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Ground Reaction Force and Mechanical Differences Between the Interim Resistive Exercise Device (iRED) and Smith Machine While Performing a Squat

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ACRONYMS

avg	average
BMD	bone mineral density
cm	centimeters
DCER	dynamic external constant resistance
Dz_{peak}	point in deflection where the peak force in the z-axis occurs
EMG	electromyography
F_x	force in the x-axis
F_y	force in the y-axis
F_z	force in the z-axis
GRF	ground reaction force
iRED	Interim Resistive Exercise Device
ISS	International Space Station
max	maximum
min	minimum
N	Newton
Rep	repetition
ROM	range of motion
$ROM_{bar/cable}$	range of motion of the bar or cable
SD	standard deviation
sec	second
SED	standard error of the difference
SEM	standard error of the mean
W	work

ABSTRACT

Background: Musculoskeletal unloading in microgravity has been shown to induce losses in bone mineral density, muscle cross-sectional area, and muscle strength. Currently, an Interim Resistive Exercise Device (iRED) is being flown on board the International Space Station to help counteract these losses. Free weight training is used as the “gold standard” for resistive exercise training and has shown successful positive musculoskeletal adaptations. In biomechanical research, ground reaction forces (GRF) trajectories are often used to define differences between exercise devices. The purpose of this evaluation is to quantify the differences in GRF between the iRED and free weight exercise performed on a Smith machine during a squat. **Hypothesis:** Due to the differences in resistance properties, inertial loading and load application to the body between the two devices, we hypothesize that subjects using iRED will produce GRF that are significantly different from the Smith machine. Additionally, there will be differences in bar/harness range of motion ($ROM_{\text{bar/harness}}$) and the time when peak GRF occurred in the ROM_{bar} . **Methods:** Three male subjects (178.8 ± 1.5 cm, 94.6 ± 8.6 kg, 26.3 ± 3.5 yrs) performed three sets of ten squats on the iRED and on the Smith Machine on two separate days at a 2-second cadence (2 seconds up; 2 seconds down). A force plate (Kistler Instrumentation Corporation, Amherst, NY) measured GRF (F_z , F_x , and F_y) and a deflection transducer measured $ROM_{\text{bar/harness}}$ during the squat. **Results:** Statistically significant differences were found between the two devices in all measured GRF variables. Average F_z (74.06 ± 12.49 ; $p < .002$) and F_x (145.16 ± 12.93 ; $p < .001$) during the Smith machine squat were significantly higher than iRED. Average F_y (16.82 ± 6.23 ; $p < .043$) was significantly lower during the Smith machine squat. The mean descent/ascent ratio (i.e. lowering and rising from the squat) of the magnitude of the resultant force vector (F_r) of all three axes for the Smith machine and iRED was 0.95 and 0.72, respectively. Also, the point at which maximum F_z occurred in the range of motion (Dz_{peak}) was at different locations with the two devices. Dz_{peak} occurred at 0.63 ± 0.28 cm from the bottom of the ROM_{bar} with the Smith machine and 28.03 ± 5.02 cm from the bottom of the ROM_{harness} with the iRED ($p < .002$). Additionally, ROM_{bar} was 26% greater when performing a squat on the Smith Machine, which contributed to a 28% greater total work value with the Smith Machine.

Conclusion: These differences in the forces experienced by the body during exercise with the two different devices may result in different mechanical stresses on the musculoskeletal system. Thus, the iRED squat should not be considered the same exercise as a Smith machine squat, as it elicits completely different GRF. The resulting physiological adaptations to training are not fully understood with iRED.

1.0 BACKGROUND

Exposure to microgravity has been shown to initiate losses in bone mineral density (BMD) (8,20), muscle strength (4,16), muscle endurance (4,19), and muscle volume (1,16,27,28). LeBlanc et al. (27) measured significant muscle specific atrophy after only 8 days of spaceflight. Organov et al. (31) studied bone loss of cosmonauts after long-term spaceflight (i.e. 4.5 – 14.5 months) and found a significant decrease in BMD at a rate of 1%, 1.3%, and 2% per month in the lumbar spine, proximal femur, and pelvis, respectively (31). With the first stage of the International Space Station (ISS) complete, and the vision of sending crewed flights to Mars, the need for countermeasures to prevent muscle atrophy and bone degradation has become crucial. It has been proposed that a mission to Mars would take between 600 – 1500 days roundtrip (12). Therefore, without adequate countermeasures, significant losses in bone and muscle could compromise the working capacity of the crewmembers during and after flight.

Resistance exercise has been proposed as a potential countermeasure to help maintain muscle strength, muscle mass, and BMD during spaceflight (5). Several investigators have confirmed that resistance training in normal gravitational conditions is an effective stimulus to increase all these variables in both trained and untrained subjects (3,6,11,17,24,26,29). The magnitude of change depends on the training intensity, volume, frequency, and mode of training (1,17,30). The most widely used mode of training in the athletic setting is free weight training. During free weight exercise, the mass moved remains constant throughout the range of motion (ROM), while the force produced by active skeletal muscle varies. The muscle force depends upon the mechanics of the skeleton (3,25), and is known as dynamic constant external resistance (DCER) exercise (17). Variable resistance training is another mode where the external resistance varies with the ROM. It often involves resistance provided by an elastic cord, spring, or cam-type plate system. Resistance training with elastic cords or springs provides a force output that is directly related to the stretch of the cord (21). Both DCER training and variable resistance training have been shown to produce positive muscle adaptations (3,11,24,29,36).

The Interim Resistive Exercise Device (iRED), currently flown on ISS, is an elastic polymer-based variable resistance device. One of the primary exercises performed by crewmembers on ISS is the squat. The squat is a multi-joint exercise that recruits thigh and hip musculature along with trunk stabilizers (i.e. rectus abdominus, spinal erectors, etc.), and produces significant skeletal axial loading (3). Axial loading, force applied by the muscle to the bone, and the rate of change of force exerted on the bone may be important factors in maintaining BMD during spaceflight (3,13,26).

Visually, the iRED squat movement is vastly different from a Smith machine squat. During an iRED squat, the line of force applied by the external resistance appears to be shifted anteriorly due to the harness configuration, which may result in different ground reaction forces (GRF), muscle recruitment patterns, joint moments, and thus different training adaptations than a Smith machine squat. Also, the actual forces experienced by the subject may be different. During a free weight squat, the peak GRF occurs near the bottom of the ROM (2). With elastic polymer systems, peak force is directly related to the stretch of the cord (21), and may occur toward the top of the movement when the cord nears maximum stretch.

