulates. Additionally, the magnetic resistance mechanism does not rely on air resistance (which could change depending on the habitat atmosphere) or water resistance (which would require a lot of mass and would introduce leakage risks). Another way to mitigate this risk would be to implement the magnetic resistance in combination with another mechanism, such as a gearbox, to enhance the resistance generated by the magnets and the flywheel.

7.8 Gamification

To ensure that they are fit enough for EVA and for their return to Earth, astronauts on Mars will need to spend multiple hours per day exercising. Since Mission Control will have less direct influence over the astronauts due to the great distance, it is important that the onerousness of critical tasks like exercise be reduced as much as possible. To that end, we recommend incorporating gamification into future iterations of our device. Although we were not able to implement it within the scope of the project, we did conduct research and a trade study on potential gamification methods.

NASA has already done research on using virtual reality (VR) as a means of incorporating gamification into exercises. Project Atlas was a project that investigated the feasibility of using a head-mounted VR display for fitness tracking and exercise augmentation. This project developed a device that used biometric information like respiration rate and heart rate to adjust parameters of the game play (e.g. intensity and environmental objects) mid-workout [5]. Such a device could foreseeably be integrated with M-HHaPS, but there are alternative gamification elements that could be implemented instead of or in combination with the elements pioneered by Project Atlas, such as VR and biometric-influenced gameplay.

The M-HHaPS team identified several such elements, including music/audio cues, competition (against other crew members and/or with a fictional competitor), and/or a reward system. The team conducted a trade study on these three elements and VR, which is included in Figure 27. Each element considered in the trade study was evaluated based on whether it might improve exercise motivation, hinder exercise movement, and improve mental health. The alternatives were then traded based on the following criteria: power consumption, entertainment, size, and durability, which were weighted 0.45, 0.25, 0.2, and 0.1, respectively. We recognize that this was not an apples-to-apples trade, so the results should be interpreted with that shortcoming in mind. Due to its high performance in all categories, music/audio scored the highest, while competition and rewards were tied for a close second. Due to its poor performance in all categories except for entertainment, VR was the lowest-scoring element. The M-HHaPS team believes that it is still worth considering VR as an exercise gamification element, since technology improvements may improve its score in those areas.

The team recommends that future work in exercise gamification strongly consider incorporating music and/or audio cues into any future system. The team also encourages future teams to consider competition and rewards as motivational game design elements.

7.9 Hand Dynamometer

Based on feedback from Dr. Emily Matula and Dr. Kathryn Clark, our advisors, astronauts must have strong forearm muscles since they are typically fatigued during zero-gravity EVAs. This is because the pressure inside the suit resists any movement of the fingers, which makes it difficult to grip tools or manipulate objects. To support such activities, the M-HHaPS team wanted to integrate hand-squeeze exercises into the device. The initial notional concept for this integration was to put hand dynamometers into the handle used for the rowing exercise. Then, the astronaut would be able to strengthen their grip muscles while also performing the rowing exercise, thus saving valuable crew time.

The team received feedback from Coach Mark Rothstein, the head coach of the women's rowing team at the University of Michigan, who indicated that such a design would be detrimental to a rower's form. When rowing, it is ideal to have as relaxed a grip as possible in order to avoid tensing up the shoulders. As discussed in the Additional Wearables section, bad rowing form can result in lower back pain, which is highly undesirable for an astronaut training for EVA. Therefore, the team abandoned this proposed integration mechanism.

As an alternative mechanism of integration, the team discussed integrating a hand dynamometer with each of the two handles on either side of the seat. This design would have similar time-saving benefits to the original design, since the astronaut would be able to exercise their hands while conducting the leg press, chest fly, or delt fly exercises. Due to time and complexity constraints, this design was not further developed beyond the notional concept stage. The team purchased a Handexer Digital Hand-Held Dynamometer and attempted to integrate its built-in sensors with our microcontrollers and display screen. While these attempts were unsuccessful, the team learned a lot about working with the very small electronic components included in the hand dynamometer.

In conclusion, the team explored a few different routes for integrating grip exercises with the device but was unable to collect sufficient evidence to recommend a specific design. We recommend further exploration of how to integrate these exercises into an astronaut's daily routine, whether it be as part of the normal exercise routine or some other aspect of their day. Hand and grip muscles are highly important to the success of EVA, so it is critical that some concept of operations and design be developed for the exercise of these muscles as part of NASA's design of missions to the Moon and Mars.

7.10 Additional Wearables

From literature review about rowing as an exercise and anecdotal information from Coach Mark Rothstein, head coach of the University of Michigan women's rowing team, the team learned that proper form is very important for people who row consistently because improper form frequently results in lower back pain for these athletes. Since the goal of the M-HHaPS device is to make astronauts more prepared for EVA, not less prepared, it is important to ensure that this detrimental effect is avoided.

It may be difficult for astronauts to have proper form for rowing because most astronauts are not professional rowers, so they will not have experience with rowing before being trained to use the device. Even after these astronauts undergo training, they will spend months in zero gravity en route to Mars, during which time they will likely not be rowing, since the device is designed for use in partial gravity. Then, these astronauts will perform rowing exercises in Martian gravity, after being trained on proper rowing form in Earth gravity. All of these factors mean that it is highly likely that astronauts will arrive on Mars without sufficient muscle memory to perform the rowing exercises with proper form.

The M-HHaPS team recommends the creation of a wearable device that would monitor an astronaut's rowing form and alert them to recommended corrective actions in real-time. A vest with an integrated suite of sensors should be sufficient to collect the requisite information. These sensors could be inertial measurement units (IMUs) or posture sensors, which are flexible rods that report the angle at which they have been bent. Either of these sensors or some combination of them should be able to collect enough information to understand whether the astronaut is rowing with the correct form. Another option, recommended by one of our advisors, Dr. Adam Lepley, would be to have the astronaut wear a motion-capture suit, set up a camera to observe their motion and use computer vision to determine whether the form is correct or not. In either case, calibration of the sensors would be difficult because each individual has different proportions. It is even possible that these proportions could change en route to Mars, or even that the ideal rowing form on Earth would differ from the ideal rowing form on Mars. For the sake of simplicity, the team recommends calibrating these sensors based on each individual's rowing with proper form during training on Earth and integrating an option for modifying that calibration once the astronaut arrives on Mars.

8 Conclusion

The development of the modified rowing machine device presented in this report was the culmination of eight months of literature review, decision-making, design, manufacturing and integration. The result is a device that enables the user to perform rowing, leg press, chest fly, seated row, delt fly, bicep curl, and tricep kickback exercises. While we are proud of how far the team has come so far, we also acknowledge that this design has room for improvement before it is mature enough to be useful to astronauts on Mars. We hope that future teams that continue working on this idea will learn from our successes and failures.

The BLiSS team was delighted to have had the opportunity to work on this project, and our institutional knowledge about space physiology and exercise has increased significantly as a result. We look forward to applying what we have learned to future X-Hab projects and other research endeavors.

9 Report on Educational Outreach

The BLiSS team participated in two notable educational outreach activities throughout the year. On April 13, 2024, BLiSS participated in Aerospace Day, an outreach event sponsored by the University of Michigan AIAA chapter. The event was catered toward 7-12th grade students from schools in and around the Ann Arbor area who came to listen to Aerospace-affiliated student teams talk about the work that they do. As BLiSS is unique among student project teams in its focus on human spaceflight, BLiSS put together a Jeopardy-themed game where students could select a question from human spaceflight-related categories and then give an answer. Each answer also featured extra information about that topic. For example, in the space exercise category, the question for 100 points read, "What part of the human body (that you use to exercise) decreases in size when in space?" The answer was muscle mass and bone density, and the answer slide featured information about how exercise is required to alleviate this problem. Questions like this, along with others in the space exercise and space medicine categories, were compiled in large part using information learned over the course of the M-HHaPS project.

On April 24, 2024, BLiSS held its first annual end-of-year symposium. As BLiSS is a large team with multiple projects, this was an opportunity for each project to present their work over the course of the academic year and hear from the other projects. For the M-HHaPS team, the event also served as our final presentation to our NASA stakeholders, and we were grateful to have had Dr. Lauren Underwood attend remotely. An invitation to the event was also extended to SGT (the Aerospace Engineering honors society) and WAA (Women in Aeronautics and Astronautics) so that other students in the Aerospace Engineering department could learn about BLiSS and the work we do. After the project presentations, the event featured a Women in Aerospace panel hosted by Norah Murphy, the WAA President, that was attended by Dr. Underwood, as well as Drs. Lori Ploutz-Snyder and Kathryn Clark, who are two of our advisors. We were excited to host this event, and we plan to continue with similar events going forward where we hope to also reach out to the Departments of Kinesiology, Biomedical Engineering, and any others related to BLiSS' work.

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  - Anthony Brunswick
  - Bryan Jiang
  - Cynthia Deneus
  - Katherine Snowdon
  - Tomas Garcia Lavanchy
  - Thomas Callen
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Appendices

A Requirements

Note from the project co-leads: this section contains all the requirements that were written for the M-HHaPS project as is. We expect that future work derived from our device will include its own systems engineering. These requirements were meant to guide our project as well as serve as a repository of the design considerations we think are important for the device. As BLiSS is a student project team, not every requirement follows proper systems engineering conventions. We intended for requirement writing to be also a learning experience for new members, and at the same time, the exercise was a learning experience for us as leaders. As we were writing requirements, we were examining the importance of systems engineering in our project and reforming how it was implemented. Thus, some requirements represent first drafts that were never revised as we determined that our limited available effort was more effectively spent on a different aspect of the project. Going forward, the experience we gained from leading this project will inform internal recommendations for how to effectively do systems engineering for future BLiSS projects.

Figure 18 shows the spec tree for our project.

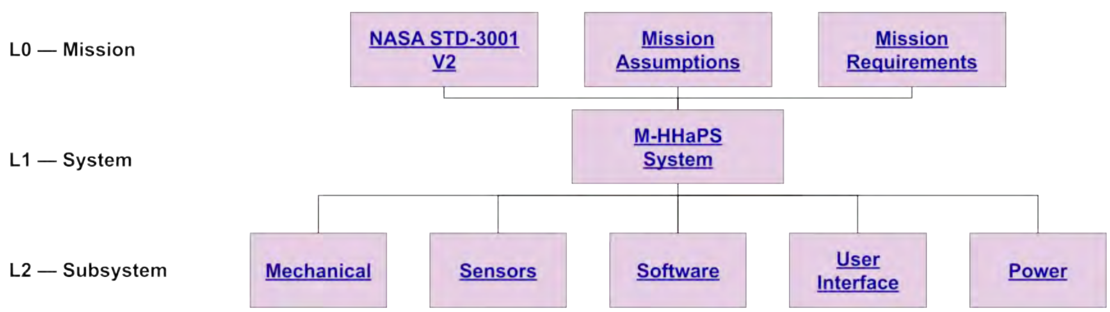


Figure 18: M-HHaPS project spec tree

A.1 L0 NASA STD-3001 Applicable Requirements

List of Applicable Requirements from NASA-STD-3001 V2. Note that referenced appendices and tables should be located in the standard [6].

1. Functional Anthropometric Accommodation - V2 4102

The system shall ensure the range of potential crewmembers can fit, reach, view, and operate the human systems interfaces by accommodating crewmembers with the anthropometric dimensions and ranges of motion as defined in data sets in Appendix F, Physical Characteristics and Capabilities, Sections F.2 and F.3.

2. Body Mass, Volume, and Surface Area Data - V2 4103

The system shall accommodate the body characteristic data for mass, volume, and surface area as defined in Appendix F, Physical Characteristics and Capabilities, Sections F.4, F.5, and F.6.

3. Muscle Effects - V2 4013

The effects of muscle endurance and fatigue shall be factored into system design.

4. Visual Capabilities - V2 5001

The system shall accommodate anticipated levels of crew visual capabilities under expected task demands.

5. Auditory Perceptual Capabilities - V2 5002

The system shall accommodate anticipated levels of crew auditory perceptual capabilities under expected task demands.

6. Sensorimotor Capabilities - V2 5003

The system shall accommodate anticipated levels of crew sensorimotor capabilities under expected task demands.

7. Cognitive Capabilities - V2 5004

The system shall accommodate anticipated levels of crew cognitive capabilities under expected tasks demands.

8. Intermittent Noise Limits - V2 6080

For hardware items that operate for eight hours or less (generating intermittent noise), the maximum noise emissions (not including impulse noise), measured 0.6 m from the loudest hardware surface, shall be determined according to Table 9, Intermittent Noise A-Weighted SPL and Corresponding Operational Duration Limits for any 24-hour period (measured at 0.6-m distance from the source). Hearing protection cannot be used to satisfy this requirement.

9. Hand Vibration - V2 6094

The system, including tools, equipment, and processes, shall limit vibration to the crewmembers' hands such that the accelerations, as computed according to ANSI/ASA S2.70-2006, Guide for the Measurement and Evaluation of Human Exposure to Vibration Transmitted to the Hand, do not exceed the Daily Exposure Action Value defined by ANSI/ASA S2.70-2006, Annex A, Figure A.1.

10. Physiological Countermeasures Capability - V2 7038

The system shall provide countermeasures to meet crew bone, muscle, sensorimotor, thermoregulation, and aerobic/cardiovascular requirements defined in NASA-STD-3001, Volume 1.

11. Physiological Countermeasure Operations - V2 7040

The physiological countermeasure system design shall allow the crew to unstow supplies, perform operations, and stow items within the allotted countermeasure schedule.

12. Design for Crew Safety - V2 9101

The system shall be designed to minimize physical hazards to the crew.

13. Mechanical Hazard - V2 9005

Systems, hardware, and equipment shall protect the crew from moving parts that may cause injury to the crew.

14. Entrapment - V2 9006

Systems, hardware, and equipment shall protect the crew from entrapment (tangles, snags, catches, etc.).

15. Potential Energy- V2 9007

Hardware and equipment shall not release stored potential energy in a manner that causes injury to the crew.

16. Sharp Corners and Edges – Fixed - V2 9009

Corners and edges of fixed and handheld equipment to which the bare skin of the crew could be exposed shall be rounded as specified in Table 16, Corners and Edges.

17. Pinch Points - V2 9013

Pinch points shall be covered or otherwise prevented from causing injury to the crew.

18. Pain/Non- Disabling Injury Skin Temperature Limits - V2 9103

Any surface to which the bare skin of the crew is exposed shall not cause skin temperature to exceed the critical injury limits in Table 20—Critical Range/Limits, Pain/Non- disabling injury/possibly resulting in illness.

19. Nominal Physiological Electrical Current Limits - V2 9019

Under nominal situations (routine human contacts to conductive housing), the program shall limit electrical current through the crewmember to $\leq$ (less than or equal to) 0.4 mA for Direct Current (DC) and $\leq$ (less than or equal to) 0.2 mA peak for Alternating Current (AC).

20. Protection - V2 9027

Systems, hardware, and equipment shall be protected from and be capable of withstanding forces imposed intentionally or unintentionally by the crew.

21. Hardware and Equipment Mounting and Installation - V2 9029

System hardware and equipment shall be designed so that it cannot be mounted or installed improperly.

22. Cable Management - V2 9034

The system shall manage cable, wire, and hose location, protection, routing, and retention to prevent physical interference with crew operations and safety.

23. Design for Maintenance - V2 9036

The system shall provide the means necessary for the crew to safely and efficiently perform routine service, maintenance, and anticipated unscheduled maintenance activities while wearing the most encumbering equipment and clothing anticipated.

24. Commercial Off-the-Shelf (COTS) Equipment Maintenance - V2 9037

Maintenance for commercial off-the-shelf equipment shall be suitable to the space flight environment.

25. Maintenance Time - V2 9039

Planned maintenance for systems and associated hardware and equipment shall be capable of being performed within the allotted crew schedule while wearing the most encumbering equipment and clothing anticipated.

26. Visual Access for Maintenance - V2 9048

Maintenance tasks that require visual feedback shall be directly visible during task performance while wearing the most encumbering equipment and clothing anticipated.

27. Fault Detection - V2 9051

The system shall provide rapid and positive fault detection and isolation of defective items.

28. Failure Notification - V2 9052

The system shall alert the crew when critical equipment has failed or is not operating within tolerance limits.

29. Crew Interface Usability - V2 10001

The system shall provide crew interfaces that result in a NASA-modified System Usability Scale (SUS) score of 85 or higher.

30. Design-Induced Error - V2 10002

The system shall provide crew interfaces that result in the maximum observed error rates listed in Table 29, Maximum Observed Design-Induced Error Rates.

31. Crew Interface Operability - V2 10003

The system shall provide interfaces that enable crewmembers to successfully perform tasks within the appropriate time frame and degree of accuracy.

32. System Health and Status - V2 10017

The system shall provide system health and status information to the crew, either automatically or by request.

33. Control Feedback - V2 10021

The system shall provide a positive indication of crew-initiated control activation.

34. Maximum System Response Times - V2 10020

The system shall provide feedback to the crew within the time specified in Table 30, Maximum System Response Time(s).

35. System Feedback - V2 12025

The system shall provide feedback to the operator indicating successful task completion.

A.2 L0 Mission Assumptions

1. The EVA suit will be the government reference for the X-EMU.
2. The goal is to maintain the health of arriving astronauts, who have been exercising en route to Mars.
   (a) They will be more fit than a 9 month ISS astronaut.
3. The launch vehicle will be the SLS.
4. Landing forces will be similar to those experienced by Mars rovers.

A.3 L0 Mission Requirements

The mission requirements are listed in Table 1.

A.4 L1 System Requirements

This section lists system requirements. The numbering scheme comes from a previous, more comprehensive spec document that included both these requirements and the archived system requirements. The archived requirements were removed from the spec and ignored during design due to team constraints on resources and ability.

1. Exercise Capability

These requirements relate to the ability of the system to meet the primary customer expectation of maintaining astronaut health through exercise and providing data on those exercises.

1.1. EVA Performance Tasks

The system shall allow for the user to perform an analogous task to each of the tasks listed in Table 2.

Rationale: Based on an extensive, relevant literature review, tasks required for EVA were identified.

1.2. Metric Reports

The system shall generate reports of the performance metrics listed in Table 3 in the form of raw data with supporting visuals.

Rationale: Metrics chosen based on literature review and conversations with industry expert advisors.

1.2.1. Metric Measurement

The system shall measure performance metrics listed in Table 3.

Rationale: The outlined metrics were selected based on their relevance in the literature, universal usage in human performance, and effectiveness in measuring muscle mass, workout intensity, and improvement in fitness over time.

1.2.2. Metric Storage

The system shall store the performance metrics listed in Table 3 for the duration of the system's useful lifetime.

Rationale: The metrics need to be accessible at all points during the mission to be useful for tracking progress over time.

1.2.3. Metric Association

The system shall store a unique collection of the performance metrics listed in Table 3 for each user.

Rationale: Each user must have their own set of metrics.

1.2.4. User Identification

The system shall record user identification.

Rationale: The system should be able to differentiate between users.

1.5. Gamification

The system shall allow for integration with gamification.

Rationale: In case the team has time to pursue gamification, the system cannot be designed to prohibit integration at a later time.

2. User Interfaces

These requirements relate to the ability of the system to interact with users.

2.1. User Dimensions

The system shall ensure the range of potential users can fit, reach, view, and operate the human systems interfaces by accommodating crewmembers with the anthropometric dimensions and ranges of motion as defined in data sets in NASA STD-3001 V2 Appendix F, Physical Characteristics and Capabilities, Sections F.2 and F.3.

Rationale: Users of varying size should be able to use the system. The specific design will influence which items from Appendix F are satisfied by default.

Parent: L0 NASA STD-3001 Applicable Requirements R1

2.8. Design-Induced Error

The system shall provide crew interfaces that result in the maximum observed error rates listed in Table 29 from NASA STD-3001 Volume 2, Maximum Observed Design-Induced Error Rates.

Rationale: This requirement ensures UI reliability.

Parent: L0 NASA STD-3001 Applicable Requirements R30

2.9. Crew Interface Operability

The system shall provide interfaces that enable crewmembers to successfully perform tasks within a time frame and degree of accuracy defined for each interface.

Rationale: Interfaces must be easily usable, accessible, and accurate to enable efficient crew performance.

Parent: L0 NASA STD-3001 Applicable Requirements R31

2.10. Control Feedback

The system shall provide a positive indication of crew-initiated control activation.

Rationale: This requirement ensures crew are aware of successful control inputs.

Parent: L0 NASA STD-3001 Applicable Requirements R33

2.11. System Feedback

The system shall notify the user upon completion of the exercise.

Rationale: This requirement ensures crew are aware of when the exercise is completed to move on to another exercise or to shut down the machine.

Parent: L0 NASA STD-3001 Applicable Requirements R35

2.12. Maximum System Response Times

The system shall provide feedback to the user within the time specified in Table 30 from NASA STD-3001 Volume 2.

Rationale: This requirement constraints feedback times to ensure crew receive information in a timely manner.

Parent: L0 NASA STD-3001 Applicable Requirements R34

3. External Interfaces

These requirements relate to the interfaces between the system and the user, the environment, other devices, and other systems.

3.1. Martian Gravity

The system shall fulfill all performance and safety requirements in 0.38 g.

Rationale: The system must be designed with Martian gravity in mind.

3.6. Power

The system shall have a nominal power draw of no more than 100 W from 120 VAC wall outlet.

Rationale: We can assume that the resistance mechanism will not require power, and that the only power necessary will be used for UI and sensors. We set this value to be no more than 100 W. The real system could be similarly constrained by this wattage, but the voltage would be the nominal (likely DC) power for the Mars habitat. The AC voltage is written for our prototype that will take power from a wall outlet in the lab. Also, in principle, an exercise device could generate power and could generate power.

3.7. Life Support System Interface

The system shall interface with the Life Support System as outlined in the External Interfaces ICD.

Rationale: Stakeholder requirement.

3.8. Remote Monitoring System Interface

The system shall interface with the Remote Monitoring System as outlined in the External Interfaces ICD.

Rationale: Stakeholder requirement.

3.9. Crew Health and Performance Monitoring System Interface

The system shall interface with the Crew Health and Performance Monitoring System as outlined in the External Interfaces ICD.

Rationale: Stakeholder requirement.

3.10. Machine Configuration Interface

The user shall be able to configure the parameters of the exercise within a time no greater than 5 minutes.

Rationale: Based on the time it takes to configure a conventional rowing machine, then adding time to account for the potential swapping out or reconfiguration of certain physical interfaces.

Parent: L0 NASA STD-3001 Applicable Requirements R11

3.11. Data Transmission

The system shall be able to transmit data to an external device.

Rationale: This will allow data to be accessed on personal devices, uploaded to Mission Control, or accessed by other habitat life support systems.

4. Reliability and Maintenance

These requirements relate to the ability of the system to operate and be maintained throughout its lifetime.

4.1. Fault Detection

The system shall allow for detection of anomalous behaviors defined in Table 4 during normal operation.

Rationale: It is important to detect anomalous behaviors of all varieties to allow for resolution of these behaviors as well as stopping further damage to other areas of the system.

Parent: L0 NASA STD-3001 Applicable Requirements R27

4.2. Fault Notification

The system shall notify users in real-time of detected anomalous behaviors listed in Table 4.

Rationale: It is important that once anomalous behaviors are detected, users are notified for their safety and to stop further damage to the system.

Anomalous Behaviors
Software Failure
Mechanical Failure
Power Failure
Hardware Failure

Table 4: Anomalous behaviors

Parent: L0 NASA STD-3001 Applicable Requirements R28

4.3. State of Health Reports

The system shall generate system state of health reports on the metrics defined in Table 5 on-demand by users.

Rationale: These metrics will provide information for device diagnostics.

Parent: L0 NASA STD-3001 Applicable Requirements R32

System State of Health Metrics
Average power draw in use
Average power draw out of use
Number of each type of anomalous behavior
Time in use

Table 5: System state of health metrics

5. Physical Characteristics

These requirements relate to size, mass, and footprint of the system.

5.1. Footprint

The system shall have a deployed footprint of no greater than 1.5 m^2.

Rationale: The system needs to be used within the Martian habitat. The largest-footprint commercial rower we could find had a footprint of 1.4 m^2, so a slightly buffered 1.5 m^2 requirement is both realistic and helpful.

Parent: L0 Mission Requirements R5

5.2. Height

The system shall have a deployed height of no greater than 2.75 m.

Rationale: The system needs to be used within the Martian habitat, which will likely have a similar (or higher) ceiling height to a typical residential space.

Parent: L0 Mission Requirements R5

5.3. Volume

The system shall have a deployed volume of no greater than 2 m^3.

Rationale: The system needs to be used within the Martian habitat. The largest commercial rower we could find had a volume of 1.76 m^3, so a slightly buffered 2 m^3 requirement is both realistic and helpful.

Parent: L0 Mission Requirements R5

6. Safety

These requirements relate to the level of redundancy required for different hazard levels.

6.1. Hazard Management

The system shall implement a hazard management system.

Rationale: A hazard management system will formalize implementing redundancies.

Parent: L0 NASA STD-3001 Applicable Requirements R12

6.1.1. Catastrophic Hazards

The system shall be two-fault tolerant for catastrophic hazards.

