



Hardware Evaluation of the Horizontal Exercise Fixture with Weight Stack

Nate Newby

Principal Investigator, Project Engineer, ExPC Project, Wyle Integrated Science and Engineering (IS&E) Group

Mark Leach

Exercise Physiologist, ExPC Project, JES Tech

Renita Fincke

Project Engineer, Exercise Physiology and Countermeasures (ExPC) Project, Wyle IS&E Group

Carwyn Sharp, Ph.D.

Project Scientist, ExPC Project, Wyle IS&E Group

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ABBREVIATIONS AND ACRONYMS

1-RM	1-repetition maximum
ARC	Ames Research Center
ASCII	American Standard Code for Information Interchange
Avg	average
BW	body weight
cm	centimeters
CPHS	Committee for the Protection of Human Subjects
CW	counterweight
HEF	Horizontal Exercise Fixture
Ht	height
HP	horsepower
IREDD	Interim Resistive Exercise Device
ISS	International Space Station
JSC	Johnson Space Center
kg	kilogram
L	load
NASA	National Aeronautics and Space Administration
Rep	repetition
ROM	range of motion
sec	second

1.0 Summary and Operational Relevance

This hardware evaluation of the Horizontal Exercise Fixture (HEF) with weight stack was conducted to determine whether the squat, prone row, bench press, heel raise, hip flexion, and hip extension exercises could be performed safely and with correct form by a subject population ranging from a 5th-percentile woman to 95th-percentile man. The evaluation had further aims of (1) determining whether HEF could withstand the type of duty cycle that may be utilized in a bed rest study, (2) developing a finalized set of hardware and software operating instructions, (3) making subjective comparisons between horizontal exercises on HEF and the same exercises performed in the upright position at a commercial fitness facility, and (4) preparing a list of recommended hardware and software improvements, if any.

2.0 Introduction

The HEF was designed by NASA engineers and exercise physiologists (U.S. Patent 7,125,370 B1). It consists of a custom-built platform that allows a person to perform a range of resistive exercises while lying in a supine or prone position (Figure 1). The HEF was originally built for use with the International Space Station (ISS) interim Resistive Exercise Device (iRED) load canisters to evaluate the original ISS exercise protocols during bed rest studies (analog to space flight), when iRED was the primary on-orbit means of resistive exercise. For a more detailed explanation of the need for completing exercise in bed rest studies, refer to the NASA Technical Report, "Evaluation of the Horizontal Exercise Fixture in Conjunction with the interim Resistive Exercise Device (iRED) for Use in Bed Rest Research."

When iRED became obsolete because more advanced space flight equipment was developed that could provide greater loading, a commercial weight stack was incorporated into HEF, which provides up to about 500 pounds of load to the subject. Initial testing of HEF with the weight stack in 2007 revealed the need for a mechanical means of starting certain exercises (squat and heel raise) with the weight stacks in an "up" position for the safety of both the subject and operators. Therefore, a motorized hoist was added to the system and a subsequent test readiness review was completed in April 2009.

In summary, since its inception, HEF has undergone significant testing in the following configurations:

Configuration 1: HEF with iRED (results noted in previous NASA Technical Report)

Configuration 2: HEF with weight stack

Configuration 3: HEF with weight stack and motorized hoist

The hardware evaluation results reported herein are of HEF in configurations 2 and 3.

3.0 Assessment Objectives

Questions that this hardware evaluation of HEF with weight stack attempted to address were:

- Does the HEF allow 5th - to 95th-percentile subjects to perform the target exercises with proper form, safety, and range of motion?
- How is the HEF best operated? How is it best configured for different exercise modalities? How does the software function? (A set of finalized procedures was developed as a result of this evaluation, Fincke et al. Wyle Document # WLSD888166)
- What are users' (subjects' and operators') opinions of HEF as determined via subjective questionnaire?
- What are exercise physiologists' opinions of HEF exercises compared with similar exercises performed in the gym?
- Do HEF hardware and/or software require any improvements for effective and efficient use during a bed rest campaign?
- What are the maintenance requirements for HEF? Is the device's duty cycle appropriate for future bed rest studies?

4.0 Methods

4.1 Equipment

The three principal components of HEF are a subject support platform, weight stack assembly with hoist, and data collection system (Figures 1 and 2). The frame of the subject support platform is composed of welded aluminum (3" × 3" × 1/8"-thick wall square tubing) that supports various arrangements of padding on which a subject lies while performing different exercises. The load is provided by two weight stacks (each containing 510 pounds of steel plates). The total load a subject can experience is 510 pounds because of the pulley system of the HEF. Although the pulleys divide the load in half, they provide twice the range of motion (ROM) allowable by the stacks alone (17 inches for the stack, 34 inches of travel by the subject). A hoist mounted at the top of the HEF frame connects to a weight stack assembly carriage and allows the position of the weight stacks to be manipulated mechanically (Figure 2). The data acquisition system consists of a data acquisition box with USB output (Personal DAQ 3000, IO Tech, Cleveland, Ohio) and a laptop computer with custom LabVIEW (National Instruments, Austin, Texas) software, which records subject loading profile and weight stack position data.

Two of the unique characteristics of the HEF hardware are the pelvic sled and shoulder tilt plate. Both sled and plate allow translational movements in the subject vertical or z-axis as noted with the coordinate system in Figure 2a. The shoulder tilt plate also allows angular rotation of the subject's shoulders in the pitch plane. The pelvic sled additionally allows fore-aft translation (in the y-axis) of the subject's hips by use of a counterweight

assembly. Together, these features may enable HEF to provide a ROM similar to that used in a normal (upright) squat exercise.

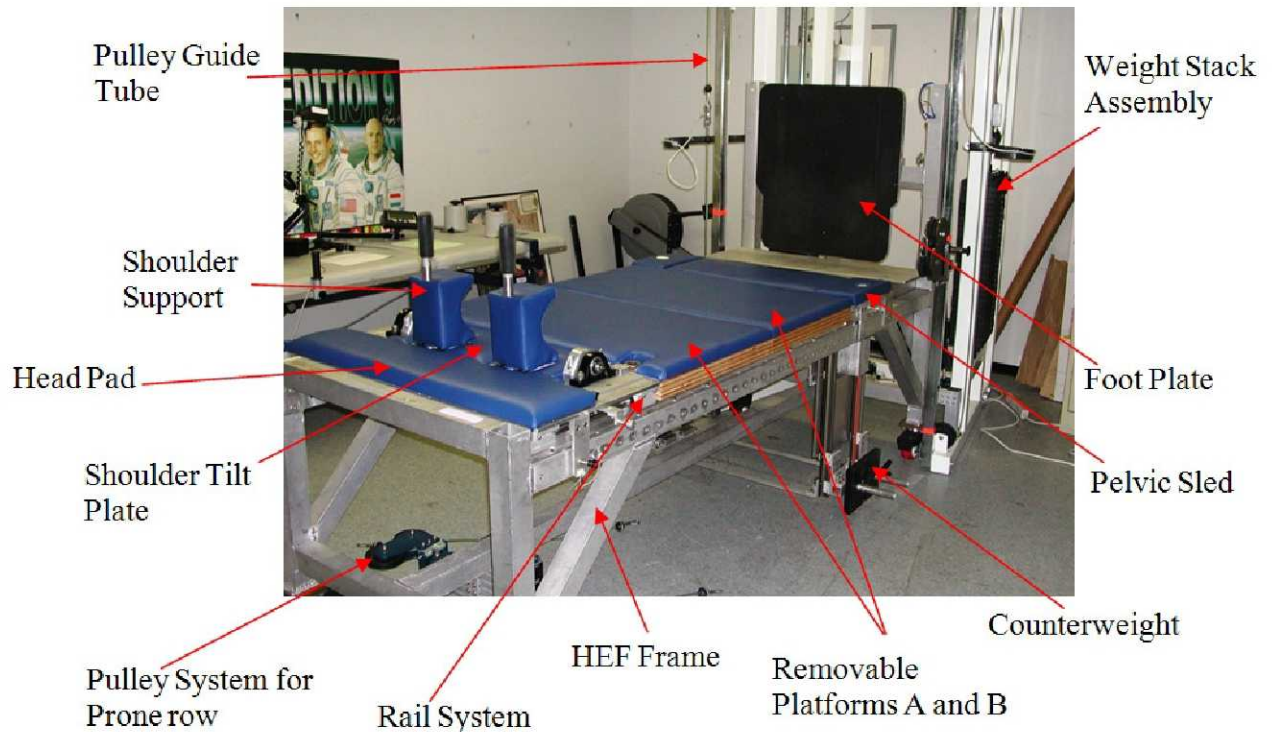


Figure 1: HEF system overview and principal components.

Upon completion of Configuration 1 testing at Ames Research Center, HEF was returned to Johnson Space Center (JSC) and placed in storage. Substitution of weight stacks (Configuration 2) for iRED canisters (Configuration 1) was subsequently completed at JSC. Configuration 2 testing revealed that the squat and heel raise exercises could not be performed without a means for starting these exercises with the weight stacks in the “up” position for the safety of both the subject and operators. To overcome this issue, a hoist and a weight-stack carriage assembly were added to the system to produce Configuration 3 (Figure 2). The hoist is mounted to a plate-and-beam assembly, which is mounted to the weight-stack frame. The hoist (Northern Industrial Tools, Burnsville, Minnesota) consists of a 2.5-HP motor rated with a 2,000-lb load capacity, and a 6,600-lb load-rated anti-twist cable. The hoist cable hooks to the carriage assembly, which supports both of the HEF weight stacks.

