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Advanced Resistive Exercise Device (ARED) Man-In-The-Loop Test (MILT)

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National Aeronautics and
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Johnson Space Center
Houston, Texas 77058-3696

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ACRONYMS

AIB	ARED Instrumentation Box
ARED	Advanced Resistive Exercise Device
CPHS	Committee for the Protection of Human Subjects
DAQ	Data Acquisition
iRED	Interim Resistive Exercise Device
ISS	International Space Station
JSC	Johnson Space Center
MCC	Mission Control Center
MILT	Man in the Loop Test
NASA	National Aeronautics and Space Administration
PC	Personal Computer
ROM	Range of Motion

INTRODUCTION

The interim Resistive Exercise Device (iRED) is currently being flown aboard the International Space Station (ISS) to mitigate the loss of muscle mass and muscular strength associated with long-duration exposure to microgravity. However, iRED is limited in the maximal loads that it can provide, and thus, is viewed as an interim solution to the loss of muscular strength. Thus, NASA has initiated the design and construction of the Advanced Resistive Exercise Device (ARED), shown in Figure 1, as a long-term solution to the preservation of muscle strength during extended habitation of microgravity environments.

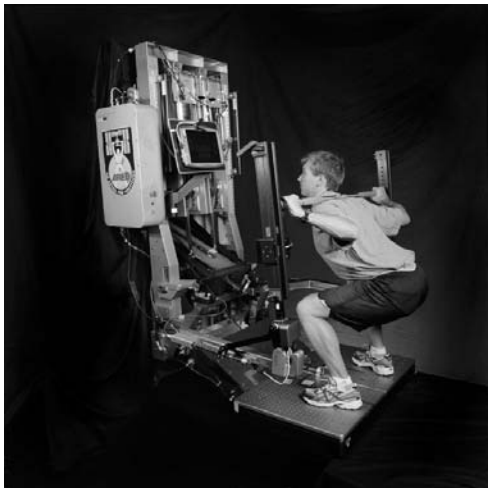

Figure 1. Subject performing squat exercise on ARED.

The ARED is designed to provide greater exercise capability than iRED. The primary resistance mechanism in the ARED is a pair of vacuum cylinders containing pistons (Figure 2).

Figure 2. ARED vacuum cylinders.

Resistance is provided by the movement of pistons within the vacuum of the cylinders. The piston rods are attached to an arm base assembly, which acts as a lever arm when the main arm assembly is moved (Figure 3).

In addition, ARED is fitted with a second resistance mechanism. This mechanism is a flywheel assembly that rotates as the arm base assembly is moved. This function provides an inertial load which, when moved, mimics the inertial load of a free-weight.

Resistive load can be changed by turning a load adjustment handle that will move the attachment point of the piston rods, thereby changing the length of the lever arm. The lever is able to provide loads ranging from 0 to 600+ pounds. ARED can be configured to provide exercises using the lift bar or the exercise cable. Using the cable, the loads are limited to a maximum of 150 pounds.

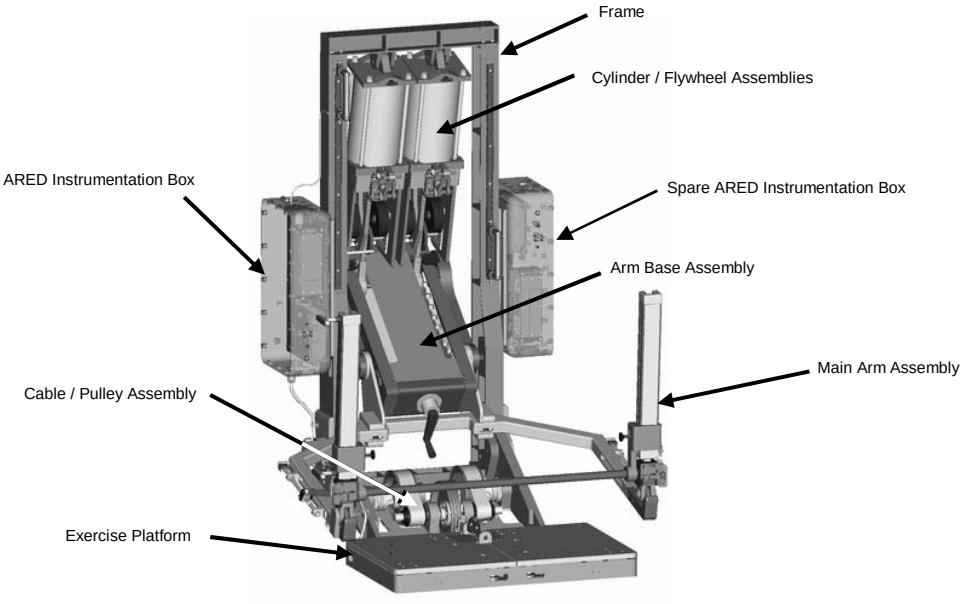

Figure 3. Diagram of ARED.

A major feature of ARED is the instrumentation system. This system includes tri-axial force sensors located in the exercise platform that are able to record force in three dimensions. In addition, load sensors in the main lift arm and the arm base assembly measure unidirectional forces. The arm base assembly also has rotational sensors that record the range of motion of the arm.

In flight, force data will be sent to the ARED Instrumentation Box (AIB) and recorded using the ARED tablet personal computer (PC). This computer will have a user interface that allows exercise prescriptions to be sent from the Mission Control Center (MCC) at JSC to the ARED tablet PC. The exercise prescription will be automatically loaded into an individual crewmember profile. The profile will be accessed during exercise sessions. During exercise, the load and number of repetitions will be simultaneously recorded and displayed on the tablet PC. On ISS, the recorded data will be automatically downloaded to an on-station server, and then down-linked to the MCC.

Preliminary life cycle testing indicates that the ARED will endure over one million cycles without critical failure. However, life cycle testing is much different than human subject testing. Often, humans put unique forces on devices that are not present during machine testing. Thus, the purpose of this evaluation was to test the functionality, durability and reliability of the ARED during exercise executed by human subjects. The objectives of the evaluation were: 1) to complete a five-month exercise protocol similar to one that would be performed on orbit by a six-person crew, 2) to determine the practicability of performing exercises listed in the Resistive Exercise Description Document (JSC-29558) by both male and female subjects, and 3) to discover potential hardware and software issues so changes may be implemented either during the course of the MILT or before the ARED enters the final flight manufacturing process.

METHODS

Subjects:

Forty-three people (30 male, 13 female) served as test subjects. Eight of the subjects had prior experience exercising on iRED. All subjects passed a modified Air Force Class III physical examination and signed a layman's summary and informed consent. The Committee for the Protection of Human Subjects at Johnson Space Center (JSC) approved the test plan.

Protocol:

Throughout the evaluation, most subjects exercised from two to four times per week. The duration of each exercise session was approximately 60 minutes. During the first two weeks, resistance settings were low to allow novice subjects to adapt to regular resistive conditioning. After the subjects were able to comfortably perform an exercise at a given load, the resistance settings were increased. During each exercise session, subjects followed an exercise prescription written for one of six hypothetical crewmembers. During each exercise session, subjects performed a designated set of core and auxiliary exercises (Table 1). Emphasis was placed on performance of the core exercises.