It is important to understand the differences between two resistive exercise modes to better understand training adaptations that may occur from their prescription. The same exercise performed on different devices may produce different results. The purpose of this study was to characterize the GRF associated with a free weight squat performed on a Smith machine and with the iRED. Due to the elastic nature of the iRED, we hypothesized that when performing a squat, peak force in the z-axis (vertical) and work will be significantly lower with the iRED. Additionally, we hypothesized that there will be differences in force in the x-axis (anterior/posterior) while squatting with the two devices. Moreover, we believe that the differences in force application properties of the two devices will result in different GRF trajectories throughout the ROM.

2.0 METHODS

2.1 Subjects

Three male subjects (178.6 ± 1.5 cm, 94.6 ± 8.6 kg, 26.7 ± 2.5 yrs) with experience in squat training on the Smith machine and iRED volunteered as test subjects for the purposes of this evaluation. Each subject signed an informed consent statement and Layman's summary before participation. All testing protocols were reviewed and approved by the NASA Johnson Space Center Committee for the Protection of Human Subjects.

Table 1: Subject Characteristics

<i>Subject</i>	<i>Ht (cm)</i>	<i>Wt (kg)</i>	<i>Testing WT Lifted (lbs/kg)</i>	<i>Testing WT Lifted (N)</i>	<i>Age (years)</i>
1	177.8	94.8	155.0 / 70.5	691.1	27
2	180.3	85.9	195.0 / 88.6	869.6	29
3	177.8	103.0	195.0 / 88.6	869.6	24

2.2 Exercise Devices

2.2.1 Smith Machine

A standard Smith machine (Bigger, Faster, Stronger 300052, Salt Lake City, UT) was used for the first condition (DCER) of testing. The Smith machine was chosen to make a direct comparison to a physiological study that was concurrently being performed in the Exercise Physiology Laboratory at Johnson Space Center.

2.2.2 Interim Resistive Exercise Device

The iRED contains a series of 16 flex packs stacked vertically and is designed to provide resistance training for crewmembers in microgravity. A flex pack (Figure 1) consists of a cylindrical aluminum outer rim, with rubber spokes protruding inward toward a center hub. The flex packs revolve about a metal axle. When the metal axle is turned, the rubber spokes are stretched, increasing the resistance offered by the device.

A nylon cord is attached to a spiral pulley at the bottom of the flex pack column that allows a gearing mechanism to rotate in the same direction as the rotating flex packs. An aluminum canister encases the 16 flex packs and spiral pulley. The nylon cord extrudes out of the bottom of the canister between two pivot pulleys. A plastic egg-shaped stopper is attached to the distal end of the nylon cord to prevent the cord from retracting back inside the canister. At the top of the flex pack column, a metal gear is attached to the metal axle. The gear is engaged or disengaged by a lever on the outside of the casing of the iRED. When engaged, the gear is turned by a hand-crank located on the top of the iRED, which rotates the splines between the flex packs counterclockwise, stretching the rubber flex packs. When the rubber is stretched, or preloaded, the resistance provided is dependent upon the degree of rotation of the inner hub of the flex packs. The resistance level is displayed via a set of twelve indicator marks on the side of the can. Each iRED canister is loaded independently.

Each can was calibrated prior to the study using load cells (ELPS-T3E-500L, Entran, NJ) to measure the peak force when the cable is pulled at a constant speed (28 cm/sec) to 56 cm. Each can was calibrated independently from mark 0-12. The peak force was recorded and used to determine the appropriate canister mark that would deliver a desired load.



Figure 1: A) Subject performing a squat on the iRED with the squat harness (left). The testing setup included a force plate between the feet and the iRED base plate. B) An individual flex pack disassembled from the iRED container (right).

When performing a squat on iRED, the subject wears a harness, modified from American football shoulder pads (Figure 1) designed to evenly distribute load across the shoulders. A brace wraps around the top shell of the football pads, and at each corner a nylon cord is attached and extends down to meet the mid-axillary line of the subject at the hip level when the subject is standing. At the distal end of the cord, a pivot pulley attaches the cord to a clip where the iRED cables are then attached to the cans.

2.3 Instrumentation

A piezoelectric force plate (Kistler Instrumentation Corporation, Amherst, NY) recorded GRF in the x (F_x), y (F_y), and z (F_z) axes during exercise (Figure 2). A rotary potentiometer deflection transducer (Patriot Sensors & Control Corporation, Costa Mesa, CA) measured ROM_{bar} (Smith machine) or ROM_{cable} (iRED) during exercise. All data were sampled and collected at 200 Hz. The data were acquired and recorded using a data acquisition board (National Instruments, Austin, TX) and LabView 4.0 software (National Instruments, Austin, TX). A Visual Basic program was developed using Microsoft Excel 2000 to evaluate the start and stop time, peak force along all axes (N), and the total work (J) for each repetition.

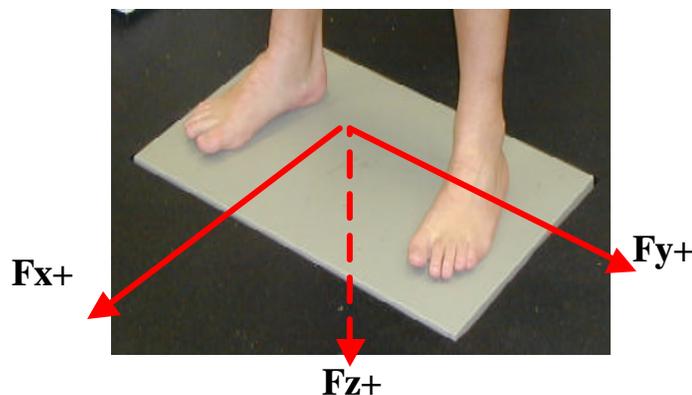


Figure 2: Force plate and axis orientation.

2.4 Testing Procedures

Each subject was tested on two separate days. The Smith machine trials occurred first. On each day, subject weight was recorded by a Metler Toledo ID1 scale (Metler Toledo Inc., Worthington, OH) and the subject performed his customary warm-up and stretching procedures. Additionally, one warm-up set of ten repetitions of the squat exercise with a 47-kg load (a typical warm-up weight for all subjects) was performed. A 2-minute rest period was given between the warm-up set and the first testing set. For both exercise modes, system weight was measured by the force plate while the subject stood directly under the load. Each subject selected for his Smith machine load. The iRED load was standardized to the Smith machine load by matching the system weight using the force plate. Subjects performed one set of 8-10 repetitions following a 2-second descent/ascent cadence. During the Smith machine squat, the subject squatted down until the thighs were parallel to the floor. However, mechanical restraints of the iRED made a full parallel squat impossible. Thus, the subjects squatted down until the plastic egg attached to the iRED cord contacted the spiral pulley. Following the initial set, the subject was given a 2-minute rest period before the second set of 8-10 repetitions. The same procedure was repeated for both testing devices.