Rationale: A catastrophic hazard must only occur after at least two independent failures.

6.1.2. Critical Hazards

The system shall be one-fault tolerant for critical hazards.

Rationale: A critical hazard must only occur after at least one independent failure.

6.2. Mechanical Hazard

Systems, hardware, and equipment shall protect the crew from moving parts that may cause injury to the crew.

Rationale: The internal components of the device should not be accessible by the user so as to accidentally cause injury.

Parent: L0 NASA STD-3001 Applicable Requirements R13

6.3. Entrapment

Systems, hardware, and equipment shall protect the crew from entrapment (tangles, snags, catches, etc.).

Rationale: Entrapment could cause injury to crew or could prevent crew from responding promptly in the event of an emergency.

Parent: L0 NASA STD-3001 Applicable Requirements R14

6.4. Potential Energy

Hardware and equipment shall not release stored potential energy in a manner that causes injury to the crew.

Rationale: Resistance-based exercise devices can store significant potential energy that could be released accidentally.

Parent: L0 NASA STD-3001 Applicable Requirements R15

6.5. Sharp Corners and Edges

Corners and edges of fixed and handheld equipment to which the bare skin of the crew could be exposed shall be deburred.

Rationale: This requirement pertains specifically to the manufacturing abilities of the M-HHaPS team. Deburred edges prevent accidental cuts.

Parent: L0 NASA STD-3001 Applicable Requirements R16

6.6. Pinch Points

Pinch points shall be covered or otherwise prevented from causing injury to the crew.

Rationale: This requirement exists to prevent accidental injury.

Parent: L0 NASA STD-3001 Applicable Requirements R17

6.8. Nominal Physiological Electrical Current Limits

Under nominal situations (routine human contacts to conductive housing), the program shall limit electrical current through the crewmember to $\leq$ (less than or equal to) 0.4 mA for Direct Current (DC) and $\leq$ (less than or equal to) 0.2 mA peak for Alternating Current (AC).

Rationale: This requirement exists to prevent accidental electrocution.

Parent: L0 NASA STD-3001 Applicable Requirements R19

6.9. Withstand Crew Forces

The system shall be able to withstand the maximum forces imposed by the crew as listed in NASA STD-3001 V2 Appendix F, Section 7: Crewmember Strength.

Rationale: This requirement ensures that the device is strong enough to withstand expected crew loads.

Parent: L0 NASA STD-3001 Applicable Requirements R20

6.13. Cable Management

The system shall manage cable, wire, and hose location, protection, routing, and retention to prevent physical interference with crew operations and safety.

Rationale: The system should limit risks associated with loose cables, wires, and hoses that could be snag hazards. This requirement will be disregarded for the prototype as the deliverable is not meant to be a flight-worthy product.

Parent: L0 NASA STD-3001 Applicable Requirements R22

A.5 External Interfaces ICD

Life Support System

Input: Takes in raw data about system power consumption from power subsystem

Output: None

Crew Health and Performance Monitoring System

Input: Receives information on astronaut health in the form of reports generated on-demand by the software subsystem

Output: Requests reports on astronaut health from the software subsystem

Remote Monitoring System

Input: Receives information on astronaut health in the form of reports generated on-demand by the software subsystem

Output: Receives information on system health in the form of reports generated on-demand by the software subsystem

Martian Habitat Power Supply

Input: None

Output: Provides power 100 W to the power subsystem

A.6 Archived L1 System Requirements

These requirements were originally written as part of a comprehensive system spec but were archived and not factored into the design due to perceived limited relevance to stakeholder needs and limited confidence in achievability.

1. **Exercise Capability**

These requirements relate to the ability of the system to meet the primary customer expectation of maintaining astronaut health through exercise and providing data on those exercises.

1.3. Minimum Exercise Baseline - *archived 10/18/2023*

The system shall maintain the 9-month ISS baseline at minimum as defined in Table 6 after an exercise time no greater than the current time spent on the ISS.

Rationale: Users of a lower state of health should be able to use the system. Data taken from NASA STD-3001 vol. 1.

Parent: L0 NASA STD-3001 Applicable Requirements R10

1.4. Maximum State of Health - *archived 10/18/2023*

The system shall accommodate users with a maximum state of health equivalent to the best-case 0 month ISS astronaut as defined in Table 6.

	0+ Month Exercise Capabilities	9+ Month Exercise Capabilities
VO_2 Max (ml/min/kg) (assuming 25% decline)	43.8	32.9
Deadlift	1 * body weight	80% 0+ month weight
Bench Press	.7 * body weight	80% 0+ month weight
Bone Mineral Densities (BMD)	DXA measurements of T-scores shall be consistent with age, sex, gender, and ethnic matched population	95% 0+ month measurement, 90% 0+ month measurement for femoral neck

Table 6: 0-month and 9-month ISS baseline [7]

Rationale: The system should be able to provide a workout to users who are at a strong state of health.

Parent: L0 NASA STD-3001 Applicable Requirements R3

2. User Interfaces

These requirements relate to the ability of the system to interact with users.

2.2. User Volume - *archived 10/18/2023*

The system shall accommodate the body characteristic data for mass, volume, and surface area as defined in NASA STD-3001 V2 Appendix F, Physical Characteristics and Capabilities, Sections F.4, F.5, and F.6.

Rationale: Users of varying masses, volumes, and surface areas should be able to use the system. The specific design will influence which items from Appendix F are satisfied by default.

Parent: L0 NASA STD-3001 Applicable Requirements R2

2.3. Visual Capabilities - *archived 10/18/2023*

TThe system shall accommodate crew visual capabilities of 20/20 vision in each eye under expected task demands.

Rationale: Users of varying visual perceptual capabilities should be able to operate the system, although NASA requires astronaut candidates to have vision that is at or correctable (via glasses, etc.) to 20/20 in each eye [8].

Parent: L0 NASA STD-3001 Applicable Requirements R4

2.4. Auditory Perceptual Capabilities - *archived 10/18/2023*

The system shall accommodate anticipated [TBR] levels of crew auditory perceptual capabilities under expected task demands.

Rationale: Users of varying auditory perceptual capabilities should be able to operate the system. This requirement is vague as is, but since it is not a prototype requirement, we will not define it further.

Parent: L0 NASA STD-3001 Applicable Requirements R5

2.5. Sensorimotor Capabilities - *archived 10/18/2023*

The system shall accommodate anticipated levels of crew sensorimotor capabilities under expected task demands.

Rationale: Users of varying sensorimotor capabilities should be able to operate the system. This requirement is vague as is, but since it is not a prototype requirement, we will not define it further.

Parent: L0 NASA STD-3001 Applicable Requirements R6

2.6. Cognitive Capabilities - *archived 10/18/2023*

The system shall accommodate anticipated levels of crew cognitive capabilities under expected task demands.

Rationale: Users of varying cognitive capabilities should be able to operate the system. This requirement is vague as is, but we only expect to apply it if we choose to implement gamification, so it will not be defined further at this time.

Parent: L0 NASA STD-3001 Applicable Requirements R7

2.7. Crew Interface Usability - *archived 10/18/2023*

The system shall provide crew interfaces that result in a NASA-modified System Usability Scale (SUS) score of 85 or higher.

Rationale: Interfaces should be easy to use.

Parent: L0 NASA STD-3001 Applicable Requirements R29

3. External Interfaces

These requirements relate to the interfaces between the system and the user, the environment, other devices, and other systems.

3.2. Axial Loads - *archived 10/18/2023*

The system shall be able to fulfill all requirements after experiencing the axial loads listed in Table 5-1 in the SLS Mission Planner's Guide for 8.5 min duration [9].

Rationale: The device must survive launch.

3.3. Lateral Loads - *archived 10/18/2023*

The system shall be able to fulfill all requirements after experiencing the lateral loads listed in Table 5-1 in the SLS Mission Planner's Guide for 8.5 min duration.

Rationale: The device must survive launch.

3.4. Acoustic Loads - *archived 10/18/2023*

The system shall be able to fulfill all requirements after experiencing the acoustic load environments listed in Table 5-17 from the SLS Mission Planner's Guide for 8.5 min duration.

Rationale: The device must survive launch.

3.5. Vibrational Loads - *archived 10/18/2023*

The system shall be able to fulfill all requirements after experiencing the sinusoidal vibrational load environments listed in Table 5-19 from the SLS Mission Planner's Guide for 8.5 min duration.

Rationale: The device must survive launch.

4. Reliability and Maintenance

These requirements relate to the ability of the system to operate and be maintained throughout its lifetime.

4.4. Lifetime - *archived 10/18/2023*

The system shall have an operational lifetime of no less than 1.5 years.

Rationale: This requirement was written for the actual device to ensure it could survive for a full Mars mission. The prototype would not have such a requirement.

4.5. Maintenance Hours - *archived 10/18/2023*

The system shall require no more than 40.75 crew-member-hours of maintenance each year.

Rationale: Based on the CHeCS Hardware Catalog Version 10.0, the ARED requires this amount of yearly maintenance [10].

Parent: L0 NASA STD-3001 Applicable Requirements R25

4.6. Design for Maintenance - *archived 10/18/2023*

The system shall provide the means necessary for users to perform maintenance while wearing typical clothing such as a t-shirt and exercise shorts or a work shirt and work pants.

Rationale: The system should be easy to maintain.

Parent: L0 NASA STD-3001 Applicable Requirements R23

4.7. Commercial Off-the-Shelf (COTS) Equipment Maintenance - *archived 10/18/2023*

The system shall provide any included spare parts for COTS equipment.

Rationale: This requirement exists in case of part failure.

Parent: L0 NASA STD-3001 Applicable Requirements R24

4.8. Visual Access for Maintenance - *archived 10/18/2023*

Maintenance tasks that require visual feedback shall be directly visible to users during task performance while wearing typical clothing such as a t-shirt and exercise shorts or a work shirt and work pants.

Rationale: Users should be able to get feedback while performing maintenance if appropriate.

Parent: L0 NASA STD-3001 Applicable Requirements R26

5. Physical Characteristics

These requirements relate to size, mass, and footprint of the system.

5.4. Stowage Footprint - *archived 10/18/2023*

The system shall have a stowed footprint of no greater than [TBR] m^2.

Rationale: The system needs to be unobtrusive when not in use. Note this requirement was not defined as it was archived before we chose a nominal value.

5.5. Stowage Volume - *archived 10/18/2023*

The system shall have a stowed volume of no greater than [TBR] m^3.

Rationale: The system needs to be unobtrusive when not in use. Note this requirement was not defined as it was archived before we chose a nominal value.

5.6. Mass - *archived 10/18/2023*

The system shall have a total mass of no greater than 1200 lbs.

Rationale: The system needs to be launched to Mars, and the mass of the ISS ARED device (1200 lbs) is being used as a baseline.

6. Safety

These requirements relate to the level of redundancy required for different hazard levels.

6.7. Pain/Non- Disabling Injury Skin Temperature Limits - *archived 10/18/2023*

Any surface to which the bare skin of the crew is exposed shall not cause skin temperature to exceed the critical injury limits in Table 20 from NASA STD-3001 V2.

Rationale: Users should not burn themselves accidentally.

Parent: L0 NASA STD-3001 Applicable Requirements R18

6.10. Intermittent Noise Limits - *archived 10/18/2023*

For hardware items that operate for eight hours or less (generating intermittent noise), the maximum noise emissions (not including impulse noise), measured 0.6 m from the loudest hardware surface, shall be determined according to Table 9 from NASA STD-3001 V2.

Rationale: The system should limit noise output to prevent disruption to the crew. Hearing protection cannot be used to satisfy this requirement.

Parent: L0 NASA STD-3001 Applicable Requirements R8

6.11. Hand Vibration - *archived 10/18/2023*

The system, including tools, equipment, and processes, shall limit vibration to the crewmembers' hands such that the accelerations, as computed according to ANSI/ASA S2.70-2006, Guide for the Measurement and Evaluation of Human Exposure to Vibration Transmitted to the Hand, do not exceed the Daily Exposure Action Value defined by ANSI/ASA S2.70-2006, Annex A, Figure A.1.

Rationale: The system should limit vibrations to prevent disruption to the crew.

Parent: L0 NASA STD-3001 Applicable Requirements R9

6.12. Hardware and Equipment Mounting and Installation - *archived 10/18/2023*

System hardware and equipment shall be designed so that it cannot be mounted or installed improperly.

Rationale: Improper installation could lead to device failure over time. This could be catastrophic and cause injury to crew.

Parent: L0 NASA STD-3001 Applicable Requirements R21

A.7 L2 Mechanical Requirements

Parent Requirement: L1 R1.1

1.1.1 The system shall enable the user to exercise the gastrocnemius muscles.

1.1.2 The system shall enable the user to exercise the soleus muscles.

1.1.3 The system shall enable the user to exercise the hamstrings.

Parent Requirement: L1.2.3

1.2.3.1 The performance metrics of each user in the software subsystem shall be accessible for each user.

1.2.3.2 The performance metrics of each user in the software subsystem shall show the performance improvements of the results made by the user to the user.

Parent Requirement: L1 R2.1

2.1.1 The system's control interface shall be positioned in a way that ensures full range of motion capabilities for all crew members.

2.1.2 The system's display screen shall be positioned in a way that ensures visibility for all crew members.

2.1.3 The system shall include adjustable components to accommodate all crew members with anthropometric dimensions and full ranges of motion.

Parent Requirement: L1 R3.1

3.1.1 The system shall automatically switch to a backup system or initiate a fail-safe mode to ensure the safety of occupants and surroundings.

3.1.2 The system shall be capable of fulfilling the performance and safety requirements across a range of environmental conditions.

Parent Requirement: L1 R6.2

6.2.1 The system shall be an encased system on as many sides as possible to prevent the user and others in the environment from interfering with the mechanism.

6.2.2 The system shall be designed to only be used by one person at a time.

6.2.3 The system shall detect when obstructions will impede its motion.

6.2.4 The system shall autonomously stop the process to prevent damage to the system and the user when obstructions are detected.

Parent Requirement: L1 R6.3

6.3.1 The system shall incorporate an emergency release mechanism to free the user from restraints used during activity.

Parent Requirement: L1 R6.13

6.13.1 The system shall include a retractable mechanism to store wires/cables neatly and to keep out of interference with other movements.

6.13.2 The system shall have an access point to the retraction pulley to resolve any tangling issues or cable derailment in the system.

A.8 L2 Sensors Requirements

Note the numbering scheme is different from the other subsystems. This was due to not having a standard requirement template, and due to a decreased emphasis on systems engineering as the project progressed, it was never rectified. The requirements are written as is to be consistent with verification and validation documentation.

Parent Requirement: L1 R1.2.1

1.1 The sensors shall measure the values in Table 3 without being distractingly uncomfortable to the user.

1.2 The sensors shall automatically measure the values in Table 3.

1.3 The sensors shall measure the values in Table 3 without hindering the astronauts' performance.

Parent Requirement: L1 R2.11

2.1 The sensor subsystem shall provide information to the microcontroller & to the data subsystem to symbolize the completion of a rep.

2.2 The sensor subsystem shall communicate the exercise completion information to the software subsystem.

Parent Requirement: L1 R2.12

2.3 The majority of system response times shall be under one second, except for exceptions described in Requirements 2.3.1-2.3.3.

2.3.1 The screen (and its continuously updating elements such as measurements or on-screen data) shall have a refresh rate of 15 Hz minimum (response time of .07 seconds maximum).

2.3.2 Updates to local elements such as popups shall have a response time of at most .5 seconds.

2.3.3 Discrete input indications shall have an on-screen response time of 0.1 seconds maximum.

2.3.4 Changing a display or display component shall have an on-screen response time of 1 second maximum.

2.3.5 Update of status like “on” or “open” shall have an on-screen response time of 1 second maximum.

2.3.6 A progress bar shall display the progress of commands that cannot be completed in under 1 second.

2.3.7 A status update showing the completion of a task that cannot be completed in under one second shall show up in 1 second after the task is completed.

2.4 The microcontroller shall be able to read changes equal to or larger than 0.01 Volts.

2.5 The microcontroller shall be capable of measuring input at 60 Hz or faster.

2.6 The microcontroller shall be capable of doing necessary calculations in under 100ms.

2.7 The microcontroller shall be able to communicate with the software subsystem.

Parent Requirement: L1 R4.1

4.1 The sensors subsystem shall at all times monitor for the anomalous behaviors in Table 4.

4.2 The sensors subsystem shall be able to detect certain types of faults by using either one or a combination of sensors.

4.3 The sensors subsystem shall communicate information about detected faults to the software subsystem.

Parent Requirement: L1 R6.1

6.1 The sensors subsystem shall shut off power to the machine in case of potentially harmful overdraw. The overdraw shall be defined as a variation of 9 or more [TBR] Watts in power draw.

6.2 The sensors subsystem shall include redundancies for hazard detection.

Parent Requirement: L1 R6.1.1

6.3 The sensors subsystem shall have sensors able to detect catastrophic hazards.

6.4 The sensors subsystem shall communicate the activation of the hazard sensors to the software subsystem in under 100ms.

Parent Requirement: L1 R6.1.2

6.5 The sensors subsystem shall have sensors able to detect critical hazards.

6.6 The sensors subsystem shall communicate the activation of the hazard sensors to the software subsystem in under 100ms.

Parent Requirements: L1 R6.3, L1 R6.13

6.7 The cable management shall be organized to ensure that the user is not tangled by them while exercising.

6.8 The wires shall be organized to ensure circuit simplicity and understanding.

Parent Requirement: L1 R6.6

6.9 The sensors shall neither pinch nor pierce the users' skin while in use.

Parent Requirement: L1 R6.8

6.10 Under nominal situations (routine human contacts to conductive housing), the sensors subsystem shall limit electrical current through the crewmember to $\leq$ (less than or equal to) 0.4 mA of Direct Current (DC).

6.11 Under nominal situations (routine human contacts to conductive housing), the sensors subsystem shall limit electrical current through the crewmember to $\leq$ (less than or equal to) 0.2 mA peak for Alternating Current (AC).

Parent Requirement: L1 R6.9

6.12 The wires and the sensors shall be sturdy enough to withstand the forces applied to them by the user while working out.

A.9 L2 Software Requirements

Note that some of the requirements correspond to the user interface. This likely happened because the Data subteam was responsible for both the user interface screen and the software. Due to a decreased emphasis on systems engineering as the project progressed, this was never rectified. The requirements are written as is to be consistent with verification and validation documentation.

Parent Requirement: L1 R1.2

1.2.1 The UI shall generate reports of the performance metrics listed in Table 3 in the form of raw data with supporting visuals by interfacing with external sensors that are measuring this data.

Parent Requirement: L1 R1.2.1

1.2.1.1 The UI shall autonomously calculate user's average heart rate over the course of exercise or set from the given output data of the external sensors.

1.2.1.2 The UI shall autonomously read and store in storage, user's VO2max over the course of the exercise or set.

1.2.1.3 The UI shall store the number of reps done in each set measured by the external sensors and include an option for the user to manually note if the set was taken to failure.

1.2.1.4 The UI shall record the external sensor's measure of the amount of force the muscle outputted during each set or exercise.

Parent Requirement: L1 R1.2.2

1.2.2.1 The UI shall store the user's average heart rate over the course of the exercise or set to the user's file in storage.

1.2.2.2 The UI shall store the user's VO2 max over the course of the exercise or set to the user's file in storage.

1.2.2.3 The UI shall store the user's number of reps done in each set and if the set was taken to failure to the user's file in storage.

1.2.2.4 The UI shall store the amount of force the targeted muscle(s) output during each set or exercise to the user's file in storage.

1.2.2.5 The UI shall store the user's strength of each muscle over time to the user's file in storage.

Parent Requirement: L1 R1.2.3

1.2.3.1 The UI shall store a unique collection of the performance metrics listed in Table 3 for each user in storage.

Parent Requirement: L1 R1.5

1.5.1 The UI shall allow for integration with gamification.

1.5.2 The gamification will be accessible from the user's perspective from the UI.

Parent Requirement: L1 R2.10

2.10.1 The UI shall provide a positive indication of crew-initiated control activation by displaying a message that can be read by the user.

Parent Requirement: L1 R2.11

2.11.1 The UI shall notify the user upon completion of the exercise.

Parent Requirement: L1 R2.12

2.12.1 The UI shall provide feedback to the user within the time specified in NASA STD-3001 Volume 2 Table 30, Maximum System Response Time(s) based on the data received from the Sensor Data Processor.

2.12.2 The UI shall provide feedback to the user within the time specified in NASA STD-3001 Volume 2 Table 30, Maximum System Response Time(s).

Parent Requirement: L1 R3.6

3.6.1 The UI shall interface with the Life Support System.

Parent Requirement: L1 R3.7

3.7.1 The UI shall interface with the Remote Monitoring System.

Parent Requirement: L1 R3.8

3.8.1 The UI shall interface with the Crew Health and Performance Monitoring System.

Parent Requirement: L1 R3.9

3.9.1 The UI shall not allow the user to configure the parameters of the exercise within a time greater than the current time spent on the ISS.

Parent Requirement: L1 R3.10

3.10.1 The UI shall be able to access saved data and transmit data to an external device.

Parent Requirement: L1 R4.1

4.1.1 The Sensor Data Processor shall allow for the processing of sensor outputs that shall allow for the detection of anomalous behaviors defined in Table 4 during normal operation.

Parent Requirement: L1 R4.2

4.2.1 The UI shall notify users in real-time of detected anomalous behaviors listed in Table 4 by receiving data and interfacing with the Sensor Data Processor.

Parent Requirement: L1 R4.3

4.3.1 The UI shall display system state of health reports on the metrics defined in Table 5 on-demand by users by interfacing with the Sensor Data Processor as well as internal storage and memory of system health.

