Training with the International Space Station Interim Resistive Exercise Device

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ABSTRACT

SCHNEIDER, S. M., W. E. AMONETTE, K. BLAZINE, J. BENTLEY, S. M. C. LEE, J. A. LOEHR, A. D. MOORE, JR., M. RAPLEY, E. R. MULDER, and S. M. SMITH. Training with the International Space Station Interim Resistive Exercise Device. *Med. Sci. Sports Exerc.*, Vol. 35, No. 11, pp. 1935–1945, 2003. A unique, interim elastomer-based resistive exercise device (iRED) is being used on the International Space Station. **Purpose:** This study characterized iRED training responses in a 1-g environment by: 1) determining whether 16 wk of high-intensity training with iRED produces increases in muscle strength and volume and bone mineral density (BMD), 2) comparing training responses with iRED to free weights, and 3) comparing iRED training responses at two training volumes. **Methods:** Twenty-eight untrained men were assigned to four groups of seven subjects each: a no exercise control group (CON), an iRED group who trained with three sets/exercise (iRED3), a free-weight group (FW) who trained with three sets/exercise, and an iRED group who trained with six sets/exercise (iRED6). Training exercises included squat (SQ), heel raise (HR), and dead lift (DL) exercises, 3 $d \cdot wk^{-1}$ for 16 wk. **Results:** For CON, no changes occurred pre- to posttraining. For iRED3, increases ($P \leq 0.05$) in one-repetition maximum (1-RM) strength (SQ 21 ± 4%, HR 17 ± 4%, DL 29 ± 5%), leg lean mass (3.1 ± 0.5%) by dual energy x-ray absorptiometry (DXA), and thigh (4.5 ± 0.9%) and calf (5.9 ± 0.7%) muscle volume (by magnetic resonance imaging) occurred after training with no changes in BMD (DXA). For FW, increases in 1-RM strength (SQ 22 ± 5%, HR 24 ± 3%, DL 41 ± 7%), whole body (3.0 ± 1.1%) and leg lean mass (5.4 ± 1.2%), thigh (9.2 ± 1.3%) and calf (4.2 ± 1.0%) muscle volumes, and lumbar BMD (4.2 ± 0.7%) occurred after training. For iRED6, all responses were similar to iRED3. **Conclusion:** High-intensity training with the iRED produced muscle responses similar to FW but was not effective in stimulating bone. Bed rest and spaceflight studies are needed to evaluate the effectiveness of the iRED to prevent microgravity deconditioning. **Key Words:** WEIGHT TRAINING, BMD, LEAN BODY MASS, SPACEFLIGHT, MICROGRAVITY, RESISTIVE EXERCISE

Muscle atrophy and bone loss are two well-documented consequences of spaceflight. Decreased muscle volume (22), reduction in myofibril cross-sectional area of both Type I and Type II fibers, altered enzymatic properties, and decreased muscle capillarity have been reported after only 5–11 d of spaceflight (10). After 4- to 14-month missions on the Russian Mir Space Station, LeBlanc and coworkers (21) reported significant decreases in lean body mass (LBM) and bone mineral density (BMD) in 14 cosmonauts and astronauts despite vigorous exercise for 1–2 $h \cdot d^{-1}$ during the flights. The exercises included treadmill and cycle ergometry and a variety of resistive exercises with elastic expanders.

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In a 1-*g* environment, high-intensity resistive exercise produces increases in skeletal muscle strength and induces myofiber hypertrophy (20). In a microgravity environment simulated by 14 d of bed rest, high-intensity leg press and plantar flexion exercises performed every other day prevented the changes in leg muscle mass and strength seen in a no-exercise, control group (5). Therefore, it has been recommended that high-intensity resistive exercise be included as a countermeasure during spaceflight to maintain muscle strength and mass (4).

Chronic resistive exercise also has been shown to increase BMD in a 1-*g* environment (8,17,23). Bone remodeling is responsive to compression, high-impact forces, and a rapid change in strain (29). In a 1-*g* environment, the constant compression from gravitational forces and impact forces during normal ambulation maintain BMD. During spaceflight or bed rest, the removal of these forces results in an early increase in bone resorption (25) and either no change or a slightly decreased bone formation (26,30). Exercise experts (4) have proposed that high-intensity resistive exercise targeting the susceptible back and lower-body regions may prevent bone demineralization during bed rest or spaceflight.

An elastomer-based resistance exercise device termed the interim Resistance Exercise Device, or iRED, was developed

TABLE 1. Subject characteristics (mean ± SD, $N = 7$ per group).

Group	Age (yr)	Height (cm)	Weight (kg)	BMI (kg·m^{-2})	Pretraining SQ 1-RM (lb)
CON	32 ± 6	179 ± 4	86 ± 7	27.0 ± 2.6	209 ± 41
FW	33 ± 7	180 ± 9	78 ± 10	24.0 ± 2.8	224 ± 54
IRED3	32 ± 7	180 ± 8	79 ± 11	24.5 ± 2.0	207 ± 33
IRED6	36 ± 7	181 ± 9	83 ± 12	25.5 ± 2.6	241 ± 51

for use on the International Space Station (ISS). Elastomer exercise is used extensively for rehabilitation and during exercise by elderly subjects in a 1-*g* environment to improve muscle strength (2,24). Such exercise devices are often small, lightweight, and require no power, making them practical for implementation on ISS. However, the force curve produced by an elastomer exercise device is not ideal for intensive weight training. Most elastomer devices have a variable-resistance force curve with the peak resistance at the end of the range of motion (ROM), which may not be optimal for performing many exercises. Also, with elastomer exercise, the resistance exponentially decreases during the eccentric or recovery phase, which also may decrease the effectiveness of the training stimulus (7,9,13). Hostler and coworkers (15) concluded that the strength and muscle volume responses after training with an elastic-exercise device were "less than those generally reported for short-term resistance-training programs using free weights."