2.5 Statistical Analysis

The first eight repetitions of each set were analyzed. Approximate system work (W) per repetition were calculated as $W = Fz * ROM_{\text{bar/cable}}$. Maximum (Fz_{max} , Fx_{max} , Fy_{max}), minimum (Fz_{min} , Fx_{min} , Fy_{min}), and average (Fz_{avg} , Fx_{avg} , Fy_{avg}) forces (N) were recorded. Range of force along all three axes (fz_{range} , fx_{range} , fy_{range}) was calculated by subtracting the minimum force from the maximum force. The amount of displacement of the cable or bar at the time of Fz_{max} was also recorded (Dz_{peak} ; cm). The magnitude of the resultant force vector (Fr) was derived using the following equation: $|Fr| = \sqrt{Fx^2 + Fy^2 + Fz^2}$. All GRF and mechanical data are expressed as mean \pm standard error of the mean while differences of means are expressed as difference \pm standard error of the difference (SED). A dependant t-test was used to compare iRED to Smith machine measures for all dependant variables. Alpha was set at .05 to determine statistical significance.

3.0 RESULTS

3.1 Repetition Kinematics

There was no significant difference in the average time per repetition between the two exercise machines ($p = .737$). However, subjects were able to attain a greater ROM ($p < .01$) on the Smith machine (See Table 2).

3.2 Ground Reaction Forces

The $F_{z_{range}}$ was greater ($p = .030$) with the Smith machine (887.9 ± 306.6 N) compared to iRED (488.7 ± 81.0 N). $F_{x_{range}}$ was also greater ($p = .001$) on the Smith machine (208.5 ± 35.1 N), compared to the iRED (120.2 ± 23.1 N). $F_{y_{range}}$ was not significantly different ($p = .399$). Complete data are presented below in Table 2 and in Appendix A.

Magnitude of the resultant force vector data was significantly higher for both devices on the ascent of the movement than the descent. Fr_{avg} during the descent of the Smith machine squat was 668.3 ± 15.4 N, compared to 698.9 ± 14.6 N during the ascent of the squat. Overall, the average Fr on the descent of the squat movement on Smith machine was 96% of the force on the ascent (Figure 3). The magnitude of Fr on the iRED revealed a larger descent-to-ascent ratio. Force on the descent of the squat on iRED was 561.5 ± 15.1 N, compared to 727.2 ± 12.0 N on the ascent (Table 3). Overall, the resultant force vector produced by subjects during the descent of the squat on iRED was 72% of the force on the ascent (Figure 3). Complete data are also represented below in Table 3 and in Appendix A.

3.3 System Work (Fz)

The difference in ROM coupled with higher $F_{z_{avg}}$ with the Smith machine squat contributed to greater system work values during a Smith machine squat compared to an iRED squat ($p < .001$). The position in the ROM at which the maximum force along the z-axis occurred also differed between the two exercise devices ($p < .002$), with the Smith

machine $F_{z_{max}}$ occurring much earlier in the ascent (i.e. bottom of the squat movement) than the iRED.

Table 2: Mechanical and Ground Reaction Dependent Variables

<i>Variable</i>	<i>Smith Mach</i>	<i>iRED</i>	<i>Difference</i>	<i>p-value</i>
Rep (sec)	2.9 \pm 0.2	2.9 \pm 0.1	0.0 \pm 0.2	0.737
ROM (cm)	57.9 \pm 2.4	43.2 \pm 0.8	14.7 \pm 2.0	<.001
W (J)	758.4 \pm 35.5	551.2 \pm 17.7	207.2 \pm 25.3	<.001
Dz_{peak} (cm)	0.6 \pm 0.3	28.0 \pm 5.0	-27.4 \pm 4.9	<.002
Fz_{min} (N)	1192.3 \pm 105.5	1364.0 \pm 50.2	-171.7 \pm 58.7	<.033
Fz_{max} (N)	2080.2 \pm 71.4	1817.4 \pm 39.2	262.8 \pm 66.8	<.011
Fz_{avg} (N)	1664.9 \pm 54.1	1590.8 \pm 42.0	74.1 \pm 12.5	<.002
Fx_{min} (N)	34.2 \pm 13.6	-70.2 \pm 8.9	104.4 \pm 12.3	<.001
Fx_{max} (N)	242.7 \pm 20.7	47.4 \pm 4.1	195.3 \pm 21.3	<.001
Fx_{avg} (N)	132.7 \pm 14.9	-12.5 \pm 5.7	145.2 \pm 12.9	<.001
Fy_{min} (N)	-47.7 \pm 5.5	-30.4 \pm 3.1	-17.3 \pm 4.7	<.014
Fy_{max} (N)	19.1 \pm 7.4	33.4 \pm 4.3	-14.3 \pm 5.5	<.050
Fy_{avg} (N)	-13.3 \pm 8.1	-3.5 \pm 3.0	-16.8 \pm 6.2	<.043

All data represented as mean \pm standard error of the mean or SED (for difference).

Fz_{min} = minimum force in the z-axis; Fz_{max} = maximum force in the z-axis; Fz_{avg} = average force in the z-axis; Fx_{min} = minimum force in the x-axis; Fx_{max} = maximum force in the x-axis; Fx_{avg} = average force in the x-axis; Fy_{min} = minimum force in the y-axis; Fy_{max} = maximum force in the y-axis; Fy_{avg} = average force in the y-axis; Dz_{peak} = the point in the range of motion at which the maximum Fz occurs.

Table 3: Magnitude of the Resultant Force Vector

	<i>Descent</i>	<i>Ascent</i>	<i>Difference</i>	<i>p-value</i>
Smith Machine	668.3 \pm 15.4	698.9 \pm 14.6	30.6 \pm 2.4	<.001
iRED	561.5 \pm 15.1	727.2 \pm 12.0	165.7 \pm 11.1	<.001

All data represented as mean \pm standard error of the mean or SED (for difference).