A.10 L2 User Interface Requirements

Parent Requirement: L1 R1.2.1

1.2.1.1 The system shall be non-invasive.

1.2.1.2 The system shall be accurate within a reasonable range.

Parent Requirement: L1 R1.2.4

1.2.4.1 The user interface system shall be capable of uniquely recognizing each crew member via pin.

1.2.4.2 The user interface system shall be capable of storing data regarding the user in the data storage system.

Parent Requirement: L1 R1.5

1.5.1 The user interface system shall allow the user to interact in real-time with the device.

1.5.2 The user interface system shall connect the users' exercise with a virtual experience.

Parent Requirement: L1 R2.9

2.9.1 The interface shall be applicable to all necessary tasks.

2.9.2 The system shall have "X many" interfaces to successfully complete "X" tasks.

2.9.3 The interface shall complete “X task” with “X” percent accuracy.

Parent Requirement: L1 R2.11

2.11.1 The system shall notify with a universal, unmistakable signal.

2.11.2 The system shall notify with appropriate signals for different exercises.

2.11.3 The system shall notify/alert user safely and comfortably.

Parent Requirement: L1 R4.2

4.2.1 The sensors subsystem shall detect when there is an anomalous behavior listed in Table 4.

4.2.2 The user interface system shall specify what anomalous behavior it has detected.

A.11 L2 Power Requirements

Parent Requirement: L1 R3.6

3.6.1 The power subsystem shall provide 100 W from 120 VAC wall outlet.

B Trade Studies

Choices Criteria	Adjustable Seat		Adjustable Footrest		Adjustable Pulleys		Adjustable Handle	
Requirements	Info	Does it s	Info	Y/N	Info	Y/N	Info	Y/N
Perform analogous EVA task	Walking, Picking up (legs)	Yes	Walking, Picking up (legs)	Yes	Walking, Picking up (arms)	Yes	Walking (telescoping handle – back), Twisting/holding	Yes
Accomodate range of users	All adjustable ->	Yes		Yes		Yes		Yes
Allows for integration with sensors	Distance sensor, force sensor, way to measure angles, resistance sensor	Yes	Distance, force sensor, resistance sensor	Yes	Resistance sensor	Yes	Force sensor, resistance sensor	Yes

Wants	WT	WT Rationale	Seat Info	Value	Score	Footrest Info	Value	Score	Pulleys Info	Value	Score	Handle Info	Value	Score
Value of analogous EVA tasks (add relative weights of each task to get final number)	0.3	EVA fitness is the goal of the device and must therefore be fulfilled by the adjustable device component.	Each of 3 tasks was ranked and assigned a possible score. Each alternative was given a score based on its relevant tasks, which was then normalized by the total possible score.	0.83	0.25	Walking - 3 pts Picking up - 2 pts Twisting - 1 pt	0.83	0.25		0.83	0.25		0.67	0.20
				0.83	0.25		0.83	0.25		0.83	0.25		0.67	0.20
				0.83	0.25		0.83	0.25		0.83	0.25		0.67	0.20
Feasibility / Complexity (internal to BLiSS team)	0.15	The BLiSS project team needs to be able to construct the device in some form in order to provide a useful proof of concept. These scores were determined based on Ilyana and Chris' judgement of the complexity of the designs	We judged that a seat will be easy to implement due to most rowing machines having one. There might be some complications depending on how adjustable we want it to be	0.60	0.09	An adjustable footrest will not be that challenging due to the limited scope of the addition.	0.50	0.08	Adjustable pulleys will require the most support, so these will be the most challenging	0.00	0.00	An adjustbale handle will not be that challenging due to the limited scope of the addition.	0.60	0.09
				0.90	0.14		0.70	0.11		0.20	0.03		0.80	0.12
				0.90	0.14		0.80	0.12		0.40	0.06		0.90	0.14
Novelty	0.25	We think that NASA does not want us to reinvent the treadmill. They are soliciting students to work on this project because we can generate new ideas	Since most rowing machines come with adjustable seats, this is not that novel	0.00	0.00	Most rowing machines do not come with adjustable footrests, and the new exercises we can do are unique to this design	0.85	0.21	Some rowing machines do not come with adjustable pulleys, and the new exercises we can do could be unique to this design	0.70	0.18	Most rowing machines do not come with adjustable handles, and the new exercises we can do are unique to this design	0.90	0.23
				0.30	0.08		0.90	0.23		0.80	0.20		0.95	0.24
				0.60	0.15		1.00	0.25		0.90	0.23		1.00	0.25
Low power consumption	0.09	Power is more important than mass or volume, since this is a very constrained resource on Mars	This addition should not add more power consumption to a base rowing machine	1.00	0.09	This addition should not add more power consumption to a base rowing machine	1.00	0.09	Depending on how the adjustments need to be made, there may be some extra power involved	0.80	0.07	This addition should not add more power consumption to a base rowing machine	1.00	0.09
				1.00	0.09		1.00	0.09		0.90	0.08		1.00	0.09
				1.00	0.09		1.00	0.09		1.00	0.09		1.00	0.09
Integration with gamification	0.05	As this is an addon to our project, we believe we should consider it but it should not rank highly	An adjustable seat does not provide any way to make the exercise more like a game	0.00	0.00	Adjustable footrests could be integrated with a game	0.60	0.03	An adjustable pulley does not provide any way to make the exercise more like a game	0.00	0.00	Adjustable handles can provide great integration with a game as the hands could be used for control	0.80	0.04
				0.00	0.00		0.80	0.04		0.00	0.00		0.90	0.05
				0.10	0.01		1.00	0.05		0.10	0.01		1.00	0.05
Added volume	0.08	There is limited volume in the Martian hab, so this needs to be considered. However, most of the other considerations are much more important	An adjustable seat should not add too much more volume besides for any spare parts	0.80	0.06	An adjustable footrest should not add too much more volume besides for any spare parts	0.80	0.06	An adjustable pulley could add a lot more volume as the adjustment could require moving the cable beyond the original confines of the machine	0.00	0.00	An adjustable handlebar should not add too much more volume besides for any spare parts	0.80	0.06
				0.85	0.07		0.85	0.07		0.30	0.02		0.85	0.07
				0.90	0.07		0.90	0.07		0.50	0.04		0.90	0.07
Added Mass	0.08	A limited amount of mass can be sent to Mars, so this needs to be considered. However, most of the other considerations are much more important.	An adjustable seat should not add too much more mass besides for any spare parts	0.80	0.06	An adjustable footrest should not add too much more mass besides for any spare parts, although the spare parts do have the potential to be heavier	0.70	0.06	Due to the design complexity of an adjustable pulley, it has the potential to add a lot more mass	0.00	0.00	An adjustable handlebar should not add too much more mass besides for any spare parts	0.80	0.06
				0.85	0.07		0.75	0.06		0.30	0.02		0.85	0.07
				0.90	0.07		0.80	0.06		0.50	0.04		0.90	0.07
Total Score			Minimum		0.56			0.78			0.50			0.77
			Nominal		**0.69**			**0.84**			**0.61**			**0.83**
			Maximum		0.77			0.90			0.71			0.87
			Variance		**0.0118**	Variance		**0.0035**	Variance		**0.0114**	Variance		**0.0023**

Figure 19: Rowing machine modification selection trade study

Choices / Criteria	Permanent Magnets		Electromagnets (Brakes)		Gear System (velocity)		Motor	
Requirements	Info	Does it satisfy	Info	Y/N	Info	Y/N	Info	Y/N
Adjustable Resistance	Manually put on or take off magnets	Yes	Adjust force of electric current to match desired mass outcome	Yes	Gear switches between different radii to increase/decrese resistance	Yes	Change speed of the rotation	Yes
Generate 2500 N Resistance Max	Need to determine number of magnets/force	Yes	Can buy brakes (max of 400Nm and we need ~60Nm)	Yes	1:10 gear ratio needed	Yes	Velocity manipulation	Yes
Generate 20 N or Lower Resistance Min	Can be zero magnets	Yes	Need to first understand how to find correct current of electric force	Yes	Can be set to have just the machine's resistance	Yes	When off it can be 0 N	Yes
Does not exceed our power budget	Does not apply	Yes	Can be less than 60W	Yes	Does not apply	Yes	Can be manipulated	Yes

Wants	WT	WT Rationale	Permanent Magnets Info	Value	Score	Electromagnets (Brakes) Info	Value	Score	Gear System (velocity) Info	Value	Score	Motor Info	Value	Score
Ease of resistance adjustability	0.3	This is how each user can personalize their workouts and will have to do this frequently, so it should not take too much time	This involves adding and taking away permanent magnets	6	1.8	User would switch between resistance setting by turning a knob or using an interface	7	2.1	Would be relatively easy to switch between gears using a gear shifter we make or manually switch gears	6	1.8	Easy to adjust (knob or dial)	7	2.1
				7	2.1		8	2.4		7.5	2.25		8	2.4
				8	2.4		9	2.7		9	2.7		9	2.7
Does not take up too much space	0.05	This could possibly affect the other mechanisms of the device or affect packaging	The size and shape and number of magnets affects this	6	0.3	Would be roughly the same size as current magnet	8	0.4	Would take up some space for the different size gear radii	5	0.25	Wouldn't take up much space; similar size to magnet or slightly bigger	7	0.35
				7	0.35		8.5	0.425		6	0.3		7.5	0.375
				8	0.4		9	0.45		7	0.35		8	0.4
Small adjustment step sizes	0.25	This allows for a more specific and individualized workout	The smaller this is the higher number of smaller magnets needed	6	1.5	Depends on the number of knob settings or digital settings	8	2	Depends on the number of gears we add	5	1.25	Lots of variability if controlled digitally	7	1.75
				7.5	1.875		8.5	2.125		6.5	1.625		7.5	1.875
				9	2.25		9	2.25		8	2		8	2
Manufacturing feasibilty	0.2	Manufacturing with novice experience in mind allows easy and quick recreation	Would only require the addition of other similar grade magnets. No additional skill needed	8.5	1.7	Would require knowledge in electrical current and electromagnets	6	1.2	Would be difficult to manufacture the different gears and assemble/attach to the machine	6	1.2	Extremely difficult if we do it ourselves; easy if purchased (only need to attach)	6	1.2
				9	1.8		7	1.4		7	1.4		7	1.4
				9.5	1.9		8	1.6		8	1.6		8	1.6
Projected Maintanence Requirement	0.2	The device must survive its lifetime without wearing down or needing to be repaired frequently	This should not affect the survival of the device or its components	8.5	1.7	This will create a lot of friction and wear down the material, it is also flammable.	4	0.8	This should not affect the survival of the material of its components	8	1.6	The motor most likely needs maintanence	5	1
				9	1.8		4.5	0.9		8.5	1.7		5.5	1.1
				9.5	1.9		5	1		9	1.8		6	1.2
Total Score			Minimum		7			6.5			6.1			6.4
			Nominal		7.925			7.25			7.275			7.15
			Maximum		8.85			8			8.45			7.9
			Variance		12.2	Variance		10.9	Variance		10.4	Variance		10.7

Figure 20: Resistance mechanism trade study

Choices / Criteria	Straight Bar		Triangle		Neutral Grip		Lat Pull-Down Bar		Ropes	
Requirements	Info	Does it s	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Works necessary muscle groups	Stimulates middle back muscles	Yes	Stimulates lats, rhomboids, and traps	Yes	Stimulates rhomboids, middle back, and lats	Yes	Stimulates middle back and biceps	Yes	Stimulates lats	Yes
Stimulates X muscle by Y amount	Stimulates middle back muscles by Y Amperes	Yes	Stimulates lats, rhomboids, and traps by Y hertz	Yes	Stimulates rhomboids, middle back, and lats by Y hertz	Yes	Stimulates middle back and biceps by Y hertz	Yes	Stimulates lats by Y hertz	Yes
Must fit multiple hand sizes comfortably	All hands can fit around bar comfortably	Yes	Hands can fit around handles with enough space between handles so hands don't touch in middle	Yes	Various wingspans can use bar. Hands can fit around bar.	Yes	Various wingspans can use bar. Circumf	Yes	All hands can comfortably grip end of ropes.	Yes
Cannot exceed X weight	Is conventional weight of 5.5 lbs	Yes	conventional weight of 4.54 lbs	Yes	conventional weight of 9.04 lbs	Yes	convential weight of 4.41 lbs	Yes	conventional weight of 1.8 lbs	Yes
Must be able to withstand crew load	Conventional weight withstands 880 lbs	Yes	Conventional weight withstands 500 lbs	Yes	Conventional weight withstands 880 lbs	Yes	Conventional weight withstands 500 lbs	Yes	Conventional weight withstands 500 lbs	Yes
Is able to attach to the rowing machine		Yes		Yes		Yes		Yes		Yes
Must be able to adjust the force delivered by the machine		Yes		Yes		Yes		Yes		Yes

Wants	WT	WT Rationale	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Attaches to a metal carabiner	0.35	Being able to attach to a metal carabiner would allow for different handles to be attached, as well as potentially attaching to the seat to work the legs more	The straight bar allows for more instability with use of a carabiner, as the lack of handles would make it easier for the user to accidentally move the bar	0.40	0.14	The shape of the triangle bar means that there is less room for the user to move it, meaning it is more secure and stable	0.70	0.25	The neutral grip is better, as it is less likely to shift, but is still not desirable.	0.50	0.18	The lat pull-down bar has handles, which means the user is less able to shift the bar, but there is still room for it to wiggle, as the bar allows for wide grip rows.	0.30	0.11	The ropes would be most inconvenient, as the shape of the ropes would make it difficult to attach.	0.20	0.07
				0.50	0.18		0.40	0.14		0.60	0.21		0.45	0.16		0.35	0.12
				0.60	0.21		1.00	0.35		0.70	0.25		0.60	0.21		0.50	0.18
Able to switch out type of handle	0.4	Being able to switch out the different handle attachments would allow us to target different muscle groups	Allows for a more versatile piece of equipment, targeting more back muscle groups.	0.20	0.08	Triangle attachment targets all of middle back and is therefore most important attachment. Thus, it receives a higher value.	1.00	0.40	The neutral grip bar is not extremely versatile, seeing as it is only able to be held in one orientation. However, the handles mean it does a good job of targeting the necessary muscle groups.	0.70	0.28	The lat pull-down bar can be held in multiple ways, making it a more versatile piece of equipment.	0.30	0.12	Not the most effective at targeting back muscles, but are versatile in the sense that the ropes pull apart, allowing for an increased strech in the muscles.	0.40	0.16
				0.30	0.12		1.00	0.40		0.75	0.30		0.40	0.16		0.50	0.20
				0.40	0.16		1.00	0.40		0.80	0.32		0.50	0.20		0.60	0.24
Rowing attachments are compactable for storage purposes	0.25	Compact rowing attachments allows for storage room to be optimized on the shuttle.	Straight bar is a long bar without attachments that point in another direction, meaning that they do not need a large storage spot and can be stored vertically.	0.30	0.08	The triangle attachment is very small, and therefore very easy to store	0.90	0.23	The neutral grip is a long bar with handles that point upwards, making it difficult to store.	0.10	0.03	This is the longest attachment, and therefore difficult to store. However, it doesn't have much width, which is helpful for storage purposes.	0.15	0.04	Ropes are extremely easy to store, as they are not rigid and can be folded or bunched up.	0.50	0.13
				0.35	0.09		0.95	0.24		0.15	0.04		0.23	0.06		0.60	0.15
				0.40	0.10		1.00	0.25		0.20	0.05		0.30	0.08		0.70	0.18
Total Score			Minimum		0.30			0.87			0.48			0.28			0.36
			Nominal		**0.38**			**0.78**			**0.55**			**0.37**			**0.47**
			Maximum		0.47			1.00			0.62			0.49			0.59
			Variance		**0.01**	Variance		**0.01**	Variance		**0.00**	Variance		**0.01**	Variance		**0.01**

Figure 21: Handle attachments trade study

Choices Criteria	Knurled Bar		Leather		Rubber		Polished Metal		Polyethylene Foam	
Requirements	Info	Does it s	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Grip long enough to fit multiple hand sizes comfortably (Above 25th percentile of females can use)	Each material can be cut to proper length.	Yes	Each material can be cut to proper length.	Yes	Each material can be cut to proper length.	Yes	Each material can be cut to proper length.	Yes	Each material can be cut to proper length.	Yes
Compatible with the bar type chosen	Can be cut and fitted to be the size and shape of bar	Yes	Can be cut and fitted to be the size and shape of bar	Yes	Can be cut and fitted to be the size and shape of bar	Yes	Can be cut and fitted to be the size and shape of bar	Yes	Can be cut and fitted to be the size and shape of bar	Yes
Grip needs to be able to stay on bar in same location	Knurled Bar is a textured bar inherent to the design, so the grip cannot move	Yes	Can be glued with strong adhesive	Yes	Can be melted on	Yes	Doesn't require an attachment	Yes	The foam attachment slides over the metal bar, which could easily slide off after use.	No
Needs to have X coefficient of friction with bare hands	Coefficient of friction is well-known to work as it is used commonly on other machines	Yes	Wet leather still has traction	Yes	Rubber has high friction even when wet	Yes	Hands slip easily when wet on polished metal	No	Foam is easily indented by gripping, and won't slip due to this	Yes
Material needs to uphold for Y amount of hours of use	Standard barbell material, very durable	Yes	With sweat, leather starts to crack and dry so limited use	No	Often used in machine grips due to durability so it would uphold	Yes	No corrosive materials will interact with the handle.	Yes	The material must reform back to original shape, which will slowly stop happening after many uses.	No

Wants	WT	WT Rationale	Knurled Bar Info	Value	Score	Leather Info	Value	Score	Rubber Info	Value	Score	Polished Metal Info	Value	Score	Polyethylene Foam Info	Value	Score
Increased grip diameter	0.2	Will activate the forearms and palm muscles for an extended period of time, hand will not undergo full range of motion	The place where the user holds the rower can be thicker, but these bars' thickness tend to be constant	0.3	0.06	Leather can be shaped to fit whatever diameter is desired pretty easily	0.75	0.15	Rubber can be placed around the bar at different amounts to increase the diameter of where the user will hold	1	0.2	Requires effort to mold to a specific size compared to other materials	0.4	0.08	Can be a slide-on attachment or fitted to the handle grips to increase diameter size.	0.9	0.18
				0.7	0.14		0.8	0.16		1	0.2		0.75	0.15		1	0.2
				0.8	0.16		0.9	0.18		1	0.2		0.8	0.16		1	0.2
Comfortable Grip Texture	0.25	Determines comfortability since it changes finger placement and it can activate slightly different muscles in the forearms	Not comfortable since it is metal textured differently but not necesarily softened.	0.5	0.125	Leather can start out pretty soft and comfortable, but over time it will crack and get tougher.	0.2	0.05	They're used for bike handles and proven to be comfortable long term use, they can easily fit multiple handsizes to increase the comfort	0.85	0.2125	Polished metal will provide a smooth surface to hold on to.	0.4	0.1	Conforms easily to form to your hand making it comfortable and the texture doesn't crack or harden with usage.	0.9	0.225
				0.7	0.175		0.65	0.1625		0.9	0.225		0.55	0.1375		0.95	0.2375
				0.8	0.2		0.75	0.1875		0.95	0.2375		0.65	0.1625		1	0.25
Bike Brake Mechanism	0.15	Will activate the hands/forearms more consistently and with open/close motion.	It could pose potential injury concerns with calouses and grip issues	0.6	0.09	Sweaty hands would cause the leather to crack over time, decreasing its efficiency	0.3	0.045	Bike handles are typically made of rubber so bike brake handles are pretty compatible with the rubber substance	1	0.15	The user's hands can slip due to the low coefficient of friction. The bike brake will be hard to comfortably hold on to for a long time.	0.45	0.0675	The polyethylene foam feels similar to rubber, but with less friction, which is less stuitable than rubber	0.8	0.12
				0.75	0.1125		0.5	0.075		1	0.15		0.55	0.0825		0.9	0.135
				0.9	0.135		0.7	0.105		1	0.15		0.6	0.09		1	0.15
Wrist Strap Attachment	0.05	Forearm activation is a priority, however, wrist straps can provide option to target the back more specifically. Can also be very helpful for heavier lifts.	Wrist straps are commonly used with these in commercial gyms because the bar's friction grips provide great stability.	0.8	0.04	Initially the leather will have a coefficient of friction to keep the wrist strap in place, but the increased friction will wear out the leather	0.3	0.015	Wrist straps can be used with rubber, as the rubber will have sufficient friction to keep the strap in place.	0.75	0.0375	Polished metal is slick so the wrist strap will move around, which decreases usefulness and comfort.	0.1	0.005	Wrist straps can be used with foam handles, but the increased pressure from the straps may increase stress and wear on the grips.	0.4	0.02
				0.9	0.045		0.5	0.025		0.8	0.04		0.2	0.01		0.6	0.03
				0.95	0.0475		0.8	0.04		0.9	0.045		0.4	0.02		0.85	0.0425
Strong and long-lasting Grip Material	0.35	The material controls whether or not the grip will break/deteriorate with use because it's related to durability, friction, and sweat resistance.	Lasts long and the only maintence is wiping off potential dirt or rust but the knurled texture can eventually be diminished	0.95	0.3325	Can easily crack and wear down as moisture gets trapped and dries the leather, causing the leather to lose it's friction over time.	0.2	0.07	Lasts pretty long but could warp and tear by usage but it's still possible that the rubber wears out in certain spots	0.875	0.30625	The metal will not wear out easily under the conditions of the habitat.	1	0.35	The more the foam handle is used, the less elasticity it will have.	0.45	0.1575
				0.975	0.34125		0.4	0.14		0.925	0.32375		1	0.35		0.55	0.1925
				1	0.35		0.6	0.21		0.95	0.3325		1	0.35		0.75	0.2625
Total Score			Minimum		0.6475			0.33			0.90625			0.6025			0.7025
			Nominal		0.81375			0.5625			0.93875			0.73			0.795
			Maximum		0.8925			0.7225			0.965			0.7825			0.905
			Variance		1.235	Variance		0.51	Variance		1.6125	Variance		1.125	Variance		1.225

Figure 22: Handle grip trade study

Choices / Criteria	Option 1: Typical Rowing footrests that allow user to latch feet in		Option 2: 2 footrests - Removable to install to two settings, upper/lower positions		Option 3: One footrest that can be used for both settings		Option 4: One big removable platform		Option 5: One stationary platform	
Requirements	Info	Does it satisfy must have?	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Must not interfere with the cable during rowing	Will work effectively as a typical rower would	Yes	the interfering footrest can be taken off	Yes	If designed properly shouldnt interfere	Yes	could potentially interfere with pulley system, can cut a hole in the middle	Yes		Yes
Must have accomodations for resting the feet during both upper and lower body exercises	Doesn't specifically address this.	Yes	If the footrests only apply to upper or lower at a given time, you cannot have both.	No	Could be built to be accomodated for both	Yes	If large enough, could accomodate both	Yes		Yes
Must allow for a wide range of motion in the transverse direction	Restricts motion due to latching	Yes	Potentially versatile due to removability	Yes	If built wide enough, should allow movement	Yes	If built wide enough should allow movement	Yes		Yes
Must be able to withstand forces exerted by the crew	Durable nylon footstraps don't tear or break easily	Yes	Depends on material used to create	Yes	Depends on material used to create	Yes	Depends on material used to create	Yes		Yes
Must be compatible to all members of the crew regarding expected weight, height, and gender/build	Straps are adjustable and can fit different foot sizes	Yes	Depends on how large each footrest is	Yes	Depends on how large the 1 footrest is	Yes	Note: Would be harder to accomdate but still plausible	Yes		Yes

Wants	WT	WT Rationale	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Ease of transition between exercises	0.3	Transitioning between exercises should not require more effort than the exercises themselves.	Easy to transition between different exercises	0.6	0.18	Easy to transition between different exercises but trickier than one because there are two to change	0.5	0.15	Easy to transition between different exercises as it's just one footrest	0.6	0.18	Going to be somewhat difficult to remove the big footrest to transition between exercises	0.4	0.12	Very easy to transition since there's no removeable pieces	0.6	0.18
				0.7	0.21		0.6	0.18		0.65	0.195		0.65	0.195		0.7	0.21
				0.8	0.24		0.7	0.21		0.8	0.24		0.8	0.24		0.8	0.24
Slightly angled for lower body mobility during leg press and calf raises	0.15	Helpful for specific exercises, but not necesarily needed for these exercises to happen.	Cannot adjust how to foot rest is angled	0	0	Could potentially be built so it is angled for lower body movements but it would be difficult	0.2	0.03	If it's one big footrest there will be less adjustability	0.3	0.045	Cannot angle the platform easily for both exercises as it's just 1 platform	0.3	0.045	Difficult to angle it correctly to work for both exercises	0.2	0.03
				0	0		0.3	0.045		0.4	0.06		0.35	0.0525		0.3	0.045
				0	0		0.5	0.075		0.5	0.075		0.4	0.06		0.31	0.0465
Comfort of footrest	0.05	As it states. Purely for comfort and to prevent one from no longer wanting to use it.	Generally comfortable; user may not enjoy having to strap in legs constantly	0.7	0.035	Somewhat comfortable. User doesn't have anything to strap themselves to	0.6	0.03	User can place feet at any distance and anywhere on the footrest; not restrictive	0.6	0.03	Comfortable due to it being just one platform; allows for range of motion	0.6	0.03	Very comfortable because it has different foot placements and no straps	0.7	0.035
				0.8	0.04		0.65	0.0325		0.7	0.035		0.62	0.031		0.75	0.0375
				0.85	0.0425		0.7	0.035		0.75	0.0375		0.7	0.035		0.8	0.04
Simplistic Design	0.2	A useful choice if it comes to reproducing these footrests, especially for mass production.	Simple to reproduce; would need to separately create strap and footrest	0.95	0.19	Going to be difficult to create 2 different footrests and the areas where they are going to fit into	0.2	0.04	Going to be difficult accomodating for both lower and upper body exercises	0.3	0.06	Very simple to produce since it is just one big block	0.65	0.13	Since its just a block, very simple	0.6	0.12
				0.95	0.19		0.25	0.05		0.5	0.1		0.7	0.14		0.7	0.14
				1	0.2		0.4	0.08		0.6	0.12		0.75	0.15		0.8	0.16
Effectiveness in targeting desired muscles	0.2	Would be ideal for the footrest to allow the user to perform as many desired exercises as possible to target as many muscles as possible	Could be problematic if user is trying to have a wider stance to target different muscles since feet are strapped into place	0.6	0.12	Very effective in targetting different muscle groups due to the removeability feature and each footrest being specialized	0.8	0.16	Very effective in training diffferent muscles due to the lack of restrictiveness	0.8	0.16	Can generally target different muscles but may not be able to target calves if not angled properly	0.6	0.12	Could be a problem targetting back or legs depending on tilt	0.4	0.08
				0.65	0.13		0.9	0.18		0.85	0.17		0.65	0.13		0.5	0.1
				0.7	0.14		0.9	0.18		0.9	0.18		0.7	0.14		0.55	0.11
Durability (1 year lifespan)	0.1	Beyond withstanding crew forces, the footrest and foot straps must hold up to the typical wear from repeated use for at least one year without service.	The straps have potential to tear with extended use and roughness	0.55	0.055	Constant removing and inserting of the different footrests, depending on material used, could damage the feature before 1 year is up	0.07	0.007	Depends on crew forces and material	0.3	0.03	depends on crew forces and material	0.2	0.02	Very durable as there are no moving pieces	0.75	0.075
				0.65	0.065		0.1	0.01		0.4	0.04		0.25	0.025		0.8	0.08
				0.8	0.08		0.3	0.03		0.45	0.045		0.3	0.03		0.95	0.095
Total Score			Minimum		0.58			0.417			0.505			0.465			0.52
			Nominal		**0.635**			**0.4975**			**0.6**			**0.5735**			**0.6125**
			Maximum		0.7025			0.61			0.6975			0.655			0.6915
			Variance		**0.003764**	Variance		**0.009397**	Variance		**0.009264**	Variance		**0.009085**	Variance		**0.007368**

