Defining Engineering Parameters for Space Resistive Exercise Hardware Design

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The space industry has prevailed over numerous design challenges in the spirit of exploration. Manned space flight entails creating products for use by humans and the Johnson Space Center has pioneered this effort as NASA's center for manned space flight. NASA Astronauts use a suite of flight exercise hardware to maintain strength for extravehicular activities and to minimize losses in muscle mass and bone mineral density. With a cycle ergometer, treadmill, and the Resistive Exercise Device available on the International Space Station (ISS), the Space Medicine community aspires to reproduce physical loading schemes that match exercise performance in Earth's gravity. The resistive exercise device presents the greatest challenge with the duty of accommodating 20 different exercises and many variations on the core set of exercises. This paper presents a methodology for capturing engineering parameters that can quantify proper resistive exercise performance techniques. For each specified exercise, the method provides engineering parameters on hand spacing, foot spacing, and positions of the point of load application at the starting point, midpoint, and end point of the exercise. As humans vary in height and fitness levels, the methodology presents values as ranges. In addition, this method shows engineers the proper load application regions on the human body. The methodology applies to resistive exercise in general and is in use for the current development of a Resistive Exercise Device. Exercise hardware systems must remain available for use and conducive to proper exercise performance as a contributor to mission success. The astronauts depend on exercise hardware to support extended stays aboard the ISS. Future plans towards exploration of Mars and beyond acknowledge the necessity of exercise. Continuous improvement in technology and our understanding of human health maintenance in space will allow us to support the exploration of Mars and the future of space exploration.

Introduction

The potential for manned space exploration depends on our ability to maintain crew health and performance levels. Resistive exercise is one countermeasure used to fight the loss of muscle mass and bone mineral density due to the space environment. The concept of using resistive exercise is to load the body's skeletal muscle and bones in a manor that simulates the load of Earth's gravity on the body. For strength training, free weight exercises are the preferred choice for ground-based exercise. The Space Medicine community at the Johnson Space Center (JSC) monitors the health and physical performance level of the astronauts. Upon their assessment, the astronauts receive unique work out regimens that are designed to address their mission objectives and health status. The countermeasures system is a part of the overall Crew Health Care System (CHeCS) and states the requirements for developing the Resistive Exercise Device.[1] One major challenge is for engineers to design a Resistive Exercise Devise that can cater to individualized exercise prescriptions for all types of crewmembers. In addition to the design requirements that apply for all flight hardware development, the engineering project team must address the human-machine interface issues for accommodating proper exercise performance techniques. Specifically, human-machine interface issues are design details that occur where a human comes into contact with the resistive exercise device and include mounting, energy transfer, and dynamic motion analysis. The present Resistive Exercise Device project uses a methodology that addresses these design details and provides engineering parameters to guide the hardware design process. Many books are available that explain proper exercise techniques.[2] In this paper, the term "Exercise Techniques" will represent proper exercise form and style. The definition of a combined-system boundary provides a framework for describing all design issues at the human-machine interface of the Resistive Exercise Device.

Combined System Definition

In general terms, the human and the exercise device are a combined system. For any activity to occur, a human will use the machine to perform resistive exercises. This combined system encapsulates all of the questions pertaining to the human-machine interface. Within the combined system boundary, the major design challenges occur at the interface between the human system boundary and the exercise device system boundary as shown in Figure 1.