4.0 DISCUSSION

The goal of this study was to identify the GRF and quantify the mechanical properties associated with a squat on a Smith machine and the iRED. As we hypothesized, this study revealed numerous differences between the two devices. ROM with iRED was less than with the Smith machine. Forces along the x-, y-, and z-axis as well as the magnitude of the resultant force vector were significantly different between machines. Dz_{peak} occurred near the top of the ascent of the movement when using the iRED, whereas Dz_{peak} occurred at the lowest position of a Smith machine squat. Average work was slightly higher on the Smith Machine as compared to the iRED, mostly due to a greater ROM_{bar} on the Smith machine. Each of these differences may result in different physiological adaptations to training.

4.1 Ground Reaction Forces

4.1.1 Force Along the z-Axis (Up/Down)

The differences observed in Fz were a function of the mechanical properties of the two devices. When squatting on the Smith machine, subjects produced a higher Fz_{max} (12.6%) than on the iRED. There are two possible explanations as to why this occurs.

Although the resistance lifted was the same between the two devices, the actual mass moved was different. With the Smith machine, the mass moved was the entire body and loaded bar. With the iRED, the mass moved was the body, the harness, and the mass of the flex packs. The mass of the flex packs is not related to the resistance provided by the flex packs. Because the mass moved with the Smith machine was much greater than that moved with the iRED, the effects of acceleration upon GRF will be different. Peak forces with the Smith machine are exerted by the musculoskeletal system near the beginning of the ascent (Figure 3) because of the inertial properties of the bar and body (2).

Another possible explanation is due to the force tension properties of the iRED. Hughs et al. (21) investigated the elastic properties of several different elastic polymer-tubing sizes and reported a linear length-force relationship of the tubing (21). Likewise,

with the iRED there is a direct relationship between the deflection of the cord and force. However, when measured dynamically, there was a noticeable difference between force resulting during the descent and ascent of the movement. At any given cord length, the GRF was less during the descent than during the ascent (Figure 3). Visual observation of the force vs. deflection curve shows an immediate drop in force during the descent phase. The drop is typical of an elastic polymer system (32). This phenomenon where systems change properties dependent upon past reactions to change is known as hysteresis (32). In the case of iRED, the reaction of the system to change is the load generated by the preloaded stretch of the rubber in the flex packs.

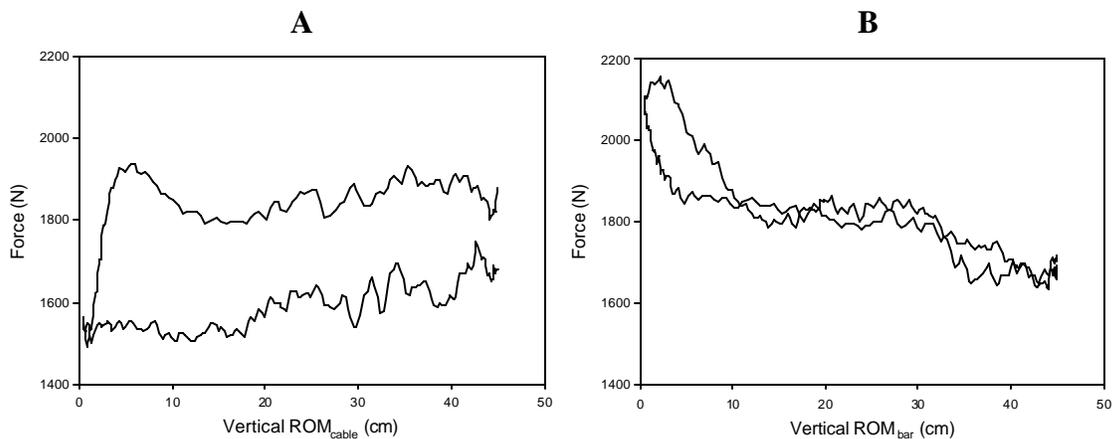


Figure 3: Comparison of Fz between the iRED (A) and Smith machine (B). The right side of each graph indicates the beginning of the squat (top) where the subject is in the standing position. 0 cm is the middle of the repetition where the plastic egg is either contacting the spiral pulleys (iRED), or the subject is in the parallel position (Smith machine). Notice the difference in force on the descent vs. ascent of the movement and the slope of the two curves.

Hughs et al. (21) performed their investigation of an elastic-based resistance device independent of acceleration. The static force was recorded with the subjects in a standard position. Under similar static conditions, iRED theoretically would reveal parallel results with the force being directly proportional to the length of the cord. However, with human movement, acceleration is highly variable. It was difficult to draw any conclusions as to a force/length relationship from the data in this study. Visual observation of force vs. time (Appendix B) curves indicates that there may indeed be a distinct relationship between acceleration and force when exercising with iRED.

However, it is unclear whether this relationship is due to hysteresis or is simply a function of the acceleration of the subject's body mass. This relationship warrants further investigation.

4.1.2 Force Along the x-Axis (Anterior/Posterior)

GRF along the x-axis (Figure 2) display the most notable differences between the iRED and Smith machine. Exercising on the Smith machine generated large positive forces along the anterior/posterior axis. Because the guide poles of the Smith machine allow only vertical movement of the bar, any fore/aft force imparted by the shoulders to the bar translates to an equal and opposite horizontal force (F_x) at the feet (Figure 4). The large positive F_x during the Smith machine are the result of the subjects leaning into the fixed bar during the repetition.

The iRED allows anterior/posterior translation at the harness; therefore, ground reactions $F_{x_{avg}}$ are minimal, compared to the Smith machine. Because the iRED harness has a pivot point at the front of the shoulders and a pulley at the bottom of the cord, when the subjects pushed their hips back, the line of force of the iRED shifts anteriorly on the shoulders, eliciting a small propulsion (negative) force at the feet. This propulsion force occurs because the iRED is pulling the body forward in the bottom of the squat (Figure 4).

Shifts in F_x due to changes in external force application can have large consequences on joint loading. Wretenburg, Feng, and Arborelius (38) demonstrated, via biomechanical modeling, that small changes in bar placement cause significant changes in joint moments. Specifically, Wretenburg et al. evaluated differences in moments at the knee and hip during low and high bar squats. In a high bar squat, the bar is placed just below the 7th cervical vertebrae and the load is believed to be altered toward the knees. In a low bar squat, the bar is placed lower on the back across the spine of the scapula and slightly posterior, compared to a high bar squat, thus generating a higher load on the hips. Significantly higher moments were calculated at the hip during both parallel and deep squats and a lower moment was calculated at the knee during low bar, compared to high bar, back squats (38).