Table 1. Exercises performed during the ARED MILT (core exercises are listed in bold).

squat	one-arm cable row
single-leg squat	bicep curl
heel raise	front arm raise
single-leg heel raise	lateral arm raise
dead lift	shoulder shrugs
straight leg dead lift	shoulder press
lunge	bench press
hip abduction/adduction	triceps extension
hip flexion	triceps press-down
hip extension	upright row
bent-over row	wrist curl

Sets and repetitions were assigned according to a typical periodization scheme prescribed by the Astronaut Strength Conditioning and Rehabilitation (ASCR) group. The mesocycle shown in Table 2 was repeated every 8 weeks of the evaluation.

Table 2. Typical mesocycle for the ARED MILT.

Week	Sets	Reps	Intensity
1	4	8-12	Low
2	4	8-12	Medium
3	4	8-12	Medium
4	4	8-12	High
5	4	6-8	Low
6	4	6-8	Medium
7	4	6-8	Medium
8	4	6-8	High

Exercise Data Logging and Analysis:

During each exercise session, the type of exercise, load, and total repetitions were recorded and tabulated in a customized Microsoft Visual Basic program. Microsoft Access was used to create a database of each exercise session. Following each exercise session, subjects were asked to complete a questionnaire (see Appendix A) to evaluate each exercise they performed on ARED and to comment on the use of ARED. The results of the questionnaire and the comments were recorded in a database.

Load Verification:

Resistance provided by the ARED was changed by adjusting the number of turns on the load adjustment handle between 0 (lowest resistance) and 80 (highest resistance) revolutions. A calibrated load chart provided the load in pounds based on the number of turns on the ARED load adjustment handle. This chart was periodically validated during the course of the evaluation. The loads from this chart were compared to the loads displayed by the ARED instrumentation system during exercise sessions allowing users to report discrepancies and potential instrumentation issues.

RESULTS

During 22 weeks of evaluation, 43 subjects performed a total of 159,000 repetitions during 752 exercise sessions. An average of 7631 ± 2873 repetitions were performed each week, and the maximum number of repetitions completed in one week was 13,621 (Table 3). Average and standard deviation (SD) of daily repetitions was 1444 ± 418 with a daily maximum total of 2654 repetitions.

Table 3. Date and accumulated repetition number.

Date	Cycles From Prior Date	Accumulative Cycles
05/01/2005	0	0
05/20/2005	21646	21646
05/27/2005	8725	30371
06/03/2005	6391	36762
06/10/2005	8298	45060
06/17/2005	7156	52216
06/24/2005	7246	59462
07/08/2005	11649	71111
07/15/2005	7348	78459
07/22/2005	13621	92080
07/28/2005	8113	100193
08/03/2005	6171	106364
08/12/2005	13073	119437
08/19/2005	6880	126317
08/26/2005	7272	133589
09/02/2005	7753	141342
09/09/2005	4535	145877
09/16/2005	6933	152810
09/23/2005	2500	155310
09/30/2005	3690	159000

Subjects performed an average of 176 repetitions per session, with a range of 40 to 400 repetitions per session. Core exercises totaled 80,965 repetitions, or 50.9% of the total repetitions, while the auxiliary exercise totaled 78,035 repetitions, or 49.1% of the total (Table 4).

Table 4. Number of core and auxiliary exercises (bar and cable) performed.

Core Exercises	Cycles	Auxiliary Bar Exercises	Cycles
Squat	22532	Bench Press	15452
Deadlift	15182	Bent Over Row	17355
Heel Raise	15694	Bicep Curl (bar)	842
Single-Leg Heel Raise	7508	Lunge	1376
Single-Leg Squat	11665	Shoulder Press	12273
Straight-Leg Deadlift	8384	Shrugs	5693
		Single-Arm Deadlift	611
		Upright Row	8063
		Wrist Curl	552
		Auxiliary Cable Exercises	**Cycles**
		Anterior Shoulder Raise	935
		Bicep Curl (cable)	2322
		Rear Shoulder Raise	592
		Hip Abduction	1299
		Hip Adduction	1153
		Hip Flexion	566
		Hip Extension	1464
		Lateral Arm Raise	1074
		One-Arm Cable Row	3346
		Tricep Extension	1286
		Tricep Pulldown	1781

Prior to the evaluation, a prescription was written for six hypothetical crewmembers by the ASCR group. The prescriptions written were for six trained crewmembers ranging from 5^{th} to 95^{th} percentile in size. This prescription predicted that 122,400 repetitions would be performed on ARED over a 16-week period. Figure 4 shows a graphical comparison of the repetition versus load distribution between the prescribed exercise and the actual exercise performed on ARED. In general, the distribution of loads lifted during the MILT tended to be slightly lower than predicted by the prescription. This may be due to the use of subjects inexperienced with lifting exercises and resistance conditioning.

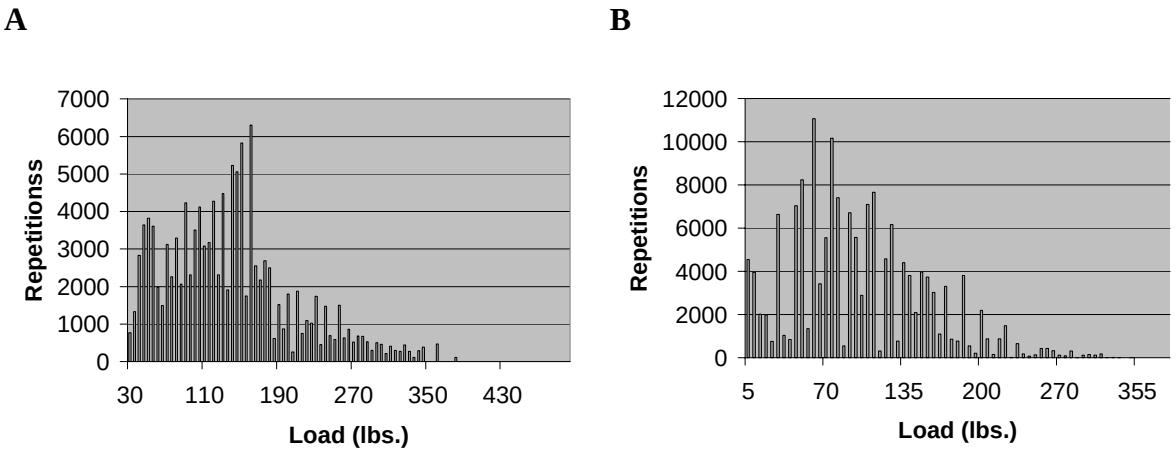

Figure 4. Repetition versus load distribution for (A) prescribed and (B) actual exercise performed on ARED.

Questionnaire Results:

Subjects were given a questionnaire (Appendix A) following every exercise session. In general, subjects felt that the exercises were fairly easy to configure, comfortable to perform, and that they could maintain proper form. Subjects also expressed that the device felt smooth and balanced, and that the exercises felt similar to free-weights. Table 5 shows the majority response to the following six statements as they apply to each exercise performed (the raw data are contained in Appendix B):

1. Exercise was easy to set up and configure.
2. I felt comfortable performing the exercise on the device.
3. It was easy to maintain proper form during the exercise.
4. The device felt smooth throughout the range of motion.
5. The concentric and eccentric loading felt balanced (equal).
6. Exercise felt similar to free-weights.