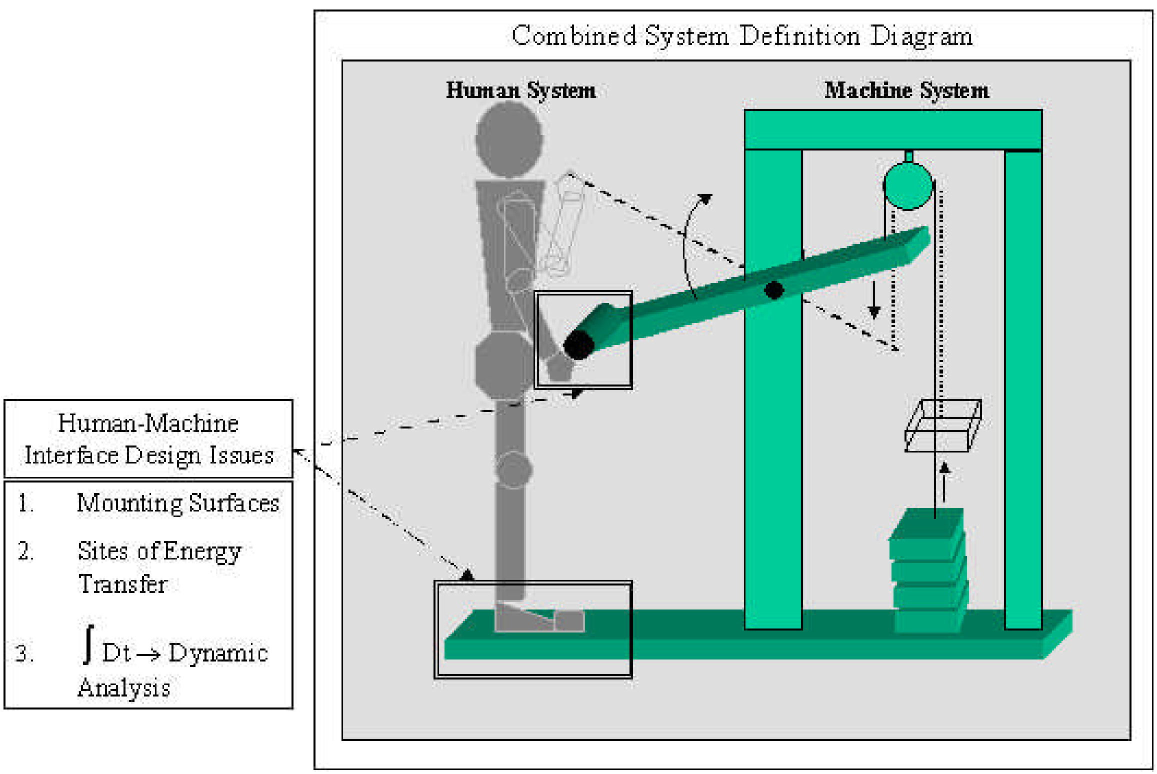

Figure 1: Combined System (Human & Exercise Device) Definition Diagram

The exercise device on its own is a system that will not move unless a force is applied to it. Humans that use the device will actuate the machine. In this way, the human is the actuator or engine of the overall system. The purpose of the exercise device is to accommodate resistive exercise and strengthen the human. If a human is trained before using exercise hardware, then Exercise Techniques control how the human will move. For this definition of the combined system, the exercise device follows the motion of the human and Exercise Techniques control the way the human moves. In order to design for the machine-human interface, the challenge is how to design the mounting interface, internal energy transfer, and dynamic conditions between the human and machine. The definition of Exercise Techniques is essential for all of these areas of design.

Mounting Interface: The human connects to the machine

Exercise Techniques for free-weight exercises illustrate the ideal methods for loading the human skeleton on Earth. Using these free-weight exercise techniques as the standard, an engineering design team has descriptive information on human posture and positioning relative to system pivot points or the load application mechanism for the resistive exercise device. However, Exercise Techniques only describe the relative positions without directly presenting engineering design parameters. In conjunction with Exercise Techniques, anthropometrics charts provide additional information for predicting the approximate positions of key anatomical landmarks and can assist in selecting locations for postural support tools or mechanisms. One of the greatest influences for the study of anthropometrics has been the design for man-machine interfaces.[3] Support from human factors and ergonomics experts can improve the man-machine mounting interface design. Some of the components that provide the mounting interface for exercise machines on Earth include benches, seat belts, leg pads, adjustable seat or lever arm positions, and various grip devices for cable exercises.

Energy Transfer Between Human and Machine

In the Combined System Definition, the human is the “driver” and the exercise device is “driven.” The capabilities of the human-actuator explain the demands on the resistive loading mechanism. As the human performs exercises, the man-machine interface displaces over time within the combined system boundary. Energy transfer occurs whenever any portion of the machine boundary exerts resistance against movement from the human at the human-machine interface. When the human does work upon the machine, energy transfer benefits the human system in the form of strength training. Exercise Techniques explain the region of load application as well as the direction of load application. The direction of load application is equivalently the orientation of the reaction force provided by the exercise device. Reaction forces, or load settings, will vary based on a human’s height, weight, and fitness levels. The best way to predict the range of load settings for a particular exercise is to use data from fitness trainers or to benchmark existing resistive exercise devices that are commercially available. Additionally, transitions between loads are important from a strength training and rehabilitation standpoint. For a structured fitness program, the fitness instructor assists individuals towards higher levels of resistance gradually to avoid muscle strain or injury. Free-weight equipment typically increments by 2.5 lbs at a time, while many free-weight machines allow for 1 lb increments to increase load settings.