Presently, there are no data to describe the force characteristics or effectiveness of the unique, elastomer-based resistive exercise device in use on ISS. The purpose of this study was to evaluate the effectiveness of a 16-wk training program using the iRED to induce increases in muscle volume, muscle strength, and BMD. We hypothesized that: 1) 16 wk of training with the iRED (3× wk^{-1} for 3 sets per 3 exercises) would produce training responses in ambulatory, 1-*g* subjects; 2) subjects training with the iRED would have smaller training responses compared with a group performing a similar training protocol with free weights (FW); and 3) doubling the iRED training volume (3× wk^{-1} for 6 sets per 3 exercises) would improve the training responses.

METHODS

Subjects. Twenty-eight healthy men completed this study (Table 1). To qualify, each subject passed a modified Air Force Class III physical, reported no history of back pain, musculoskeletal problems, or hypertension, and passed a treadmill stress test with 12-lead EKG to screen for cardiovascular disease. They had not participated in a resistive exercise program for at least 6 months before the start of the study. Each volunteer signed an informed consent statement after receiving oral and written description of the procedures as well as the risks and benefits of participation in the study. The protocol for this study was approved by Committee for the Protection of Human Subjects from the Johnson Space Center and the Baylor College of Medicine Institutional Review Board.

The subjects were separated into cohorts of four, matched for body size (height and weight), age, and pretraining squat strength as determined by one-repetition maximum (1-RM) strength testing. Each cohort was then randomly divided and assigned to one of four groups: no exercise (CON), iRED training with three sets per exercise (iRED3), iRED training with six sets per exercise (iRED6), and free-weight training with three sets per exercise (FW). Each group contained seven subjects.

Overall protocol. The study was completed in two phases, with three or four of the subjects in each group studied in each phase. The protocol for each phase was identical and consisted of a 4-wk pretraining baseline period and a 16-wk resistive training period. The exercise groups performed monitored resistive exercise training 3× wk^{-1} during the 16-wk training period using their group-specific strength conditioning device (iRED or FW). CON subjects did not perform resistance training during the 16-wk period. Throughout the study, all subjects were instructed to maintain a consistent dietary and activity lifestyle.

During the baseline period, familiarization sessions were performed not more often than once per week to minimize any pretraining physiologic response. All subjects were instructed in the proper techniques for performing squat (SQ), heel raise (HR), and dead lift (DL) exercises. A 1-RM strength test was determined for each exercise at the end of each familiarization session. Other measurements obtained during the baseline period included whole body lean mass (LBM), lean leg mass (LLM), BMD, muscle volume of the calf and thigh muscles, and determination of urinary markers for bone resorption and muscle metabolism.

Exercise hardware. Strength testing for all groups was performed using a standard Smith machine (Bigger, Faster, Stronger 30052, Salt Lake City, UT) for SQ and HR exercises, and a standard Olympic bar and weights were used for the DL exercise. The FW group also used this hardware for training.

Strength training for the iRED3 and iRED6 groups was performed with the iRED. The iRED (Fig. 1A) consists of two independent canisters that each encase 16 circular, elastomer FlexPacks. FlexPacks (Fig. 1B) are made of an outer aluminum wheel with tapered elastomer spokes that connect the outer wheel to a smaller inner hub. Dynamic resistance is created during the exercise when a strong, nonelastic cable (Edelrid, Edelmann and Ridder, Allgau, Germany) connected to a spiral pulley is extended from the canisters, turning a spline which rotates the inner ring of the FlexPacks stretching the elastomer spokes. A handle attached to the top of each canister is used to rotate and prestretch the FlexPacks to attain the desired resistance range when the cable is extended.

Several limitations were identified when exercising with the iRED. First, it was found that cable extension beyond 56

A B

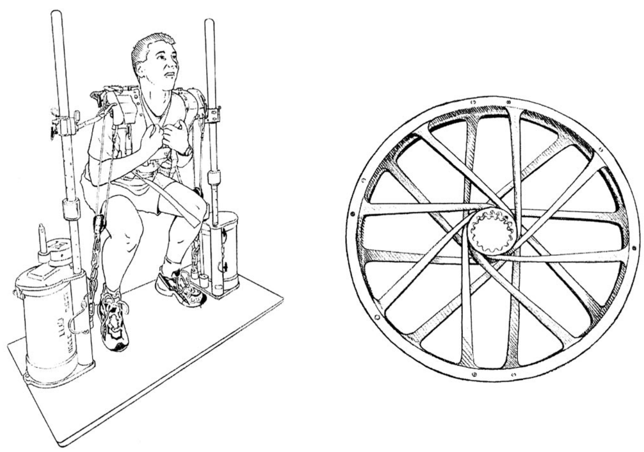

FIGURE 1—Sketch of the interim resistive exercise device (iRED), left panel, and a FlexPack from one of the canisters, right panel.

cm (22 inches) at high resistance resulted in excessive wear and breakage of the elastomer spokes. To perform exercises involving a larger ROM, adjustable straps were attached between the iRED cables and a pulley on each side of the shoulder harness to allow a full ROM without overextension of the FlexPacks. Another limitation discovered when exercising with the iRED was that the FlexPacks could be damaged if the force exceeded 150 lb (68 kg). Therefore, for subjects who required training forces greater than 150 lb from a single canister (a total resistance > 300 lb), the resistance was "augmented" by attaching bungee cords in parallel with the iRED cable. Each pair of bungees provided an additional 100 lb (45.5 kg) of force when fully extended.