Table 5. Majority response per exercise performed. SD = Strongly Disagree; D = Disagree; NDA = Neither Disagree or Agree; A = Agree; SA = Strongly Agree

Exercise:	Statement:					
	1	2	3	4	5	6
Bench Press	NDA	A	A	SA	SA	A
Bent Over Row	A	A	A	SA	SA	A
Bicep Curl – Bar	A	A	A	SA	A	A
Bicep Curl – Cable	A	A	A	A	A	A
Cable Rear Shoulder Raise	A	A	A	A	A	A
Deadlift	A	A	A	SA	SA	A
Anterior Arm Raise	A	A	A	A	A	A
Heel Raise	A	A	A	SA	SA	A
Hip Abduction	A	A	A	A	A	A
Hip Adduction	A	A	D	A	A	A
Hip Extension	A	A	A	A	A	A
Hip Flexion	A	A	A	A	A	A
Lateral Arm Raise	A	A	A	A	A	A
Lunge	A	SA	A	A	SA	SA
One Arm Cable Row	A	A	A	A	A	A
Single Leg Heel Raise	A	A	A	A	A	A
Single Leg Squat	A	A	A	A	SA	A
Shoulder Press	SA	A	A	A	SA	A
Shrugs	SA	SA	A	SA	SA	A
Single Arm Deadlift	SA	A	A	A	A	A
Squat	SA	A	A	SA	SA	A
Straight-leg Deadlift	SA	A	A	A	SA	A
Tricep Extension	SA	A	A	A	A	A
Tricep Pressdown	SA	A	A	A	A	A
Upright Row	SA	A	A	A	A	A
Wrist Curl	A	A	A	A	A	A

As subjects gained more experience on the ARED, their opinions regarding the six statements changed with some exercises. Table 6 shows this learning curve by tracking subject's level of agreement with the six statements from sessions 1, 5, and 10; however, not all exercises were performed over 10 sessions. The exercises listed were performed over 10 sessions by at least 4 subjects.

Table 6. Questionnaire results from sessions 1, 5, and 10. Numerical results represent the subject's average (mean) level of agreement: 1 = Strongly Disagree; 2 = Disagree; 3 = Neither Disagree or Agree; 4= Agree; 5 = Strongly Agree.

Exercise:		Statement:					
		1	2	3	4	5	6
Bench Press	Session 1	3.8	3.8	3.7	4.2	4.3	3.8
	Session 5	4.1	4.2	4.1	4.4	4.4	4.2
	Session 10	4.2	4.5	4.5	4.5	4.5	4.3
Bent Over Row	Session 1	3.9	4.0	3.8	4.0	4.1	3.5
	Session 5	4.4	4.4	4.2	4.3	4.5	4.2
	Session 10	4.4	4.3	4.3	4.4	4.4	4.3
Deadlift	Session 1	3.7	3.9	3.8	4.3	4.5	3.6
	Session 5	4.3	4.3	4.3	4.5	4.5	4.2
	Session 10	4.4	4.4	4.4	4.5	4.6	4.5
Heel Raise	Session 1	3.7	3.4	3.2	3.9	4.2	3.7
	Session 5	4.2	4.1	4.0	4.2	4.2	4.0
	Session 10	4.1	4.0	4.1	4.2	4.2	3.9
Single Leg Heel Raise	Session 1	4.0	3.4	3.4	4.1	4.3	3.9
	Session 5	4.4	3.8	3.6	4.1	4.3	3.9
	Session 10	4.8	4.6	4.6	4.8	4.8	4.6
Single Leg Squat	Session 1	4.0	3.6	3.6	4.2	4.4	3.8
	Session 5	4.5	4.0	4.1	4.5	4.4	4.1
	Session 10	4.6	4.4	4.4	4.4	4.6	4.3
Shoulder Press	Session 1	3.9	4.0	4.0	4.2	4.3	4.1
	Session 5	4.3	4.2	4.3	4.3	4.4	4.1
	Session 10	4.4	4.3	4.5	4.5	4.4	4.2
Shrugs	Session 1	4.1	4.0	4.0	4.3	4.4	3.9
	Session 5	4.6	4.7	4.7	4.8	4.8	4.7
	Session 10	4.8	4.8	4.5	4.8	4.8	4.8
Squat	Session 1	3.9	4.1	4.0	4.1	4.3	3.8
	Session 5	4.3	4.2	4.2	4.4	4.4	4.2
	Session 10	4.4	4.5	4.5	4.6	4.6	4.5
Straight-leg Deadlift	Session 1	4.2	4.2	4.1	4.4	4.4	4.1
	Session 5	4.4	4.4	4.4	4.5	4.5	4.2
	Session 10	4.7	4.5	4.5	4.7	4.7	4.3
Upright Row	Session 1	3.9	3.8	3.6	4.0	4.2	3.9
	Session 5	4.2	4.2	4.2	4.3	4.3	4.2
	Session 10	4.7	4.3	5.0	5.0	5.0	4.7

Subjects also provided feedback regarding the general use of ARED (Table 7).

Table 7. General questionnaire results listed by percentage of response.

Statement:	ARED was easy to set up (n = 112)	Control panel was easy to use (n = 265)	Overall, ARED performed well (n = 266)
Strongly Disagree	2%	2%	0%
Disagree	1%	4%	2%
Neither Agree or Disagree	23%	3%	7%
Agree	73%	36%	48%
Strongly Agree	1%	55%	43%

ARED Hardware Issues:

The MILT identified a number of hardware issues. (See Table 8 for a summary of hardware issues.)

1. **Uncontrolled spin of load adjustment handle.** Prior to the start of the MILT, the ARED engineering team determined that the loading handle (see Figure 5) was not performing the way it was expected. It was originally designed for single-handed operation, where if the user accidentally let go of the handle while adjusting the load, a spring would cause the handle locking pins to engage. However, if the handle did not lock in place, it would freely spin and could cause damage to the hardware and potentially an injury if the user tried to stop the handle from spinning. The only workaround for this during the MILT was operational: the user needed to use two hands while adjusting the load. This worked out fine for the MILT, but engineering has made changes to the flight design.

Figure 5. Load adjustment handle.

2. **Ineffective bar racking indicators.** One of the first issues discovered during the MILT were the ineffective racking indicators that alert the subject as to when the bar is in the racked position on the upper stops. These are used during certain exercises such as squats and heel raises. The engineering team developed and implemented new indicators (Figure 6) that are easily viewed by the subject.

Figure 6. Racking indicator.

3. **Slippage of heel block.** Since the ARED heel block had not yet been developed, we used a wooden model for a heel block. However, the base of the heel block did not adhere to the ARED platform very well. To remedy this, a thin layer of non-slip foam was added to the base of the heel block. This was adequate to prevent slippage during exercise. However, it should be noted that the flight design for the heel block will attach to the platform and will not be able to slip.