Figure 23: Footrest modification trade study

Choices Criteria			Option 1: Two distinct swappable seats			Option 2: Attachable backrest with 3 lock-in positions			Option 3: Rotating seat with backrest in one lock-in position (3 swivels)		
Requirements			Info		Does it s	Info		Y/N	Info		Y/N
Seat must withstand force of all exercises					Yes			Yes			Yes
Must be able to be removed to allow for rowing					Yes			Yes			Yes
Must be compatible with seat mechanisms of rowing machine					Yes			Yes			Yes
Wants	**WT**	**WT Rationale**	Info	Value	Score	Info	Value	Score	Info	Value	Score
User is able to install it easily	0.3	If installation is difficult, too much time and effort would be spend on a task that isn't directly helpful towards building astronaut strength. If installation is too difficult, it could be installed incorrectly and break a component	Moving full seats may be a bit awkward and unwieldy. Attaching the seat for each pec fly direction would be difficult as the user would have to remove and re-attach the seat just to switch directions.	0.10	0.03	Installation should be easier than the entire seat, since it's only moving a backrest. However, having to move the entire backrest just to switch sides for pec flies would be a bit cumbersome.	0.40	0.12	This option would be the easiest to install as the user would simply rotate the seat 90 degrees based on what excersice they want to complete.	0.75	0.23
				0.30	0.09		0.45	0.14		0.80	0.24
				0.40	0.12		0.55	0.17		0.85	0.26
Lightweight	0.125	Users will be in microgravity, so seats should be easy to carry anyways	This would be the heaviest option of the three, as we're moving an entire seat + backrest versus just a backrest	0.20	0.03	This would be lighter than moving the entire seat, as it is just the backrest. The backrest will weigh the same in Option 3	0.40	0.05	This would be lighter than moving the entire seat, as it is just the backrest. The backrest will weigh the same in Option 3	0.40	0.05
				0.35	0.04		0.50	0.06		0.50	0.06
				0.40	0.05		0.60	0.08		0.60	0.08
Comfortable to use for all 3 exercises	0.4	Comfort is necessary for long exercise sessions; if not comfortable enough for astronauts, takes away from actual excersice/purpose. Uncomfortable equipment may also risk harm to the user.	All back rests would be made out of the same material. Seat contours would be designed to be most comfortable with the direction the user is sitting.	0.70	0.28	All back rests would be made out of the same material. However, the seat bottom contours will be absent in this option, as the seat will need to be more symmetrical, thus earning it a slightly lower comfortability score	0.60	0.24	All back rests would be made out of the same material. Seat contours would be designed to be most comfortable with the direction the user is sitting.	0.70	0.28
				0.80	0.32		0.70	0.28		0.80	0.32
				0.90	0.36		0.80	0.32		0.90	0.36
Ease of manufacturabilty (in terms of our team's capabilities)	0.175	We only have so many resources and time to make this machine and if we can't manufacture it to work the way it's intended then it's a difficult design to support	Designing and manufacturing this wouldn't be too difficult as we would just have to rotate the rail-attachment mechanism by 90 degrees.	0.30	0.05	Manufacturing for any position would be slightly more difficult than Option 1 in terms of the seat-to-chair attachment since it would have to have a detachment mechanism. It would be difficult to contend with space for the handles, as they would be on the sides of the seat where the backrest would also have to attach.	0.40	0.07	Getting the rotating disc/ swivel mechanism to work would require working on the seat fundamentally, and changing how it's attached to the rower so it would be slightly difficult	0.25	0.04
				0.35	0.06		0.50	0.09		0.30	0.05
				0.45	0.08		0.55	0.10		0.35	0.06
Total Score			Minimum		0.39			0.48			0.60
			Nominal		**0.52**			**0.57**			**0.68**
			Maximum		0.61			0.66			0.75
			Variance		**0.01**	Variance		**0.01**	Variance		**0.01**

Figure 24: Seat and backrest modification trade study

Choices / Criteria			Touch Screen			Fitness Watch (wearable)			Remote Desktop			Laptop		
Requirements			Info		Does it s	Info		Y/N	Info		Y/N	Info		Y/N
Ability to retrieve data					Yes	Input it on watch		Yes			Yes			Yes
Ability to analyze data					Yes	Depends on the type of watch		Yes			Yes			Yes
Show system health					Yes	Not feasible		No			Yes			Yes
Wants	**WT**	**WT Rationale**	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Processing Power	0.15	Processing power is important; however, the amount of processing power for a UI is typically low (it only has to retrieve and display data; it doesn't have to run		0.4	0.06		0.2	0.03		0.8	0.12		0.7	0.11
				0.6	0.09		0.3	0.05		0.9	0.14		0.7	0.11
				0.6	0.09		0.4	0.06		1	0.15		0.8	0.12
Durability	0.15	Although we may only have one of these devices, the use of the device causes the risk of damaging the device to be low, so the weight is low		0.5	0.08		0.8	0.12		0.7	0.11		0.6	0.09
				0.6	0.09		0.9	0.14		0.8	0.12		0.7	0.11
				0.6	0.09		1	0.15		0.9	0.14		0.8	0.12
Accessibility	0.3	This is a workout device, not some supercomputer. It's not suppose to be hard to use.		0.9	0.27		0.3	0.09		0.2	0.06		0.6	0.18
				1	0.30		0.4	0.12		0.3	0.09		0.7	0.21
				1	0.30		0.5	0.15		0.4	0.12		0.8	0.24
Size	0.15	This device may be mounted on the workout device, so you don't want it to be too big that it gets in the way of the astronaut. We also don't want it to be too small		0.8	0.12		0.4	0.06		0.2	0.03		0.7	0.11
				0.9	0.14		0.5	0.08		0.3	0.05		0.8	0.12
				1	0.15		0.6	0.09		0.4	0.06		0.9	0.14
Power consumption	0.25	We are going to be limited to a certain level of power consumption, and the UI may or may not be important in the grand scheme of things, so it's best to just use the		0.6	0.15		1	0.25		0	0.00		0.3	0.08
				0.7	0.18		1	0.25		0.1	0.03		0.4	0.10
				0.7	0.18		1	0.25		0.2	0.05		0.5	0.13
Total Score			Minimum		0.68			0.55			0.32			0.56
			Nominal		**0.79**			**0.63**			**0.42**			**0.64**
			Maximum		0.81			0.70			0.52			0.74
			Variance		**0.01**	Variance		**0.01**	Variance		**0.01**	Variance		**0.01**

Figure 25: User interface trade study

Choices Criteria			Java			Python			C++		
Requirements			Info		Does it s	Info		Y/N	Info		Y/N
Interact with sensors and read outputs			Requires additional hardware		Yes	Arduino library		Yes	Arduino based on C++		Yes
Read data from storage					Yes			Yes			Yes
Transfer data from storage					Yes			Yes			Yes
Able to write function					Yes			Yes			Yes
Wants	**WT**	**WT Rationale**	Info	Value	Score	Info	Value	Score	Info	Value	Score
Speed	0.2	An efficient and fast program will allow the UI to be more accessible and satisfying for users.		0.4	0.08		0.3	0.06		0.6	0.12
				0.5	0.10		0.4	0.08		0.7	0.14
				0.7	0.14		0.7	0.14		0.8	0.16
Ease of use	0.1	A language that is easier to learn and use is good and may lower development time, but avoiding having to learn a new language should be prioritized.		0.2	0.02		0.7	0.07		0.5	0.05
				0.4	0.04		0.7	0.07		0.5	0.05
				0.6	0.06		0.8	0.08		0.8	0.08
Familiarity	0.2	Utilizing a language that team members are proficient in will streamline the work process.		0.2	0.04		0.5	0.10		0.6	0.12
				0.3	0.06		0.6	0.12		0.8	0.16
				0.5	0.10		0.8	0.16		0.8	0.16
GUI accessibility	0.35	The ability to provide an intuitive and professional user interface and experience is the focal point of our project.		0.5	0.18		0.4	0.14		0.2	0.07
				0.6	0.21		0.6	0.21		0.4	0.14
				0.9	0.32		0.8	0.28		0.5	0.18
Data visualization	0.2	We want users to be able to view and understand their training results and data		0.2	0.04		0.6	0.12		0.4	0.08
				0.3	0.06		0.8	0.16		0.5	0.10
				0.4	0.08		0.9	0.18		0.6	0.12
Total Score			Minimum		0.4			0.5			0.4
			Nominal		**0.5**			**0.6**			**0.6**
			Maximum		0.7			0.8			0.7
			Variance		**0.0**	Variance		**0.0**	Variance		**0.0**

Figure 26: Programming language trade study

Choices Criteria	Virtual Reality		Music/Audio		Competition/Game		Reward System	
Requirements	Info	Does it sat	Info	Does it s	Info	Does it s	Info	Does it s
Improve Excersice Motivation	Could act as a sense of adventure, visually motivating	Yes	Serves as a motivator, elevates mood, could have a motivational voice speaking during excersice	Yes	Motivates to be better than either themselves or someone else, incentives	Yes	encouraging them to continue to excersice	Yes
Does not hinder excersice movement	Depends on the type of excersice or VR system(will not hinder movement if it is out of the way during the excersice)	Maybe	either being played out loud or with eaarbuds/headphones which are small enough to no get in the way	Yes	Is not a physical thing, should be a mental or visual game/competition.	Yes	Could be a mental, visual, or physical sets of rewards given after excersice. Would not interfere with movements	Yes
Improves mental Health	Can have visual stimuli which would improve mental health	Yes	Music has been know to directly affect mood, it can be encouraging and reduce anxiety	Yes	Making people feel better about their efforts, motivation, and enjoy life more (motivation)	Yes	Positive impact from increased motivation and morale	Yes

Wants	**WT**	**WT Rationale**	Virtual Reality	Value	Score	Music/Audio	Value	Score	Competition/Game	Value	Score	Reward System	Value	Score
Size	0.2	Size could get in the way of movement so it is the second highest ranked criteria		0.3	0.06		0.8	0.16		0.7	0.14		0.6	0.12
				0.4	0.08		0.85	0.17		0.85	0.17		0.75	0.15
				0.5	0.10		0.9	0.18		0.9	0.18		0.9	0.18
Durability	0.1	Durability should not be a big factor with the Choice criteria we have		0.4	0.04		0.8	0.08		0.8	0.08		0.8	0.06
				0.3	0.03		0.85	0.09		0.85	0.09		0.85	0.09
				0.5	0.05		0.9	0.09		0.9	0.09		0.9	0.09
Power Consumption	0.45	Power consumption is the biggest factor, since power is a very constrained resource on mars, especially since gammafication is an addon		0.1	0.05		0.7	0.32		0.5	0.23		0.5	0.23
				0.35	0.16		0.8	0.36		0.7	0.32		0.68	0.31
				0.6	0.27		0.85	0.38		0.8	0.36		0.8	0.36
Entertainment	0.25	Entertainment could act as a motivator, keep the astronaunt engaged		0.9	0.23		0.65	0.16		0.7	0.18		0.6	0.15
				0.9	0.23		0.8	0.20		0.8	0.20		0.75	0.19
				0.9	0.23		0.9	0.23		0.9	0.23		0.9	0.23
Total Score			Minimum		0.37			0.72			0.62			0.58
			Nominal		**0.49**			**0.82**			**0.77**			**0.73**
			Maximum		0.65			0.88			0.86			0.86
			Variance		**0.02**	Variance		**0.01**	Variance		**0.01**	Variance		**0.02**

Figure 27: Gamification trade study

C Risk Matrices and Fever Charts

C.1 Mission Risk

The mission risks can be found in the attached document.

Risk ID	Subsystem Risk ID	Risk Item Title	Risk Description	Impacted Areas	Technical/Cost/Schedule/Safety?	Accept/Watch/Mitigate?	Consequence	Likelihood	Risk Score	Justification	Mitigation Strategy	Consequence after Mitigation	Likelihood after Mitigation	Risk Score after Mitigation
1	ME-1	Magnetic system failure	If the permanent magnet housing fractures or malfunctions, the machine's ability to provide the intended resistance during exercises may be compromised.	Resistance mechanism	Technical	Mitigate	3	2	6	Less or no resistance is generated if the permanenet magnet housing does not function as intended.	Add structural reinforcements and redundancies to account for unanticipated mechanical loads (TBR).	3	1	2
2	ME-2	Insufficient Handle Friction	If the handle does not provide the user with sufficient grip (due to perspiration on hands, etc.), the handle could mechanically damage components due to a sudden release.	User Interface, resistance assembly	Technical	Mitigate	3	2	6	Depending on where the handle hits, the UI could suffer damaged and astronaut would lose access to user data.	Add extra grip to the handles or provide gloves with grip for user, add mechanical gaurds to the UI.	1	2	2
3	ME-3	User Interface Damage	If the user interface suffers operational damage, then the user will not be able to access performance data, hindering their ability to monitor progress and adjust workouts accordingly.	User Interface	Technical	Mitigate	3	2	6	Screen could burn out due to over use.	Screen replacement	1	2	2
4	ME-4	Magnetic interference with electronics	If stronger magnets interfere with the performance of crucial sensors and electronics, then accurate data collection and a smooth user interface are rendered unfeasible, impacting the overall functionality of the system.	Electronics	Technical	Mitigate	3	2	6	Magnetic fields can interfere with sensor functions.	Add shielding elements to the magnet assembly	3	1	3
5	ME-5	Forgotten Password	If a user forgets their passcode, then access to personalized settings and performance data is limited or lost.	Device Usability	Technical	Mitigate	3	3	9	The user may forget their password (human error).	Add a forgot your password feature	1	3	3
6	ME-6	Dial for magnet	If the geared resistance shifter mechanism breaks then the user will not be able to perform some exercises successfully.	Resistance mechanism, EVA fitness	Technical	Mitigate	2	1	2	The shifter could suffer mechanical damage or mishandling.	Reduandant shifters	1	1	1
7	ME-7	Stoppers break	If the seat roll stoppers become damaged or altered, they could fail to stop the seat's motion, limiting the machine's usability for specific exercises requiring a stationary seat.	EVA fitness	Technical	Mitigate	3	2	6	Being unable to perform some of the intended exercises would significantly disrupt the users' planned exercise routines.	Add redundancy to stopping mechanism by additional stoppers and/or another mechanism	1	1	1
8	PW-1	Too much voltage	If too much voltage is applied across any component, then it will overheat, risking damage to the equipment and potential safety hazards.	Sensors, arduino, electronics	Technical	Mitigate	3	2	6	Heat dissipation due to electricity can lead to premature component failure.	Include voltage regulators in the design	3	1	3
9	PW-2	Power failure	If there is a power failure, the sensors and user interfaces will fail to collect, calculate and store performance metrics..	Performance metrics	Technical	Mitigate	3	1	3	Power supply to the sensors and software system fails, but the user can exercise since the resistance system is not electronically powered.	Backup battery/ generator	2	1	2
10	PW-4	Damage to wiring	If an astronaut or moving part breaks a wire, then power and data signals could be lost, impacting the functionality of the system.	Sensors, arduinos, other compute devices, and the User Interface	Technical	Mitigate	4	2	8	Wire breakage will cause circuits to fail, resulting in loss of data collection and/or failure of device operation all together	Carefully placing wires out of the way of astranauts and moving parts	4	1	4
11	SE-1	Arduino liquid exposure	If the astronaut drinks water while exercising, potential liquid spillage can damage the Arduino Nano, leading to equipment failure.	Pulse system functionality	Technical	Mitigate	4	3	12	If entire arduino nano shuts down then all data is lost and arduino is damaged.	Use waterproof cover or enclosure for electrical system	4	1	4
12	SE-2	Pulse sensor liquid exposure	If the astronaut drinks water or sweats while exercising, potential liquid spillage can reduce resistance and accuracy of pulse readings, affecting the effectiveness of the workout.	Performance metrics	Technical	Mitigate	3	4	12	If sensor gets too wet then inaccurate pulse and blood oxygen readings will poor health monitoring system. However this will be overcome once the sensor dries out and will not damage it.	Use biocompatible material for sensor enclosure in the wearable	3	2	6
13	SE-3	Pulse sensor light exposure	If the sensor is exposed to light beyond (TBR exposure), sensor could suffer damage and measure data inaccurately.	Performance metrics	Technical	Mitigate	3	4	12	If there is external light not from the skin shining on the sensor then our readings will not be accurate due to interference of light with sensor functionality	Wearable sensor lights must only be adapted to be exposed to user's skin.	3	1	3
14	SE-4	heartbeat / VO2 sensor gets physically damaged by user	If the user handles the heartbeat sensor improperly, then it could suffer permanenet damage, affecting the accuracy of heart rate measurements.	Performance metrics	Technical	Mitigate	3	2	6	If the sensor sustains physical damage, heartbeat data will no longer be collected	Design a protective case for the sensor	2	1	2

Risk ID	Subsystem Risk ID	Risk Item Title	Risk Description	Impacted Areas	Technical/Cost/Schedule/Safety?	Accept/Watch/Mitigate?	Consequence	Likelihood	Risk Score	Justification	Mitigation Strategy	Consequence after Mitigation	Likelihood after Mitigation	Risk Score after Mitigation
15	SO-1	Running out of Storage	If storage runs out of space, then future exercise metrics will not be stored.	Loss of Future Data	Technical	Mitigate	4	1	4	Depending on how many astronauts are logging daily data for x years, storage may be finite	Warning user when avaliable data is low for replacement with a new chip	2	1	2
16	SO-2	Radiation Bit Flip	If a bit flip occurs, the software could be altered, leading to potential system errors or malfunctions.	Loss of Functionality	Technical	Accept	3	1	3	Bit flip can ruin any and all code or storage, but has low likelihood of impacting anything important	None	3	1	3
17	SO-3	Security Breach	If an unauthorized personnel accesses the data, then crew privacy and security is compromised.	User Data	Safety	Mitigate	3	2	6	Leaking medical information about users violates HIPAA	Cyber security, dual authentication implementation	3	1	3
18	SO-4	Data Processing Inaccuracy Failure	If the software doesn't read data from the sensors correctly, then users could receive inaccurate information, leading to potentially incorrect exercise decisions.	Loss of Data	Technical	Mitigate	2	2	4	buggy code	Thorough test case implementation	1	1	1

Mission Risks

Fever Chart - Before Mitigation

Estimated Likelihood	Negligible	Minor	Moderate	Critical	Catastrophic
80%-100%					
60%-80%			12,13		
40%-60%			5	11	
20%-40%		18	1,2,3,4,7,8,14,17	10	
0%-20%		6	9,16	15	

Consequence

Fever Chart - After Mitigation

Estimated Likelihood	Negligible	Minor	Moderate	Critical	Catastrophic
80%-100%					
60%-80%					
40%-60%	5				
20%-40%	2,3		12		
0%-20%	1,6,7,18	9,14,15	4,8,13,16,17	10,11	

Consequence

Figure 28: Mission risk fever chart

C.2 Human Risk

The human risks can be found in the attached document.

Risk ID	Subsystem Risk ID	Risk Item Title	Risk Description	Impacted Areas	Technical/Cost/Schedule/Safety?	Accept/ Watch/ Mitigate ?	Consequence	Likelihood	Risk Score	Justification	Mitigation Strategy	Consequence after Mitigation	Likelihood after Mitigation	Risk Score after Mitigation
1	ME-1	Seat stoppers failure	If the stoppers preventing seat movement are improperly inserted, then during lateral flies exercise, the seat could slip forward, potentially causing the user to fall or injure themselves with the handle.	User, mechanical seat assembly	Technical, Safety	Mitigate	3	2	6	Doorstop-like design should cause the stoppers to be pushed in more securely as the user begins exercise, so an installation that causes this problem should be unlikely.	Make the stopper with a brightly-colored line, marking how far the stopper should be inserted under the rollers.	3	1	3
2	ME-2	Improper form	If the user fails to maintain proper form during the retraction motion in cardio rowing, then there's a risk of slipping off the equipment and sustaining injuries.	User, mechanical assembly	Technical, Safety	Mitigate	3	3	9	When using the rower for purely cardio, if there is too much force from the user the inertia could result in the seat sliding out from under the user. The likelihood of this would be even higher on Mars due to lesser gravity	Train the user on how to properly use a rower in order to lower the risk. Also, mark where to sit in the seat to prevent the user from slipping out	3	1	3
3	ME-3	Footrest friction failure	If the footrest plate lacks sufficient texture for traction during leg press, then there's a risk of the user's feet slipping off during the exercise.	User	Safety	Mitigate	2	2	4	Since the user's feet aren't strapped into place during the leg press exercise, the foot place must be texturized to mitigate slippage. Risk of slipping off is low because footplate is large.	Texturize the footrest to or add rubber traction pad to provide ample traction such that the user's feet are firmly held in place during leg press	2	1	2
4	ME-4	Pin Lock Fault	If the user inadequately inserts the pin while performing flies in the horizontal position, causing the seat to rapidly rotate towards the cable, there's a risk of injury to the user's legs and disruption of the exercise.	Seat	Technical, Safety	Mitigate	4	2	8	If the pin is not inserted all the way while performing lateral flies in a horizontal orientation, the seat will kick back and rotate back to the default alignment and injure the user as well as interrupting the workout.	Instruct the user to insert the pins in completely. Also, mark a red ring around the pin and instrcut the user that if the red mark is visible then the pin has not been inserted completely.	4	1	4
5	ME-5	Handle brake attachment failure	If the attachment designed to prevent the leg press from moving too close to the front of the machine breaks, then the seat may move too far forward, potentially constricting the astronaut's body.	User convenience	Technical, Safety	Mitigate	3	2	6	Injury could occur from legs being bent too far inward when it doesn't stop. You can either harm your legs, or whatever other part of your body your legs impact with.	Inclusion in astronaut training	3	1	3
6	ME-6	Tether malfunction	If the tether connecting the handle to the magnet wheel breaks during motion, there's a risk that the user may experience discomfort or injury due to a sudden change in resistance.	User, mechanical assembly	Safety	Mitigate	4	2	8	This risk is easy to mitigate. We need to ensure that our connection tether is strong enough and resistant enough to wear for an extended period of time. The tether needs to be able to handle significant loads if we want it to be used for leg press.	Implement a steel wired cable that is coated in nylon (the standard practice for weightlifting), add replacement cables	4	1	4
7	SE-1	Sensor overheating	If wearable electronic devices exceed 43 degrees Celsius, there's a risk of damaging human skin.	Crew health, Unsafe bodily exposure	safety	Mitigate	4	2	8	component overheating can cause 2nd degree burns - https://www.comsol.com/blogs/design-safe-wearable-technology-with-heat-transfer-modeling/#:~:text=The%20standards%20outline%20the%20maximum,device%20as%20over%20ten%20minutes	Add voltage regulators to keep sensors from overheating	1	2	2

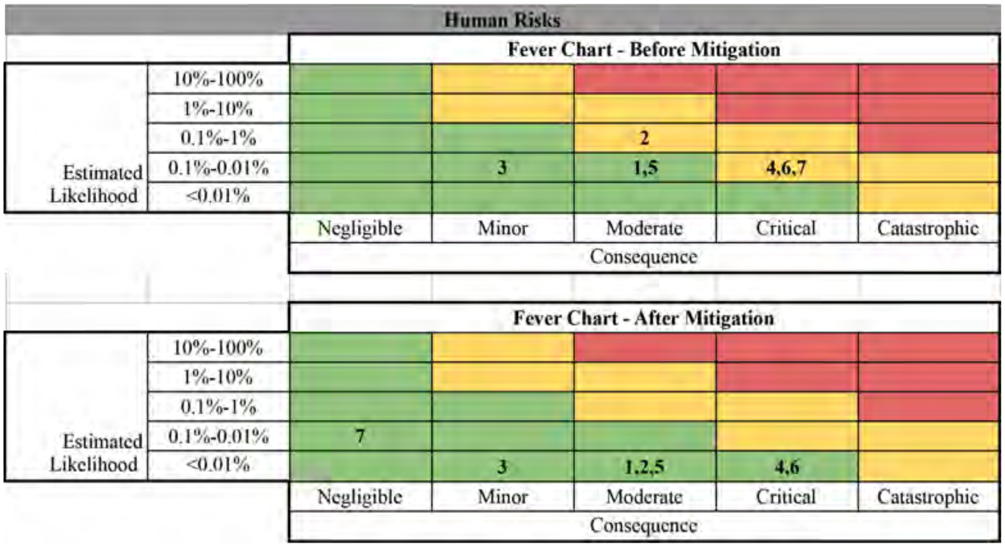


Figure 29: Human risk fever chart

D User Guide

The User Guide for the device can be found in the attached document.

Mars Human Health and Performance Monitoring System (M-HHaPS) User Guide

Introduction

Welcome to the Mars Human Health and Performance Monitoring System (M-HHaPS)! This is your tool to remain fit enough for regular Extravehicular Activity (EVA) during your time on Mars. Before you begin, please take a moment to review the information presented in this user guide, both for your safety and the safety of the device.