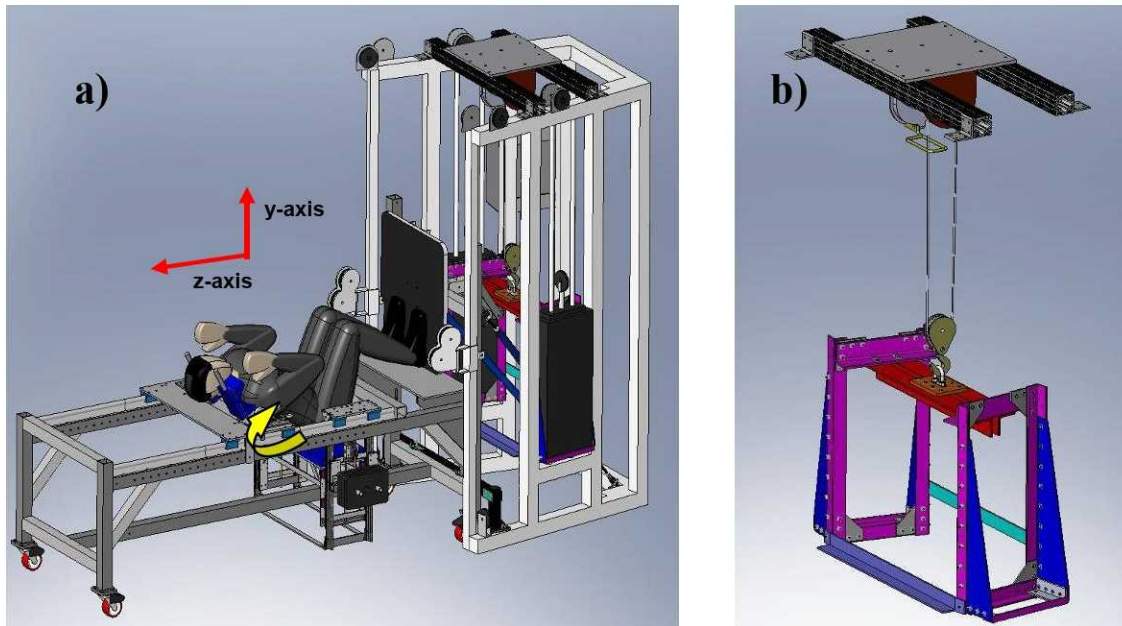


Figure 2: Hoist configuration.

a) Computer drawing of HEF integrated with the hoist and weight-stack carriage assembly and, **b)** Computer drawing of the hoist and weight-stack carriage assembly.

Three other changes have been made to the HEF hardware since Configuration 2. First, a climbing harness was added to the system to secure the subject to the pelvic sled more comfortably and safely (Figure 3). Second, a set of spotting handles were added to the system to make spotting squat and heel raise exercises safer for the test operators (Figure 4). Third, the software was modified to provide faster data sampling rates (100 Hz vs. 10 Hz).



Figure 3: Test operator wearing the pelvic sled climbing harness.

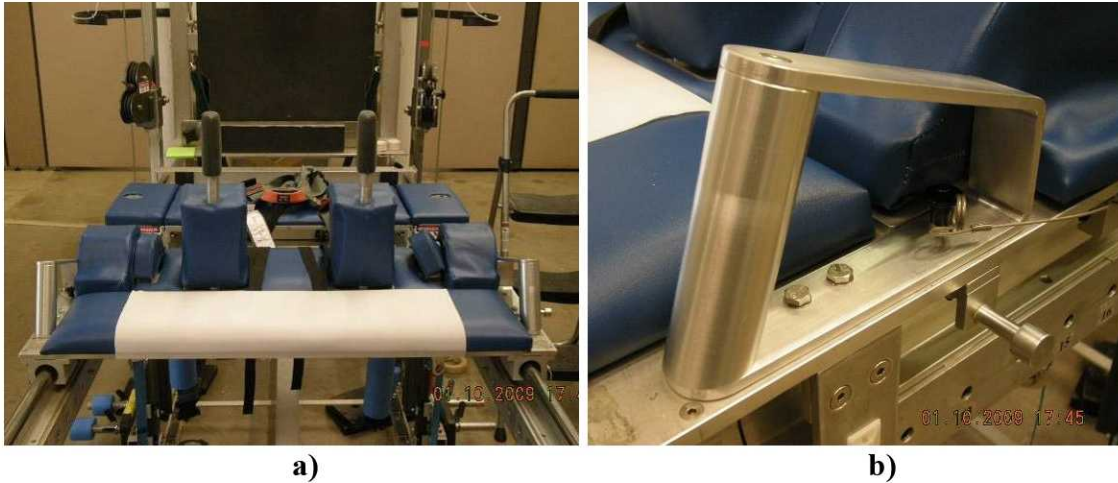


Figure 4: Spotting handle.

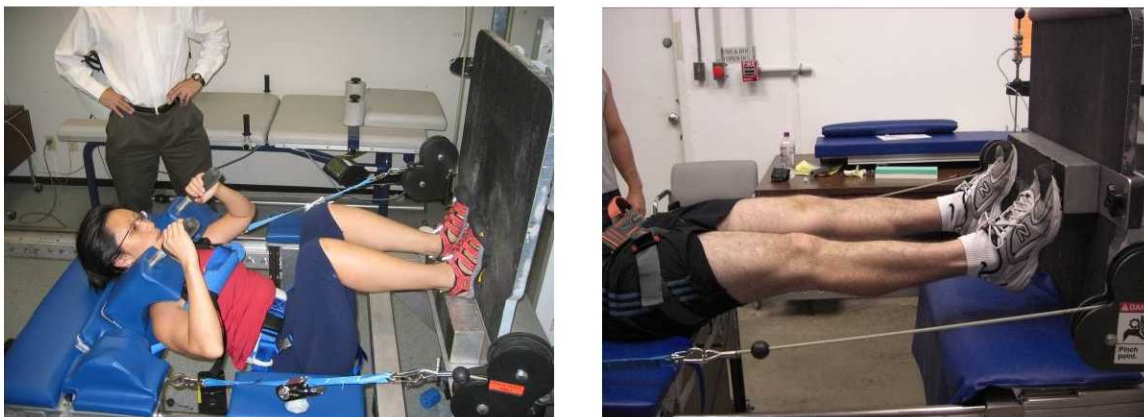
a) HEF with spotting handles located on either side of the shoulder tilt plate. b) Close-up view of a spotting handle.

Use of HEF requires two or three test operators (depending on the type of exercise) to ensure safety and proper operations during each exercise.

A footprint of about 20' × 22' × 8' is needed to house the equipment. A standard 110-volt, 20-ampere power supply is required for the hoist motor and laptop computer.

4.2 HEF Exercise Setups

Six different exercises were examined in this evaluation: squat, heel raise, bench press, prone row, hip flexion, and hip extension. The various HEF setups that permit this range of exercises are depicted in Figure 5.



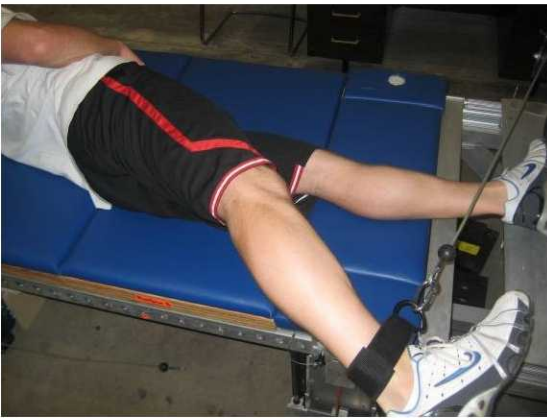
a) Squat (note motion freedom at shoulder and hips) b) Heel Raise with bar set atop the footplate



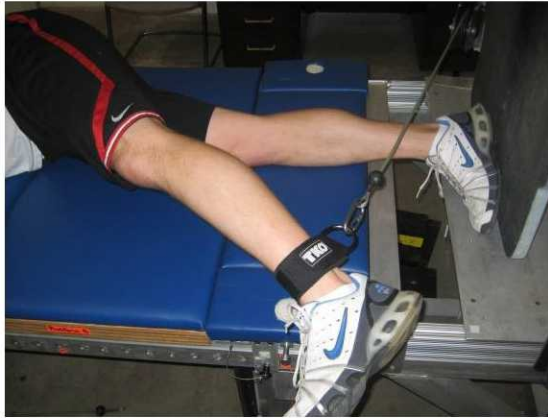
c) Bench Press



d) Prone Row



e) Hip Extension



(f) Hip Flexion

Figure 5: HEF exercise setups.

4.3 Subjects

All subjects in this evaluation passed a modified Air Force Class III physical examination and gave informed consent prior to participation in this evaluation. The NASA Committee for the Protection of Human Subjects (CPHS) reviewed and approved this evaluation.

Ten subjects were enrolled for participation in the Configuration 2 evaluation, but only seven participated in the protocol (one of whom was a 5th-percentile woman, and one of whom was a 95th-percentile man) because hardware issues prevented the completion of all ten subjects.