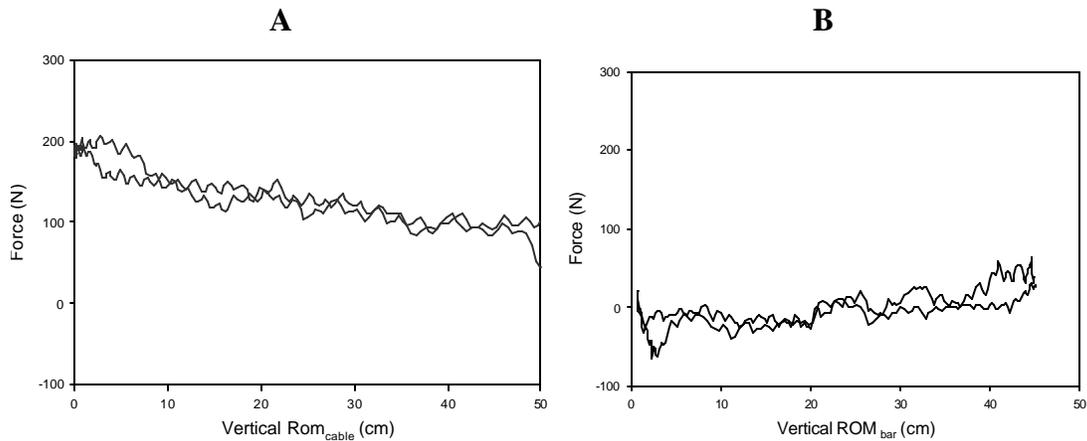
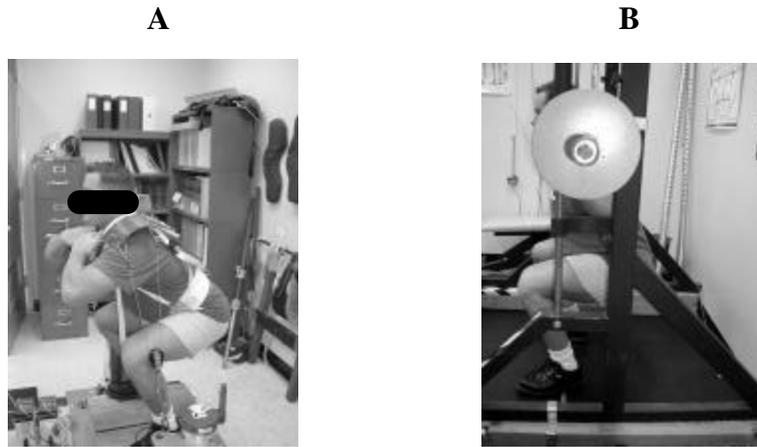


Figure 4: Smith Machine (A) and iRED (B) Fx vs. deflection curves.

The differences in joint moments observed in the Wretenberg et al. study are related to differences in hip angles between the two types of squats. A low bar back squat, which is typically used in powerlifting, causes the lifter to flex at the hip to a greater degree than a high bar back squat (38). The result is a greater moment at the hips, which is precisely what Wretenberg et al. observed. In fact, for a given force, the exercise that causes the greatest degree of trunk flexion will produce the greatest moment. However, the relationship between iRED and the Smith machine is different. Visual observations and unpublished data (personal communications with Tony Dial) from the Exercise Physiology Laboratory show that subjects flex more at the hip during an iRED squat (more similar to low bar squat) than the Smith machine (more similar to high bar squat). The data from this study show that there is a -36% difference in net GRF during an iRED compared to Smith machine of the bottom of the movement. Because moments are a product of both the perpendicular distance of the line of force (bar or cable) from the joint and the resultant force, a 36% difference in force at the bottom of the iRED squat likely would result in a much lower moment about the hips. The difference in joint moments may impact the effect of the squat on bone and muscle.



**Figure 5: iRED squat (A) and Smith machine squat (B).
Notice the differences in trunk flexion at the bottom of the movement.**

Changes in BMD are attributed to axial loading, the rate of change of loading, and the force being applied to bone by the muscle (1,13,26). Each of these variables are affected by joint moments. Several studies have evaluated bone loss during spaceflight (8,31,37). Caillot-Augusseau et al. showed profound bone remodeling after 180 days of spaceflight (8). Vico et al. also reported losses in bone density in the distal tibia in cosmonauts on *Mir* after only 30 days of flight. Furthermore, Vico et al. suggested site-specific loss of bone and even site-specific loss within the same bone (37). A review on bone density and progressive resistance exercise by Layne and Nelson (26) suggests that changes in bone density are site-specific within bone. These data may suggest that if a smaller moment is placed on the hips in a zero-g squat using the iRED, the BMD in the pelvis, hips, and proximal femur may not be as positively affected by the exercise, compared to a terrestrial free weight squat. This is of great concern because BMD loss in the femur occurs at a rapid rate during spaceflight (31), and long-term exposure to microgravity without an adequate countermeasure might increase the risk of fracture in astronauts upon returning to Earth.

4.1.3 Force Along the y-Axis (Lateral)

Force along the y-axis (Figure 2) differed significantly between the two exercise conditions, but physiologically to a minor extent. The differences in the y-axis may be attributed to individual squatting technique or unbalanced loads between the two iRED canisters. When performing a high-intensity squat, it is not uncommon for a lifter to alter

his or her lifting technique and shift the center of mass under the dominant leg, thus pushing with a higher force with that leg (35). By doing this, the subjects would cause a net positive or negative GRF along the y-axis.

Another possible cause of lateral GRF positive or negative F_y might be the mechanical properties of the iRED and its rubber flex packs. Because the iRED has two canisters that are loaded independent of each other, it is nearly impossible to achieve identical loading from each canister. During the course of a 1-hour training session, the rubber within the iRED flex packs may become more compliant due to stretching and heating of the flex packs. The degree to which this occurs depends upon a number of variables (e.g. heat, number of cycles, and rest between sets). Even if the flex packs have been matched in terms of age and use, resistance properties may differ between cans and may change between sets. Such variations could have contributed to the differences in the F_y . If the subject detected different load characteristics in one canister, he may have accommodated by shifting his center of mass, causing a relatively higher positive or negative F_y in shifted direction.