4. **Bar height adjustment pins.** Another issue that occurred as the MILT progressed was that the bar height adjustment pins (Figure 7) were difficult to fasten. This resulted from an inadequate tolerance between the pin and the receiving hole. The pin would also occasionally only partially engage, causing the bar to slip when it was lifted. This issue was resolved by resizing the receiving holes, adding some lubrication, and an indicator was added to the mechanism allowing subjects to determine if the pin had fully engaged.

Figure 7. Bar height adjustment pin.

5. **Cable Slack.** One issue that was not resolved during the course of the MILT was the excess slack in the exercise cable (Figure 8). This affected some of the cable exercises since the range of motion was limited (e.g., hip abduction and adduction). The cause of the problem was an incorrect cable length; unfortunately, a cable of the correct length was not able to be installed before the conclusion of the MILT. However, this will be implemented prior to flight.

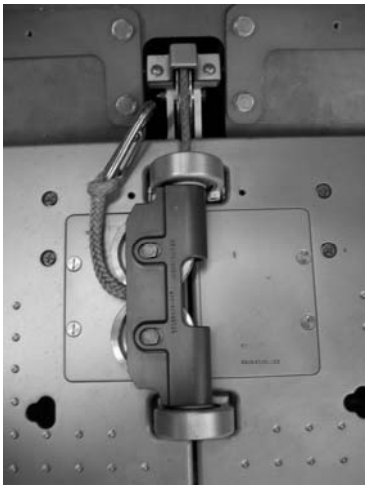

Figure 8. Cable slack.

6. **Failure of left racking mechanism.** Occasionally, the racking mechanism (Figure 9) on the left side would not engage properly. The cause of this issue was that the design tolerances in the mechanism were not correct. By adding some lubrication to the cable inside the mechanism, the problem was alleviated; however, a design change will be necessary before flight production begins.

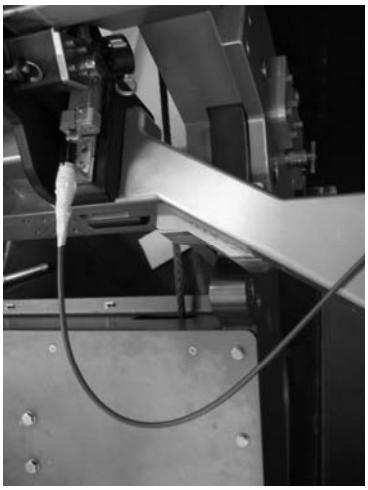

Figure 9. Racking mechanism.

7. **Cable exercises difficult to perform.** In order to perform bar exercises on ARED in 1-g, counterweights were added to the arm base that offset the weight of the bar. However, this caused issues with cable exercises due to excess friction in the system. Even though this problem is only applicable to 1-g ARED use, it is worth mentioning that in order to perform cable exercises correctly, it was necessary to remove the counterweights. They were reattached for bar exercises.

Table 8. Summary of ARED hardware issues during MILT.

Issue	Cause	Resolution
1. Uncontrolled spin of load adjustment handle if accidentally released	Spring-loaded locking pin does not function correctly	Two-handed operation while adjusting loads; flight design changed to improve locking mechanism
2. Ineffective bar racking indicators	Poorly designed indicators	Better indicators designed, manufactured, and installed; flight design includes new indicators
3. Slippage of heel block on the metal platform	Wooden block did not adhere well to the smooth metal platform surface	Thin foam added to the heel block providing ample friction; flight design uses different heel block
4. Bar height adjustment pins were difficult to adjust	Tight tolerance and sub-optimal interface between pin and hole	Tolerance adjusted, pins lubricated, and locking indicators added to the pins; tolerances adjusted and indicators added to flight design
5. Slack in the exercise cable	Incorrect cable length	Unresolved for prototype; flight version will have correct cable length
6. Failure of left racking mechanism to engage	Tight tolerance in the manufacturing of the mechanism	Cable and mechanism adjusted and lubricated; flight design changed to allow greater tolerance
7. Some cable exercises difficult to perform	Increased friction from 1-g counterweight system	Counterweights removed for cable exercise; issue only in 1-g, flight version does not use counterweights

ARED Software Issues:

The MILT identified a number of software issues. (See Table 9 for a summary of software issues.)

1. **Accidental opening of programming window.** One of the first issues noticed by subjects was that the software displayed two windows on the taskbar while running. One window was the user interface, while the other was the programming window. The programming window was normally minimized, but if the user accidentally touches this window on the taskbar, they are not able to revert back to the interface window. This required the user to reboot the computer. This issue was resolved by automatically hiding the taskbar.
2. **Exercise sets at the end of the set list were not completed.** In order to make the interface more user-friendly, subjects requested that the exercise lists in the prescription window automatically scroll as exercise sets are completed. Without this feature, some subjects did not see the last line on the exercise prescription unless they scrolled down the list. This was resolved by incorporating an auto-scroll feature with an updated version of the ARED software.
3. **DAQ failure.** Occasionally when the software was running, an error would occur in the data acquisition (DAQ) modules within the AIB. This would cause the software to suspend normal activity and the recording of erroneous data. The user was often not aware a problem had occurred until at least one set of exercise was completed. Although the cause of the DAQ error was not resolved during the

MILT, a work around was implemented by updating the software. In this update, when an error did occur, a warning window and a set of procedures was displayed. The procedure instructed the use to cycle the power on the computer and the AIB.

4. **Software would not count repetitions.** The ARED software was designed to count repetitions as they were performed within an exercise set. However, this function did not initially work for several exercises (e.g., heel raise, cable row, bicep curl, shrugs, and tricep extensions). The cause of this was two-fold: 1) the displacement sensor reference point was set incorrectly within the software, and 2) threshold values, that is the level of bar or cable displacement necessary for the system to recognize the movement as a repetition, were incorrect for some exercises. Both of these issues were resolved during the MILT.
5. **Start/stop accidentally "double-clicked."** There was a tendency for the tablet computer, which was mounted on a bogen arm, to slightly bounce when the start button was pressed causing it to spring back and impact the user's fingertip. Since the computer registered an accidental "double-click," this would cause the software to stop collecting data. A software update was made which disabled the stop button for a few milliseconds so the "double-click" problem was avoided.
6. **Users forgot to press Start button.** Data collection was frequently not initiated because subjects would forget to manually press the start button. A flashing border was added to the start button to act as a reminder to the subjects to initiate data collection prior to initiating the exercise set.
7. **Incorrect selection of exercise from drop-down menu.** On some occasions, subjects would select the wrong exercise from the "drop-down" menu. This occurred because the height of the menu option was smaller than the width of the subject's finger, and thus required precision in selecting the exercise option (Figure 10). ARED software engineers solved this problem by making the selection height for the menu options larger and better able to accommodate larger fingers. However, this was not implemented before the completion of the ARED MILT, but was to be installed in the flight version of the software.

Figure 10. Exercise drop-down menu.

8. **Incorrect loads displayed.** On occasion, the software would display incorrect loads. The main cause was due to the lift arms occasionally impacting the main arm pivot lug causing damage to the sensors located in the lift arm (Figure 11). This was avoided during the MILT by having the spotters hold the lift arms vertical during the execution of certain exercises to prevent contact between the main arm pivot lug and the load sensors. Since holding the lift arm was possible during the MILT, the sensors functioned properly and correct loads were displayed. However, engineering is currently investigating design changes that would eliminate this problem.