Each iRED canister was calibrated every 1–2 wk throughout the study. The resistance across the ROM of each canister was measured by using a PS-30 load cell (Entran Sensors & Electronics, Fairfield, NJ) attached in line with the iRED cable. Because force measurements were dependent on the rate of stretching of the elastomer FlexPacks, a dynamic calibration was performed by extending the iRED cable through a full ROM (0–56 cm) at a rate of pull of approximately 2 s for each cable extension or retraction. During each calibration and during all iRED training sessions, the force and ROM (Ergotest Technology linear encoder, Langesund, Norway) were measured during each repetition and the data were stored on a laptop computer (Labview 5.1, National Instruments, Austin, TX). The peak force, average force, and ROM for each repetition were calculated using customized computer software.

The exercises. SQ, HR, and DL exercises were selected for this study to represent the type of exercises prescribed for crewmembers on ISS. These exercises stress the hip, lower back, and spine, body regions that show the greatest decrements in muscle volume and BMD postflight (21,22). For the SQ exercise, the subjects performed a normal stance, high-bar SQ starting from a standing position in a Smith machine (2). A similar technique was used to perform a SQ exercise using the iRED, except the subjects wore a modified football shoulder harness (Fig. 1A), which applied the load across the shoulders. During both FW and iRED squats, the subjects started in a standing position and lowered themselves to a parallel squat position. During the HR exercise, the subjects started in a standing position with the balls of their feet positioned on the edge of a 7.6-cm (3-inch) high heel raise block. Identical movements were performed when using FW and iRED except that the harness, rather than the bar, applied force to the shoulder during the iRED exercise. The DL exercise also started in a standing position. When exercising with FW, two spotters handed the deadlift bar to the subject, who then lowered and raised the bar in a controlled manner. When the DL exercise was performed with the iRED, a short bar was attached to the iRED cables in place of the harness and the exercise was performed in a similar manner.

Training protocol. For iRED and FW groups, training was performed for each exercise 3 $d \cdot wk^{-1}$ and consisted of one warm-up set (10 reps at approximately 50% of the most recent 1-RM) and three training sets for each exercise for the FW and iRED3 groups. The iRED6 group also performed exercise 3 $d \cdot wk^{-1}$, but it consisted of a warm-up set and six training sets for each exercise. During the first 3 wk of training for all groups, the intensity was determined using a percentage of each subject's 1-RM: week 1 was 50%, week 2 was 60%, and week 3 was 70% 1-RM during all 3 d. The subjects performed 10 reps/set. Starting with the fourth training week, a weekly microperiodization cycle was initiated and continued throughout the remainder of the training period. Each exercise started with the usual warm-up set, but the intensity of the training sets was varied within each week. The first training session was performed at a resistance that could be lifted for 6–8 reps (approximately 83% of 1-RM, HI day). The second training session was performed at a resistance that could be lifted for 10–12 reps (approximately 75% 1-RM, LO day). The third training session used a resistance that could be lifted for 8–10 reps (approximately 78% 1-RM, MED day). The resistances were adjusted accordingly throughout the training sessions to maintain the targeted number of maximal effort repetitions. During the weeks immediately before the mid- and posttraining 1-RM testing sessions, the training intensities were reduced by 10%.

1-RM strength testing. 1-RM strength testing could not be performed with the iRED. We found the peak force results were unreliable and varied with lifting technique and the rate of cable extension. Therefore, strength testing for all groups was performed using free weights. Strength tests were performed at least four times during the baseline period and after 8 and 16 wk of training. During the first baseline session, the ROM for each exercise was recorded and used as a target value for future testing and exercise. After two warm-up sets of 10 reps with 50 lb (22.7 kg), each subject performed a set of 5 reps followed by a set of 3 reps, and finally sets of 1 rep until a 1-RM was achieved. Between each set, the subject rested 3–5 min. The resistances for each progressive testing set were increased incrementally based upon the subject's completion of the previous set. A 1-RM session was terminated when the subject failed to perform a rep with additional load, or the subject could not perform a rep through the full ROM with proper form. In no case was more than six 1-RM attempts required during a testing session.

Training records. As a second indicator of strength gains during the study, we documented the changes in training loads during the 16 wk of training. We examined the peak force data from the iRED3 and iRED6 groups and the weight lifted in the FW group during the HI, LO, and MED training days closest to the start of microcycle training (week 4, EARLY), before the mid-training 1-RM test (week 7, MID), and before the posttraining 1-RM test (week 15, LATE).

BMD and lean body mass measurements. BMD ($g \cdot cm^{-2}$) was measured using the dual energy x-ray absorptiometry (DXA) technique for each of three body scan sites (whole body, spine, and left hip) pre- and posttraining. Measurements were obtained in triplicate for each site. Before each measurement session, a calibration phantom was scanned and the results evaluated. The precision of measurements for BMD using this system (Hologic Inc. 4500W ELITE fan-beam x-ray densitometer, Bedford, MA) is 1% for the whole body, 0.9% for the lumbar spine, and 2% for the femoral neck. Also from the DXA scans, whole body lean mass (LBM) and leg lean mass (LLM) were calculated. The precision for these lean tissue measurements was ± 2% for each site. To improve the reliability of the DXA measurements, all pre- and posttraining scans were conducted and analyzed by the same operator.

Muscle volume measurements. Muscle volumes of the thigh and calf were measured pre- and posttraining using a GE 1.5-T unit (General Electric Company, Waukesha, WI) MRI. To control for fluid shifts caused by lying supine after standing upright, the subjects were recumbent for at least 15 min before the start of data acquisition. Both limbs were imaged simultaneously and the total muscle volume was calculated from the cross-sectional data using a trapezoidal technique that integrates the area under the curve of the muscle area versus position along the leg. Each scan was "landmarked" at the base of the patella and 32 contiguous 1-cm slices were taken with standard offsets. The percent change in muscle volume after training was calculated. The reliability of repeated muscle volume changes was < 2.3%.