4.1.4 Magnitude of the Resultant Force Vector (F_r)

Perhaps the most significant finding of this study was the difference in the magnitude of the resultant force vector. Although the amount of force needed to improve strength during the eccentric contraction is not yet clearly defined, several researchers have shown that eccentric forces during contractions are crucial (10,14). One training study performed by Dudley et al. (14) over 19 weeks showed greater increases in 3RM leg press and leg extension when training using both eccentric and concentric contractions, compared to a concentric-only group. To eliminate volume of training as a conflicting variable, a second concentric group performed twice as many concentric leg presses and leg extensions during the study to equal the total number of contractions performed by the concentric/eccentric group. Again, the group using both concentric and eccentric contractions had a greater increase in strength than the concentric-only group using equal volume.

During an iRED squat, average force during the eccentric portion of the movement decreases by 28% as compared to a 4% reduction during a Smith machine squat. Therefore, when performing a squat on the iRED, the quadriceps muscle fibers are not subjected to as much eccentric stress on the iRED as on a Smith machine. This might prove to be suboptimal for improvement in muscular strength and maintenance of muscle fiber density.

4.1.5 $ROM_{\text{bar/cable}}$

The $ROM_{\text{bar/cable}}$ was limited on the iRED, compared to the Smith machine. When the iRED is used at higher loads (> 48 kg), the flex packs are endangered. Therefore, at loads greater than 48 kg, the cable extension during exercise is limited to 56 cm. If the goal of strength training is to maintain functional strength, it is crucial to train throughout a full-joint ROM. Many activities of daily living require strength at knee and hip flexion angles of around 90° . Limited cable length and decreased ROM with the iRED may result in losses of strength at greater knee and hip flexion angles. This could be detrimental to returning crewmembers' health and ability to perform activities of daily living (e.g. standing up from a chair). It could also jeopardize the crewmembers' ability to perform an emergency egress. Muscles will gain strength only slightly beyond the ROM that they are trained in (18,23). Kitai and Sale (23) measured plantar/dorsi flexor isometric strength in 5° intervals from 0° to 40° . After 6 weeks of training, strength gains occurred only at the angle trained and at the two adjacent angles. Similarly, Graves et al. (18) tested joint angle specificity of training with variable resistance using the knee extensor exercise. Isometric knee extensor strength was measured at eight different angles. Subjects were assigned to three separate variable resistance-training groups: 90° to 45° , 45° to 0° , and 90° to 0° . Increases in strength were observed at all three measured joint angles for all three groups, but greater increases occurred at all angles for the group that trained from 90° to 0° .

Training with a limited-joint ROM could potentially affect muscle activation. The hamstring muscles are often indirectly trained with the squat exercise, as they act synergistically with the quadriceps during the descent of the movement (3). With the

iRED's limited ROM_{cable} , it is rarely possible to achieve more than 90° of knee flexion. Pilot data from the Exercise Physiology Laboratory show an average knee flexion angle of 80° in the bottom of the squat on iRED. Ebben, Leigh, and Randall (15) cite an increase in hamstring activity with an increase in knee flexion angle during the eccentric portion of the squat to 120° of knee flexion. Wright et al. (39) also examined EMG activity of the hamstrings during a squat, stiff-legged deadlift, and supine hamstring curl. The researchers concluded that both the supine leg curl and straight-legged deadlift produced hamstring EMG activity twice as high as traditional parallel back squats (39). This research suggests that Romanian deadlifts, straight-legged deadlifts, or standing knee flexion could be increasingly more important with ISS training especially in light of the limited ROM of the iRED and possible lack of stress on the hamstrings during the iRED squat. Both Romanian deadlifts and straight-legged deadlifts would put a significant amount of stress on the hip, pelvic girdle, and lumbar spine. These exercises also may elicit positive adaptations in localized bone density in these site-specific areas.

The limited ROM_{cable} of iRED was one of the main contributors to differences in total work between the exercise conditions. Work is a function of force multiplied by distance, therefore the 12.7 cm less ROM in iRED exercise greatly affected total work. Had the subjects been permitted to descend the extra 12.7 cm, and distance traveled was standardized, total work values may have been more similar between the iRED and Smith machine squats. However, with the current limitations on the flex packs, this is not a plausible option.

5.0 CONCLUSIONS AND PRACTICAL APPLICATION

This investigation revealed significant GRF and $ROM_{bar/cable}$ differences between performing a squat with the Smith machine and with the iRED that may affect training responses. One obvious problem with the iRED is the limited ROM. Training with the iRED would require additional exercises in order to stress all muscle groups targeted by ISS countermeasures to reduce musculoskeletal losses associated with spaceflight. Even with modified exercises, it is doubtful that the eccentric forces imposed by the device would sufficiently stress the muscles to counteract deconditioning. Along with the

limited ROM_{cable} , the iRED may produce a suboptimal line of force for bone density changes in the hip. This problem may be further exaggerated by the lack of gravity acting on the body's center of mass. Differences in the Dz_{peak} may also contribute to muscle recruitment differences between the two machines. Specifically, small GRF at the bottom of the ROM may result in little activation of the posterior muscles of the leg that are crucial to bone density adaptation. Solutions to each of these problems should be evaluated in order to develop more effective countermeasures. For instance, altering the force curve of the resistance device to more closely mimic free weights may have a positive effect. Adding an inertial wheel in line with the iRED cords would dramatically change the resistance of the iRED. Making the eccentric-to-concentric force ratio more similar to free weights might create a more ideal adaptation stimulus. This would likely need to be done with a resistance other than rubber. Harness modifications designed to shift the line of force of the iRED posteriorly also might change muscle recruitment patterns and joint moment forces.

With ISS being operational and mission durations becoming longer, exercise is at the forefront of the countermeasures program for human spaceflight. During long-term spaceflight missions, and eventually missions to Mars, crewmembers undoubtedly would be required to perform tasks that require lifting and other dynamic muscular movements. It is imperative to design and implement an effective resistive exercise system so that the astronauts can perform lifting movements while on Mars and can quickly rehabilitate to their preflight status upon returning to Earth.

APPENDIX A

Table 4: Force Values for Free Weights

Each cell within the table is an individual subject and each row is an individual set.

SET	Fxmin(N)	Fxmax(N)	Fxavg(N)	Fymin(N)	Fymax(N)	Fyavg(N)	Fzmin(N)	Fzmax(N)	Fzavg(N)
1	55.2	298.5	160.6	-66.3	-10.4	-41.2	1349.7	2312.1	1821.0
2	61.3	312.8	178.9	-63.1	5.5	-34.6	1537.2	2147.3	1820.1
1	52.1	216.7	135.2	-37.2	29.3	3.2	1278.3	1879.2	1649.8
2	53.4	231.4	141.5	-38.3	35.7	5.7	1208.2	1880.6	1647.7
1	-3.3	192.2	89.9	-37.4	32.6	-4.2	890.4	2062.4	1525.9
2	-13.3	204.6	89.9	-43.9	21.8	-8.9	889.9	2199.6	1524.7
AVG	34.2	242.7	132.7	-47.7	19.1	-13.3	1192.3	2080.2	1664.9
SD	33.2	50.7	36.5	13.4	18.0	19.8	258.5	175.0	132.6

Table 5: Force Values for iRED

Each cell within the table is an individual subject and each row is an individual set.