Safety

While this device has been designed with safety in mind, there are some behaviors that may increase your risk of injury and should be avoided. These include but are not limited to the following:

1. Loose articles and hair
    a. Keep loose articles and hair secure at all times to avoid them getting stuck in the machine. This can damage the machine and reduce the validity of the exercise metrics. Can also cause severe injury.
2. Cardio Rowing:
    a. Failure to maintain proper form while performing retraction during cardio rowing may lead to the seat slipping and subsequent injury.
    b. Ensure that the seat is in the correct position for your height
    c. While cardio rowing, take care to avoid using excessive force while pulling so that the seat does not slide out.
    d. Sit down at the appropriate position based on your height to avoid falling off the seat.
3. Leg Press:
    a. During leg press, take care to secure feet to the footrest using the provided loops in order to avoid injury due to feet slipping off while pressing.
    b. Avoid full lockout of your legs to reduce the risk of knee injury.
4. Pin Lock for Arm Fly Exercises:
    a. Ensure that the pin is secured into the appropriate hole prior to performing arm fly exercises. If the pin is not secured, then there is a risk of the seat wiggling during the movement, which can cause significant leg injury and disruption of the exercise.
    b. Insert the pin completely and fully attach the pin head.
5. Backrest Attachment:

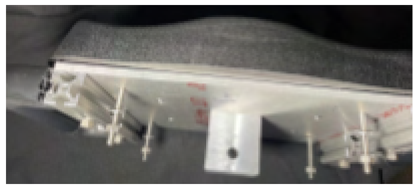
a. For applicable exercises, ensure the backrest is securely attached to the seat, and the stabilizer bar is properly installed. If these components are not properly secured, and detach during exercise, there is a risk of injury to the user.

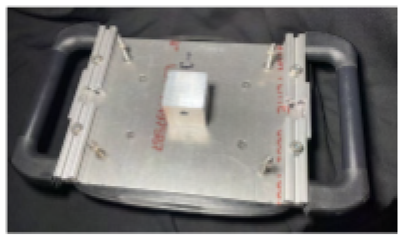
Components

Seat (Top):

Side

Front

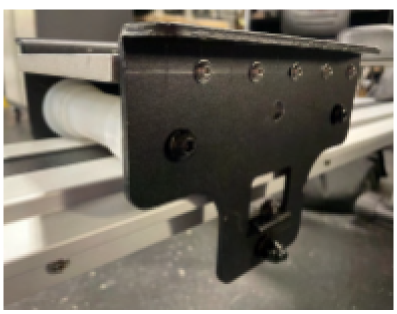




Bottom

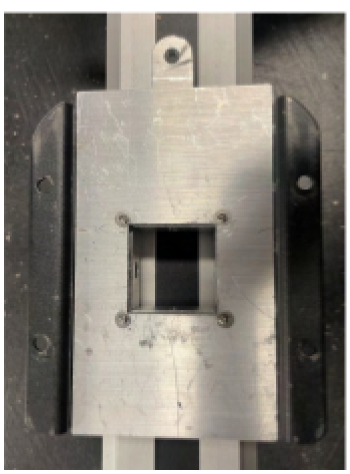
Top

Seat (Bottom):



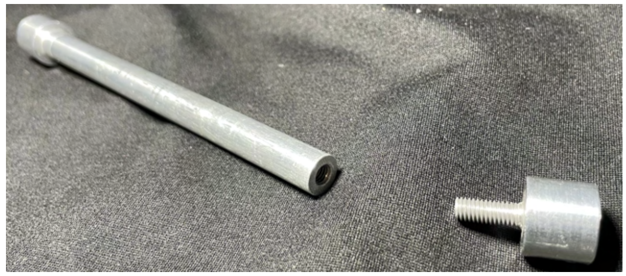
Back-Right

Side

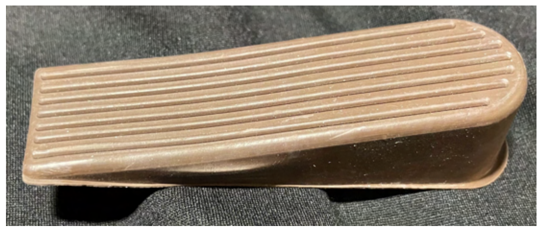


Top

Seat Pin:



Doorstops:



Backrest:

Back

Front

Stabilizer Bar:

Front Side Back

Handle Attachments:

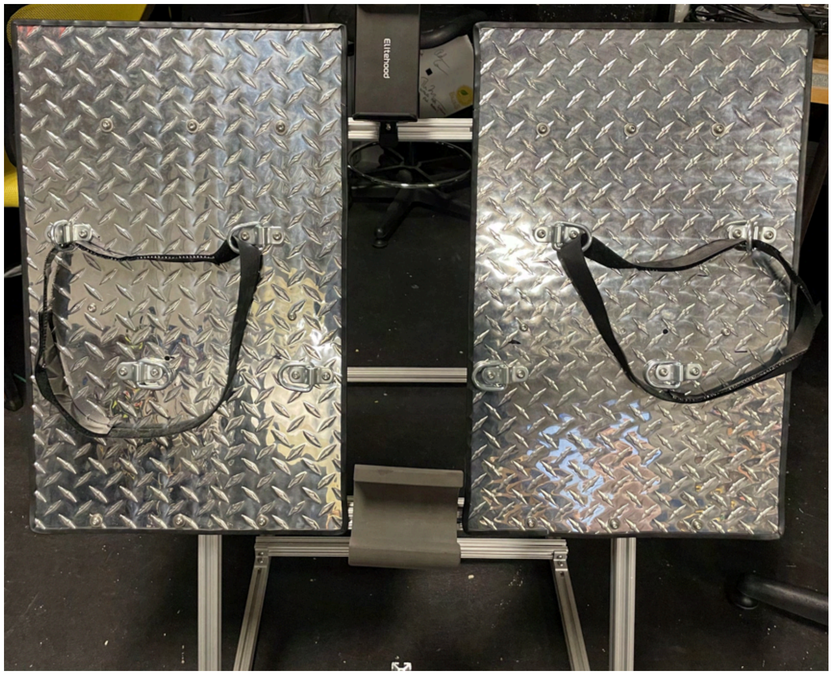
Seated Row Handle

Row Handle 1

Arm Fly Exercise Handle

Row Handle 2

Footplate:



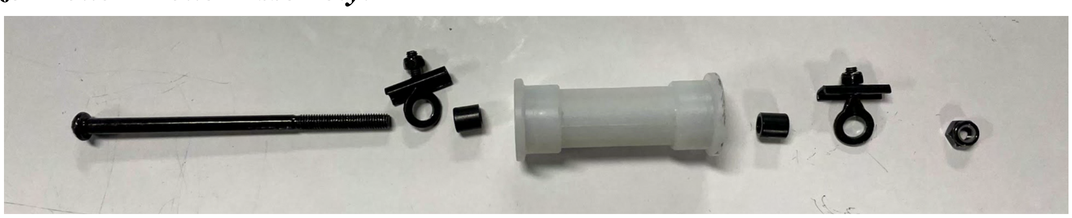
Magnet Housing:

Pin

Magnet Bar

Magnet Housing Assembly

Stabilizer Bottom Roller Assembly:



Installation

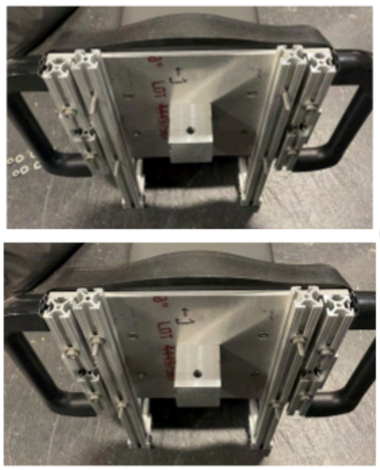
Backrest

- Installation
    1) Pull out the orientation-locking pin underneath the seat, and remove the seat from the rowing machine by lifting it up and off of the rolling base.
    2) Lay out the backrest on a flat surface with the front of the backrest (cushion) pointing up.
    3) Place the seat over the shorter metal bars, which are pointing up. Line up the four bolts sticking out of the bottom of the seat, with the four holes in the bars. Ensure the seat is facing the correct direction – the “front” should be pointing upwards.
    4) Insert the bolts through the holes, and secure them in place using ¼”-20 nuts.
    5) Lift the entire seat/backrest assembly, and place it back into the rolling base on the exercise machine. Ensure its orientation is correct for the next exercise that will be performed.
    6) Insert the orientation-locking pin underneath the seat, to lock it in place.
    7) Place the stabilizer bar on the track of the exercise machine, behind the seat. Roll it forward, so the screws on the back of the backrest align with the brackets in the stabilizer bar.
    8) Use size 8-32 nuts to attach the backrest and stabilizer.
    9) Insert the stabilizer bottom roller assembly into the corresponding hole below the stabilizer bar and below the rower seat track. Secure this assembly in place by tightening the assembly’s central bolt with an allen key and adjustable wrench. It is also important to tighten the nuts that hold this roller against the bottom of the rower seat track using the adjustable wrench.

(1)

(2)

(3)



(4)

(5)

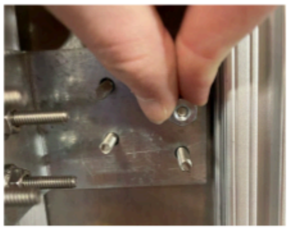
(6)

(7)

(8)

(9)

- Removal
    1) Unscrew the nuts attaching the stabilizer bar to the backrest.
        a) For easy storage, it is recommended that these nuts be screwed back onto their respective screws.
    2) Remove the stabilizer bottom roller assembly by loosening its central bolt using an allen key and adjustable wrench.
    3) Lift the stabilizer bar off of the exercise machine's track, and set it aside.
    4) Remove the orientation-locking pin underneath the seat.
    5) Lift the seat, and attached backrest, off of the exercise machine.
    6) Place the seat assembly on a flat surface, with the backrest metal plate against the surface, the backrest pad facing up, and the front of the seat pointing upwards.
    7) Unscrew the nuts connecting the bottom of the seat to the backrest's connector bars.
        a) For easy storage, it is recommended that these nuts and washers be screwed back onto their respective screws.
    8) Pull the seat off of the backrest's connector bars. Set aside the backrest assembly.
    9) Place the seat on its rolling base on the exercise machine, in the correct orientation for the next exercise that will be performed.
    10) Reinsert the orientation-locking pin under the seat.

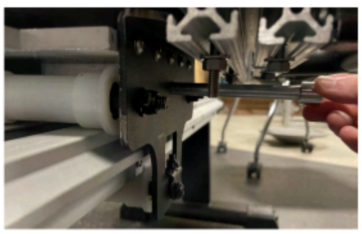
(1)


(1a)


(2)

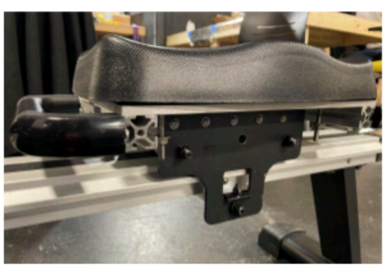


(3)


(4)

(6)

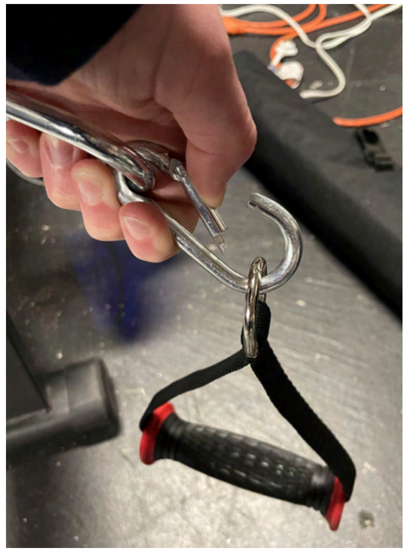

(7a)


(9)



(10)

Handles

- Installation (same for all handle attachments)
    - Attach via carabiner

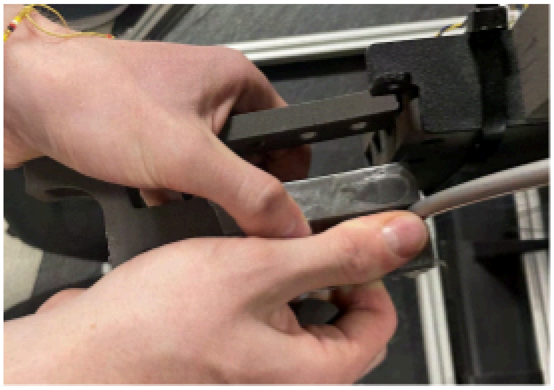


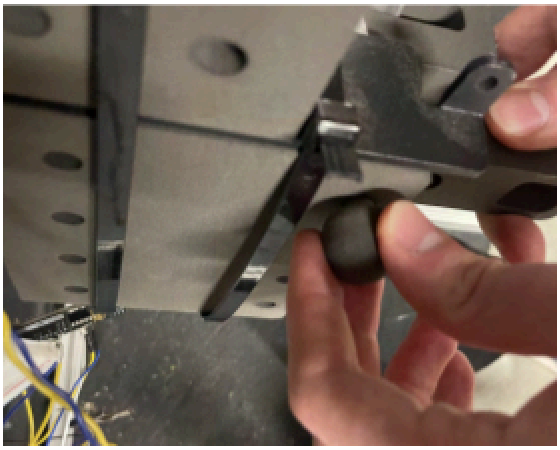
- Removal (same for all handle attachments)
    - Detach via carabiner

Magnet housing

Increase resistance by inserting a new magnet bar or adjusting one that is already installed in the magnet housing. Decrease resistance by removing or adjusting a magnet bar that is already installed in the magnet housing.

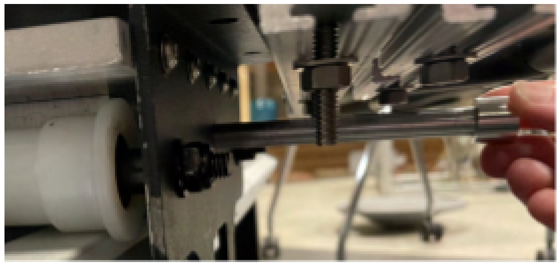
- Installing magnet bar
    1) Insert magnet bar into magnet housing with magnetic legs on either side of the flywheel and the leg with holes inside the magnet housing
        a) You may have to hold the legs outwards in order to fit them around the flywheel
    2) Insert pin to secure magnet bar in desired location
- Removing magnet bar
    1) Remove pin securing magnet bar
    2) Slide magnet bar out of magnet housing
- Adjusting magnet bar
    1) Remove pin securing magnet bar
    2) Move magnet bar further onto wheel to increase resistance or further off of wheel to decrease resistance
    3) Insert pin to secure magnet bar in desired location





Seat

- Rotation
    1) Remove the orientation-locking pin from beneath the seat
    2) Lift the seat off of the bottom seat roller
    3) Rotate the seat by a multiple of 90-degrees (90, 180, 270, or 360)
    4) Set the seat back down on the bottom seat roller and ensure that you feel the seat cube slides down into its sleeve
    5) Replace the orientation-locking pin.



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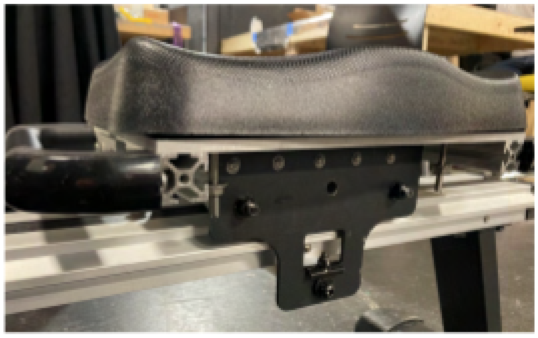
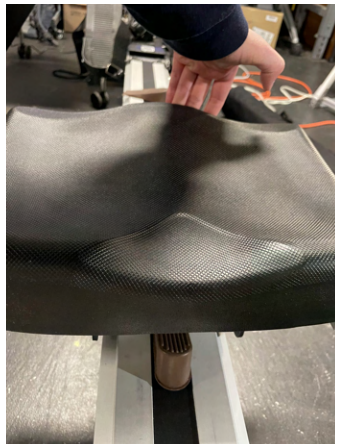


(2, 3, 4)

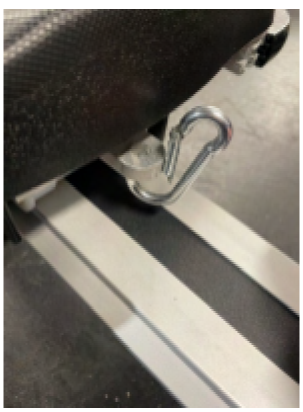
(5)

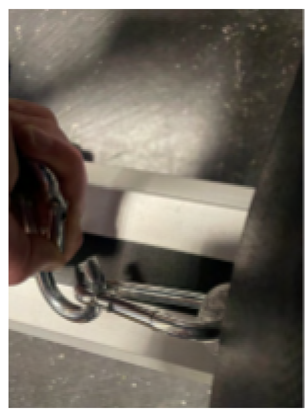
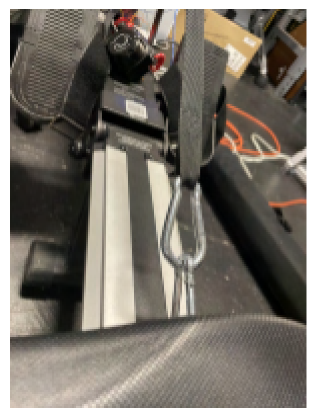
- Stoppers
    1) Place one stopper centered on the top of the exercise machine's track, and behind the seat.
    2) Roll the seat backwards as far as it will go, so the stopper "wedges" under its back roller, like a doorstop.
    3) "Wedge" another stopper in front of the front roller, in the same way.
    4) Before performing any exercise, manually attempt to push the seat forwards and backwards, to ensure the stoppers are properly installed


Seat Carabiner

- Installation
    1) Clip smaller carabiner into hole on front of seat roller
    2) Clip larger carabiner (already attached to cable) onto smaller carabiner



- Removal
    1) Unclip larger carabiner from smaller carabiner
    2) Unclip smaller carabiner from hole on front of seat roller

Use

Electronic User Interface

New Account. To create a new account, the user must select the available **Sign Up** button. A random 4-digit code will be presented to the user. If the user wants a new code, another random code can be generated by pressing the **Refresh** button. Once the code is to the user's liking, they must press the **Confirm** button. This will direct them back to the initial screen to log in. This code will represent the user for all future workouts; the user must remember this code to access all previous data for workouts.

Login. The user is presented with a login screen. They must enter their unique four-digit combination previously assigned to them, and proceed by clicking the **Login** button. After logging in, there will be a screen presented with three buttons: **History**, **Workout**, and **Diagnostic**.

History. To view workout history and trends, click the **History** button available after logging in. After clicking this button, there will be a screen of three buttons: **Daily History**, **Monthly History**, and **All Time History**.

Daily History. To view daily workout history and trends, click the **Daily History** button. A list of sessions organized by dates should be displayed. Each session can be selected to see the average heart rate, VO2 max, number of reps, and force for each exercise in the session. A graph showing the progression of each of these over the course of the individual workout is available by clicking on the **Trend** button, and selecting the desired measurement. To leave any of these screens and return to the previous screen click the **Back** button.

Monthly History. To view monthly workout history and trends, click the **Monthly History** button. A list of months organized chronologically should be displayed. Each month can be selected to see the average heart rate, VO2 max, number of reps, and force for each exercise over the course of the month. A graph showing the progression of each of these during monthly use is available by clicking on the **Trend** button, and selecting the desired measurement. To leave any of these screens and return to the previous screen click the **Back** button.

All Time History. To view the user's complete workout history and trends, click the **All Time History** button. A table showing the overall average heart rate, VO2 max, number of reps, and force for each exercise will appear. A graph showing the progression of each of these throughout the user's time using the machine is available by clicking on the

Trend button, and selecting the desired measurement. To leave any of these screens and return to the previous screen click the **Back** button.

Workout. To begin a workout, click the **Workout** button available after logging in. The user will automatically be directed to the rowing workout, with a 45-minute timer counting down to the end of the workout. During the workout, a table showing the user's heart rate, VO2 max, number of reps, and force will constantly update. Once 45 minutes have been completed (recommended time for cardio) the timer will switch colors. To end the rowing exercise, select the **End Rowing** button at the bottom.

Users will then be directed to a screen with the option to choose any other workout. The timer will remain in the corner as a reminder, but will not increase in time until a workout is selected. The user has the option to select between the **Leg Press**, **Calf Raises**, **Chest Fly**, **Bicep Curl**, **Hand Squeeze**, and **Rowing** buttons. Each of these will take them to a screen with a table showing the user's heart rate, VO2 max, number of reps, and force for the respective exercise, which will constantly update. Once a total of 2 hours has been completed (recommended time for total workout) the timer will switch colors. To exit and switch to a different exercise, select the exercise's respective **End [type of workout]** button in the bottom right corner of the screen.

To pause the workout at any time, select the pause button. Once paused, to end the workout, select **End Workout** or to continue, select **Continue**. An additional button exists on the "Choose Workout" page labeled **End**, which will allow the user to end the workout completely.

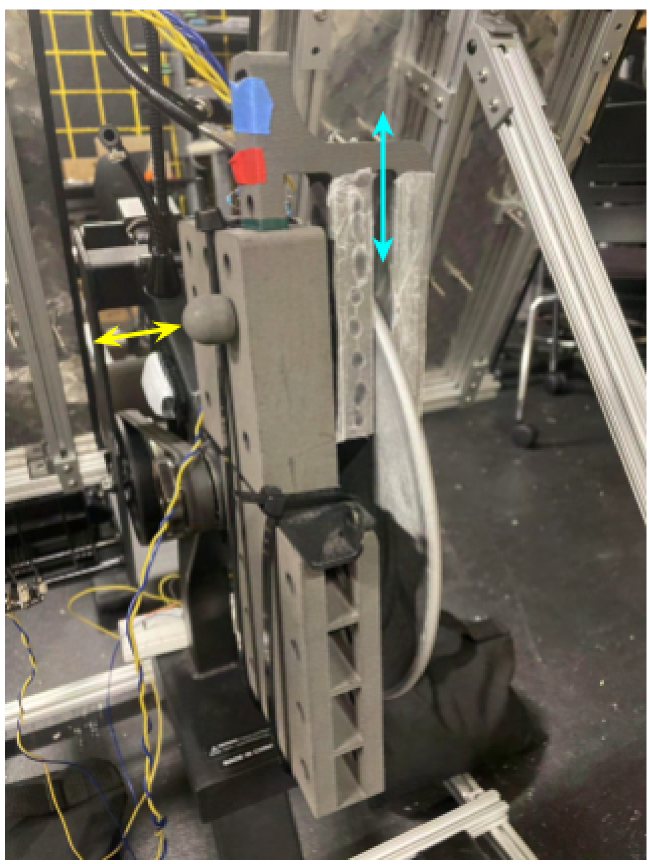
Diagnostic. To run system diagnostics, click the **Diagnostic** button available after logging in. A display showing the status of individual fault detections will appear. To leave this screen, click the **Back** button.

Sensors Setup

The sensor on the wearable device must be snugly touching the user's skin on the underside of the wrist. The color sensor must be facing the colored tape on the magnet racks. Proper illumination is required to ensure accurate color readings.

Resistance Adjustment

The user will adjust the resistance by utilizing the magnetic housing, magnet racks and pins. Adjust the magnet rack location by taking the pin out (yellow arrow), moving the rack to where you want it to be (blue arrow), and putting the pin back in (yellow arrow). To increase resistance, increase the surface area of the magnet racks on the wheel. To decrease resistance, decrease the surface area of the magnet racks on the wheel.



Based on current data collection, each pair of magnets that is on the surface area of the wheel correlates to a 9.5lb increase in resistance. Magnet racks can also be removed completely for 0 additional resistance.

With the tension of the rower at max level (8), the base resistance without any additional magnets is approximately 25lb.