Urinary bone and muscle markers. Pooled 24-h urine samples were collected during the baseline period, and after 8 and 16 wk of training. The total 24-h volume was measured, and an aliquot was frozen at −70°C until later analyses. Urinary total calcium was measured with a Perkin-Elmer 4000 atomic absorption spectrophotometer (Perkin-Elmer, Norwalk, MA). Hydroxyproline analysis was performed on a Hitachi L-8800 Amino Acid Analyzer (Hitachi Corp, San Jose, CA). Intra-assay and interassay coefficients of variation for hydroxyproline in our laboratory are 10.4% and 9.8%, respectively. Collagen crosslinks were analyzed to provide an estimate of bone resorption. Samples were analyzed for pyridinium and deoxypyridinoline crosslinks with the commercially available Pyrilinks™ and Pyrilinks™-D kits (Metra Biosystems, Palo Alto, CA). N-telopeptide concentrations were determined with the Osteomark ELISA kit (Ostex Int., Seattle, WA). In our laboratory, coefficients of variation for the low-level control for total pyridinium, deoxypyridinoline, and n-telopeptide were 4.7%, 11.7%, and 10.7%, respectively; the high-level control yielded coefficients of variation of 7.7%, 8.3%, and 6.4%, respectively. Urinary creatinine was determined spectrophotometrically and was used as a marker of lean body mass. 3-methyhistidine was determined using the same Hitachi amino acid analyzer mentioned above and was used as a marker of muscle degradation.

Statistical analyses. The pretraining group comparisons of physical characteristics and 1-RM squat strength data were compared using a one-factor ANOVA model. The data are presented in Table 1 as the mean ± SD for each group. For the pretraining 1-RM strength values, the third and fourth baseline 1-RM trials were averaged to represent the baseline strength value.

To ensure consistency of the training stimulus between groups, we compared the number of training sessions completed, the number of days required to complete the training sessions, and the average number of training sessions per week between the groups using a one-way ANOVA in which groups were a nonrepeated measure.

The 1-RM, DXA, and urine biochemistry pre-, mid-, and posttraining data were compared using a two-factor ANOVA, where factor 1 was the nonrepeated measures group effect and factor 2 was the repeated measures training effect (pre-, mid-, or posttraining). MRI results were analyzed in the same manner, comparing pre- and posttraining data. Pre- and posttraining DXA measurements were compared for each measurement site using the average of the two closest triplicate measurements for the pre- to posttraining comparisons. When a significant main effect was found, *post hoc* analyses were performed using a Tukey's honest significant difference test.

For comparison of training loads across time during the EARLY, MID, and LATE training sessions, we performed a two-way ANOVA for each exercise intensity (LO, MED, and HI), where load was a repeated measure effect and group was a nonrepeated measure effect. Because load was applied in a different manner in the iRED and FW groups, load progression during training between groups was assessed by comparing the percent changes from pretraining by using a single-factor ANOVA model.

All statistical analyses were performed using Statistica software (Statsoft, Tulsa, OK) with significance set as $P \leq 0.05$. All data are presented as the mean ± the standard error of the mean.

RESULTS

Subject Issues and Subject Compliance

There were no significant differences between the subject groups pretraining for age, height, weight, body mass index, or squat 1-RM strength (Table 1). During the study, several subjects experienced muscle soreness and one subject fractured two cervical spinous processes (Clay Shovel-

TABLE 2. Medical issues which arose during the training study.

Subject	Group	Issue	Suspected Cause	Treatment
17	FW	Lower back pain	Overtraining	15% reduced training load 1–2 wk
1	iRED6	Hip bursitis	Overtraining	1 wk off, then reduced training 2 wk
9	iRED6	Clay shovellers' fracture	Equipment failure	Continued training, no final 1RM SQ or HR
12	iRED6	Quadriceps strain	Flag football injury	Reduced training 5 d
25	iRED6	Patella tendonitis	Overtraining	Work on form, continued training
26	iRED6	Patella tendonitis	Basketball	Reduced training 3 wk, no 1RM SQ
29	iRED6	Quad, tendonitis	Overtraining; patella tracking	Reduced training 1 wk

ler's fracture) when performing a 1-RM HR after 8 wk of training. A summary of the medical issues that resulted in a temporary reduction in training load or a missed 1-RM session is presented in Table 2. In each case of muscle soreness, the training load for the exercise affected was reduced or did not increase until the subject recovered (a few days to 3 wk). If a training session was missed for soreness or scheduling issues, an additional training session was performed the following week. As a result, no significant differences in the number of training sessions, the days to complete the training program, or the average number of training sessions per week occurred among the training groups (Table 3).

Changes in 1-RM Strength

During the baseline period, 1-RM measurements during the third and fourth testing sessions repeated within 5% and were averaged to represent the pretraining value. For each exercise, no significant differences in 1-RM strength occurred between groups pretraining. For the CON group, one subject was unable to perform the mid-training 1-RM tests due to schedule conflicts. Two subjects in the iRED6 group were unable to perform squat 1-RM testing during the posttraining sessions due to medical issues (see above). Therefore, the 1-RM data in Fig. 2A consists of six CON subjects, seven FW subjects, seven iRED3 subjects, and five iRED6 subjects. For HR and DL exercises, the data are from six CON subjects, seven FW subjects, seven iRED3 subjects, and seven iRED6 subjects (Fig. 2, B and C).