Dynamics between the human and hardware

Engineers can define the working envelope of the combined system by studying Exercise Techniques and deriving engineering parameters. The machine must move along with the human while applying the appropriate resistance or reactive force throughout the path of motion. The motion for any exercise is a cycle that is counted in terms of repetitions as the motion is repeated. One full cycle starts at a beginning position, transitions to the midpoint position, and ends back into the beginning position. A simplified way to define the working envelope for an exercise is to record the position of the point of load application at the three positions during a repetition for an exercise. A complete definition of the working envelope requires specification of the starting stance and posture for each exercise. For the most part, exercises can be performed in a single plane of action, but others introduce more three-dimensional motion with smaller out of plane movements. Mock-ups and computer models can assist with dynamic motion validation and confirm that proper Exercise Techniques are accommodated. The loading scheme for free weights introduces inertial loads due to acceleration and deceleration of mass as well. With an understanding of the expected range in load settings, engineers can factor in the dynamics for a particular exercise and design mechanisms that administer representative inertial loads from free weights on the human.

Extracting Engineering Parameters from Exercise Techniques

At JSC, the Astronaut Strength Conditioning and Rehabilitation (ASCR) group provides instruction on proper Exercise Techniques. The Exercise Techniques for crewmembers follow the general suggestions of strength conditioning reference books.[2] Excerpts from these reference books explain how supports are needed to protect posture and stability during exercise. ASCR support and NASA standards documents provide information for the mounting interface between astronauts and the resistive exercise device. ASCR-recommended Exercise Techniques illustrate the proper positions of the feet, arms, torso, neck, and head. At the same time, the International Space Station Flight Crew Integration Standard provides all anthropometrics information to support the design of Space Station flight hardware.[4]

The ASCR group also has an extensive log of exercise performance levels to accurately predict the necessary load ranges for each exercise. For energy transfer design issues, our engineering teams want parameters on direction of load application, point or region of load application, and range of load application. Exercise Techniques from the ASCR group complement the available data on exercise loads by specifying the direction and region of application for the load setting. Given that only astronauts use the hardware on orbit, all ranges in engineering parameters come from the “largest” and “smallest” crewmember to specify the upper and lower limits for each parameter’s range of values. The values obtained by this method closely fit calculations using the NASA Standards document for anthropometric data, which presents information in percentiles for the 95th percentile American male and 5th percentile Japanese female.

Exercise cadence and posture suggestions from these Exercise Techniques provide constraints on the boundary displacement dynamics of the astronaut-resistive exercise device interface. Mock-ups provide visual and operational evidence of compliance with Exercise Techniques. For dynamics in load settings, the inertial loading mechanism relies on dynamic position information at a given load setting to introduce inertial loads during exercise. Additionally, when Exercise Techniques require movements that travel out of a single plane of action, engineers need an additional explanation of the out-of-plane movements for these exercises. All exercises, whether planar or three-dimensional, require a base reference coordinate system to define measurements of positions in x, y, and z directions.

The requirements for the Resistive Exercise Device in CHeCS countermeasures system reference a document with quantified parameters for engineering design teams. The Resistive Exercise Parameters Document includes all exercises, or variations thereof, on separate pages with sections that present the muscle groups that are exercised, images of the exercise using free weights, parameters for exercise performance, and a description of proper Exercise Techniques.[5] The layout for these sections describing a sample exercise is shown here in Figure 2.