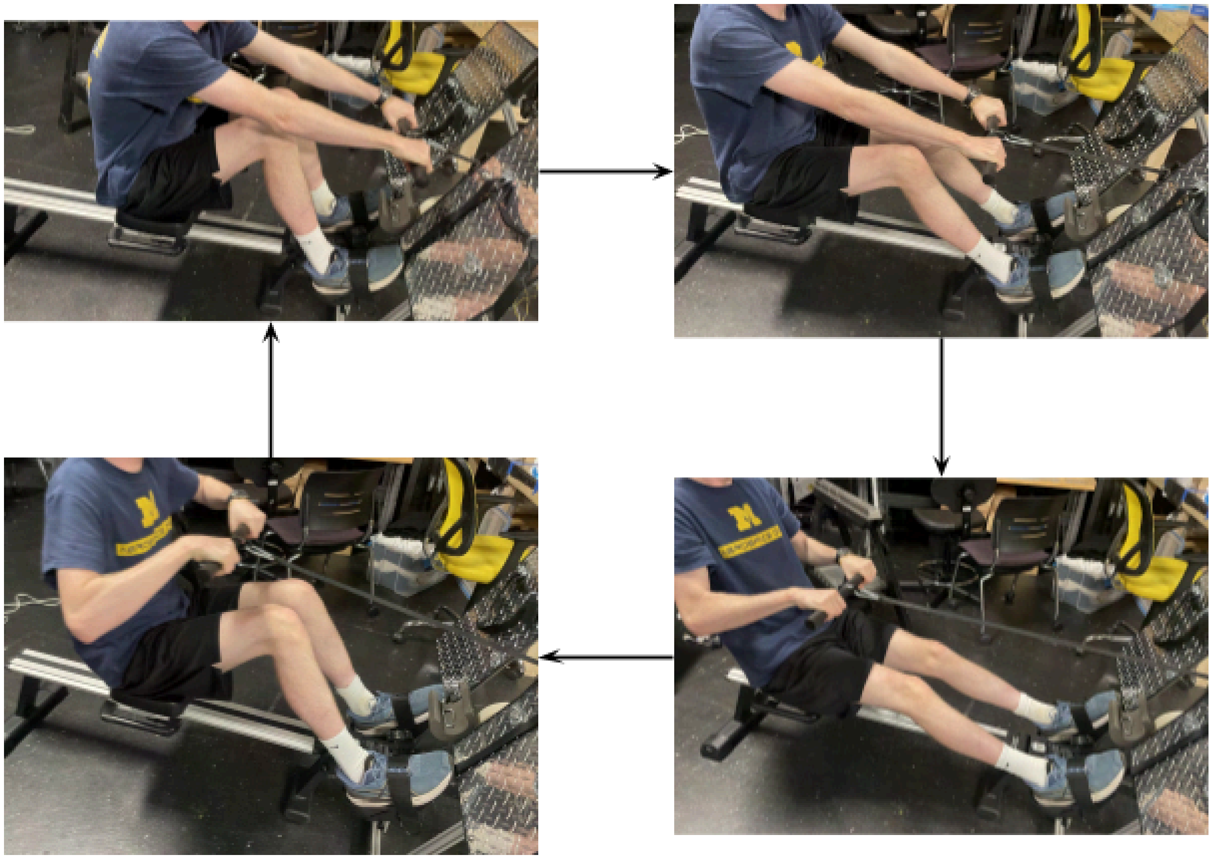
*****Very rough estimates, for a healthy and fit individual such as an astronaut**
Rowing Exercise: 80-200lb (6 pairs of magnets - 16 pairs of magnets)

Leg Press Exercise:	100 - 300lb (8 pairs of magnets - 27 pairs of magnets)
Delt Fly:	10 - 40lb (0 pairs - 2 pairs of magnets)
Chest Fly:	20 - 100lb (0 pairs - 8 pairs of magnets)
Lat/Seated Row:	130 - 250lb (11 pairs - 22 pairs of magnets)
Bicep Curl:	5 - 40lb (0 pairs - 2 pairs of magnets)
Tricep Kickbacks:	10 - 50 lb (0 pairs - 3 pairs of magnets)

Rowing Exercise
Configuration: Seat facing forwards, no backrest, cable attached to rowing handle, no stoppers.

Use: To perform this exercise the user must ensure the carabiner is attached to the rowing handle, and not the seat. No backrest should be installed, and the stoppers should not be used so the seat is free to move. Feet should be strapped into the smaller rowing footrests on either side of the machine, and now on the larger footrest plate.

Risk Mitigations: In order to mitigate risks, feet should be positioned on either side of the machine in the strapable rowing footrests. Feet should then be strapped into a close-fitting adjustment. The user should be comfortably seated in the center of the seat. When holding the rowing handle, the user should have hands fully wrapped around either side of the handle, and they should be symmetrically placed so that when the user rows back, the weight is evenly distributed between both grips. To perform the rowing exercise, the user should begin with their legs bent and the seat at the front of the rower. The user should then use their legs to push their body backward, use the handles to pull the handle to their chest while leaning back, then allow the arms to return to the neutral position and bring their legs back in, so the seat returns to the initial position at the front of the rower.

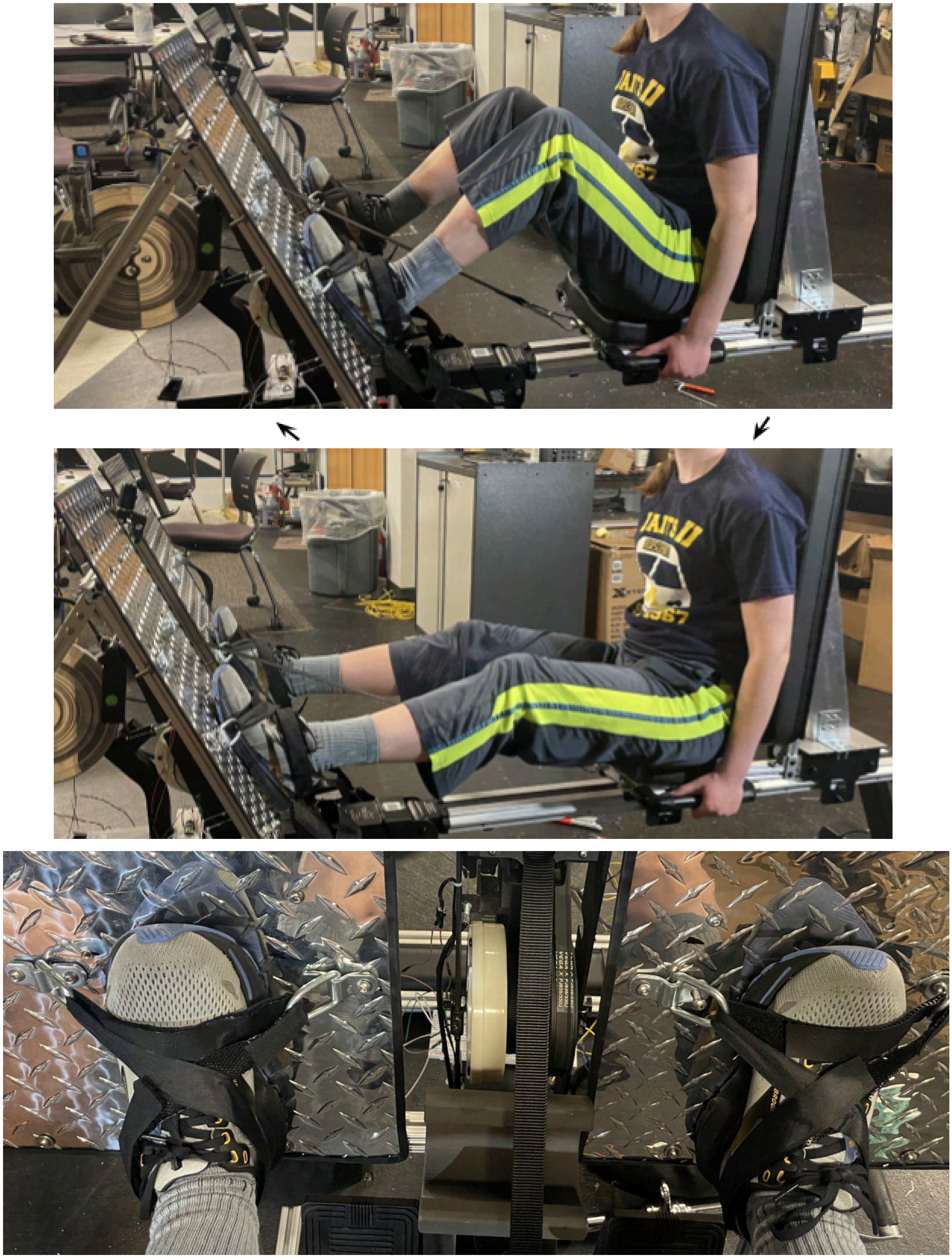


Leg Press Exercise

Configuration: Seat facing forwards, backrest installed, cable attached to seat base, no stoppers.

Use: To perform this exercise, the user should ensure that the backrest is properly installed to the back of the seat on the rower. The cable should be attached to the base of the seat by attaching the carabiner to the loop protruding from the front of the seat. The user should place feet on either side of the larger footrest plate, roughly shoulder width apart. Users may want to hold the handles on either side of the seat. Using their legs, the user should then push out against the footrests at their chosen resistance. They should straighten their legs until a little before full extension, they should not lock their knees. They should hold this extended position for three seconds, and then slowly return to the starting position.

Risk Mitigation: To properly perform this exercise the user should position their feet flat and completely on their respective sides of the machine's leg press footrests. The user should sit centered on the seat and ensure the machine's resistance is equally distributed between both legs as they push against the footplates to straighten their legs, stopping a little before complete leg extension. The user must not lock their knees during this exercise. They should then bend their legs slowly back into the original position before continuing or finishing the work out.

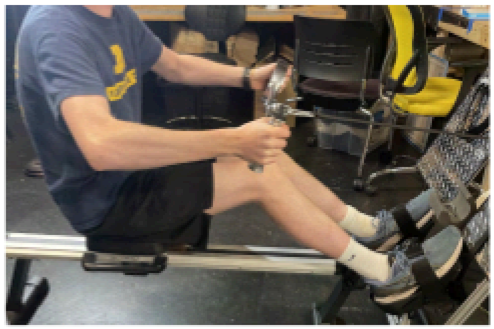


Chest Fly
Configuration: Seat pushed to the front of the machine. Stoppers installed in front of and behind the seat. Attach a single handle attachment to the carabiner. Backrest not attached to the seat.

Use: Holding the handle with the right hand, stand on the right side of the machine. Face perpendicular to the flywheel while looking towards the seat. While keeping your arm outstretched, pull towards the opposite shoulder (in this case to the left shoulder). To exercise the other pectoral, stand on the other side of the machine, hold the handle with the other hand, and pull towards the opposite shoulder.

Seated Row
Configuration: Seat set up, facing forward, at a distance where the user can comfortably fit their feet in the strapped footrests with a slight bend at the knees. Stoppers installed in front of and behind the seat. Attach carabiner to double handle attachment.

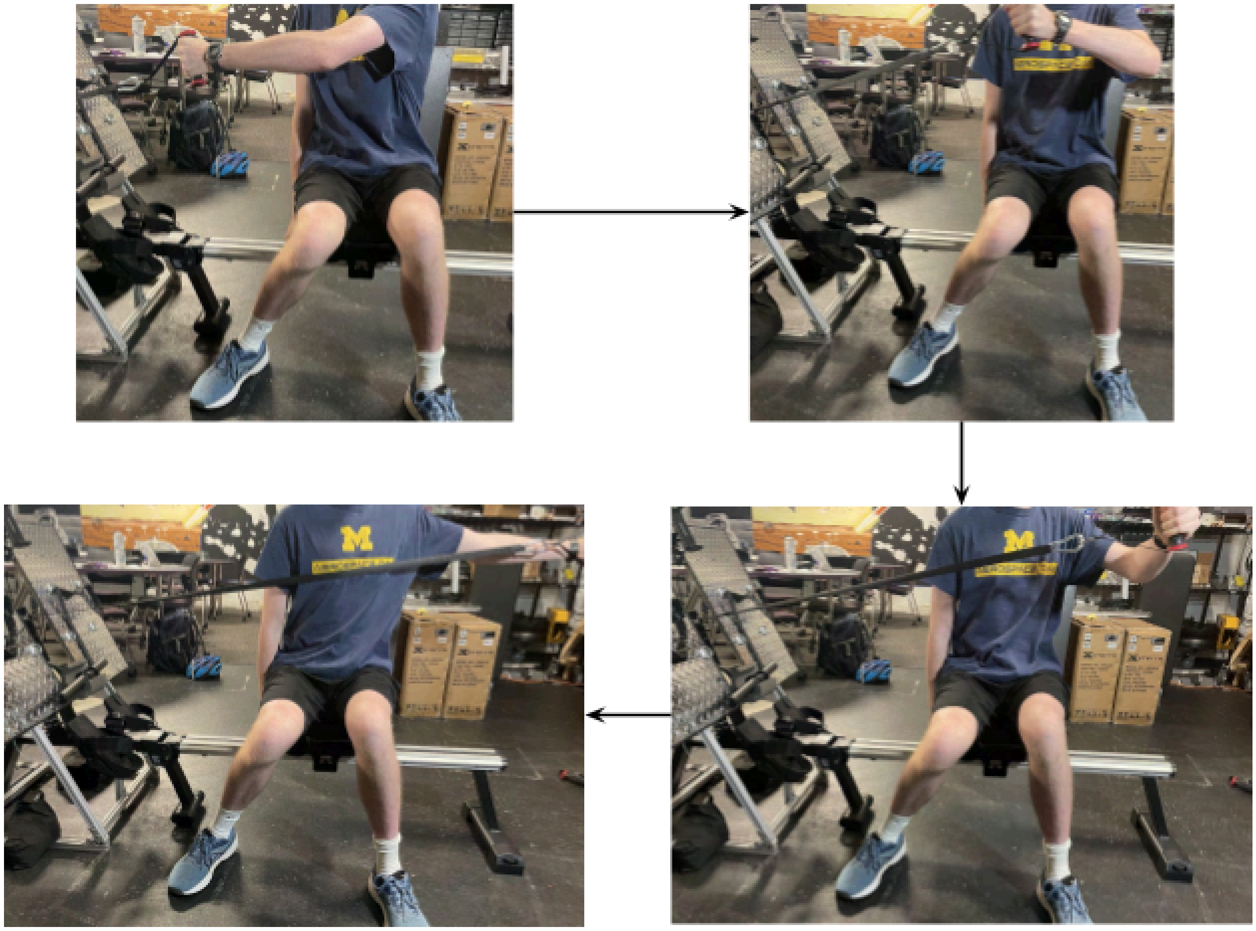
Use: To perform the seated row, attach the triangle bar to the cable using the carabiner. Wedge the door stops into the wheels of the seat, resting the stops on the track of the rower. The desired positioning of the seat should be where the feet can rest on the velcro footrests and where the legs can comfortably bend. The leg positioning should be the same as when performing the rowing exercises. When ready to perform the exercise, pull the bar toward the body while maintaining good posture. The back should still be straight with the shoulders retracted back. The motion of the exercise includes the pulling of the bar to the chest and then straightening the arms repeated several times.



Delt Fly

Configuration: Seat pushed to the front of the machine. Stoppers installed in front of and behind the seat. Detach the carabiner from the seat and attach a single handle attachment to the carabiner. Backrest not attached to the seat.

Use: Sit on the seat with feet firmly on the floor. Hold the handle with the hand farthest from the cable. Arm should be placed straight in front. With outstretched arms with a slight bend at the elbow, pull the handle with straight arms until arms are in line with the torso. At the end of the motion, the user should have created a 90 degree angle between the user's torso and outstretched arm.



Bicep Curl

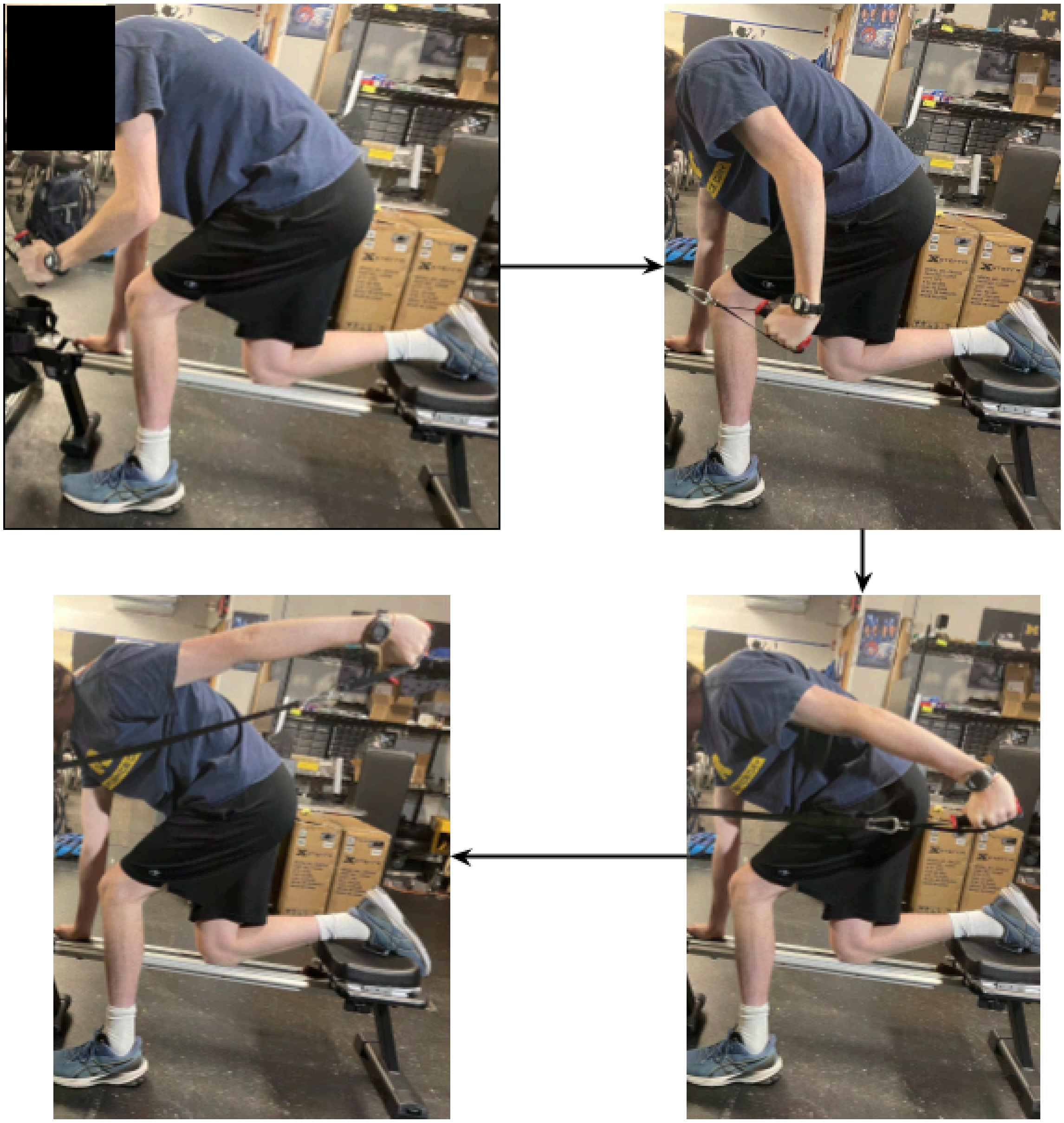
Configuration: Seat facing forward leg-length from the front of the machine. Install stoppers on front and back of the seat Attach single-hand handle to cable via carabiner.

Use: Sit on seat and secure feet to footrest using Velcro. Holding the handle in one hand, lean back until the back is parallel to the ground. Fully extend arm holding handle toward feet, then curl up until bicep is fully contracted. Extend arm again to begin another repetition.

Tricep Kickbacks

Configuration: Seat pushed to the front of the machine. No backrest. Stoppers installed in front of and behind the seat. Carabiner attached to (which handle?). Stand facing towards the handle.

Use: One leg kneels on the seat while another leg stands on the ground. Bend forward slightly at the waist so the torso is almost parallel to the floor. Keep the head, neck, and spine in one line. Place one hand (the same side as the kneeling leg) on the seat for support. Grab the handle using another hand and bring the elbow up, so that the upper arms are parallel to the floor. Kick back the lower arm until the arm is fully extended while keeping the arm tight by the side of the body. Slowly lower the handle to the starting position. Repeat.



Hand Squeeze

Configuration: Take both hand dynamometers out of the rowing machine's pocket. If the user prefers, they can perform this exercise sitting anywhere, including on the rowing machine seat. If they are sitting on the rowing machine seat, they should install the stoppers so the seat does not move unexpectedly. The user can also install the backrest if they prefer.

Use: Hold the dynamometers in the hands, with the arm at a right angle to the body. Ensure that the base rests on the heel of the palm while the handle rests on the middle of the four fingers. Then, squeeze the hand dynamometers. Users can use the hand dynamometers anywhere they feel comfortable. They do not have to be sitting on the rower. However, if they do choose to perform the exercise while sitting on the rowing machine, they need to make sure that the stopper of the seat is in place so that the seat remains still.

Maintenance

Some components of your M-HHaPS may be lost or degrade over time. Due to this, we have included with your M-HHaPS several spare components:

- 8-32 nuts for attaching backrest to seat and stabilizer bar to backrest (Quantity: 50)
    - These nuts are small and may be lost during backrest installation and/or removal
- Doorstops for seat securement (Quantity: 2)
    - These doorstops may degrade with repeated use
- Additional handle grip material (Quantity: 1 square meter)
    - The original grip material on the handles may degrade with time, so we have included grip tape that can be secured over the existing material if it wears down.
- Cable (Quantity: 2)
    - The extent of the cable's resilience with repeated use at increased resistance levels is unknown. As such, we have included two replacement cables in case the original one fails.

Acknowledgments

In addition to the rest of the BLiSS M-HHaPS team, contributors to this document include: Megan Foulk, Vamsi Gollapalli, Zoe Hekneby, Luthien Liu, Darin Noronha, Ollie Paulus, Megan Piper, Hamza Qureshi, Ilyana Smith, Katherine Snowdon, Rachelle Winterberger.

E Verification & Validation

The Verification & Validation documentation can be found in the attached document.

Engineering Test Report

Bioastronautics and Life Support Systems

Test Name: *Verification and Validation Testing Procedure*		
Prepared by:	Approved by: Tanushree Shinde	Date Created: 2/5/24 Date Last Edited: 05/06/2024

Table of Contents

Introduction

This project involves the development of hardware for the Moon to Mars eXploration Systems and Habitation (M2M X-Hab) 2024 Academic innovation Challenge. The document presents a description of the project, applicable supplementary documentation, and adopted testing methodologies adopted for the validation of the design.

Purpose

The Verification and Validation (V&V) plan is prepared by Bioastronautics and Life Support Systems (BLiSS) for the NPAS NASA Autonomous Systems, Mars Campaign Development and Exploration Capabilities project for the development of Intelligent Devices/Equipment/Instruments (IDEI) for enabling crew health and performance on Mars. This plan has the following purposes:

(1) This V&V plan establishes a framework of V&V activities performed by BLiSS with the IDEI prototype components and integrated system.
(2) This V&V develops the prototype conceptually for its adaptation to the Martian Habitat.

The V&V document benefits this project in the following ways:

(1) detection and correction of anomalies
(2) management of process and product risks
(3) early assessment of system performance

Problem Statement

Extended periods of habitation in space environments can lead to severe muscle and bone loss. The purpose of this project is to cater to this challenge for the implementation of a prototype that enables astronauts to train and manage their physical health in a Martian Habitat. Exercises that can be performed on this prototype must be analogous to astronaut extravehicular activities (EVA) to strengthen the muscles most needed for strenuous capabilities. This prototype provides the crew with a user interface through which they can access personalized health reports in terms of metrics calculated and stored after their workouts through semi-autonomous data collection. The developed requirements led to an integrated system. The verification and validation of these requirements performed by methodologies and procedures on components and the integrated system are discussed further in this document.

Applicable Documents

Industry Standards

1. IEEE Std 1012-2016 "IEEE Standard for System, Software, and Hardware Verification, and Validation"
2. INCOSE Systems Engineering Handbook, 5th Edition

BLiSS Internal Documents

These applicable documents relevant to the validation processes have been attached in the appendix of this report.

1. BLiSS Requirements Verification Matrix
2. BLiSS V&V Outline
3. BLiSS V&V Schedule

Testing Methodology

Hardware verification and validation are crucial aspects of ensuring the reliability, functionality, and safety of hardware systems in various engineering domains. The following methodologies will be adopted and followed for the verification and validation of this system.

1. Verification by Inspection

This method involves a thorough examination of hardware designs, documentation, and specifications to identify and correct any errors, inconsistencies, or deviations from requirements. Inspection can be conducted by individual reviewers or teams, and it focuses on static analysis without executing the hardware. It ensures that the hardware design meets the specified requirements and standards.

2. Verification by Analysis

Analysis involves using mathematical models, simulations, and computational tools to assess the behavior, performance, and reliability of hardware systems. It includes techniques such as finite element analysis, computational fluid dynamics, and reliability analysis to predict how the hardware will perform under various conditions. Verification by analysis provides insights into potential design flaws or weaknesses before physical prototypes are built.

3. Verification by Demonstration

Demonstration involves physically testing hardware prototypes or mock-ups to validate their functionality, performance, and safety. This method verifies that the hardware behaves as intended and meets the specified requirements when subjected to real-world conditions.

Demonstration tests may include functional testing, environmental testing, and durability testing to validate the hardware's performance and reliability.

4. Verification by Test

Testing is a dynamic process that involves executing hardware systems under controlled conditions to verify their functionality, performance, and compliance with requirements. This method includes various types of tests such as unit testing, integration testing, system testing, and acceptance testing. Verification by test validates the hardware's behavior and identifies any defects or issues that need to be addressed before deployment.

5. Validation by Inspection

Validation by inspection involves reviewing and assessing hardware systems to ensure they meet the needs and expectations of stakeholders. This method focuses on validating the overall effectiveness, usability, and suitability of the hardware for its intended purpose through direct observation and feedback from stakeholders. Validation by inspection helps confirm that the hardware meets user requirements and addresses their concerns.

6. Validation by Analysis

Validation by analysis involves using modeling, simulation, and analytical techniques to verify that the hardware system meets its intended objectives and performance criteria. This method evaluates the system's effectiveness, reliability, and safety through mathematical and computational analysis. Validation by analysis provides confidence in the hardware's capabilities and helps identify any discrepancies between expected and actual performance.