Six subjects completed Configuration 3 testing, including the 5th-percentile woman and 95th-percentile man.

4.4 Protocol

Configuration 2 Protocol

The Configuration 2 protocol is shown in Table 1. The protocol consisted of 10 total (nonconsecutive) testing sessions. Sessions 1-3, were familiarization sessions during which subjects completed a one-repetition maximum (1-RM) for six different exercises (squat, heel raise, bench press, prone row, hip flexion, and hip extension). During these familiarization sessions, subjects were taught proper exercise technique and acquainted with the hardware and testing procedures. Familiarization sessions were not used for data analysis, but the highest load attained for each exercise during these sessions was used to calculate the 50%-90% workloads that were used during the next two 1-RM sessions. During sessions 4-6, subjects performed the first recorded 1-RM tests (1-RM#1); 1-RM#2 tests were collected during sessions 7-9. The last session was a multi-repetition session, during which two sets of each of the six exercises were performed at either 7-RM or 10-RM load levels depending on the exercise.

Table 1: One-repetition maximum (1-RM) exercise sessions.

Session Type	Familiarization Session																																			
Session #	1								2								3																			
Exercise	Squat				Heel Raise				Bench Press				Prone Row				Hip Flexion				Hip Extension															
# of Reps	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1
% est 1-RM	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100

Session Type	1-RM#1																																			
Session #	4								5								6																			
Exercise	Squat				Heel Raise				Bench Press				Prone Row				Hip Flexion				Hip Extension															
# of Reps	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1
% FAM 1-RM	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100

Session Type	1-RM#2																																			
Session #	7								8								9																			
Exercise	Squat				Heel Raise				Bench Press				Prone Row				Hip Flexion				Hip Extension															
# of Reps	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1
% 1-RM#1	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100

Session Type	Multi Rep																
Session #	10																
Exercise	Squat	Prone Row	Bench Press	Heel Raise	Hip Flexion	Hip Extension											
# of Reps	7	7	7	7	7	7	7	7	10	10	10	10					
% 1-RM#2	60	60	60	60	60	60	60	60	50	50	50	50					

At the start of each session, subjects were instructed to perform a 5-minute warm-up on a recumbent cycle ergometer (Lode, AN Groningen, The Netherlands). After their warm-up, all subjects were encouraged to stretch the key muscles involved in that day's exercises. For each familiarization session, two sets of eight repetitions at a moderate

load (estimated to be about 50 and 60 percent of estimated maximum load, as reported by the test subject) were then conducted, followed by a set of five repetitions at 70 percent of maximum load, and then a set of three repetitions at 80 percent of maximum load. Finally, beginning with 90 percent of the estimated maximum load, sets of one repetition were performed with increasing load, until the subject could not lift the load through the desired ROM or with proper technique. The load was increased incrementally for each set according to the subject's level of performance. The 1-RM session was terminated if the subject failed after two attempts to perform a repetition with additional load or the technique or form was poor. Two minutes of rest was given between each set.

The remaining 1-RM sessions for each exercise followed the same protocol as the familiarization session, except that the loads for each set were based on percentages of the 1-RM determined in the previous test session. Including in-processing, warm-up, setup, exercise, and out-processing time, each session lasted about 1 to 2 hours. Testing sessions were separated by at least 48 hours. A 10 minute rest was given between the two exercises of each 1-RM session.

Configuration 3 Protocol

The Configuration 3 Protocol was designed to capture the data missing from the Configuration 2 protocol, namely data from the the 1-RM and multi-repetition squat and heel raise sessions. The 1-RM and multi-repetition sessions were conducted using the Configuration 2 protocol outlined above.

Table 2: Configuration 3 protocol.

Session Type	Familiarization 1-RM										1-RM#1										Multi Rep																	
Session #	1										2										3																	
Exercise	Squat					Heel Raise					Squat					Heel Raise					Squat	Row	Bench	Heel R	Hip Fix	Hip Ext												
# of Reps	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	8	8	5	3	1	1	7	7	7	7	7	7	7	7	10	10	10	10		
% est 1-RM	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	50	60	70	80	90	100	60	60	60	60	60	60	60	60	60	60	50	50	50	50

1-RM, one-repetition maximum.

4.5 Subject Questionnaire

Subjects who participated in the Configuration 3 Protocol were asked to fill out a questionnaire designed to assess the ease of use of the equipment. Subjects were also asked to provide any other comments they had about the hardware.

4.6 Data Processing

Load cell and linear position data collected throughout testing were saved to ASCII files. Number of repetitions completed, exercise load, repetition pass/fail information, and any comments, were stored in separate Excel files. ASCII data were processed using customized MATLAB (The Mathworks, Natwick, Massachusetts) scripts. Because of sample rate problems with the software, all load and position data were interpolated using a cubic spline technique and then resampled at 100 Hz. For some analyses, a 2nd-order, low-pass Butterworth filter was used with corner frequency of 10 Hz to reduce signal noise.

5.0 Results

Seven of the ten enrolled subjects participated in Configuration 2 testing (Table 3). The squat and heel-raise 1-RM sessions were discontinued because of safety concerns for both the operators and test subjects. These exercises involved loads that were too heavy for the operators to lift by hand; thus, it was difficult if not impossible for subjects to begin these movements in the proper starting position. All multi-repetition sessions were also discontinued from the protocol because they included the squat and heel raise exercises.

Table 3: Exercise sessions completed in Configuration 2.

Sessions	Familiarization 1RM						1RM #1						1RM #2						Multi-Rep
	Squat	Heel Raise	Bench Press	Bent-over Row	Hip Flexion	Hip Extension	Squat	Heel Raise	Bench Press	Bent-over Row	Hip Flexion	Hip Extension	Squat	Heel Raise	Bench Press	Bent-over Row	Hip Flexion	Hip Extension	
1	X	X	X	X	X	X	X		X	X	X	X			X	X	X	X	
2	X	X	X	X	X	X			X	X	X	X			X	X	X	X	
3	X	X	X	X	X	X			X	X	X	X			X	X	X	X	
6			X	X	X	X			X	X	X	X			X	X	X	X	
7			X	X	X	X													
8	X		X	X	X	X			X	X	X	X			X	X	X	X	
9			X	X	X	X			X	X	X	X			X	X	X	X	

1RM, one-repetition maximum.

After hardware modifications were made as described in section 4.1, six subjects participated in Configuration 3 testing. Once again, the 1-RM squat and heel raise sessions were discontinued because of concerns for subject safety. Some of the subjects complained of shoulder soreness and were observed to have contusions in the shoulder area. Table 4 indicates the sessions that were completed.

Table 4: Configuration 3 protocol sessions completed.

Subject #	Familiarization 1RM		1RM #1		Multi-Rep
	Day 1		Day 2		Day 3
	Squat	Heel Raise	Squat	Heel Raise	All Exercises
1	Y	Y	Y	Y	Y
2	Y	Y	Y	Y	Y
3					Y
4	Y	Y			Y
5	Y	Y			Y
6	Y	Y			Y

A blank cell denotes a session that was not completed.

5.1 Physiological and Biomechanical Variables

Table 5 summarizes physiologists' and engineers' observations regarding the mechanics of the different exercises utilized in this hardware evaluation. All exercise types either passed or conditionally passed this qualitative rating schema in terms of subjects' abilities to perform the exercises with proper form. Some exercises were passed conditionally only because the exercise ROM did not accommodate the entire range of 5th- to 95th-percentile subjects.

The HEF with iRED and HEF with weight stacks evaluations demonstrate the versatility of this device to allow many different types of resistive exercise.

Table 5: Summary of exercise observations.

<i>Exercise</i>	<i>Pass</i>	<i>Cond. Pass</i>	<i>Fail</i>	<i>Reason for Failure</i>
<i>Squat</i>		✓		<ul style="list-style-type: none"> - Shorter subjects tend to bottom out the sled (and weight stack) at the bottom of the ROM - Loading at the shoulders unacceptable for 1-RM - Difficult to maintain proper form, abdominal activation appears to differ from upright squat - Pelvic counterweight not optimal, and adds inertial load to the movement
<i>Prone Row</i>		✓		<ul style="list-style-type: none"> - Fixed distance from chest to cable causes subjects with longer arms to not receive resistance through the entire ROM (bottom out at full arm extension)
<i>Bench Press</i>	✓			<ul style="list-style-type: none"> - Load seems inconsistent throughout ROM, more akin to a cable chest press
<i>Heel Raise</i>		✓		<ul style="list-style-type: none"> - Loading at the shoulders unacceptable for 1-RM. Leads to some shoulder/ankle discomfort - Some subjects lifted the entire weight stack and a 1-RM could not be established
<i>Hip Extension/Flexion</i>		✓		<ul style="list-style-type: none"> - Lack of hip restraints make maintaining proper form difficult for most subjects - 95th-percentile male maxed out ROM

The load, position, and velocity profiles for a typical 8RM squat exercise (as part of the 1-RM protocol) are presented in Figure 6. Position was measured at the weight stack using a string potentiometer. The left side of the position trace indicates that the weight stack was supported in the top position by the hoist. The hoist was then lowered until the subject was supporting the weight stack. Because of the 2:1 ratio provided by the pulley arrangement, subject sled position was obtained by multiplying the weight stack position signal by two. The velocity trace was obtained by taking the first derivative of the position data. Load data were obtained from two in-line load cells located in series with the cables that were connected to the subject sled (one on either side of the sled). The load trace in the figure was produced by a simple summation of the two load-cell signals.