SET	Fxmin(N)	Fxmax(N)	Fxavg(N)	Fymin(N)	Fymax(N)	Fyavg(N)	Fzmin(N)	Fzmax(N)	Fzavg(N)
1	-94.2	32.9	-22.5	-29.5	22.2	-2.5	1497.6	1937.6	1715.3
2	-10.0	132.7	59.1	-26.9	20.3	-1.2	959.5	1598.1	1259.4
1	-43.3	49.2	0.8	-21.9	32.0	6.2	1369.9	1797.2	1580.1
2	-45.3	44.6	-0.7	-26.4	31.4	3.1	1362.4	1791.7	1568.5
1	-88.8	41.1	-32.1	-25.4	45.9	11.0	1228.2	1742.0	1492.4
2	-80.3	58.3	-19.3	-39.7	45.8	10.7	1223.0	1706.1	1477.9
AVG	-70.1	47.4	-12.5	-30.4	33.3	3.5	1364.0	1817.4	1590.8
SD	32.9	36.7	32.8	6.1	11.1	5.8	184.7	112.6	151.3

Table 6: Mechanical Variables Related to the Type of Resistance and Length of the Repetition for the Smith Machine

Each cell within the table is an individual subject and each row is an individual set.

SET	ROM_{bar} (cm)	Dz_{peak}(cm)	TW(N/m)	Rep (sec)
1	50.5	0.0	744.4	2.5
2	51.9	0.0	759.9	3.3
1	58.2	1.7	852.8	3.5
2	51.7	1.2	862.7	3.5
1	62.6	0.6	649.2	2.5
2	65.2	0.3	681.1	2.3
AVG	57.9	0.6	758.4	2.9
SD	6.3	0.7	87.1	0.6

Table 7: Mechanical Variables Related to the Type of Resistance and Length of the repetition for the iRED

Each cell within the table is an individual subject and each row is an individual set.

SET	ROM_{bar} (cm)	Dz_{peak}(cm)	TW(N/m)	Dtime(sec)
1	42.9	35.6	584.2	3.2
2	42.8	9.3	527.7	2.2
1	42.3	40.1	587.8	3.3
2	41.6	37.0	563.0	3.3
1	34.0	18.0	507.1	2.1
2	45.5	8.7	487.0	2.1
AVG	43.1	28.08	551.1	2.9
SD	3.9	14.4	41.9	0.6

Table 8: Smith Machine Resultant Force Divided Into the Descent and Ascent of the Squat

Each cell within the table is an individual subject and each row is an individual set.

Set	Fr(D)	Fr(A)	Ratio
1	521.0	553.1	0.94
2	518.1	563.1	0.92
1	755.9	765.2	0.99
2	747.1	778.5	0.96
1	734.7	767.5	0.96
2	733.2	766.2	0.96
AVG	668.3	698.9	0.96
SD	115.5	109.3	0.02

Table 9: iRED Resultant Force Divided Into the Descent and Ascent of the Squat

Each cell within the table is an individual subject and each row is an individual set.

Set	Fr(D)	Fr(A)	Ratio
1	458.7	623.8	0.74
2	441.0	603.2	0.73
1	556.4	790.8	0.70
2	547.3	779.4	0.70
1	593.8	791.0	0.75
2	563.1	788.9	0.71
AVG	561.5	727.2	0.72
SD	61.8	90.2	0.00

APPENDIX B

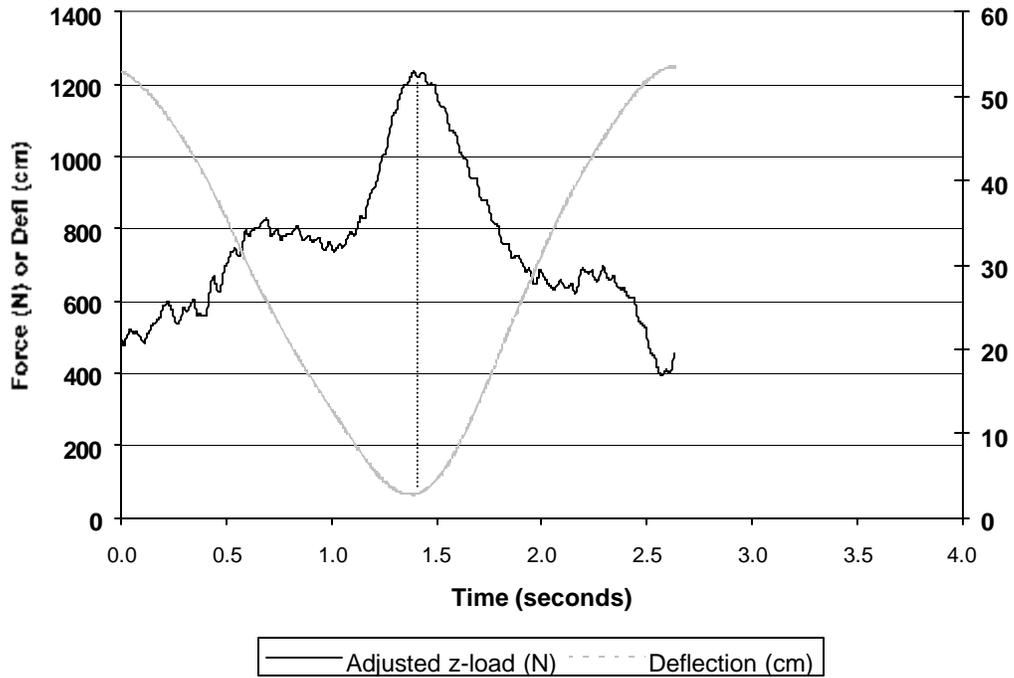


Figure 6: Force/deflection vs. time graph for one repetition with a subject performing a squat on the Smith machine with 870 N of static force. Notice the peak force occurs at the bottom of the movement.