Figure 11. ARED lift arm shown with load cell and pivot lug.

Table 9. Summary of ARED software issues during MILT.

Issue	Cause	Resolution
1. Accidental opening of programming window forcing user to reboot	Programming window accidentally touched on taskbar	Taskbar set to auto-hide; flight software also updated with this change
2. Exercise sets at the end of the set list are not completed	Users forget to scroll down to see last sets of exercise	List will automatically scroll as sets are completed; flight software was updated with this feature
3. DAQ failure causing software malfunction	Failure of DAQ board in AIB (cause is still being investigated)	Software set to display dialogue with instructions upon failure detection; flight software also updated
4. Software would not count repetitions for certain exercises	Incorrect sensor reference point and incorrect thresholds	Sensor reference point fixed and correct thresholds were set for all exercises; flight software updated
5. Start/stop accidentally "double-clicked" causing data loss	PC mounted on bogen arm bounced back on user's fingertip	Start button set so that stop function is not immediately functional; flight software also updated
6. Users forget to press start before exercise	Software requires manual start and novice users easily forget	Start button updated with a flashing border as a reminder for users; flight software updated
7. Incorrect exercise selected from drop-down menu	Drop-down menu options too small in size	Menu options will be larger in the updated flight software version
8. Incorrect loads displayed in software	Forceful contact of main arm pivot lug and load sensors	Spotters held lift arms to prevent contact; flight unit still undergoing changes to prevent this

Subject Comments:

After each exercise session, subjects were asked to make comments about the use of ARED, including the setup of the hardware, the user interface and software, the exercise bench, the heel block, and the overall performance of ARED. Responses were summarized in the following paragraphs.

Setup: The hardware is very easy to configure for bar exercise. The adjustments needed to convert the ARED from bar to cable exercises are somewhat cumbersome in a 1-g environment because the counterweights on the rear of the ARED needed to be removed. However, this will not be necessary in the weightless environment of space.

Some subjects felt that there should be markings on the hardware to identify where the bench and the heel block should be placed. This was identified during the early stages of the MILT, and indicators for placement of the bench and the heel block have since been added to the ARED.

It took about three sessions to determine each subject's proper bar height for exercises such as squat and heel raise. Most subjects remembered their settings for these exercises, but comments were made that it would be helpful if users could enter this information into their computer profile and have them appear when the exercises are selected from the menu.

Control Panel: Some subjects disliked having to press the start/stop button before and after each set. They felt it was tedious and difficult to perform in 1-g when performing certain exercises. Others thought it was difficult to remember to press the button before each set. A flashing green border was added to the "Start" button to remind users to press start, but some subjects still had to be reminded prior to beginning exercise while others found it to be an annoyance.

Some of the taller test subjects had a difficult time using the control panel during heel raise. They had to move the computer off to the side to refrain from hitting the lift bar against it when racking and un-racking the bar. This was frustrating because they were unable to see the progress they were making with their repetitions and loads. However, since the bogen arm holding the computer was not a flight version, it was not possible to determine if this would be a problem in flight.

The ARED software allows subjects 5 minutes between sets before the subject is automatically logged out. Some subjects felt that the auto-logout time should be longer since it was frustrating to have to re-login after short breaks. Also, comments were made that a timer should be added so users can keep track of the rest time between sets.

Exercise Bench: Even though the flight bench was not used for the MILT, the bench used did closely approximate the height of the flight bench. Subjects felt that the exercise bench was a good height and that it was easy to get in and out of while performing bench press and shoulder press.

Heel Block: The ARED team attempted to determine the appropriate placement of the heel block; however, some subjects felt more comfortable with the heel block further forward on the platform than others. It was difficult for some subjects to keep balance during heel raise. Many balance issues were corrected by changing the height of the lift bar.

Written Procedures and Familiarization Sessions: Subjects requested more visual aids for certain exercises and configurations. It was difficult during the first few sessions for some subjects to remember which direction the lift bar should face and what height it needed to be.

Subjects requested that comprehensive procedures be developed for converting between bar and cable exercises. Also, some subjects felt that the cable pulley assembly posed a tripping hazard in some instances while standing on the platform.

Overall Performance of ARED: Overall, ARED received good reviews from all subjects. Many issues were identified and corrected during the MILT. However, not all issues could be resolved.

Many subjects felt that the exercise platform on ARED was too small to perform some of the exercises. For example, it was very difficult or impossible to perform hip adduction and lunges, especially for taller subjects. In addition, some subjects found it difficult to find the correct bar height; however, once the proper bar height was determined, the ARED felt smooth and comfortable.

Some exercises felt awkward since they required a combination of balance and strength (i.e., heel raise, squat, single leg exercises). These exercises required greater assistance from spotters in the beginning of the MILT, but as the subjects became trained in the use of ARED, they required little or no assistance from the spotters.

DISCUSSION

During the ARED MILT, the hardware did not experience any major malfunction that would prevent subjects from being able to perform resistive exercise. However, a number of hardware and software issues were discovered, allowing improvements and updates to be made before ARED enters final flight production.

In general, subjects felt that ARED workouts were vigorous and would be beneficial to gaining strength. Those with free-weight exercise experience felt that the ARED workout was, in many respects, similar to free-weights. Those with experience on iRED immediately noted the increased capability of ARED and felt that ARED was a closer analogue to free-weight exercise.

One question is how the repetition-load profile of the ARED MILT compares with the profile for iRED on ISS. Figure 12shows the repetition-load profile for exercises performed on iRED from ISS Expedition 1 through Expedition 11. This distribution shows uniformity in repetitions across loads from 30 to 305 lbs. This is likely due to differences in prescriptions among expeditions, load limitations and operational constraints, and the weightless environment which allows astronauts to lift greater loads because their body weight is zero. In contrast, the repetition-load profile for ARED (Figure 4, above) shows more repetitions being conducted from 5 to 200 lbs. This difference is likely due to the ARED MILT exercises being conducted in a 1-g terrestrial environment where one is required to lift their own body weight compared to ISS iRED exercise in microgravity. In addition, this difference could be due to more exercises of different types being performed during the ARED MILT than are normally performed on ISS.

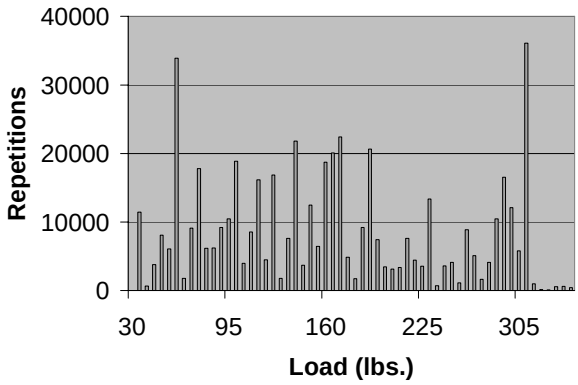

Figure 12. Repetition versus load distribution for ISS on iRED through Expedition 11 (504,243 repetitions).