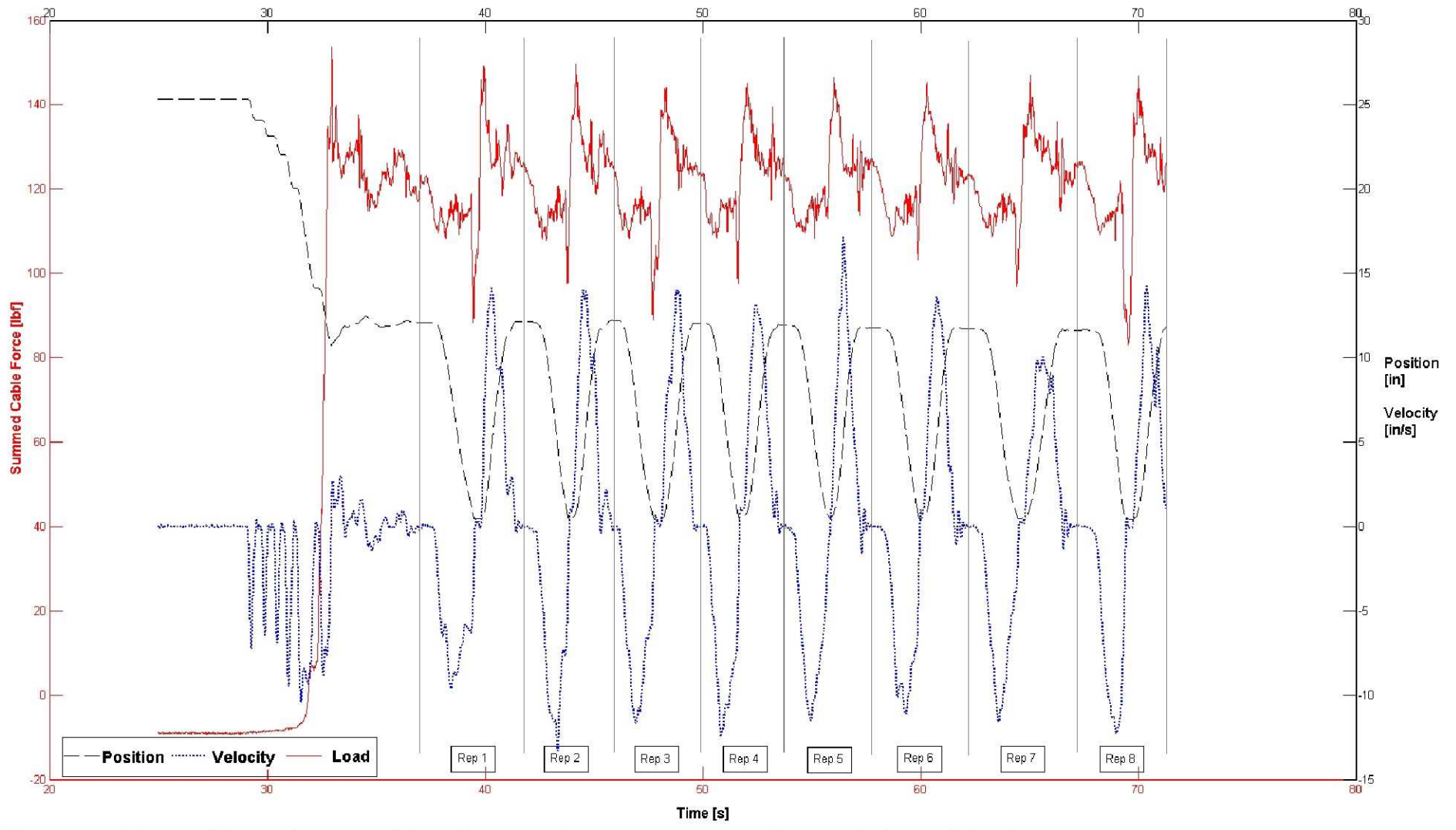


Figure 6: Cable position, velocity, and load for an 8-RM squat exercise with a static load of 120 lb.

Figure 7 depicts the eccentric and concentric load profile for repetition 1 shown in Figure 6. The right side of the graph indicates the starting or upright position for the squat exercise. The left side of the graph is the bottom of the movement. The plot demonstrates a clear difference between the peak concentric and peak eccentric portions of this exercise. The peak eccentric load is only 60 percent the of peak concentric load. The eccentric component of resistance exercise is a major factor in strength adaptations; eccentric loading of only 60-70% of concentric load results in attenuated strength gains (Dudley et al. 1991). While the peak eccentric to concentric loading ratio is poor, the plot indicates a much higher ratio during the “steady state” portion of the exercise.

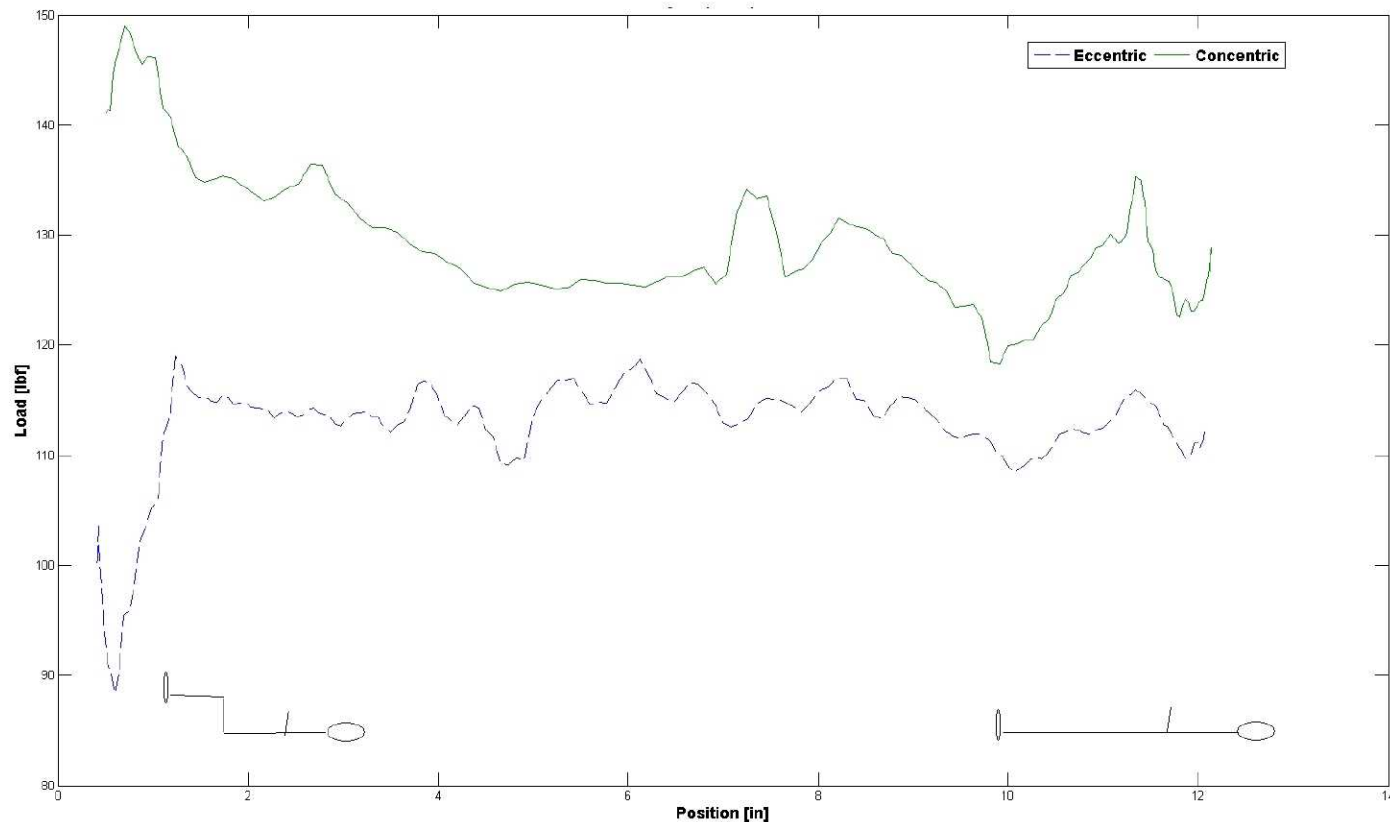


Figure 7: Force trajectory for squat exercise with 120-lb static load.

5.2 Questionnaire

The results of the subject questionnaire are presented in Appendix A. A high degree of variability is evident in these responses. For the squat, about half the subject pool felt the exercise was comfortable and that it was easy to perform using proper form, while the other half of the subject pool strongly disagreed. Similar differences were seen with the bench press and heel raise, with one subject reporting muscle soreness or discomfort during the heel raise. The prone row and hip flexion and extension exercises were rated fairly well in terms of comfort and form by most subjects in this evaluation.

5.3 Hardware

The hardware system operated as intended for a duty cycle similar to that in a bed rest study. Testing was completed with 9 subjects for 6 sessions each, with a total of more than 3200 repetitions completed over the course of testing in Configurations 2 and 3. The system calibration process revealed a discrepancy between the load that each weight-stack plate was listed at and the actual weight of the plate. A look-up table was developed with more accurate values, and a new set of labels were applied to the weight stacks.