For the SQ exercise (Fig. 2A), after 8 wk of training, 1-RM strength increased significantly (16 ± 6%) only in the FW group. After 16 wk of training, 1-RM increased in the FW group (22 ± 5%) and was significantly increased in the iRED3 group (21 ± 4%). The change in 1-RM in the iRED6 group after 16 wk of training (10 ± 5%) was not significant. For the HR exercise (Fig. 2B), after 8 wk of training, 1-RM increased significantly only in the FW group (18 ± 5%). After 16 wk of training, 1-RM increased significantly in FW (24 ± 3%), iRED3 (17 ± 4%), and iRED6 (22 ± 6%) groups. For the DL exercise (Fig. 2C), after 8 wk of training, 1-RM strength increased significantly for both the FW (20 ± 4%) and the iRED6 (22 ± 8%) groups. After 16 wk, 1-RM strength increased significantly in each of the training groups: FW (41 ± 7%), iRED3 (29 ± 5%), and iRED6 (30 ± 6%).

TABLE 3. Training compliance from start of training to posttraining 1-repetition maximum test (mean ± SE).

Group	Training Sessions	Days to Complete	Average per Week
FW	48 ± 0	117 ± 3	2.9 ± 0.1
IRED3	48 ± 0	121 ± 3	2.8 ± 0.1
IRED6	47 ± 1	129 ± 4	2.6 ± 0.1

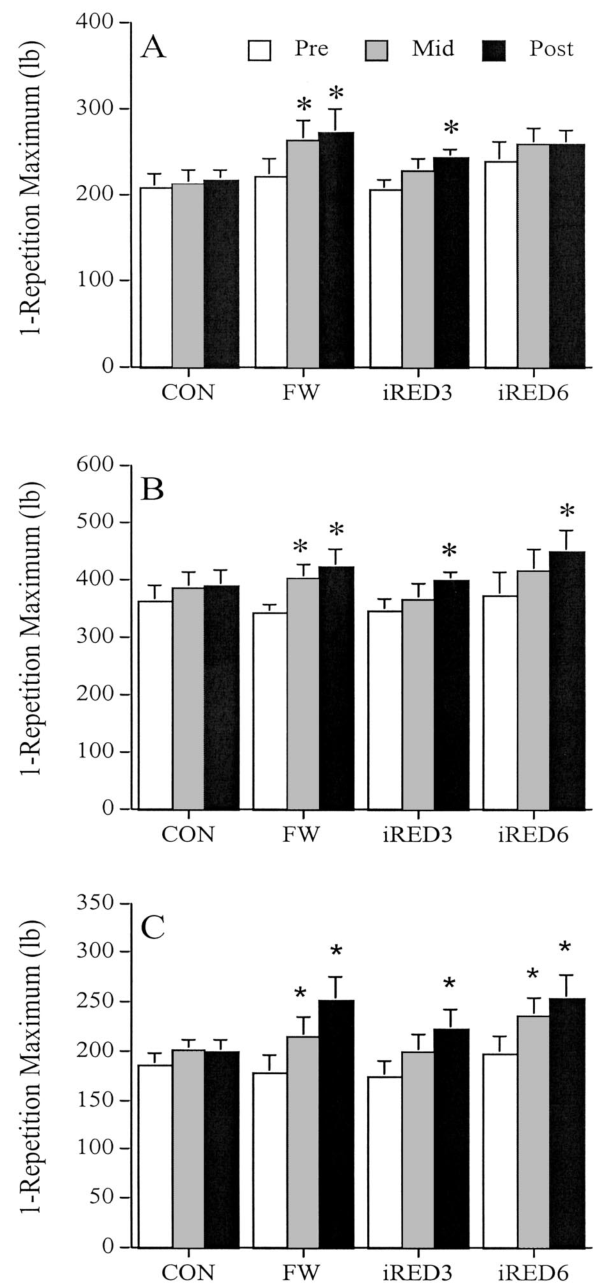

FIGURE 2—Muscle strength measurements (1 repetition max, 1-RM) before (Pre) and after 8 (Mid) and 16 wk (Post) of training for the control (CON), free-weight (FW), and iRED3 and iRED6 groups. Values shown are the mean ± SE for each group. * Significantly different from pretraining. A, squat; B, heel raise; C, dead lift data.

TABLE 4. Percent changes during training (mean ± SE).

		Percent Change (%) from Early Training					
		Squat		Deadlift		Heel Raise	
Group	Intensity	Early to Mid	Early to Late	Early to Mid	Early to Late	Early to Mid	Early to Late
FW	HI	12 ± 4	31 ± 5	4 ± 2	24 ± 4	17 ± 7	42 ± 7
	MED	9 ± 2	27 ± 7	2 ± 3	23 ± 5	20 ± 10	53 ± 11
	LO	7 ± 3	24 ± 6	4 ± 1	21 ± 5	13 ± 8	42 ± 9
IRED3	HI	14 ± 4	31 ± 4	9 ± 4	18 ± 5	27 ± 7	52 ± 12
	MED	17 ± 4	30 ± 6	10 ± 4	17 ± 5	31 ± 11	61 ± 20
	LO	12 ± 3	31 ± 6	12 ± 4	24 ± 5	27 ± 8	49 ± 12
IRED6	HI	22 ± 9	30 ± 11	4 ± 3	12 ± 6	6 ± 2	41 ± 12
	MED	16 ± 5	30 ± 9	7 ± 3	12 ± 3	15 ± 8	43 ± 14
	LO	15 ± 4	23 ± 7	6 ± 3	14 ± 4	9 ± 5	48 ± 14

Changes in Peak Resistance from the Training Records

The increases in peak training resistance after 8 and 16 wk of training are shown in Table 4 and are expressed as the percent change from pretraining. For each of the three exercises, the increases in peak resistance after 8 and 16 wk of training were similar among the three training groups and significant changes were found after 16 wk. A similar finding was seen for each of the three exercise intensities.