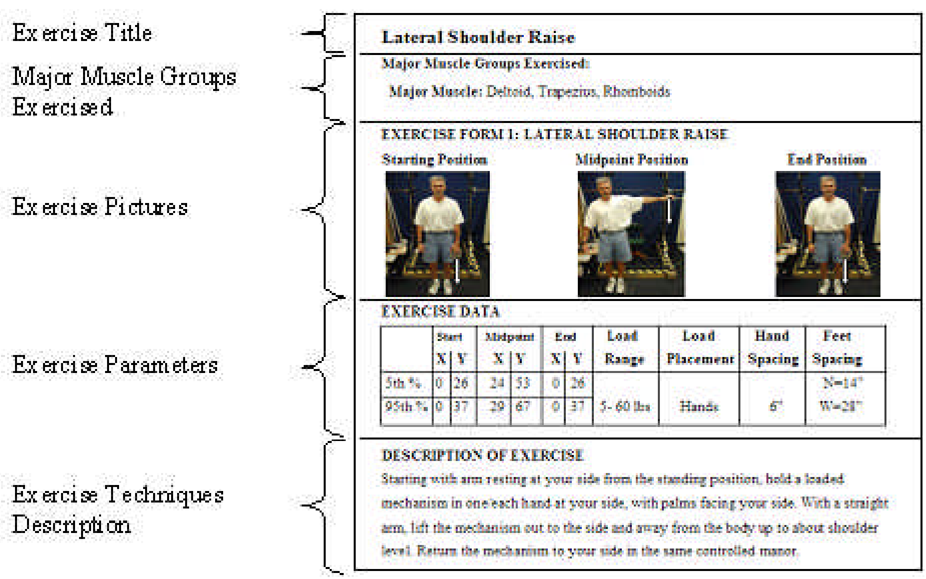

Figure 2: Sample Layout of Resistive Exercise Parameters Document

Immediately following the Exercise Title, the Major Muscle Groups Exercised section lists the primary muscle groups that the featured exercise isolates. When applicable, secondary muscle groups are listed as well. Next, the Exercise Pictures section shows planar motion for the exercise with still shots at the starting position, midpoint position, and end position. Superimposed upon the pictures, load application arrows show the orientation of the load application in the vicinity of the proper load application region. The arrow relates to the position and direction of the load that the Resistive Exercise Device should accommodate. The Exercise Parameters section quickly displays a great deal of information that engineers can use directly to begin modeling mechanisms that a crewmember will interface with. The load range explains the capacity of the resistive loading module that is required to support the exercise. Load placement identifies the region of a crewmember's body that must bear the resistance of the loading mechanism. With respect to the ground and centerline of the human body, the exercise data chart provides the position of the load application region at the moments presented by the pictures in the previous section. Row headings point out the upper and lower bounds as 5^{th} % and 95^{th} %. The hand and feet spacing values help to define requirements at the mounting interface where a crewmember must interface with the Resistive Exercise Device. Certain exercise variants call for a single-leg stance, and the value placed under feet spacing reflects the width of the foot. For regular stances, the value reflects the distance between the outside edges of the feet under the categories of narrow (N) and wide (W). The designation of these categories reveals crewmember variation in size and Exercise Technique. The same is true for the hands spacing category regarding single-handed or two-handed grip. Lastly, the Exercise Techniques Description section provides commentary on exercise form, style, posture, and safety.

Conclusion

Exercise parameters are vital for engineering design and development. For validation and reliability purposes, quantifiable measurements justify the performance level of hardware. In order to define these exercise parameters, the Combined System Definition and Exercise Techniques established the baseline to define our challenge of designing a Resistive Exercise Device. The first conjecture was that Exercise Techniques, the proper exercise forms and styles, are a standard and uniform practice. Using the Combined System Definition, the internal human-machine interface design issues included mounting the human to the machine, viewing exercise as an energy transfer between the human and machine, and dynamic issues with the mounting interface and energy transfer conditions. The methodology for defining engineering parameters presented under the Combined System Definition section is explained for general applications, whereas the section on Extracting Engineering Parameters is focused on space applications. Figure 2 demonstrated a sample layout of exercise parameters as found in the Resistive Exercise Parameters Document. The layout provided an exercise explanation with the Exercise Pictures and Exercise Techniques Description sections similar to the storyboarding technique used in movie productions. With the addition of the Engineering Parameters section, the layout serves as a powerful overview on Exercise Techniques that engineers can directly apply to the hardware design process.

Despite the many design guidelines that stem directly from Exercise Techniques, other requirements on vehicle allocations and logistics create conflicts or trade offs. The design process requires sound judgment by project managers and team leaders to decide how to resolve conflicts. As another challenge, ground-based mock-ups cannot prove a device's ability to accommodate proper exercise techniques in space. We must remember that manned space flight implies that human health is an area that is equally critical for our ability to continue in the business of space exploration.[6] More research and understanding of crew health maintenance through exercise will allow us to venture further out into the space environment and bring back information to help discover the origins of life and the potential for our future in space.

References

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