5.4 Software

Testing of the data acquisition and software system for HEF revealed several minor changes necessary to improve usage efficiency. The data sample rate selected for this evaluation was set such that 1 data sample should be collected every 0.01 seconds (100 Hz). However, what was observed (Figure 9) was a largely bimodal distribution of sample rates with peaks occurring at about 0.017 and 0.0071 seconds between consecutive samples (equivalent to 60 Hz and 140 Hz, respectively), with almost no samples collected at .01 seconds between consecutive samples. Further, when viewed as a time series, the sample rates tended to oscillate back and forth between too fast and too slow.

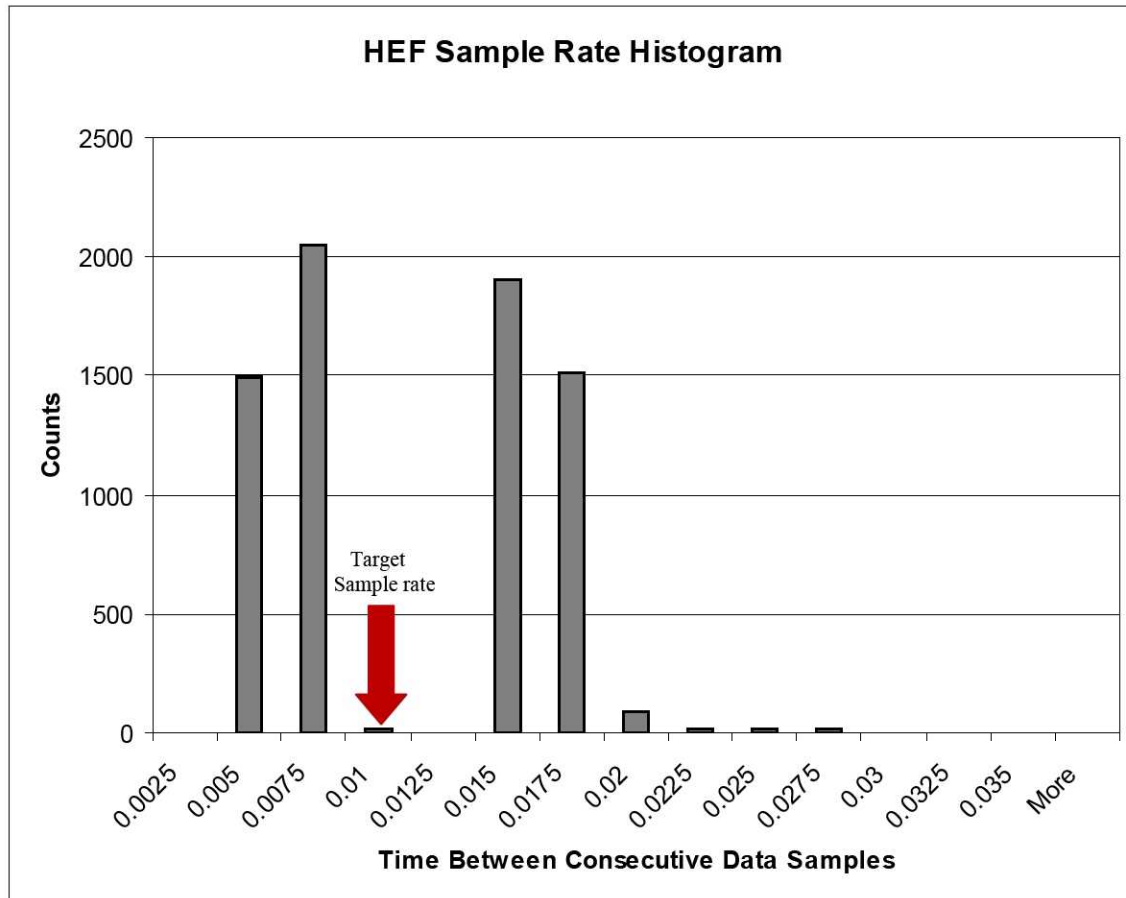


Figure 8: Histogram of the elapsed time between consecutive data samples for a single 8-RM exercise trial (0.01 seconds = 100 Hz on the x-axis).

Examination of the saved ASCII output file revealed the use of a nonstandard data file structure. The format of the file begins with header information containing information such as subject identification number, date, test operators, and scale factors; the header information is followed by column headers, and then numeric data. However, once the set number is incremented a new set of header information is inserted into the file, followed by the numeric data for that set. This format requires custom software to be written to enable reading of the data file, as the file import functions of most off-the-shelf software programs cannot accommodate this sort of structure.

The software included a feature that caused an alarm to sound once the weight stack reached a certain position. This alarm could be set for two different positions, and would be ideal for establishing an exercise ROM for users of HEF. However, the feature did not work properly and would sound an alarm at random times.

6.0 Discussion

6.1 Physiological and Biomechanical Aspects

During this hardware evaluation, six different exercises were tested. The expectation was that performing these exercises on HEF would provide similar loading and biomechanical profiles as performing them in an upright starting position. However, meeting this expectation is challenging, as inherent differences exist between performing these exercises in horizontal (supine) and upright positions. For example, in the supine position any whole-body movement exercise such as the squat will not require a person to react against their own body weight. For a squat exercise in the supine position to be comparable with an upright 1-RM squat, one needs a total load of the 1-RM plus body weight. Applying this entire load on the shoulders may not prove acceptable.

6.1.1 Squat Exercise

The squat exercise is considered by many to be the most efficient strength-training exercise (Escamilla 2001). The squat activates large muscle groups in both the upper and lower body, while simultaneously activating core stabilization muscle groups. This seems to also be true of squat performance on HEF. The load is applied at the shoulders and travels through the spine, hips, knees, and ankles.

Proper performance of squats on HEF is crucial since the subject is able to lift a greater load than he/she would be capable of in an upright position. The ability to move the hips in two degrees of freedom within the sagittal plane (z- and y-axes) allows the subject to push backward toward the floor while rotating the shoulders; this facilitates a proper squat descent which includes maintaining a rigid core, a flat back, and a balanced center of mass (with respect to the horizontal positioning), as the hips and knees are flexed during the eccentric phase of the lift.

HEF also seemed to permit appropriate mechanics during the concentric phase of the lift, although there was a much greater force on the shoulders during the eccentric/concentric changeover. The excess load on the shoulders created difficulty in maintaining proper form throughout the entire ROM for some subjects. Difficulty maintaining an appropriate fore/aft position with the hips and knees during the concentric portion of the lift was also observed (Table 5). It may be possible to correct this issue through familiarization training which would allow integration of the proprioceptive cues that an experienced lifter develops during upright exercise. It was also noted that when shorter subjects (<160 cm) descended to 90° knee flexion, the pelvic sled bottomed out on the lower end of the machine, near the footplate (Table 5). This could affect the stretch reflex and the ability to economically change direction during performance of the squat exercise.

One difference between performing squats on HEF and performing them in an upright position is an apparent increase in abdominal musculature involvement. Although only anecdotal, it seems that a greater activation of the abdominal muscle groups is required to bring the body back into a fully extended position. Ideally, the pelvic counterweight system would completely preclude this additional exertion. However, selecting the appropriate pelvic counterweight for each subject was a trial-and-error process. Selection

of too low a weight resulted in excess abdominal work in order to bring the body back to the “upright” position, and too much weight required the subject to work against the counterweight to move the hips downward at the start of the movement. The convention used in the evaluation was to start with 60% of the subject’s body weight and then adjust the counterweight load until proper form was most easily attained by the subject (see the HEF with iRED report for further details). An additional difficulty was that subjects of identical weight and stature often had different distributions of weight at the pelvis. It may be that a static load is not the optimal counterweight solution. A system that provides less resistance at the beginning of the movement and a higher force at the end of the movement might prove to mimic the hip movements involved in a true squat more accurately. Another observation regarding the pelvic counterweight is that it supplied an additional inertial load throughout the squat movement (Table 5). The subject is coupled to the mass of the pelvic counterweight system by the harness. Since inertia is proportional to velocity, the faster the subject performs this movement, the higher the inertial load of the system. This load (~60-80 % of body weight) presumably is applied at the hips and is most pronounced at the changeover from eccentric to concentric movement. A full dynamic assessment of the squat would also have to account for the inertial effects of the shoulder support system, which has relatively lower mass, as well as friction along the rails and within the pulley and cable system.

Although a comprehensive evaluation of the load profile data was not conducted, it was noted that HEF produced a lower peak eccentric than peak concentric load (Figure 7), as determined from the in-line load cells. As discussed previously, many benefits of resistive training are lost when the eccentric component is reduced (Dudley et al.). The decrease in eccentric resistance could be caused by a combination of factors including, the added inertial load from the pelvic counterweight system, the rate of acceleration to the bottom of the ROM, and/or the friction of the pulley system. Another issue is that subjects are unable to view their movement during the exercise; although spotters provided verbal feedback, visual feedback likely would have been helpful to insure proper execution of this exercise.