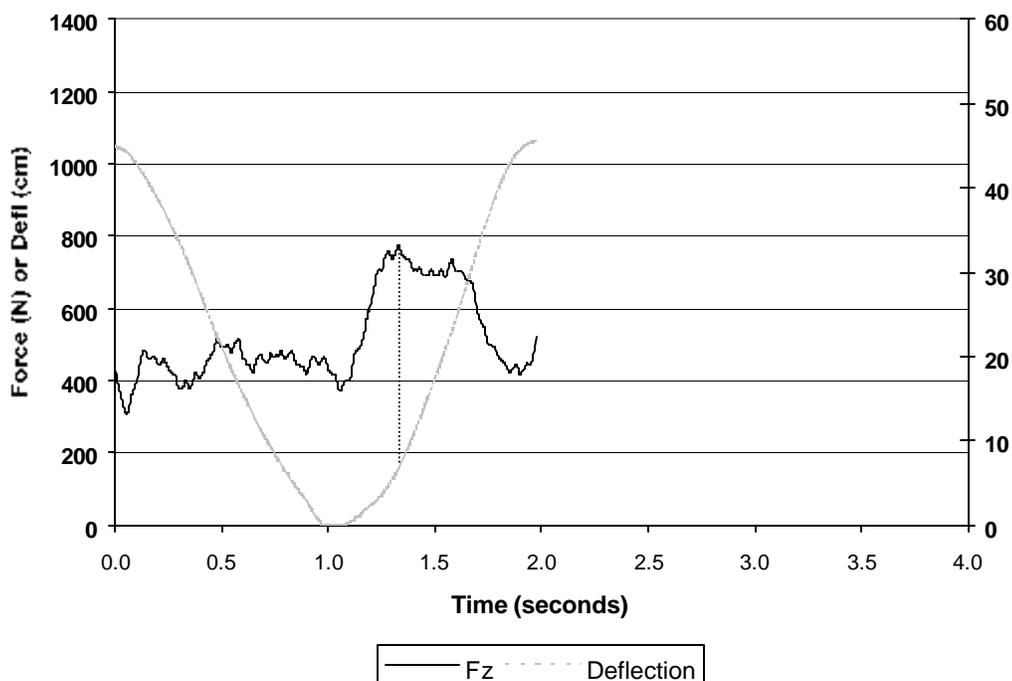


Figure 7: Force/deflection vs. time graph for one repetition with a subject performing a squat on the iRED with 690 N of static force. Despite efforts to control cadence, this subject accelerated out of the bottom of the squat noticeably faster. Notice there are two peaks in the graph. The first peak that occurs low in the deflection is probably due the inertia of the subject accelerating his body mass, where the second spike that occurs higher in the deflection is related to the stretch of the rubber flex packs.

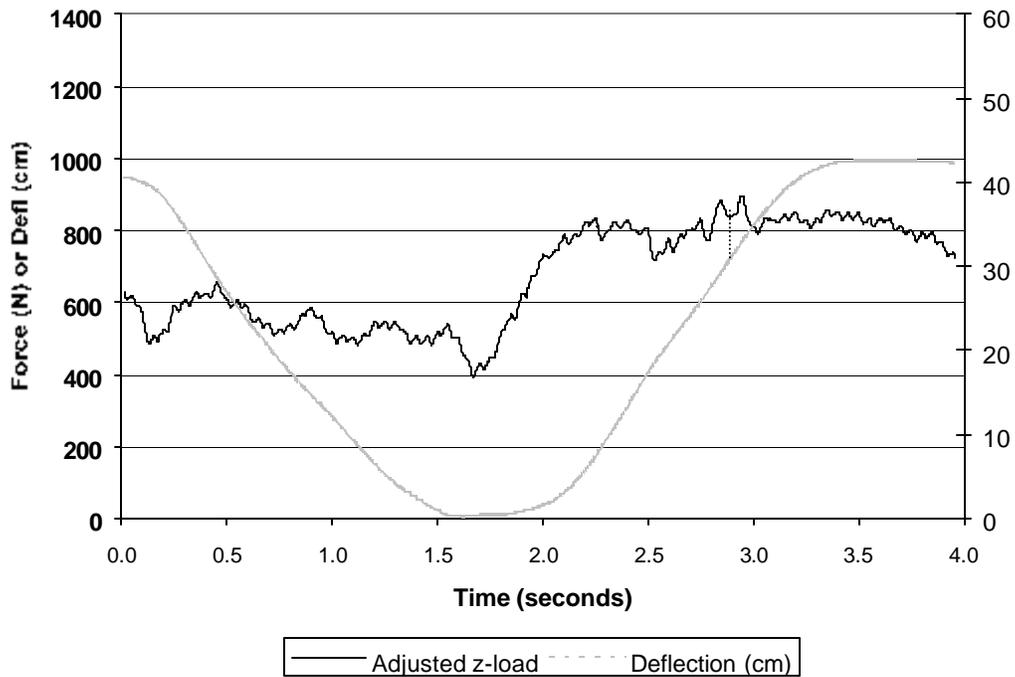


Figure 8: Force/deflection vs. time graph for one repetition with a subject performing a squat on the iRED with 870 N of static force. This subject performed a noticeably more controlled squat. Notice that the peak due to accelerating the body mass is gone and the only remaining peak is due to the stretch of the rubber flex packs.

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13. ABSTRACT (Maximum 200 words) Musculoskeletal unloading in microgravity has been shown to induce losses in bone mineral density, muscle cross-sectional area, and muscle strength. Currently, an Interim Resistive Exercise Device (iRED) is being flown on board the ISS to help counteract these losses. Free weight training has shown successful positive musculoskeletal adaptations. In biomechanical research, ground reaction forces (GRF) trajectories are used to define differences between exercise devices. The purpose of this evaluation is to quantify the differences in GRF between the iRED and free weight exercise performed on a Smith machine during a squat. Due to the differences in resistance properties, inertial loading and load application to the body between the two devices, we hypothesize that subjects using iRED will produce GRF that are significantly different from the Smith machine. There will be differences in bar/harness range of motion and the time when peak GRF occurred in the ROMbar. Three male subjects performed three sets of ten squats on the iRED and on the Smith Machine on two separate days at a 2-second cadence. Statistically significant differences were found between the two devices in all measured GRF variables. Average Fz and Fx during the Smith machine squat were significantly higher than iRED. Average Fy (16.82 ± 6.23 ; $p < .043$) was significantly lower during the Smith machine squat. The mean descent/ascent ratio of the magnitude of the resultant force vector of all three axes for the Smith machine and iRED was 0.95 and 0.72, respectively. Also, the point at which maximum Fz occurred in the range of motion (Dzpeak) was at different locations with the two devices.				
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