Whole Body Lean Mass (LBM) and Leg Lean Mass (LLM)

LBM was similar between groups before training and was not different pre- to posttraining in the CON group (Fig. 3). After 16 wk of training, LBM increased significantly only in the FW group, by 3.0 ± 1.1%. Leg lean mass did not differ among groups pretraining and in the CON group did not change pre- to posttraining. However, after 16 wk of training, LLM increased significantly in each training group: FW (5.4 ± 1.2%), iRED3 (3.1 ± 0.5%), and iRED6 (4.3 ± 0.7%). The percent increases in LLM were similar for the three training groups.

Muscle Volume Results

MRI measurements were obtained from all but two subjects, a subject in the FW group who was sick and could not be rescheduled and a subject in the iRED6 group who experienced claustrophobia and could not complete scans pre- or posttraining. Significant increases in thigh muscle volume occurred after training in the FW (9.2 ± 1.3%) and the iRED6 (6.8 ± 1.5%) groups, whereas changes in the iRED3 (4.5 ± 0.9%) and the CON (1.8 ± 0.8%) groups were not significant (Fig. 4). Significant increases in calf muscle volume occurred in each of the training groups: FW (4.2 ± 1.0%), iRED3 (5.9 ± 0.7%), and iRED6 (5.9 ± 1.2%). The increases in calf muscle volume were similar for the three training groups, and no significant change occurred in the CON group (3.2 ± 0.7%) during the study.

Bone Densitometry Results

Whole body, lumbar spine, hip, and leg BMD were similar among groups pretraining. Whole body, hip, and leg BMD did not change significantly from baseline in any group at the end of the study (Table 5). After 16 wk of training, total lumbar spine BMD increased significantly (4.2 ± 0.7%) only in the FW group. Of the four specific lumbar vertebrae scanned (L1-L4), significant increases in BMD occurred for the FW group in L1, L2, and L4.

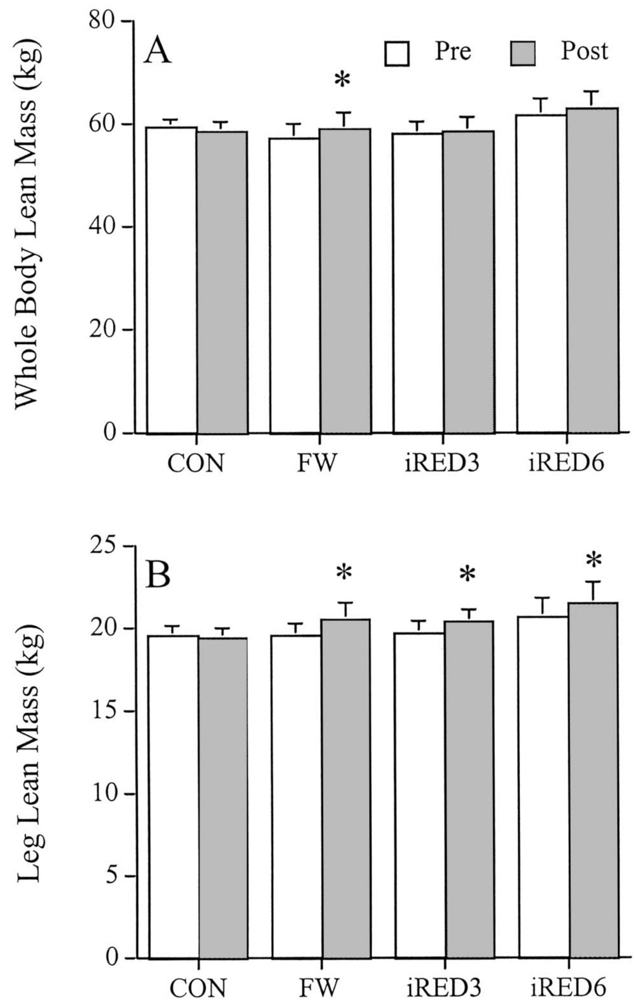

FIGURE 3—Whole body lean mass (top) and lean leg mass (bottom) results (mean ± SE) obtained by DXA from pre- (Pre) and posttraining (Post) for the control (CON), free-weight (FW), iRED3, and iRED6 groups. * Significantly different from pretraining.

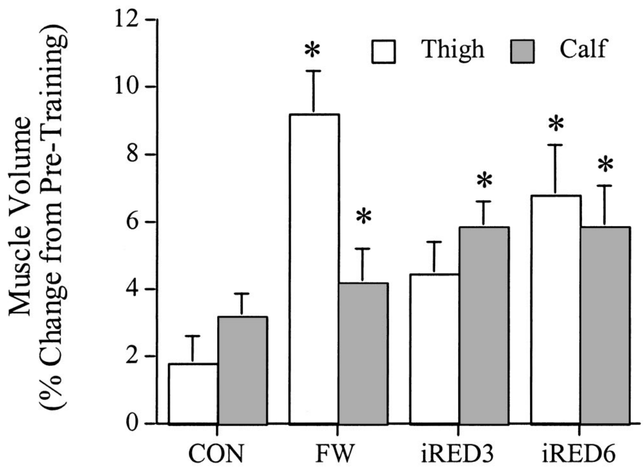

FIGURE 4—Percent change (mean ± SE) in muscle volume obtained by MRI, pre- vs posttraining, for the thigh and calf muscles of the control (CON), free-weight (FW), iRED3, and iRED6 groups. * Significantly different from pretraining.

Urine Biochemical Markers

Bone markers. There were no significant differences between groups for urinary calcium, hydroxyproline, pyridinium, deoxypyridinoline, or n-telopeptide before or during training (Table 6).

Muscle markers. Urinary 3-methyl-histidine excretion was similar among groups and did not change significantly during training (Table 6). Urinary creatinine concentration also did not differ significantly between groups at any measurement time during the study. However, there was a significant main effect of time for the combined data, such that during the first 8 wk of training urinary creatinine concentration declined from pretraining. During 8–16 wk of training, there was no consistent trend in the direction of change in creatinine concentration.