Load Verification:

The ARED loads were calibrated at the start of the MILT. However, no load verifications or calibrations were conducted during approximately the first six weeks of the MILT. After delivery of the calibration tool, engineering verified the calibration of ARED approximately once per week. It is fair to note that with repeated use of ARED, there was a minimal amount of leakage that occurs within the cylinders that caused the loading capacity to diminish. However, as long as the cylinders were evacuated at least once per week, there were no major changes (in this case, major was defined as ±5 lbs.) in calibrated load. The evacuation procedure was very simple and took approximately 3 minutes to complete.

ARED has the capacity to measure load and displacement during exercise. Figure 13 shows typical load versus displacement curves for three core exercises during concentric and eccentric muscle contractions. Although the load appears fairly constant over the range of motion, there appears to be some loss of load experienced during the eccentric phases of the movements, especially when the movement of the arm exceeds about 10 inches. These curves suggest that eccentric muscle contractions will be conducted with lower force than concentric contractions. Further studies need to be conducted to verify that ARED eccentric loads are 80-90% of concentric loads.

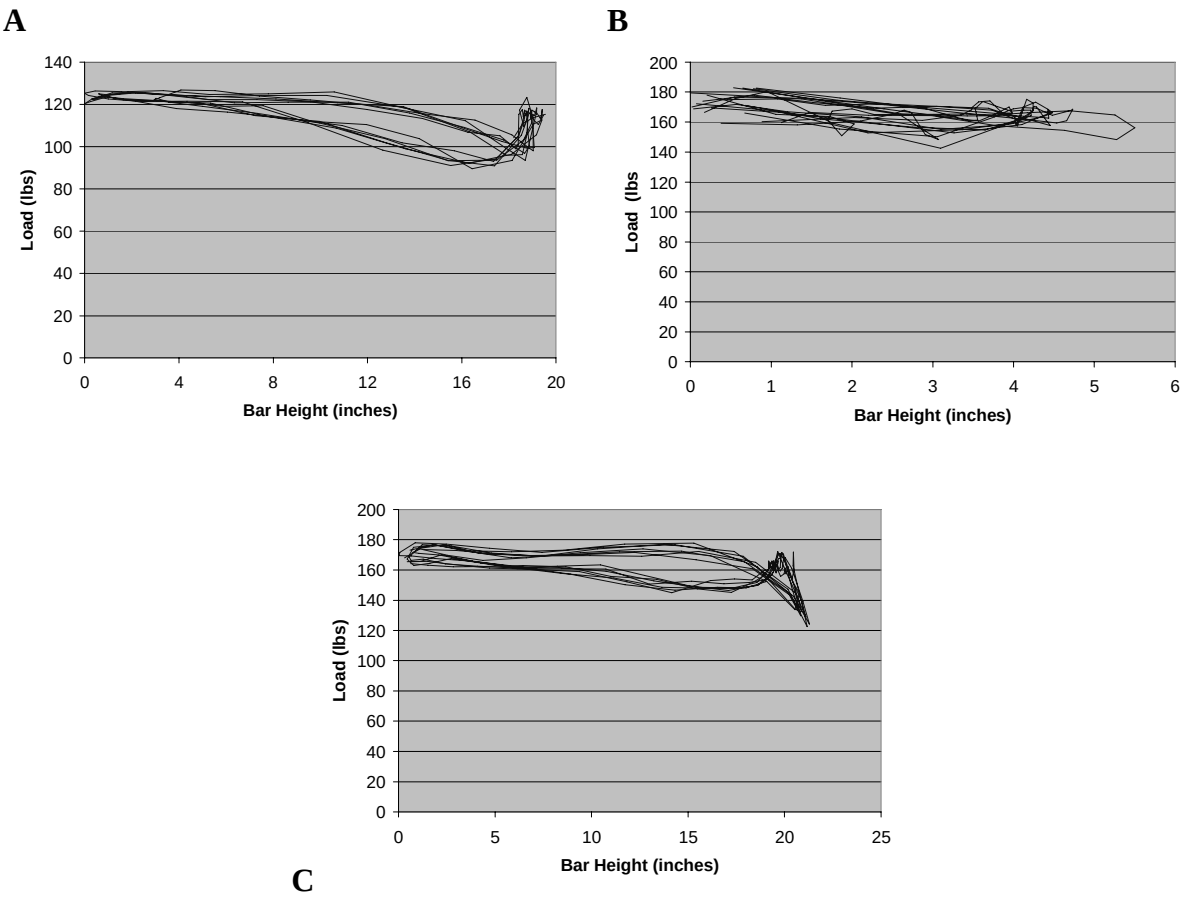

Figure 13. Typical load versus displacement curves for 3 core exercises: (A) squat, (B) heel raise, (C) dead lift.

During the course of the MILT, no subject approached the maximal load capacity of the ARED, which is approximately 600 lbs. The maximal load lifted on ARED was 425 lbs. This demonstrates the increased capability of ARED over iRED. The increased load capacity of ARED is a distinct advantage over iRED which has a maximum load capacity of 300 lbs. With iRED, once the maximal load is reached, one must increase the number of repetitions per load to achieve "overload" and potential force gains in muscular strength. This limits the application of a periodized exercise prescription.

In the ARED MILT, a few female subjects approached the 5th percentile size demographic. In general, these subjects were able to perform a typical exercise prescription including core and auxiliary exercises. However, there were some auxiliary exercises that were difficult or impossible for them to perform. Examples of these were the lateral and front arm raises and shoulder press. The inability to perform these exercises could be due to the fact that the exercise was performed in 1-g. Females in the 5th percentile size demographic may find it easier to perform these exercises in a weightless environment.

Some ARED functions could not be tested in our 1-g environment. One of these was the operation and functionality of the ARED bench. For the MILT, a modified exercise bench that supports the head and neck was used. However, the flight bench is much smaller and is only designed to support the upper and lower back.

In addition, it was not possible to determine if one subject alone could setup and operate ARED. For example, it may be difficult for one person to adjust the bar height and support of the lift arm assembly while performing exercises such as dead lifts and bench press in microgravity. Tests to determine operation of ARED by a single person must await evaluation in the C-9 reduced gravity aircraft.

CONCLUSION:

During 22 weeks of exercise using the ARED, subjects completed 159,000 repetitions. On average, subjects completed 1444 repetitions per day, 7631 repetitions per week, and 33,289 repetitions per month. During this time, there were no significant changes in the performance of the ARED.

Findings show that the ARED is durable, reliable, and meets or exceeds the requirements evaluated. The increased reliability of the ARED over current resistive exercise modalities employed on ISS could save NASA resources and crew time on orbit. In addition, the increased capability may reduce the loss of bone and muscle mass experienced by crewmembers while on board ISS. This will be examined in future studies involving the ARED.

APPENDIX A

SUBJECT QUESTIONNAIRE

Please describe each statement below as it applies to the exercises in the following table:

1 – Strongly Disagree **2** – Disagree **3** – Neither **4** – Agree **5** – Strongly Agree

Disagree or Agree

Statement #1: Exercise was easy to set up and configure.

Statement #2: I felt comfortable performing the exercise on the device.