A few noteworthy issues arose during evaluation of the squat exercise. The limitations of the machine make it impossible to offer a full ROM to individuals larger than a 95th-percentile man (>185 cm) and someone smaller than a 5th-percentile woman (<150 cm). Also, the shoulder pads through which the load is delivered to the subject do not distribute the load across the breadth of the shoulders as a bar would, but rather isolate the load directly over the subject’s shoulders, superior to the clavicle. Adding body weight to subjects’ upright 1-RM further compounds this situation. The musculoskeletal safety risk from this loading method is unclear, but contusions and abrasions were observed in some subjects, which ultimately led to the discontinuation of 1-RM squat testing.

HEF seems to mimic the squat movement more closely than any other supine exercise device known to the authors at the time of publication. Although HEF has some noticeable differences in comparison to free weights, performing squats on this machine seems to load the same muscle groups in a similar manner. Subjects can be trained to

perform this exercise with the correct form and ROM. With hardware modifications to the loading method (i.e. how/where the load is applied to the subject) and perhaps the pelvic sled counterweight system, this device would even more closely mimic an upright squat.

6.1.2 Prone Row Exercise

While performing the prone row on HEF, subjects were comfortable and were easily able to maintain proper form throughout the ROM (according to operator observation and subject questionnaire). This movement on HEF is quite comparable to a seated row, except that the subject lies in the prone position with arms extended toward the floor and pulls the loaded cable handles up to 90° of elbow flexion. The support platform that the subjects lie on is at a fixed distance from the cable pulleys and handgrips located near the floor. This was a limitation for subjects with longer arms, as they were unloaded before their elbows reached full extension (Table 5). Exercisers with extremely short arms (< 5th percentile female) will need assistance (from the spotters or via the hoist) to grasp the handgrips before starting the exercise. For subjects who could engage the load through the entire ROM, this exercise seemed to be virtually identical to a seated cable row with similar activation of muscle groups in the upper back and arms.

6.1.3 Bench Press Exercise

Loading during the bench press on HEF seemed to differ from free weights or other universal machine exercise equipment. HEF's loading is more comparable to that of a Bowflex® machine or cable chest press. Although the kinematics do not appear to differ from free weights or other machine bench press systems, the load seemed inconsistent through the ROM, likely a result of the pulley system (Table 5). The additional set of pulleys utilized for this exercise may alter the friction profile of the system, thereby creating a greater load. The general consensus of the subjects and operators was that although the same muscle groups (muscles of the chest and shoulders) were activated, the bench press on HEF did not have the same feel as a free-weight bench press. Further analysis is needed to determine the actual biomechanical differences between HEF and free weights during performance of the bench press exercise. These differences aside, bench press can be performed with proper form using HEF and apparent activation of the targeted muscle groups.

6.1.3 Heel Raise Exercise

While performing the heel raise on HEF, subjects reported that it closely mimicked the same exercise on a Smith machine. The shoulders and hips are locked into a supported position and the movement is isolated to the ankle joint. Subjects were able to flex slightly at the knees if needed, but were trained to limit knee flexion to only a slight bend while performing the exercise to take the stress off the knee joint. Since the shoulders and hips are locked, no core activation occurs and no balance component is involved in performance of this exercise as would be required in the upright position. As desired, HEF delivered an isolated load to the ankle and calf muscles. Just like the squat exercise, subjects experienced discomfort as the entire load is applied through two relatively small points of contact on subjects' shoulders; there were also reports of ankle pain. Pain in both of these joints was likely caused by the high workloads attained as a function of

supine, as opposed to upright, exercise. Lastly, some subjects were unable to attain a 1-RM because they lifted the entire 510 lb weight stack (Table 5).

One hardware limitation was noted: because of the mechanical stops, subjects taller than a 95th-percentile male cannot perform heel raise exercise on HEF without topping out the hoist travel distance. Another issue was that subjects were unable to easily view their lower leg during the exercise to determine whether the proper ROM was being achieved. An audible and adjustable position alarm was included with the software for this purpose, but unfortunately this feature did not function properly during this evaluation (see section 5.4). The addition of ruler markings on both sides of the foot plate would make positioning of the heel raise bar more reproducible. Heel raises on HEF seem to activate the desired muscle groups and good form is easily maintained during the entire ROM.

6.1.5 Hip Extension/Flexion Exercise

Performance of hip extension and flexion exercises on HEF is similar to that using comparable commercially available devices. However, there is no restraint for the hips and this makes it difficult to maintain proper form. With no pad or brace holding the hips in place nor an adequate handgrip, it was easy for subjects to rotate the hips forward or backward to improve their mechanical advantage (Table 5). Based on observation, subjects maintained good form and utilized the appropriate prime movers to perform the exercise. One other observed issue was that the 95th-percentile male reached the end of the ROM during exercise as did several of the taller subjects (Table 5).

6.2 Hardware

During testing of Configurations 2 and 3, 3200 repetitions were completed. Notably, no maintenance was required during this testing. Daily checks of the cable sheathing were made, and no noticeable wear occurred. The life cycle of the hoist motor and cable should be verified as these are critical components for subject and operator safety.

Various engineering modifications were made during the evaluation to optimize operations, safety, and comfort. The addition of a climbing harness to secure subjects' hips to the pelvic sled ensured that subjects would not slip off and become trapped between the two moving support pads. This harness was also better for squat exercise, as the previous harness caused some pain in the groin area for some subjects. A set of spotting handles made it easier for operators to properly spot the various exercises. The hoist may have been the most beneficial hardware addition. It enabled the proper performance of the squat and heel raise exercises beginning in the "up" position. However, the hoist changed the position of the weight stacks in a somewhat jerky manner, so subjects experienced additional loading for a brief moment (< 1 second) while the hoist was being engaged or disengaged.

6.3 Software

The custom LabVIEW software developed for HEF fulfilled its primary objective which was to support operation of HEF by displaying and recording the load cell and position signal data. The user interface was adequate for this evaluation, but improvements to

make operations more intuitive would be beneficial. The position alarm feature provided beneficial ROM information to users. Unfortunately, the system operated correctly only when data was not being recorded. This is suggestive of a file input/output, cache, or buffering issue. At a sample rate selection of 100 Hz, the system did not perform well; lower sample rates might have worked better. The underlying issue here is unclear, but a few possibilities are: a) the LabVIEW loops are performing erratically with respect to duration, b) interrupt requests are tying up the machine's resources or, c) the code is relying on an inaccurate Windows clock to time sample collection. More investigation into this problem is warranted; resolution of these issues is essential before HEF can be used in a bed rest study. As mentioned in the results section, the format in which the data files are written should be revised to make post-processing of data more efficient.

In general the software could use some modification to make it more user-friendly and economical with regard to its functional operation. For example, every time the exercise changed, a new calibration of the load cells and linear position cells was required. This was time-consuming and should be corrected. Also, the data stored in the Excel spreadsheet (such as pass/fail data for a given set) should be combined with the main HEF interface software.

6.4 Operations

HEF is a versatile and therefore complex piece of machinery that requires a moderate level of training for both operators and subjects before it can be safely operated with human subjects. Reconfiguring HEF from one exercise to another involves changing the support padding, pulleys, cabling, and pip pins. However, for the six exercises examined in this evaluation, it never took trained operators more than 5 minutes to change from one exercise to the next. The system contains quite a number of pip pins to secure various mechanisms into place. During operations, it is easy to lose track of these pins, but most of them are tethered to HEF. Some of the pins were slightly difficult to get into place; reborring of the holes would help to resolve this issue.

HEF currently requires three test operators. Some exercises involving small, isolated muscle groups may only require one spotter along with the hoist operator (two total operators), but two spotters and a hoist operator are essential for all exercises that activate large muscle groups (i.e., the squat, heel raise, and bench press). One operator is needed to run the software and operate the hoist. The other two operators act as spotters during exercise and are additionally responsible for coaching the subject on proper form. All operators were involved in changing components to reconfigure HEF from one exercise to the next.

The calibration procedure for the linear potentiometers worked well. The calibration process for the load cells, however, needs improvement. Limitations of the force gauge made it necessary for the cable load to be divided in half with the use of an additional cable and pulley. One end of this cable attached to the shoulder support sled and the other end was wrapped around the back corner post of the HEF frame. During the calibration process, a slight bend in the HEF frame was noticed when load was applied along this axis. A force gauge with greater loading capabilities would be advisable for future use.

One question that this evaluation did not address is the ease with which a potentially debilitated bed rest subject can be loaded onto HEF. Observations made during this evaluation suggest that this is possible, with perhaps a few slight modifications to the hardware or procedures.

As a result of this evaluation, a comprehensive Operations Manual (Wyle Document # WLSD888166) was developed to assist with setting up HEF exercise configurations, performing calibrations, and operating the software.

6.5 Recommended Improvements

This evaluation revealed a few minor deficiencies in the HEF hardware, software, and operations procedures. This section summarizes these findings along with some suggestions for potential remedies.

For the squat and heel raise exercises on HEF, a problem was identified with applying a 1-RM plus body weight load to the shoulders, which resulted in bruising for some test subjects. As a first step toward resolving this issue, the shoulder support plate should be redesigned to distribute this load over a wider area of the shoulders and upper back. Another step could be to examine methods for distributing some of this load to the hips. For example, perhaps one body weight could be applied to the pelvic sled through the use of bungees or some other loading mechanism. This approach might also alleviate the need for more loading from the system, as a true 1-RM heel raise could not be obtained for some subjects with the 510 lb available load. However, coupling of the pelvic sled mass to the subject may present additional problems.