7. Validation by Demonstration

Validation by demonstration entails conducting real-world tests or experiments to validate the hardware's performance, functionality, and safety in operational environments. This method verifies that the hardware meets the operational requirements and can perform reliably under normal operating conditions. Validation by demonstration provides empirical evidence of the hardware's suitability for its intended application and helps build confidence in its reliability and effectiveness.

8. Validation by Test

Validation by test involves conducting comprehensive testing of the hardware system under realistic conditions to validate its performance, reliability, and safety. This method includes field testing, user testing, and performance testing to assess the hardware's behavior in operational environments. Validation by test confirms that the hardware meets user needs and requirements and is ready for deployment.

V&V Procedures

Test cases related to system performance metrics and user interaction

1. Minimum Exercise Baseline:

   The system shall allow for the user to perform an analogous task to each of the tasks listed in Table 1 (R1.1).

EVA Performance Tasks
Walk with heavy pack
Squat down and pick up item
Manipulate item with hand

Table 1 - EVA Performance Tasks

1.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion.

1.2. Procedure steps:

- To verify “Walk with heavy pack”:
    - Demonstrate that leg press can be performed on the device by starting at legs fully extended with the feet shoulder-width apart on the footrest, then hinging at the knees simulating a squat motion and extending the legs back to the initial position.
    - Demonstrate that calf raises can be performed on the device by planting the balls of both feet on the lower edge of the footrest, and relaxing the heels towards the footrest, then away from the footrest in a controlled motion.
    - Demonstrate that rows can be performed on the device by starting with the handle attachment at the initially neutral fully retrieved position, and pull towards the seat in a controlled motion engaging back muscles.
- To verify “Squat down and pick up item”:
    - [Automatically satisfied if steps 1-3 of above are satisfied, since the analogous exercises are leg press, calf raises, and rows]

- To verify "Manipulate item with hand":
  - Demonstrate that pec fly can be performed on the device by pulling the cable with the handle unilaterally from the cable feeder towards the front of your chest with a neutral grip while contracting chest muscles, and release to the initial position in a controlled motion for the next repetition.
  - Demonstrate that delt fly can be performed on the device with the seat rotated by 90° and pulling the cable from the cable feeder to the side of the farther arm with your father arm using a neutral grip and retracting the arm towards the cable feeder to complete one repetition.
  - Demonstrate that hand squeeze can be performed on the device
  - Demonstrate that bicep curl can be performed on the device by holding a bar with a supinated grip with both hands and pulling towards the chest, then retracting to the relaxed position to complete one repetition.
  - Demonstrate that tricep kickbacks can be performed on the device by pulling the cable with a single handed neutral grip away from the cable feeder with elbow tucked in place beside the ribs.

1.3. Results

Verification performed by Darin Noronha on April 8, 2024 and by Ollie Paulus and Tanushree Manohar Shinde on April 15, 2024.

"Walk with heavy pack" and "Squat down and pick up item" Verification

Task	**Y/N**	**Notes**
Leg press can be performed?	Y	
Calf raises can be performed?	Y	
Rows can be performed?	Y	No negative resistance

"Manipulate item with hand" Verification

Task	**Y/N**	**Notes**
Pec fly can be performed?	Y	Machine lifts off the ground if you exert too high an initial force
Delt fly can be performed?	Y	Machine lifts off the ground if you exert too high an initial force
Hand squeeze can be performed?	N	Hand dynamometer integration with the rest of the device was not achieved but will be suggested under future improvements to the design.

Bicep curl can be performed?	Y	No resistance during the eccentric part of the motion
Tricep kickbacks can be performed?	Y	Machine lifts off the ground at high forces

2. Metric Reports:

The system shall generate reports of the performance metrics listed in Table 2 in the form of raw data with supporting visuals (R1.2).

Performance Metrics
Heart rate
VO2max
Reps (note if to failure)
Muscle Strength

Table 2 - Performance metrics

2.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion.

2.2. Procedure steps

- Perform an exercise of choice and analyze the displayed heart rate report (Requirement R1.2.1.1).
- Perform an exercise of choice and analyze the displayed VO2max report (Requirement R1.2.1.2).
- Perform an exercise of choice and analyze the displayed number of repsRequirement R1.2.1.3).
- Perform an exercise of choice and analyze the displayed amount of force Requirement R1.2.1.4).
- Perform an exercise of choice and analyze the displayed muscle strengthRequirement R1.2.1.5).

2.3. Results

Requirement R1.2.1.1 verified April 22, 2024.
Requirement R1.2.1.2 verified April 22, 2024.
Requirement R1.2.1.3 verified April 22, 2024.
Requirement R1.2.1.4 verified April 15th, 2024.
Requirement R1.2.1.5 verified April 15th, 2024.

3. The system shall autonomously calculate the user's average heart rate over the course of exercise or set (R1.2.1.1).

3.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion. Workout procedure has been selected by the user through the user interface.

3.2. Procedure steps

- Perform full workout procedure, as guided by the user interface
- Utilize separate heart rate sensor to collect heart rate data for the user during their exercise
- Inspect post-workout display screen and workout reports screens to ensure that:
    - Average heart rate is displayed for the selected timeframe
    - Average heart rate displayed is supported by data collected by separate heart rate sensor
    - Supporting visuals for heart rate are displayed for the selected timeframe

3.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Check	**Y/N**	**Notes**
Average HR displayed for selected timeframe?	Y	
Average HR displayed supported by data collected by separate HR sensor?	Y	
Supporting visuals for HR are displayed for selected timeframe?	Y	

4. The system shall autonomously measure user's VO2max over the course of the exercise or set (R1.2.1.2).

   4.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion. Workout procedure has been selected by the user through the user interface.

   4.2. Procedure steps

   - Perform full workout procedure, as guided by the user interface
   - Inspect post-workout display screen and workout reports screens to ensure that:
     - Average VO2max is displayed for the selected timeframe
     - Supporting visuals for VO2max are displayed for the selected timeframe

   4.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Check	**Y/N**	**Notes**
Average VO2max displayed for selected timeframe?	Y	
Supporting visuals for VO2max are displayed for selected timeframe?	Y	

5. The system shall autonomously record the number of reps done in each set and include an option for the user to manually note if the set was taken to failure (R1.2.1.3).

5.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion. Workout procedure has been selected by the user through the user interface.

5.2. Procedure steps

- Perform full workout procedure, as guided by the user interface
- A second person will count the number of reps performed by the person performing the workouts procedure
- Inspect post-workout display screen and workout reports screens to ensure that:
  - Raw data for #reps is displayed
  - #reps displayed is equal to the number of reps counted by the second tester
  - Supporting visuals for #reps are displayed
- Demonstrate that the set can be marked as "taken to failure."
  - Move to a different page of the user interface
  - Return to workout summary screen
  - Inspect that set is still marked as "taken to failure"

5.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Check	**Y/N**	**Notes**
Raw data for #reps is displayed?	Y	
#reps displayed equals number of reps counted?	Y	
Supporting visuals for #reps are displayed?	Y	
Set is successfully marked as "taken to failure?"	Y	
Set is still marked as "taken to failure?"	Y	

6. The system shall autonomously measure the amount of force the muscle outputted during each set or exercise (R1.2.1.4).

6.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. Workout procedure has been selected by the user through the user interface.

6.2. Procedure steps

- Configure machine to perform a leg press exercise
- Connect hanging scale to machine cable
- Pull on cable using hanging scale
- Use “hold” button on hanging scale at peak of motion to record maximum force output
- Move to post-workout screen
- Compare maximum force output recorded by hanging scale and maximum force output recorded by exercise device and ensure they are the same

6.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Force output read on hanging scale:	57.6 lbs
Maximum force output recorded by exercise device:	58 lbs
Force outputs match?	Yes
Notes	

7. The system shall autonomously calculate the strength of the muscle over time based on previous metrics (R1.2.1.5).

7.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion. Workout procedure has been selected by the user through the user interface.

7.2. Procedure steps

- Perform full workout procedure, as guided by the user interface
- Inspect post-workout display screen and workout reports screens to ensure that:
  - Raw data for muscle strength is displayed
- Inspect workout summary screen to ensure that:
  - Supporting visuals for muscle strength are displayed

7.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Check	**Y/N**	**Notes**
Raw data for muscle strength is displayed?	Y	Muscle strength data is displayed on the UI
Supporting visuals for muscle strength are displayed?	N	Visuals using data record from a workout were not implemented in this system

8. Metric Storage:

The system shall store the performance metrics listed in Table 2 for the duration of the system's useful lifetime (R1.2.2).

8.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion. Workout procedure has been selected by the user through the user interface.

8.2. Procedure steps

- Verify requirement R1.2.2.1 and inspect stored metrics.
- Verify requirement R1.2.2.2 and inspect stored metrics.
- Verify requirement R1.2.2.3 and inspect stored metrics.
- Verify requirement R1.2.2.4 and inspect stored metrics.

8.3. Results

Requirement R1.2.2.1 verified April 22, 2024.
Requirement R1.2.2.2 verified April 22, 2024.
Requirement R1.2.2.3 verified April 22, 2024.
Requirement R1.2.2.4 verified April 22, 2024.

9. The system shall store the user's average heart rate over the course of the exercise or set to the user's file (R1.2.2.1).

9.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion.

9.2. Procedure steps

- Perform full workout procedure, as guided by the user interface device
- View and record heart rate results displayed on post-workout page
- View and record heart rate results displayed on user's workout summary page
    - Inspect that these results match results recorded from post-workout page
- Log out user and log in as a different user
- Inspect that different user's workout summary page does not include data from initial user's workout
- Log out different user and log in as initial user
- Inspect that heart rate data from initial user's workout is still visible on the workout summary page
    - Inspect that these results match results recorded from post-workout page

9.3. Results

Verification performed by JD Dell on April 22nd, 2024.

HR results displayed on post-workout page	85
HR results displayed on user's workout summary page	85
HR results match?	Yes
Different user's workout summary page does not include data from initial user's workout?	Yes
HR results displayed on initial user's workout summary page	Yes
Current HR results match workout summary page recorded previously?	Yes
Notes	

10. The system shall store the user's VO2 max over the course of the exercise or set to the user's file (R1.2.2.2).

10.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion.

10.2. Procedure steps

- Perform full workout procedure, as guided by the user interface device
- View and record VO2max results displayed on post-workout page
- View and record VO2max results displayed on user's workout summary page
    - Inspect that these results match results recorded from post-workout page
- Log out user and log in as a different user
- Inspect that different user's workout summary page does not include data from initial user's workout
- Log out different user and log in as initial user
- Inspect that VO2max data from initial user's workout is still visible on the workout summary page
    - Inspect that these results match results recorded from post-workout page

10.3. Results

Verification performed by JD Dell on April 22nd, 2024.

VO2max results displayed on post-workout page	47
VO2max results displayed on user's workout summary page	45.3
VO2max results match?	Yes
Different user's workout summary page does not include data from initial user's workout?	Yes
VO2max results displayed on initial user's workout summary page	Yes
Current VO2max results match workout summary page recorded previously?	Yes
Notes	

11. The system shall store the user's number of reps done in each set and if the set was taken to failure to the user's file (R1.2.2.3).

11.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion.

11.2. Procedure steps

- Perform full workout procedure, as guided by the user interface device
- View and record #reps displayed on post-workout page
- View and record #reps displayed on user's workout summary page
  - Inspect that these results match results recorded from post-workout page
- Log out user and log in as a different user
- Inspect that different user's workout summary page does not include data from initial user's workout
- Log out different user and log in as initial user
- Inspect that #reps from initial user's workout is still visible on the workout summary page
  - Inspect that these results match results recorded from post-workout page

11.3. Results

Verification performed by JD Dell on April 22nd, 2024.

#reps results displayed on post-workout page	3
#reps results displayed on user's workout summary page	3
#reps results match?	Yes
Different user's workout summary page does not include data from initial user's workout?	Yes
#reps results displayed on initial user's workout summary page	Yes
Current #reps results match workout summary page recorded previously?	Yes
Notes	

12. The system shall store the amount of force the targeted muscle(s) output during each set or exercise to the user's file (R1.2.2.4).

12.1. Assumptions and Preconditions

The user has followed the instructions on the user guide to set the machine into the appropriate configuration before demonstrating each procedure, including but not limited to seat configuration, handle attachment, user interface options and resistance level. The user logs into the machine with their user ID. The cable hook/handle attachment is in a fully retrieved neutral position at the start of the pulling motion.

12.2. Procedure steps

- Perform full workout procedure, as guided by the user interface device
- View and record force output results displayed on post-workout page
- View and record force output results displayed on user's workout summary page
    - Inspect that these results match results recorded from post-workout page
- Log out user and log in as a different user
- Inspect that different user's workout summary page does not include data from initial user's workout
- Log out different user and log in as initial user
- Inspect that force output data from initial user's workout is still visible on the workout summary page
    - Inspect that these results match results recorded from post-workout page

12.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Force output results displayed on post-workout page	No
Force output results displayed on user's workout summary page	No
Force output results match?	No
Different user's workout summary page does not include data from initial user's workout?	No
Force output results displayed on initial user's workout summary page	No
Current force output results match workout summary page recorded previously?	No
Notes	The post workout page or user summary

	page were not yet implemented in the design

13. Metric Association:

The system shall store a unique collection of the performance metrics listed in Table 2 for each user (R1.2.3).

13.1. Assumptions and Preconditions

13.2. Procedure steps

- [Automatically verified by successful completion of verification procedure for R1.2.2]

13.3. Results

Requirement R1.2.2 verified XXX, 2024.

14. Performance Report:

The UI shall generate reports of the performance metrics listed in Table 2 in the form of raw data with supporting visuals by interfacing with external sensors that are measuring this data (R1.2.4).

14.1. Assumptions and Preconditions

14.2. Procedure steps

- Verify requirement R1.2.2.1
- Verify requirement R1.2.2.2
- Verify requirement R1.2.2.3
- Verify requirement R1.2.2.4

14.3. Results

Requirement R1.2.2.1 verified April 22, 2024.
Requirement R1.2.2.2 verified April 22, 2024.
Requirement R1.2.2.3 verified April 22, 2024.
Requirement R1.2.2.4 verified XXX, 2024.

15. User Identification:

The system shall record user identification (R1.2.5).

15.1. Assumptions and Preconditions

15.2. Procedure steps

- User A completes a workout, and data from that workout is manually recorded
- User B completes a workout, and data from that workout is manually recorded
- User A uses their pin to access their data
    - Inspect that this data is the same as the data collected manually for User A
- User B uses their pin to access their data
    - Inspect that this data is the same as the data collected manually for User B

15.3. Results

Verification performed by JD Dell on April 22nd, 2024.

User A workout data	No
User B workout data	No
User A recorded data matches displayed data?	No
User B recorded data matches displayed data?	No
Notes	System did not have the feature of data storage

Test cases related to human-system interaction, error rates, feedback, and response times

1. User Dimensions:

   The system shall ensure the range of potential users can fit, reach, view, and operate the human systems interfaces by accommodating crewmembers with the anthropometric dimensions and ranges of motion as defined in data sets in NASA STD-3001 V2 Appendix F, Physical Characteristics and Capabilities, Sections F.2 and F.3 (R2.1).

   1.1. Assumptions and Preconditions

   1.2. Procedure steps:
   - Verify requirement R2.1.1
   - Verify requirement R2.1.2
   - Verify requirement R2.1.3

   1.3. Results

Requirement R2.1.1 verified April 15, 2024.
Requirement R2.1.2 verified April 17, 2024.
Requirement R2.1.3 verified April 15, 2024.

2. The system's control interface shall be positioned in a way that ensures full range of motion capabilities for all crew members (R2.1.1).
   2.1. Assumptions and Preconditions
   2.2. Procedure steps:
   - Select Subjects A and B
     - Subject A will be the tallest member of the BLiSS M-HHaPS team
     - Subject B will be the shortest member of the BLiSS M-HHaPS team
     - Perform test with additional subjects as time and resources allow
   - Demonstrate that Subject A can reach the apparatus to adjust the resistance easily when they're standing
   - Demonstrate that Subject B can reach the apparatus to adjust the resistance easily when they're standing
   - Demonstrate that Subject A is unable to accidentally hit the resistance adjustment apparatus when they're doing each of the supported exercises
   - Demonstrate that Subject B is unable to accidentally hit the resistance adjustment apparatus when they're doing each of the supported exercises
   - Demonstrate that Subject A can reach and use the handles for chest flys and seated cable rows
   - Demonstrate that Subject B can reach and use the handles for chest flys and seated cable rows
   - Demonstrate that Subject A can easily adjust the seat location while standing
   - Demonstrate that Subject B can easily adjust the seat location while standing
   - Demonstrate that Subject A can properly install the backrest and use it while performing a leg press
   - Demonstrate that Subject B can properly install the backrest and use it while performing a leg press
   - Demonstrate that Subject A can properly reach the footrest during a rowing exercise
   - Demonstrate that Subject B can properly reach the footrest during a rowing exercise
   - Demonstrate that Subject A can properly reach the footrest during a leg press exercise
   - Demonstrate that Subject B can properly reach the footrest during a leg press exercise
   - Demonstrate that Subject A can properly reach the footrest during a calf raise exercise
   - Demonstrate that Subject B can properly reach the footrest during a calf raise exercise

   2.3. Results

Verification performed by Ollie Paulus and Tanushree Manohar Shinde on April 15, 2024.

Subject A height:	6’1” (73”)
Subject B height:	5’2” (62”)

Check	**Subject A (Y/N)**	**Subject B (Y/N)**	**Notes**
Able to easily reach apparatus to adjust resistance while standing	Y	Y	Easy to get out of seat and adjust magnets
Unable to accidentally hit the resistance adjustment apparatus while performing leg press	Y	Y	Unable to get anywhere near resistance mechanism
Unable to accidentally hit the resistance adjustment apparatus while performing calf raise	Y	Y	Subjects were very far way from resistance mechanism
Unable to accidentally hit the resistance adjustment apparatus while rowing	Y	Y	Subject was far enough away that there was no interference
Unable to accidentally hit the resistance adjustment apparatus while performing pec fly	Y	Y	Subject must hold on to seat handle for stability
Unable to accidentally hit the resistance adjustment apparatus while performing delt fly	Y	Y	Subject must hold on to seat handle for stability
Unable to accidentally hit the resistance adjustment apparatus while performing bicep curl	Y	Y	Subject must sit on seat and lean back for a wider range of motion for a shorter subject, whereas a taller subject can stand up and perform bicep curls. Resistance “starts” too late for a shorter user to be able to do the full exercise.
Unable to accidentally hit the resistance adjustment apparatus while performing tricep kickback	Y	Y	

Able to reach and use handles for chest flys and seated cable rows	Y	Y	
Able to easily adjust the seat location while standing Able to properly install the backrest	Y	Y	
Able to properly use backrest while performing leg press	Y	Y	Stabilizer bar may not be necessary for taller users, to allow for full leg extension
Able to properly reach the footrest while performing calf raise exercise	Y	Y	

3. The system's display screen shall be positioned in a way that ensures visibility for all crew members (R2.1.2).

3.1. Assumptions and Preconditions

3.2. Procedure steps

- Select Subjects A and B
  - Subject A will be the tallest member of the BLiSS M-HHaPS team
  - Subject B will be the shortest member of the BLiSS M-HHaPS team
  - Perform test with additional subjects as time and resources allow
- Demonstrate that Subject A can read all words on the workout screen of the display while in each of the following states:
  - While rowing
  - While performing the leg press exercise
  - While performing the calf raise exercise
  - While sitting on the seat rotated to the left for chest flys
  - While sitting on the seat rotated to the right for chest flys
- Demonstrate that Subject B can read all words on the workout screen of the display while in each of the following states:
  - While rowing
  - While performing the leg press exercise
  - While performing the calf raise exercise
  - While sitting on the seat rotated to the left for chest flys
  - While sitting on the seat rotated to the right for chest flys

3.3. Results

Verification performed by Ollie Paulus and Zoe Hekneby on April 17, 2024.

Subject A height:	6'1" (73")
Subject B height:	5'2" (62")

Check that subject is able to read all words on workout screen of display while:	**Subject A (Y/N)**	**Subject B (Y/N)**	**Notes**
Rowing	Y	Y	
Performing leg press exercise	Y	Y	Font size is very readable
Performing calf raise exercise	Y	Y	
Sitting on seat rotated to the left, as	Y	Y	

for performing chest flys			
Sitting on seat rotated to the right, as for performing chest flys	Y	Y	

4. The system shall include adjustable components to accommodate all crew members with anthropometric dimensions and full ranges of motion (R2.1.3).
    4.1. *Assumptions and Preconditions*
    4.2. *Procedure steps:*
    - Select Subjects A, B, and C
        - Subject A will be the tallest member of the BLiSS M-HHaPS team
        - Subject B will be the shortest member of the BLiSS M-HHaPS team
        - Subject C will be a member of the BLiSS M-HHaPS team of approximately average height
        - Perform test with additional subjects as time and resources allow
    - Each of the subjects performs the following tasks (with time in between to rest as needed):
        - Perform 10 leg press reps with a wide stance, demonstrating that full extension and contraction is possible
        - Perform 10 leg press reps with a narrow stance, demonstrating that full extension and contraction is possible
        - Perform 10 calf raise reps, demonstrating that full extension and contraction is possible
        - Adjust seat position for chest flys
        - Perform 10 chest fly reps with the left arm, demonstrating that full extension and contraction is possible
        - Perform 10 chest fly reps with the right arm, demonstrating that full extension and contraction is possible
        - Perform 3 minutes of rowing, demonstrating that full extension and contraction is possible
        - [Successful demonstration of each of the above tasks by each of the subjects fulfills this requirement]
        - Rate level of comfort during each of the tasks above on a scale from 1-10
    - Analyze subjects' ratings to assess subjects' perceived comfort and where there is room for improvement
    4.3. *Results*

Verification performed by Ollie Paulus, Tanushree Manohar Shinde, and Megan Foulk on April 15, 2024.

Subject A height:	6'1" (73")
Subject B height:	5'2" (62")
Subject C height:	5'7 (67")

Ability to perform task	Subject A (Y/N)	Subject B (Y/N)	Subject C (Y/N)	Notes
Achieve full extension and contraction during leg press with wide stance	N w/ stabilizer, Y w/o stabilizer	Y	Y	Stabilizer bar should be removed for tallest users
Achieve full extension and contraction during leg press with narrow stance	N w/ stabilizer, Y w/o stabilizer	Y	Y	Stabilizer bar should be removed for tallest users
Achieve full extension and contraction during calf raise	Y	Y	Y	Stabilizer bar should be removed for tallest users
Achieve full extension and contraction during chest fly with left arm	Y	Y	Y	Cable hits chest during full extension Lowest resistance is not low enough
Achieve full extension and contraction during chest fly with right arm	Y	Y	Y	Cable hits chest during full extension Lowest resistance is not low enough
Achieve full extension and contraction during rowing	Y	Y	Y	Ease of use Grip should be wider

Comfort level (1-10) during task	Subject A	Subject B	Subject C	Notes
Leg press with wide stance	10	7	10	The straps were the most uncomfortable part about it
Leg press with narrow stance	NA	NA	NA	Not currently an option with the device as built.
Calf raise	7	6	8	Feels like seat doesn’t pull you in enough to do the exercise right
Chest fly with left arm	9	7.5	9	Cable hits chest during

				full extension Lowest resistance is not low enough
Chest fly with right arm	9	7.5	9	Cable hits chest during full extension Lowest resistance is not low enough
Rowing	7	9	9	Bar is heavy and grip is awkward

5. Design-Induced Error:

The system shall provide crew interfaces that result in the maximum observed error rates listed in Table 3, Maximum Observed Design-Induced Error Rates (R2.8).

Type of Error	Maximum Observed Error Rate
Catastrophic Error	0%
Non-Catastrophic Errors per User per Task	5%
Non-Catastrophic Errors per Step per Task	10%

Table 3 - Maximum Observed Design-Induced Error Rates
(Table 29 from NASA STD-3001 Volume 2)

5.1. Assumptions and Preconditions

A catastrophic error is an error in which the user or device is damaged.

5.2. Procedure steps

- Count the number of steps involved in each of the following tasks:
  - Turn on and log into device
  - Perform full workout as directed by the user interface
  - Find workout history for the day and read off what workout was performed
- Perform the following steps for 5 [TBR] different users:
  - User performs the 3 tasks above
  - Record the number of errors for each task
- Calculate error rates and compare them to the values in Table 3

5.3. Results

Verification performed by XXX on XXX, 2024.

Task	# Steps
Turn on and log into device	
Perform full workout as directed by the user interface	
Find workout history for the day and read off what workout was performed	

Number of Non-Catastrophic Errors for Users 1-5

Task	1	2	3	4	5
Turn on and log into device					
Perform full workout as directed by the user interface					
Find workout history for the day and read off what workout was performed					

Task	# Catastrophic Errors
Turn on and log into device	
Perform full workout as directed by the user interface	
Find workout history for the day and read off what workout was performed	

Non-Catastrophic Error Rates

Task	Errors/User/Task	Errors/Step/Task
Turn on and log into device		
Perform full workout as directed by the user interface		
Find workout history for the day and read off what workout was performed		

This requirement was unverified.