Statement #3: It was easy to maintain proper form during the exercise.

Statement #4: The device felt smooth throughout the range of motion.

Statement #5: The concentric and eccentric loading felt balanced (equal).

Statement #6: Exercise felt similar to free-weights.

Exercises	Statement					
	#1	#2	#3	#4	#5	#6
Squat						
Heel raise						
Dead lift						
One-leg squat						
One-leg heel raise						
Straight-leg dead lift						
Lunge						
Hip abduction						
Hip adduction						
Hip flexion						
Hip extension						
Bent-over row						
One-arm cable row						
Bicep curl - bar						
Bicep curl - cable						
Front arm raise						
Lateral arm raise						
Shrugs						
Shoulder press						
Bench press						
Triceps extension						
Triceps pull-down						
Upright row						
Wrist curl						

Please respond to the following general statements using the same scale above:

ARED was easy to set up. ____

Comments: _____

_____

ARED control panel was easy to use. ____

Comments: _____

_____

Overall, ARED performed well. ____

Comments: _____

_____

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APPENDIX B

INDIVIDUAL EXERCISE QUESTIONNAIRE RAW DATA

S-1 = Statement 1: Exercise was easy to set up and configure.
S-2 = Statement 2: I felt comfortable performing the exercise on the device.
S-3 = Statement 3: It was easy to maintain proper form during the exercise.
S-4 = Statement 4: The device felt smooth throughout the range of motion.
S-5 = Statement 5: The concentric and eccentric loading felt balanced (equal).
S-6 = Statement 6: Exercise felt similar to free-weights.

SD = Strongly Disagree
D = Disagree
NDA = Neither Disagree or Agree
A = Agree
SA= Strongly Agree

Bench Press	**S-1**	**%**	**S-2**	**%**	**S-3**	**%**	**S-4**	**%**	**S-5**	**%**	**S-6**	**%**
SD	7	2%	0	0%	0	0%	1	0%	0	0%	3	1%
D	39	11%	14	4%	15	5%	5	2%	3	1%	12	4%
NDA	186	55%	14	4%	24	7%	13	4%	4	1%	32	10%
A	109	32%	161	50%	148	45%	144	44%	155	47%	147	46%
SA	0	0%	136	42%	139	43%	163	50%	165	50%	129	40%
Total	341		325		326		326		327		323	

Bent Over Row	**S-1**	**%**	**S-2**	**%**	**S-3**	**%**	**S-4**	**%**	**S-5**	**%**	**S-6**	**%**
SD	0	0%	0	0%	0	0%	1	0%	1	0%	1	0%
D	0	0%	6	1%	9	2%	9	2%	1	0%	7	2%
NDA	0	0%	19	5%	17	4%	15	4%	3	1%	34	8%
A	432	100%	222	53%	212	51%	175	42%	189	46%	201	49%
SA	0	0%	169	41%	176	43%	213	52%	219	53%	168	41%
Total	432		416		414		413		413		411	

Bicep Curl-Bar	**S-1**	**%**	**S-2**	**%**	**S-3**	**%**	**S-4**	**%**	**S-5**	**%**	**S-6**	**%**
SD	0	0%	0	0%	0	0%	1	5%	2	10%	1	5%
D	0	0%	1	6%	2	11%	1	5%	0	0%	3	16%
NDA	0	0%	1	6%	1	6%	4	21%	3	14%	2	11%
A	19	100%	10	56%	8	44%	6	32%	9	43%	8	42%
SA	0	0%	6	33%	7	39%	7	37%	7	33%	5	26%
Total	19		18		18		19		21		19	

Bicep Curl-Cable	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	2%	0	0%	4	7%	8	14%	5	9%
D	0	0%	1	2%	1	2%	10	18%	6	11%	10	18%
NDA	0	0%	2	4%	6	11%	3	5%	4	7%	7	13%
A	58	100%	32	57%	31	55%	25	45%	24	43%	23	42%
SA	0	0%	20	36%	18	32%	14	25%	14	25%	10	18%
Total	58		56		56		56		56		55	

Cable Rear Shoulder Raise	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
D	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
NDA	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
A	2	100%	2	100%	2	100%	2	100%	2	100%	2	100%
SA	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
Total	2		2		2		2		2		2	

Dead Lift	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	1	0%	0	0%	0	0%	0	0%
D	0	0%	8	2%	8	2%	3	1%	0	0%	5	1%
NDA	0	0%	17	5%	22	6%	7	2%	3	1%	37	10%
A	385	100%	216	58%	201	54%	171	46%	171	46%	195	53%
SA	0	0%	132	35%	141	38%	192	51%	198	53%	130	35%
Total	385		373		373		373		372		367	

Anterior Arm Raise	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
D	0	0%	0	0%	0	0%	1	6%	2	12%	2	12%
NDA	0	0%	0	0%	1	6%	3	18%	2	12%	2	12%
A	18	100%	15	88%	14	82%	9	53%	9	53%	11	65%
SA	0	0%	2	12%	2	12%	4	24%	4	24%	2	12%
Total	18		17		17		17		17		17	

Heel Raise	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	7	2%	7	2%	1	0%	1	0%	5	1%
D	0	0%	14	4%	17	5%	8	2%	4	1%	9	2%
NDA	0	0%	29	8%	28	7%	20	5%	11	3%	44	12%
A	392	100%	196	52%	183	49%	164	44%	173	46%	182	48%
SA	0	0%	130	35%	142	38%	184	49%	188	50%	137	36%
Total	392		376		377		377		377		377	

Hip Abduction	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	3%	1	3%	1	3%	2	5%	2	6%
D	0	0%	7	19%	8	22%	7	19%	8	22%	7	19%
NDA	0	0%	4	11%	6	16%	3	8%	2	5%	6	17%
A	38	100%	19	51%	19	51%	18	49%	17	46%	17	47%
SA	0	0%	6	16%	3	8%	8	22%	8	22%	4	11%
Total	38		37		37		37		37		36	

Hip Adduction	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	2	6%	2	6%	2	6%	3	9%	3	9%
D	0	0%	11	33%	14	42%	7	21%	8	25%	11	34%
NDA	0	0%	3	9%	4	12%	1	3%	3	9%	3	9%
A	33	100%	15	45%	12	36%	18	55%	16	50%	15	47%
SA	0	0%	2	6%	1	3%	5	15%	2	6%	0	0%
Total	33		33		33		33		32		32	

Hip Extension	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	3	9%	3	9%	1	3%	2	6%	4	13%
D	0	0%	0	0%	1	3%	2	6%	2	6%	2	6%
NDA	0	0%	2	6%	3	9%	3	9%	4	12%	4	13%
A	33	100%	20	61%	18	55%	17	52%	16	48%	15	48%
SA	0	0%	8	24%	8	24%	10	30%	9	27%	6	19%
Total	33		33		33		33		33		31	

Hip Flexion	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	6%	1	6%	0	0%	0	0%	1	6%
D	0	0%	1	6%	2	11%	2	11%	3	17%	2	12%
NDA	0	0%	2	11%	2	11%	1	6%	0	0%	2	12%
A	18	100%	13	72%	12	67%	13	72%	11	61%	11	65%
SA	0	0%	1	6%	1	6%	2	11%	4	22%	1	6%
Total	18		18		18		18		18		17	