The pelvic counterweight system utilized in the squat might also be improved by further analysis. It is questionable whether applying a static load is the best solution for offsetting the mass of the hips. A system that provides less loading on the downstroke (with gravity) than on the upstroke (against gravity) of this movement may be more appropriate. It is also unclear how the coupled mass of the pelvic counterweight system (on the order of 60-80% of the subject's body weight) affects the performance of squats on HEF. Methods for lowering and decoupling this mass from subjects should be explored.

This evaluation showed that the prone row did not provide the proper ROM for all subjects. Those with longer arms did not engage the load through the entire ROM. This should be relatively easy to fix. Either the support platform needs to be adjustable (by addition of extra pads, for example) or the height needs to be fixed so that the subjects with the longest arms have the proper ROM (in this instance, stops could be designed to assist subjects with shorter arms).

For hip flexion and extension it was noted that a pad or brace for the hips would help subjects maintain proper form throughout this exercise. A secure location for the hands would also be useful. Furthermore, HEF needs to provide a greater ROM for this exercise, as subjects with longer legs need a ROM larger than the one provided.

On the whole, the hoist performed well during this evaluation. One minor issue encountered is that the controller allowed the position of the weight stacks to move only in rather large, discrete movements (~1 inch of resolution). Much finer control of this motion is desirable to minimize or eliminate the jerkiness of the load when the hoist engages or disengages the weight stack. This may or may not be achievable with the current hoist. A screw-driven system would be another way to resolve this issue. Another minor problem with the hoist was the amount of noise it made when in operation. For this evaluation, HEF was located such that the noise was bothersome only to the subjects and operators. However, excessive noise could be a serious problem in a hospital or bed rest setting.

A few prominent areas for software improvement were noted in this evaluation. The position sensor alarm did not work properly, which forced the operators to determine the proper ROM by sight. The data sampling rate was erratic. The file structure could be modified slightly to make data processing smoother, and the user interface should be improved to make it more intuitive.

Generally, HEF operations proceeded quite smoothly. Use of a force gauge with a higher operating range for the calibration process is recommended. Loading and unloading of bed rest or deconditioned subjects also merits closer examination. The addition of mirrors or cameras for subjects to observe their exercise form may also help subjects to perform the exercises properly and safely.

A study of exercise on HEF using a motion capture system would allow a kinematic comparison to upright exercise. Such an evaluation is already planned for the Advanced Resistive Exercise Device (ARED) on the ISS; it might be desirable to compare those results with kinematic data from HEF exercise.

7.0 Conclusion

HEF with weight stack seems to be a very sturdy and reliable exercise device that should function well in a bed rest training setting. A few improvements should be made to both the hardware and software to improve usage efficiency, but largely, this evaluation has demonstrated HEF's robustness. The hardware offers loading to muscles, bones, and joints, potentially sufficient to mitigate the loss of muscle mass and bone mineral density during long-duration bed rest campaigns. With some minor modifications, the HEF with weight stack equipment provides the best currently available means of performing squat, heel raise, prone row, bench press, and hip flexion/extension exercise in a supine orientation.

8.0 References

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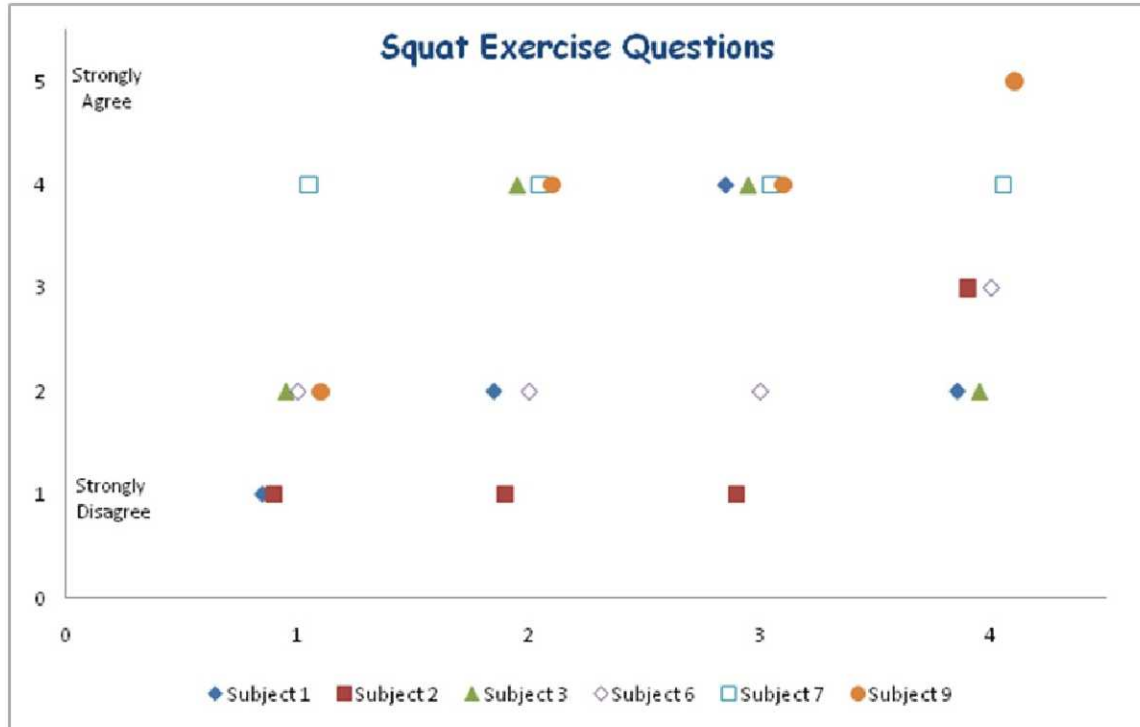
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Appendix A: HEF Subject Questionnaire



Squat Exercise Questions:

1. During the exercise, it was easy to maintain the proper form.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

2. It was comfortable to perform the exercise.

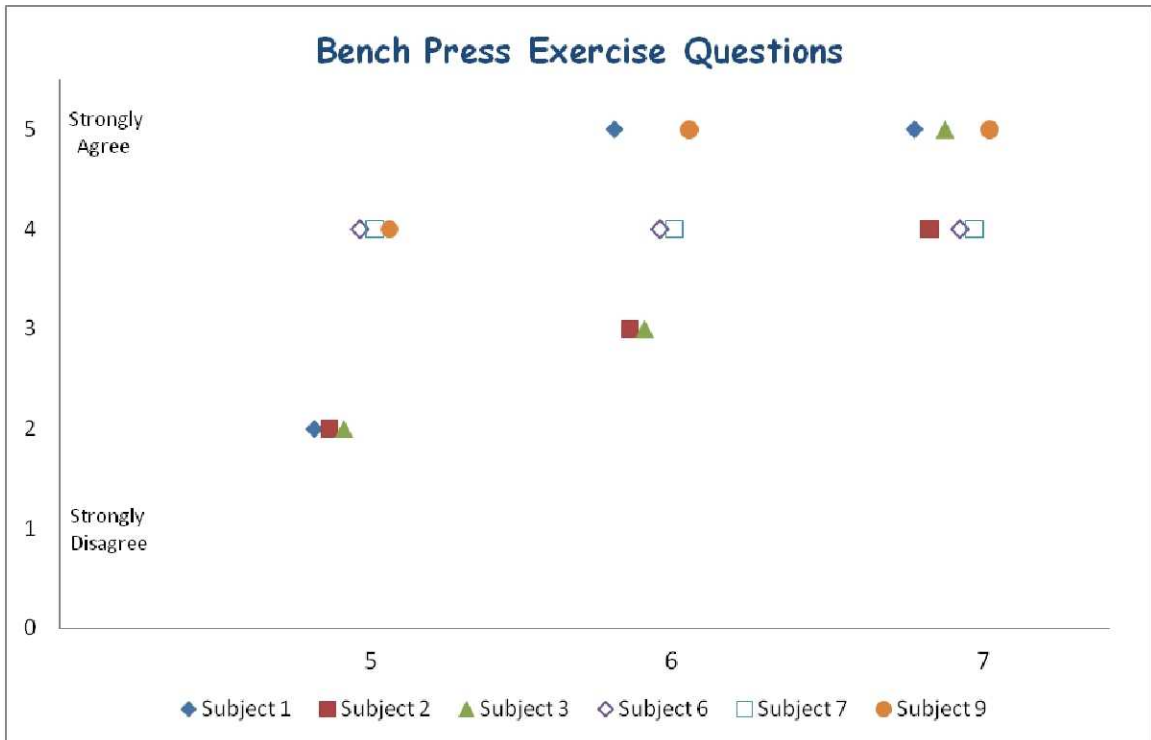
1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

3. My hips were properly supported during the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

4. I did not experience any joint or muscle discomfort while performing the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable



Bench Press Exercise Questions:

5. During the exercise, it was easy to maintain the proper form.

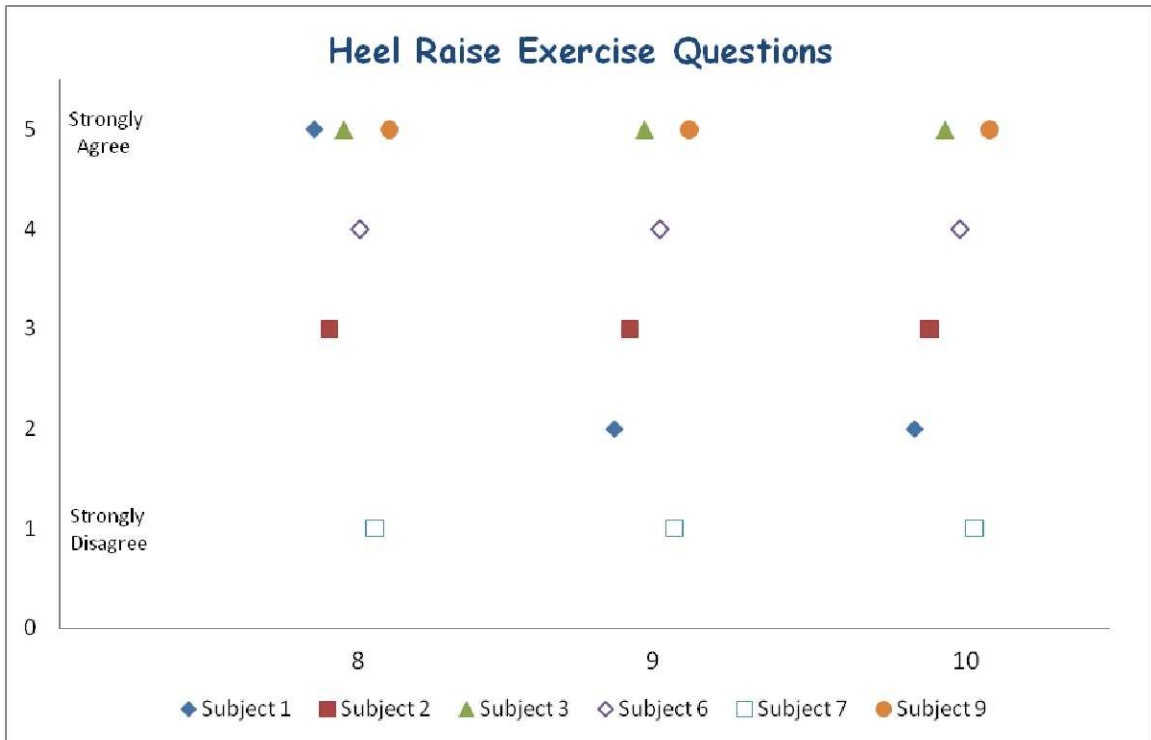
1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

6. It was comfortable to perform the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

7. I did not experience any joint or muscle discomfort while performing the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable



Heel Raise Exercise Questions:

8. During the exercise, it was easy to maintain the proper form.

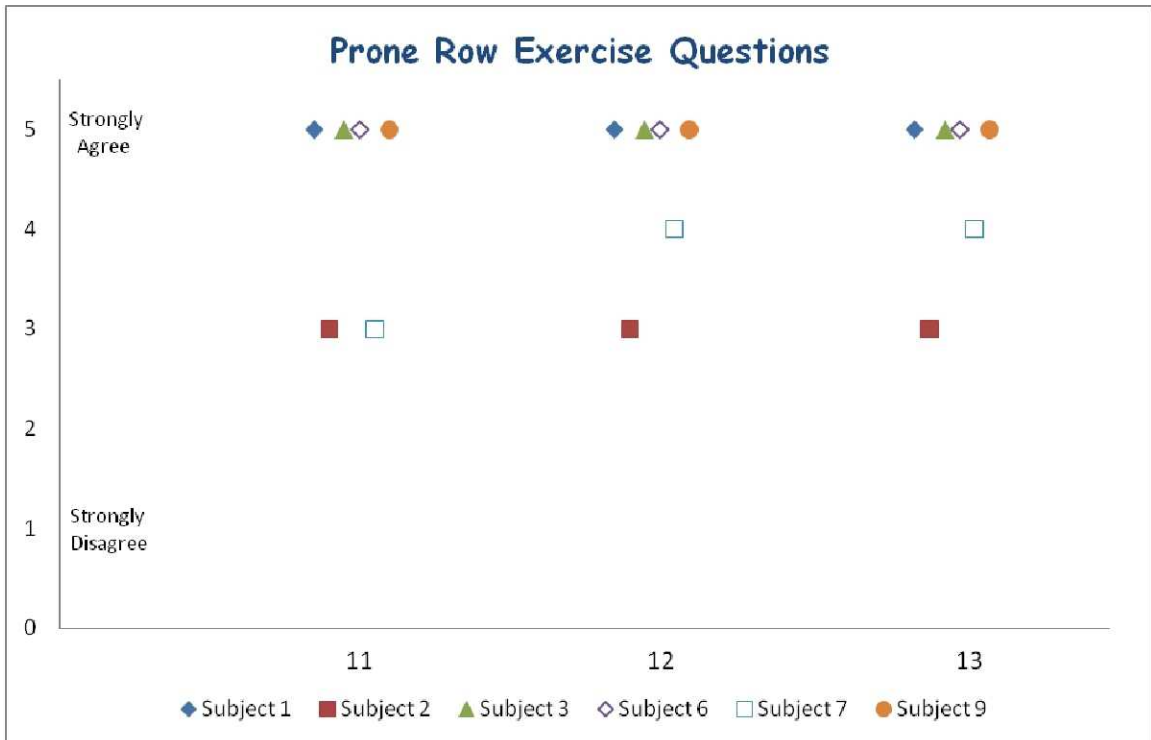
1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

9. It was comfortable to perform the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

10. I did not experience any joint or muscle discomfort while performing the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable



Prone Row Exercise Questions:

11. During the exercise, it was easy to maintain the proper form.

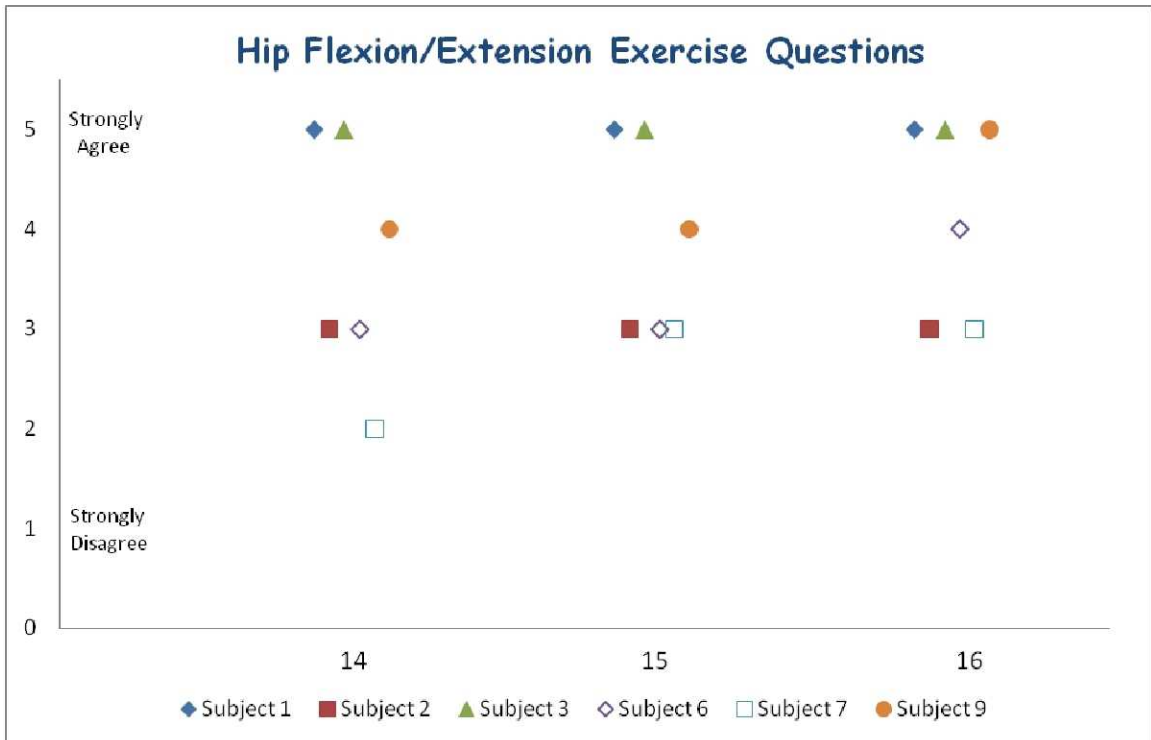
1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

12. It was comfortable to perform the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

13. I did not experience any joint or muscle discomfort while performing the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable



Hip Flexion/Extension Exercise Questions:

14. During the exercise, it was easy to maintain the proper form.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

15. It was comfortable to perform the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

16. I did not experience any joint or muscle discomfort while performing the exercise.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

Figure A.1: Results from the HEF subject questionnaire, grouped by exercise.

Other Questions:

17. It was easy to get on or off the bed rest fixture.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

18. The harness was comfortable.

1- Strongly Disagree 2- Disagree 3- Neither 4- Agree 5- Strongly Agree N/A – Not Applicable

19. Did you feel uncomfortable pressure while exercising? If yes, where?

20. Did you experience any pinching while exercising? If yes, where?

21. Did you feel that supine exercise on the bed rest fixture simulated upright exercise?
Why or why not?

22. Did you feel safe on the equipment? Why or why not?

23. Do you have any additional comments?