6. Control Feedback:

The system shall provide a positive indication of crew-initiated control activation (R2.10).

6.1. Assumptions and Preconditions

6.2. Procedure steps

- User begins a workout
- Inspect that a screen pops up after hitting start, confirming the beginning of a workout

6.3. Results

Verification performed by Rachelle Winterberger and Tommy Callen on April 17th, 2024.

Check	**Y/N**	**Notes**
Screen pops up after hitting start to confirm the beginning of a workout	Y	Possible workouts appear, a timer starts. Clicking a workout leads to current performance metrics.

7. System Feedback:

The system shall notify the user upon completion of the exercise (R2.11).

7.1. Assumptions and Preconditions

7.2. Procedure steps:

- Verify requirement R2.11.1
- Verify requirement R2.11.2
- Verify requirement R2.11.4
- Verify requirement R2.11.5

7.3. Results

Requirement R2.11.1 verified April 22, 2024.
Requirement R2.11.2 verified April 22, 2024.
Requirement R2.11.4 verified April 22, 2024.
Requirement R2.11.5 verified April 22, 2024.

8. The system shall notify with a universal, unmistakable signal (R2.11.1).
    8.1. *Assumptions and Preconditions*
    8.2. *Procedure steps:*
        - Verify requirement R2.11.2
    8.3. *Results*

Requirement R2.11.2 verified April 22, 2024.

9. The system shall notify with appropriate signals for different exercises (R2.11.2).
    9.1. *Assumptions and Preconditions*
    9.2. *Procedure steps:*
        - User begins workout procedure
        - Demonstrate that for each exercise, the user can correctly identify the exercise expected by the machine.
    9.3. *Results*

Verification performed by Zoe Hekneby on April 22nd, 2024.

Check	**Y/N**	**Notes**
User correctly identifies when rowing is expected	Y	
User correctly identifies when leg press is expected	N	User has the option to select leg press but does not know when is expected to select it.
User correctly identifies when calf raise is expected	N	User has the option to select calf raise but does not know when it is expected to select it.
User correctly identifies when pec fly is expected	N	User has the option to select pec fly but does not know when it is expected to select it.
User correctly identifies when delt fly is expected	N	User has the option to select delt fly but does not know when it is expected to select it.

10. The sensor subsystem shall communicate the exercise completion information to the software subsystem (R2.11.4).

10.1. Assumptions and Preconditions

10.2. Procedure steps

- Subject configures and begins a rep-based exercise
- Manually count the reps completed
- When the manually noted reps completed matches the number necessary to end the session, inspect that the screen displays that the session has ended.

10.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Exercise performed	Yes
Manually counted reps completed	Yes
Screen displays that the session has ended when manually noted reps matches the number required to end the session?	Yes
Notes	

11. The UI shall notify the user upon completion of the exercise (R2.11.5).

11.1. Assumptions and Preconditions

11.2. Procedure steps

- User performs a full time-based workout
- Inspect that workout screen changes once the time on the workout is completed

11.3. Results

Verification performed by Zoe Hekneby on April 22nd, 2024.

Exercise performed	Yes
Screen displays that the session has ended when session time elapses?	No, timer is present, but force stop is not included.
Notes	

System Response	Example	Maximum Time(s)*
Continuous input: cursor and onscreen dynamic elements	Cursor and symbol motion, flight instruments	0.07 (15 Hz)**
Discrete input: Indication of a visual, auditory, or tactile discrete input	On-screen keystroke echo; click or beep; detent/physical feedback	0.1
Update to local element	Display of popup menu	0.5
Display of a requested Graphical User Interface (GUI)	Calling up a new display or display component	1.0
Display of updated data on crew command of a state change	Status of "on" when commanded on; status of "open" when commanded open	1.0
Feedback for commands that cannot be completed within 1 second:		
Indication that a command or process is progress	A progress bar showing time remaining or a progress message	1.0
Status of the command/process after request completed	After request is completed – status message of success/fail/unknown	1.0
** Note that systems with "Short time to effect" scenarios may require faster response times, as determined in the task analysis*		
*** Polling rate, DPI, and screen refresh rate are factors that affect cursor and screen dynamic elements*		

Table 4 - Maximum System Response Time(s); Source: Table 30 from NASA STD-3001 Volume 2

12. Maximum System Response Time:

The system shall provide feedback to the user within the time specified in Table 4 (R2.12).

12.1. Assumptions and Preconditions

12.2. Procedure steps

- Verify requirement R2.12.1
- Verify requirement R2.12.2
- Verify requirement R2.12.3
- Verify requirement R2.12.4
- Verify requirement R2.12.6
- Verify requirement R2.12.7
- Verify requirement R2.12.8

12.3. Results

Requirement R2.12.1 verified April 22, 2024.
Requirement R2.12.2 verified April 22, 2024.
Requirement R2.12.3 verified April 22, 2024.
Requirement R2.12.4 verified April 22, 2024.
Requirement R2.12.6 verified April 22, 2024.
Requirement R2.12.7 verified April 22, 2024.
Requirement R2.12.8 verified April 22, 2024.

13. The screen (and its continuously updating elements such as measurements or on-screen data) shall have a refresh rate of 15 Hz minimum (response time of.07 seconds maximum) (R2.12.1).

13.1. Assumptions and Preconditions

13.2. Procedure steps

- Attach an oscilloscope between the UI and the arduino
- Measure the frequency of frame signals between the two devices
- Inspect whether this is higher than 15 Hz

13.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Frequency of frame signals between UI and arduino (Hz)	60Hz
Notes	Rough estimate but is for sure higher than 15hz

14. Updates to local elements such as popups shall have a response time of at most 0.5 seconds (R2.12.2).

14.1. Assumptions and Preconditions

14.2. Procedure steps

- Run the test popup code created by the data team
- Record a video of the user interacting with the popup
- Measure the duration of the video between interacting, and the popup responding
- Inspect whether this duration is under 0.5 seconds

14.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Duration between user interaction and popup response (s)	Under 0.5 seconds
Notes	

15. Discrete input indications shall have an on-screen response time of 0.1 seconds maximum (R2.12.3).
   15.1. Assumptions and Preconditions
   15.2. Procedure steps
   - Record a video of a user inputting their user ID into the login screen
   - Measure the duration of time between typing and the appearance of each user ID digit on the screen
   - Inspect whether this duration is under 0.1 seconds

   15.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Average duration between user typing and digit appearance (s)	Under 0.1 seconds
Notes	

16. Changing a display or display component shall have an on-screen response time of 1 seconds maximum (R2.12.4).
   16.1. Assumptions and Preconditions
   16.2. Procedure steps
   - Record UI screen
   - User turns on UI, logs in, and navigates through UI to begin workout
   - Measure the time between user interaction causing a transition to a new screen and the full resolution of that new screen

   16.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Average duration between user interaction and full resolution of new screen (s)	Under 0.1 seconds
Notes	

17. A progress bar shall display the progress of commands that cannot be completed in under 1 second (R2.12.6).

17.1. Assumptions and Preconditions

17.2. Procedure steps:

- User begins workout
- Inspect whether a progress bar appears for each exercise
    - Inspect whether this progress bar progresses accurately to reflect user's workout progress

17.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Progress bar appears for leg press	Not included
Leg press progress bar progresses accurately	Not included
Progress bar appears for calf raise	Not included
Calf raise progress bar progresses accurately	Not included
Progress bar appears for rowing	Not included
Rowing progress bar progresses accurately	Not included
Progress bar appears for pec fly	Not included
Pec fly progress bar progresses accurately	Not included
Progress bar appears for delt fly	Not included
Delt fly progress bar progresses accurately	Not included
Notes	Progress bar was not implemented for the final design

18. A status update showing the completion of a task that cannot be completed in under one second shall show up in 1 second after the task is completed (R2.12.7).

18.1. Assumptions and Preconditions

18.2. Procedure steps

- User enters the rowing workout
- User then holds bar fully out triggering an error message
- Inspect whether the time taken for the UI to report the error is under (1 second + time required to trigger error)

18.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Time for UI to report error	N/A
Time required to trigger error	N/A
Notes	Error detection was not implemented.

19. The UI shall provide feedback to the user within the time specified in Table 4, Maximum System Response Time(s) based on the data received from the Sensor Data Processor (R2.12.8).

19.1. Assumptions and Preconditions

19.2. Procedure steps

- User enters the rowing workout
- Record a video of the UI and the rep sensor
- User completes 1 rep
- Inspect whether the time taken for the UI to display the rep completion after the rep is completed is under 0.5 seconds

19.3. Results

Verification performed by Zoe Hekneby on April 22nd, 2024.

Time for UI to display rep completion	Under 0.5 seconds
Notes	

Test cases related to power draw, exercise configuration, and data transmission

1. Power:

   The system shall have a nominal power draw of no more than 100 W from 120 VAC wall outlet. (R3.6)

   1.1. Assumptions and Preconditions

   1.2. Procedure Steps

   - Attach the setup to our wall outlet, through a power draw outlet attachment
   - Subject demonstrates normal use of the device:
     - Perform rowing exercise
     - Perform leg press exercise
     - Perform chest fly exercise
   - Record the peak power measured by the outlet attachment during subject's use of device

   1.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Peak power measured by outlet attachment (W)	4.5
Notes	

2. Machine Configuration Interface:

The user shall be able to configure the parameters of the exercise within a time no greater than 5 minutes. (R3.10)

2.1. Assumptions and Preconditions

2.2. Procedure Steps

- Start timer
- Participant configures machine from chest fly configuration to leg press configuration
    - This transition was chosen because it is the longest transition time between exercises
- Stop Timer
- Confirm that configuration time is under 5 minutes

2.3. Results

Verification performed by Ilyana Smith and Chris May on April 30, 2024.

Configuration time (min)	7 min
Notes	Time without installation of the stabilizer bar was 3.5 minutes. If this bar is determined to be unnecessary, this requirement can be easily verified. It is highly possible that this component is not required, but further analysis and tests would need to be conducted.

3. Data Transmission:

The system shall be able to transmit data to an external device. (R3.11)

3.1. Assumptions and Preconditions

3.2. Procedure Steps

- Verify requirement R3.11.1

3.3. Results

Requirement R3.11.1 left unverified April 22, 2024

4. The UI shall be able to access saved data and transmit data to an external device. (R3.11.1)

   4.1. Assumptions and Preconditions

   4.2. Procedure Steps

   - User completes a full workout under their unique User ID
   - Store data in external SD card
   - Remove SD card from machine
   - Wipe user data from machine
   - Reinsert SD card into machine
   - Demonstrate that the user can access the workout history that was stored on the SD card

   4.3. Results

Verification performed by JD Dell on April 22, 2024.

Able to access workout history from SD card?	**No**
Notes	**SD card compatibility not implemented in this system**

Test cases related to anomaly detection and reporting

1. Fault Detection:

Anomalous Behaviors
Software Failure
Mechanical Failure
Power Failure
Hardware Failure

Table 8 - Anomalous Behaviors

The system shall allow for the detection of anomalous behaviors defined in Table 8 during normal operation. (R4.1)

1.1. Assumptions and Preconditions

1.2. Procedure Steps:

- User begins UI-guided workout
- User holds back the handle to trigger a mechanical error
  - Verify that error message is displayed indicating mechanical error
- User unplugs sensor to trigger hardware/software error
  - Verify that error message is displayed indicating hardware/software error
- User pauses workout
- User unplugs the machine, then plugs it back in
  - Verify that error message is displayed indicating power failure error

1.3. Results

Verification performed by Zoe Hekneby on April 22nd, 2024.

Error message is displayed indicating mechanical error?	N/A
Error message is displayed indicating hardware/software error?	N/A
Error message is displayed indicating power failure error?	N/A
Notes	Error detection was not implemented.

2. The sensors subsystem shall at all times monitor for the anomalous behaviors in Table 8. (R4.1.1)
    2.1. Assumptions and Preconditions
    2.2. Procedure Steps
        - Simulate Mechanical failure by feeding abnormal values into force and resistance sensors
            - Ensure signals are being sent from the appropriate sensors to report this issue
        - Cut off power to the devices
            - Ensure signals are being sent from the appropriate sensors to report this issue, using power from temporary energy storage devices to send the signals and warn the user
        - Simulate Mechanical failure by feeding abnormal values into pulse oximetry
            - Ensure signals are being sent from the appropriate sensors to report this issue
    2.3. Results

Verification performed by Zoe Hekneby on April 22nd, 2024.

Sensors report mechanical failure?	No
Sensors report power failure?	No
Sensors report pulse oximetry abnormality?	No
Notes	Error detection was not implemented.

3. The sensors subsystem shall communicate information about detected faults to the software subsystem. (R4.1.3)
    3.1. Assumptions and Preconditions
    3.2. Procedure Steps
        - Verify requirement R4.1
    3.3. Results

Requirement R4.1 left unverified April 22, 2024.

4. Fault Notification:

The system shall notify users in real-time of detected anomalous behaviors listed in Table 8. (R4.2)

4.1. Assumptions and Preconditions

4.2. Procedure Steps:

- Verify requirement R4.1

4.3. Results

Requirement R4.1 left unverified April 22, 2024.

5. State of Health Reports:

The system shall generate system state of health reports on the metrics defined in Table 9 on-demand by users. (R4.3)

5.1. Assumptions and Preconditions

5.2. Procedure Steps

- User opens the system health status report tab on the UI to verify it is there
- User will begin a workout
- User opens the health status report again during the workout to make sure it is functioning.
- The user unplugs a sensor
- Observe whether the health status report displays the error

5.3. Results

Verification performed by Zoe Hekneby on April 22nd, 2024.

System health status tab exists?	No
System health status tab functions during workout?	No
System health status tab displays error?	No
Notes	Error detection was not implemented.

Test cases related to hazard management, crew protection, and system durability

1. Hazard Management:

   The system shall implement a hazard management system. (R6.1)

   1.1. Assumptions and Preconditions

   1.2. Procedure Steps:

   - Verify requirement R4.1

   1.3. Results

Requirement R4.1 left unverified April 22, 2024.

2. Catastrophic Hazards:

   The system shall be two-fault tolerant for catastrophic hazards. (R6.1.1)

   2.1. Assumptions and Preconditions

   2.2. Procedure Steps:

   - Verify requirement R6.1

   2.3. Results

Requirement R6.1 left unverified April 22, 2024.

3. The sensors subsystem shall communicate the activation of the hazard sensors to the software subsystem in under 100ms. (R6.1.1.2)

   3.1. Assumptions and Preconditions

   3.2. Procedure Steps:

   - Verify requirement R6.1

   3.3. Results

Requirement R6.1 left unverified April 22, 2024.

4. Critical Hazards:

   The system shall be one-fault tolerant for critical hazards. (R6.1.2)

   4.1. Assumptions and Preconditions

   4.2. Procedure Steps:

   - Verify requirement R6.1

   4.3. Results

Requirement R6.1 left unverified April 22, 2024.

5. The sensors subsystem shall communicate the activation of the hazard sensors to the software subsystem in under 100ms. (R6.1.2.2)
    5.1. Assumptions and Preconditions
    5.2. Procedure Steps
    - Verify requirement R6.1
    5.3. Results

Requirement R6.1 left unverified April 22, 2024.

6. Mechanical Hazards:

    Systems, hardware, and equipment shall protect the crew from moving parts that may cause injury to the crew. (R6.2)

    6.1. Assumptions and Preconditions

    Assume that the system only protects the crew member using the device from these moving parts that may cause injury to the crew.

    6.2. Procedure Steps:
    - Verify requirement R6.2.2
    - Verify requirement R6.2.3
    6.3. Results

Requirement R6.2.2 verified March 21, 2024.
Requirement R6.2.3 left unverified April 22, 2024.

7. The system shall be designed to only be used by one person at a time. (R6.2.2)
    7.1. Assumptions and Preconditions
    7.2. Procedure Steps
    - Count number of seats able to be installed on device at one time
    - Count number of cable handles able to be installed on device at one time
    7.3. Results

Verification performed by Megan Foulk, Chris May, Landon Butcher, Ilyana Smith, JD Dell, Tanu Shinde on March 21, 2024.

Number of seats able to be installed on device at one time	**1**
Number of cable handles able to be installed on device at one time	**1**
Notes	**none**

8. The system shall detect when obstructions will impede its motion. (R6.2.3)
   8.1. *Assumptions and Preconditions*
   8.2. *Procedure Steps*
   - User begins workout
   - User holds handle of rowing machine back from rower
     - Do not pause the workout
   - Observe whether system throws an error message
   - Observe whether workout pauses and remains paused until error is cleared and user presses “error resolved” button on screen
   8.3. *Results*

Verification performed by Zoe Hekneby on April 22nd, 2024.

System throws error message?	No
Workout pauses and remains paused until error is cleared and user presses “error resolved” button?	No
Notes	Error detection was not implemented.

9. The system shall autonomously stop the process to prevent damage to the system and the user when obstructions are detected. (R6.2.4)
   9.1. *Assumptions and Preconditions*
   9.2. *Procedure Steps:*
   - Verify requirement R6.2.3
   9.3. *Results*

Requirement R6.2.3 left unverified April 22, 2024.

10. Entrapment:

    Systems, hardware, and equipment shall protect the crew from entrapment (tangles, snags, catches, etc.). (R6.3)

    10.1. *Assumptions and Preconditions*
    10.2. *Procedure Steps:*
    - Verify requirement R6.3.1
    10.3. *Results*

Requirement R6.3.1 left unverified April 30, 2024.

11. The system shall incorporate an emergency release mechanism to free user from restraints used during activity. (R6.3.1)

11.1. Assumptions and Preconditions

11.2. Procedure Steps:

- Participant straps themselves into the device to the greatest extent possible
    - This is defined as the configuration of the machine during the leg press exercise, since the participant's feet are strapped into the Velcro loops on the footplate.
- Start timer
- Participant gets out of device as fast as they can
- Stop timer
- Confirm that escape time is less than 1 second

11.3. Results

Verification performed by Ilyana Smith and Chris May on April 30, 2024.

Participant escape time (s)	2 seconds
Notes	Did not achieve 1 second threshold

12. Sharp Corners and Edges:

Corners and edges of fixed and handheld equipment to which the bare skin of the crew could be exposed shall be deburred. (R6.5)

12.1. Assumptions and Preconditions

12.2. Procedure Steps:

- For each manufactured part:
    - Team members will manually inspect each edge by touch to ensure it is adequately deburred
    - Team members will manually inspect each hole by touch to ensure its edges are adequately deburred

12.3. Results

Verification performed by Colin Badgero on April 15, 2024.

Check for whether deburred:	**Y/N**	**Notes**
Footplate	Y	Rubber covering around edges
Seat upper plate	Y	
Seat lower plate and roller	Y	
Seat back	Y	

13. Nominal Physiological Electrical Current Limits:

Under nominal situations (routine human contacts to conductive housing), the program shall limit electrical current through the crewmember to ≤ (less than or equal to) 0.4 mA for Direct Current (DC) and ≤ (less than or equal to) 0.2 mA peak for Alternating Current (AC). (R6.8)

13.1. Assumptions and Preconditions

13.2. Procedure Steps

- Inspect main body of machine to observe whether any non-insulated wires exist with a path from them to the crew member while conducting an exercise
- Inspect wearable sensor component to observe whether any non-insulated wires exist with a path from them to the crew member while wearing the sensor

13.3. Results

Verification performed by JD Dell on April 22nd, 2024.

Non-insulated wires on the main body of the machine?	Yes
Non-insulated wires on wearable sensors?	Yes
Notes	Wires were mostly insulated but some of the ends on the main body of the machine were slightly exposed. This included the wires running from the wearable to the body of the device

14. Under nominal situations (routine human contacts to conductive housing), the sensors subsystem shall limit electrical current through the crewmember to ≤ (less than or equal to) 0.4 mA of Direct Current (DC). (R6.8.1)

14.1. Assumptions and Preconditions

14.2. Procedure Steps

- Verify requirement R6.8

14.3. Results

Requirement R6.8 verified April 22, 2024.

15. Under nominal situations (routine human contacts to conductive housing), the sensors subsystem shall limit electrical current through the crewmember to ≤ (less than or equal to) 0.2 mA peak for Alternating Current (AC). (R6.8.2)

15.1. Assumptions and Preconditions

15.2. Procedure Steps

- Verify requirement R6.8

15.3. Results

Requirement R6.8 verified April 22, 2024.

16. Withstand Crew Forces:

The system shall be able to withstand the maximum forces imposed by the crew as listed in NASA STD-3001 V2 Appendix F, Section 7: Crewmember Strength. (R6.9)

16.1. Assumptions and Preconditions

Assume that COTS components used in prototype design are capable of withstanding crew forces.

16.2. Procedure Steps:

- Apply 581 pounds of force from each of two legs pushing on the footplate (1162 pounds of force total)
- Inspect footplate for signs of damage

16.3. Results

Verification performed by JD on April 22nd, 2024.

Simulation indicates the footplate can withstand 581 pounds of force from each of two legs?	N/A
Notes	Amount of force cannot be generated for testing.

17. The wires and the sensors shall be sturdy enough to withstand the forces applied to them by the user while working out. (R6.9.1)

17.1. Assumptions and Preconditions

17.2. Procedure Steps

- Verify requirement R6.13
- Demonstrate that wearable sensor component collects data successfully in 3 subsequent workout sessions

17.3. Results

Requirement R6.13 verified April 22nd, 2024.

Verification performed by JD Dell on April 22nd, 2024.

Successful data collection in session 1?	**Yes**
Successful data collection in session 2?	**Yes**
Successful data collection in session 3?	**Yes**
Notes	

18. Cable Management:

The system shall manage cable, wire, and hose location, protection, routing, and retention to prevent physical interference with crew operations and safety. (R6.13)

18.1. Assumptions and Preconditions

18.2. Procedure Steps

- User performs workout, as guided by user interface
- Inspect machine to observe whether any wires or cables exist with which the crew member comes into contact while conducting the workout

18.3. Results

Verification performed by JD Dell on April 22nd, 2024.

User comes into contact with wires or cables during workout?	**No**
Notes	

Validation

The device shall semi-autonomously collect performance metric data. (R0.2)

Heart rate: Heart rate refers to the number of times a person's heart beats per minute. It is an important metric because it is used to measure VO2max as well as a very common method of measuring a user's cardiovascular endurance. Also, if it is measured over time it is a way in which the growth in a user's cardiovascular endurance has grown.

VO2max: VO2max or maximum volume of oxygen refers to the amount of oxygen a person's body absorbs and uses during physical activity. It is one of the best metrics to measure a person's cardiovascular fitness according to (VO2 max: How To Measure and Improve It (clevelandclinic.org)). VO2max is also a requirement in Table 3 below.

Reps: Measured in the number of reps or dignified as "to failure" if the set was done to as many reps as the user could do. This metric is important because it shows if a user was able to perform an exercise for a certain amount of weight which applies to the requirements in Table 3 below as well as show growth in a user's strength. Seeing a change in reps over time shows growth in the fitness of a user as well.

Muscular Strength: measured in newtons, refers to the force output by the muscles. This is calculated using the weight/resistance of the movement with the speed of the flywheel on the rowing machine. This is an important metric because it helps confirm the requirements in Table 3 referring to the deadlift and benchpress requirements. With this requirement, it can be determined the weight at which each exercise can be performed for each person.

	0+ Month Exercise Capabilities	9+ Month Exercise Capabilities
VO2 Max (ml/min/kg) (assuming 25% decline)	43.8	32.9
Deadlift	1 * body weight	80% 0+ month weight
Bench Press	.7 * body weight	80% 0+ month weight
Bone Mineral Densities (BMD)	DXA measurements of T-scores shall be consistent with age, sex, gender, and ethnic matched population	95% 0+ month measurement 90% 0+ month measurement for femoral neck

Table 3 - 0 month and 9 month ISS Baseline

Advisor Feedback for Validation

The validation of the device, guided by feedback from advisors obtained through several review meetings, underscores its effectiveness in facilitating exercise routines tailored to the demands of Extravehicular Activities (EVA). Dr. Emily Matula and Josh Cassada, among other advisors, emphasized the importance of exercising specific muscle groups crucial for EVA, such as forearms/hands, rotator cuff, legs, and core. Their affirmation that the device effectively targets these muscle groups corroborates its alignment with the intended objectives.

In a recent meeting, Josh Cassada highlighted the significance of exercising muscles essential for EVA, particularly in zero-gravity environments. Notably, he identified the same muscle groups that our device focuses on, reaffirming its relevance and efficacy in addressing the fitness needs of astronauts during space missions.

The validation report meticulously summarizes the device's capabilities, affirming its suitability for achieving its intended objectives. The device's ability to effectively exercise the specified muscle groups, as validated through rigorous testing and analysis, further reinforces its alignment with the project's objectives.

Additionally, feedback from advisors revealed that the device addresses specific challenges encountered during exercise sessions in space, as articulated by Josh Cassada. Notably, the device addresses concerns regarding the perceived ease of using the T2 cardio machine and the complexities associated with securing oneself to the ARED resistance machine during weighted exercises. By mitigating these inconveniences, the device enhances the overall exercise experience for astronauts, thereby contributing to improved performance metrics and overall well-being during space missions.