DISCUSSION

The iRED. In 2001, the iRED was launched to the International Space Station for use by the first ISS crew. To date, during all following increments it has been available for crewmembers to perform resistive exercise as a countermeasure against the musculoskeletal deconditioning associated with long duration spaceflight. The iRED provides a unique elastomer-based resistance force curve. It is important to understand the specific training characteristics of this device before selecting exercises to target specific muscle groups or before prescribing protocols designed to produce specific training responses.

We examined the force curve characteristics of the iRED during a recent pilot study and compared these results to the forces produced when subjects exercised with free weights (1). We measured ground reaction forces with a force plate while three subjects performed squats with the iRED and with free weights. Free-weight squats were performed on the first testing day using a resistance of 8–10 RM. On a second day, iRED squats were performed with the resistance preloaded to equal the static ground reaction force measured immediately before the free-weight squat. The peak ground reaction force averaged 13% less (263 N) during an iRED squat compared with during a free-weight squat, and the total work per repetition was 27% less. The point of application of peak force in the ROM (measured with a linear potentiometer) was attained near the top (nearly upright) of the ROM with the iRED and near the bottom (while squatting) of the ROM with free weights. Another difference was that the eccentric/concentric ratio of the average force during descent and ascent was less with the iRED (0.72) compared with free weights (0.95). Based on these observed differences in iRED compared with FW exercise, the lower peak force, lower total work, and lower eccentric loading, we hypothesized that our iRED3 group would have smaller training responses as compared to the more traditional FW training when performing the same number of sets and reps.

Musculoskeletal responses to training with the iRED. This study employed an aggressive training protocol that involved maximal exertions, multiple sets, and three training sessions per week. According to ACSM guidelines (20), improvements in muscle strength and increases in muscle mass should occur when the training intensity is greater than 60–70% of 1-RM (8–12 RM), and exercise is performed for one to three sets, for 2 to 3× wk^{-1}. Therefore, the training intensities used in this study should have been sufficient to induce increases in muscle strength and mass. However, it should be noted that because of the limited maximal force available from the iRED, the training intensity on the HI training days was lower than the 4–6 RM intensity recommended by ACSM for optimum strength improvement. Despite this limitation, the training intensities used in this study were sufficient and training responses from the iRED3 group confirmed that the iRED can produce improvements in strength. The resistance during 1-RM testing and the peak forces during the training sessions increased significantly for each of the three exercises during this training study.

To induce muscle hypertrophy, a similar training intensity and volume must be followed, but the duration of the training program must exceed 8 wk for untrained subjects (20). In the iRED3 group, we found increases in muscle mass after 16 wk of training. This effect was found only in the leg muscles with no significant change in whole body lean mass.

The minimum training stimulus required to increase BMD is less understood than for muscle. In cross-sectional studies, an increased BMD is reported in athletes engaged in either high-impact aerobic (16) or high-intensity weight-lifting exercises (8,23) as compared with nonathletic subjects. Cappozzo and coworkers (6) calculated that compressive forces of 6–10 times body weight are applied to the lumbar region when weight lifters perform a squat. Weight lifters have been shown to have 10% greater whole body BMD and 13% greater lumbar BMD compared with non-weight lifters (17). Menkes et al. (23) reported a 3.8% increase in BMD of the femoral neck and a 2.0% increase in BMD of the spine after only 16 wk of training with a

TABLE 5. Bone mineral density results (g·cm²), mean (±SE).

	CON	FW	iRED3	iRED6
Whole body				
Pre	1.242 ± 0.041	1.289 ± 0.037	1.254 ± 0.035	1.285 ± 0.049
Post	1.253 ± 0.039	1.289 ± 0.038	1.262 ± 0.034	1.296 ± 0.055
Total lumbar				
Pre	1.079 ± 0.088	1.089 ± 0.057*	0.092 ± 0.041	1.066 ± 0.067
Post	1.094 ± 0.083	1.128 ± 0.059)*	1.110 ± 0.045	1.092 ± 0.064
L1				
Pre	1.045 ± 0.096	1.034 ± 0.055*	1.002 ± 0.049	1.008 ± 0.062
Post	1.079 ± 0.083	1.078 ± 0.061*	1.032 ± 0.053	1.025 ± 0.055
L2				
Pre	1.100 ± 0.101	1.085 ± 0.070*	1.130 ± 0.058	1.064 ± 0.066
Post	1.128 ± 0.101	1.181 ± 0.068*	1.152 ± 0.060	1.105 ± 0.061
L3				
Pre	1.086 ± 0.088	1.123 ± 0.060	1.126 ± 0.040	1.080 ± 0.075
Post	1.100 ± 0.084	1.155 ± 0.064	1.136 ± 0.048	1.110 ± 0.070
L4				
Pre	1.082 ± 0.081	1.106 ± 0.050*	1.100 ± 0.037	1.101 ± 0.075
Post	1.074 ± 0.075	1.141 ± 0.052*	1.114 ± 0.036	1.118 ± 0.077
Total hip				
Pre	1.095 ± 0.071	1.141 ± 0.050	1.029 ± 0.054	1.081 ± 0.064
Post	1.106 ± 0.071	1.146 ± 0.046	1.042 ± 0.054	1.088 ± 0.063
Trochanter				
Pre	0.837 ± 0.057	0.876 ± 0.050	0.770 ± 0.043	0.815 ± 0.057
Post	0.831 ± 0.060	0.876 ± 0.044	0.775 ± 0.043	0.822 ± 0.056
Femoral neck				
Pre	0.942 ± 0.064	1.001 ± 0.059	0.891 ± 0.063	0.921 ± 0.061
Post	0.939 ± 0.062	0.998 ± 0.059	0.897 ± 0.062	0.906 ± 0.059
Intertrochanter				
Pre	1.295 ± 0.085	1.321 ± 0.052	1.198 ± 0.062	1.255 ± 0.072
Post	1.302 ± 0.084	1.330 ± 0.047	1.215 ± 0.060	1.268 ± 0.071
Leg				
Pre	1.402 ± 0.058	1.507 ± 0.053	1.414 ± 0.049	1.473 ± 0.074
Post	1.412 ± 0.054	1.485 ± 0.054	1.424 ± 0.045	1.489 ± 0.081