Lateral Arm Raise	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	2	8%	0	0%
D	0	0%	2	8%	2	8%	7	27%	6	23%	9	35%
NDA	0	0%	0	0%	3	12%	3	12%	2	8%	3	12%
A	28	100%	18	69%	15	58%	11	42%	12	46%	10	38%
SA	0	0%	6	23%	6	23%	5	19%	4	15%	4	15%
Total	28		26		26		26		26		26	

Lunge	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	6%	1	6%	1	5%	0	0%	1	6%
D	0	0%	3	17%	4	22%	0	0%	0	0%	3	17%
NDA	0	0%	3	17%	2	11%	1	5%	0	0%	3	17%
A	19	100%	5	28%	6	33%	9	47%	9	50%	5	28%
SA	0	0%	6	33%	5	28%	8	42%	9	50%	6	33%
Total	19		18		18		19		18		18	

One Arm Cable Row	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	1	2%	3	5%	0	0%
D	0	0%	1	2%	2	3%	4	6%	5	8%	9	14%
NDA	0	0%	3	5%	2	3%	8	12%	4	6%	13	20%
A	69	100%	36	55%	35	54%	28	42%	28	43%	24	37%
SA	0	0%	25	38%	26	40%	25	38%	25	38%	19	29%
Total	69		65		65		66		65		65	

Single Leg Heel Raise	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	3	2%	2	1%	0	0%	0	0%	1	1%
D	0	0%	18	11%	30	18%	7	4%	0	0%	4	2%
NDA	0	0%	32	19%	26	16%	12	7%	8	5%	29	18%
A	166	100%	66	40%	60	36%	78	47%	87	52%	78	47%
SA	0	0%	47	28%	47	28%	68	41%	71	43%	53	32%
Total	166		166		165		165		166		165	

Single Leg Squat	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	1%	0	0%	0	0%	0	0%	0	0%
D	0	0%	4	3%	9	5%	2	1%	0	0%	6	4%
NDA	0	0%	4	3%	9	5%	2	1%	0	0%	6	4%
A	101	57%	91	58%	94	57%	86	50%	86	49%	98	60%
SA	76	43%	58	37%	52	32%	81	47%	88	51%	52	32%
Total	177		158		164		171		174		162	

Shoulder Press	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
D	0	0%	3	1%	2	1%	1	0%	0	0%	2	1%
NDA	0	0%	14	5%	13	5%	10	4%	6	2%	31	12%
A	0	0%	143	55%	141	54%	126	48%	126	48%	124	48%
SA	270	100%	100	38%	103	40%	123	47%	128	49%	102	39%
Total	270		260		259		260		260		259	

Shrugs	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
D	0	0%	1	1%	1	1%	0	0%	0	0%	1	1%
NDA	0	0%	5	4%	5	4%	2	2%	0	0%	8	7%
A	0	0%	55	46%	60	50%	51	43%	52	43%	57	47%
SA	125	100%	59	49%	54	45%	67	56%	68	57%	55	45%
Total	125		120		120		120		120		121	

Single Arm Dead Lift	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	5%	1	5%	1	5%	1	5%	2	11%
D	0	0%	4	21%	4	21%	1	5%	0	0%	0	0%
NDA	0	0%	3	16%	2	11%	0	0%	0	0%	2	11%
A	1	5%	6	32%	8	42%	12	63%	13	68%	10	56%
SA	18	95%	5	26%	4	21%	5	26%	5	26%	4	22%
Total	19		19		19		19		19		18	

Squat	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
D	0	0%	4	1%	7	2%	2	0%	2	0%	6	1%
NDA	0	0%	16	4%	22	5%	12	3%	2	0%	30	7%
A	0	0%	256	58%	238	54%	200	45%	202	46%	239	55%
SA	453	100%	163	37%	173	39%	226	51%	234	53%	163	37%
Total	453		439		440		440		440		438	

Straight Leg Dead Lift	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	1	1%	1	1%	1	1%	1	1%	1	1%
D	0	0%	2	1%	2	1%	0	0%	0	0%	1	1%
NDA	0	0%	2	1%	2	1%	0	0%	0	0%	1	1%
A	0	0%	107	57%	107	58%	97	51%	94	49%	104	59%
SA	196	100%	75	40%	73	39%	92	48%	95	50%	68	39%
Total	196		187		185		190		190		175	

Tricep Extension	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	2	5%	2	5%	1	3%
D	0	0%	2	5%	2	5%	5	13%	4	10%	6	15%
NDA	0	0%	5	13%	7	18%	5	13%	5	13%	8	20%
A	0	0%	19	48%	19	48%	16	40%	17	43%	14	35%
SA	43	100%	14	35%	12	30%	12	30%	12	30%	11	28%
Total	43		40		40		40		40		40	

Tricep Pressdown	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	1	4%
D	0	0%	0	0%	0	0%	1	4%	1	4%	1	4%
NDA	0	0%	2	7%	1	4%	0	0%	1	4%	3	12%
A	0	0%	16	59%	18	67%	16	59%	17	63%	16	62%
SA	28	100%	9	33%	8	30%	10	37%	8	30%	5	19%
Total	28		27		27		27		27		26	

Upright Row	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	4	2%	4	2%	4	2%	1	1%	4	2%
D	0	0%	5	3%	7	4%	6	3%	6	3%	5	3%
NDA	0	0%	13	7%	19	10%	10	5%	4	2%	20	11%
A	0	0%	99	53%	89	48%	90	49%	92	49%	87	48%
SA	113	100%	65	35%	66	36%	75	41%	83	45%	67	37%
Total	113		186		185		185		186		183	

Wrist Curl	S-1	%	S-2	%	S-3	%	S-4	%	S-5	%	S-6	%
SD	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
D	0	0%	0	0%	0	0%	0	0%	0	0%	0	0%
NDA	0	0%	1	14%	1	14%	0	0%	0	0%	1	14%
A	0	0%	4	57%	4	57%	4	57%	5	71%	5	71%
SA	0	0%	2	29%	2	29%	3	43%	2	29%	1	14%
Total	0		7		7		7		7		7	

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13. ABSTRACT *(Maximum 200 words)*
The interim Resistive Exercise Device (iRED) is currently being flown aboard the International Space Starion to mitigate the loss of muscle mass and muscular strength associated with long-duration exposure to microgravity. However, iRED is limited in the maximal loads that it can provide, and thus, is viewed as an interim solution to the loss of muscular strength. Thus, NASA has initiated the design and construction of the Advanced Resistive Exercise Device (ARED as a long-term solution to the preservation of muscle strength during extended habitation of microgravity environments. The ARED is designed to provide greater exercise capability than iRED. The primary resistance mechanism in the ARED is a pair of vacuum cylinders containing pistons. Preliminary life cycle testing indicates that the ARED will endure over one million cycles without critical failure. However, life cycle testing is much different than human subject testing. Often, humans put unique forces on devices that are not present during machine testing. Thus, the purpose of this evaluation was to test the functionality durability and reliability of the ARED during exercise executed by human subjects.

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