*Significantly different from pretraining.

pneumatic variable-resistance device. Their untrained men performed leg press, leg extension, and leg curl exercises, 3× wk^{-1} for two sets of 15 reps to fatigue. In the present study, training with the iRED for 16 wk did not increase BMD in the whole body, hip, or legs. We suspect that the failure of the iRED to alter BMD may have been due to an inability of the elastomer resistance to place sufficient compressive forces on the bone during the exercises. The lower peak forces we found during our pilot study may have been due to an absence or reduction of inertial forces that occurs with free weights when mass is suddenly lifted or during a change in direction. Further studies are required to more closely characterize the forces provided by the iRED and to determine whether the exercises can be modified to induce an effective stimulus to bone tissue.

Comparison of iRED and free-weight training. We predicted smaller increases in muscle strength, muscle mass, and BMD after training with the iRED compared with FW, even when using the same intensity training protocol. This prediction was based on previous reports in the literature (15) and the findings from our pilot study, where we observed lower peak forces, less total work, and less eccentric work for a given resistance when exercising with the iRED. Several investigators have emphasized the importance of eccentric loading to acquire the maximal strength and hypertrophic responses to resistance training (7,9,13). For example, Hortobagyi and colleagues (14) reported greater strength gains in a group who performed eccentric-only actions compared with a group who trained with concentric-only contractions, even though the load was maximal for the concentric group and submaximal (approximately 80% 1-RM) for the eccentric group. Gardiner (12) reviewed possible molecular mechanisms whereby eccentric loading would be more effective in stimulating morphological changes than concentric loading. Muscle lengthening during eccentric actions results in a greater stretching of the myofibrillar and myotendinous structures of the muscles. This increased stretch initially may cause greater muscle damage and reductions in strength. However, the damage response together with the greater stretch may activate intracellular signals (e.g., platelet-derived growth factor, fibroblast growth factor, interleukins, transforming growth factors, and tumor necrosis factor), which enhance protein synthesis and result in greater muscle hypertrophy and strength gains as compared to concentric loading (12). The higher peak forces during eccentric training also may optimize the neuromotor adaptations responsible for strength improvements during the initial weeks of training (9,14) and increase the compressive forces on bone to stimulate a greater increase in BMD.

Overall, we found similar significant increases in muscle strength for the iRED3 and the FW groups after 16 wk of training. From the 1-RM data for each of the exercises, strength increases appeared to have occurred sooner in the FW group compared with the iRED3 group. However, this apparent difference in rate of strength development was not evident from the training record data, where significant increases in training resistance did not appear until after 16

TABLE 6. Urine data (mean ± SE).

	CON	FW	iRED3	iRED6
Muscle markers				
3-methyl-histidine (μmol·d^{-1})				
Pre	331 ± 61	298 ± 25	264 ± 25	348 ± 27
Mid	279 ± 77	319 ± 30	284 ± 55	267 ± 30
Post	322 ± 28	328 ± 33	318 ± 58	372 ± 96
Creatinine (g·d^{-1})				
Pre	2156 ± 352	1916 ± 182	1735 ± 81	2228 ± 175
Mid	1827 ± 145	1737 ± 141	1637 ± 175	1786 ± 164
Post	2012 ± 237	1762 ± 155	1876 ± 345	2047 ± 114
Bone markers				
Calcium (mmol·d^{-1})				
Pre	6.5 ± 2.6	4.5 ± 1.0	5.2 ± 0.6	5.2 ± 1.3
Mid	5.3 ± 1.7	4.7 ± 0.9	4.8 ± 1.1	4.6 ± 1.1
Post	5.4 ± 1.6	4.8 ± 1.1	5.8 ± 1.6	3.6 ± 0.5
Hydroxyproline (μmol·d^{-1})				
Pre	88 ± 15	82 ± 9	91 ± 14	110 ± 26
Mid	89 ± 10	107 ± 16	133 ± 50	92 ± 19
Post	112 ± 14	92 ± 18	74 ± 15	108 ± 22
Pyridinium (nmol·d^{-1})				
Pre	335 ± 42	251 ± 20	256 ± 13	315 ± 47
Mid	269 ± 27	274 ± 28	271 ± 25	234 ± 36
Post	304 ± 23	283 ± 27	281 ± 57	272 ± 43
Deoxypyridinoline (nmol·d^{-1})				
Pre	81 ± 8	75 ± 11	73 ± 4	82 ± 15
Mid	70 ± 10	75 ± 12	75 ± 5	74 ± 13
Post	78 ± 17	88 ± 14	77 ± 12	68 ± 10
n-telopeptide (nmol·d^{-1})				
Pre	530 ± 103	576 ± 54	486 ± 45	567 ± 131
Mid	565 ± 133	556 ± 78	549 ± 90	502 ± 110
Post	550 ± 129	661 ± 87	482 ± 98	625 ± 141
n-telopeptide (nmol·mmol^{-1} creatine)				
Pre	29 ± 5	33 ± 2	32 ± 3	30 ± 7
Mid	35 ± 7	36 ± 4	37 ± 2	33 ± 7
Post	30 ± 6	42 ± 4*	29 ± 1	35 ± 8

*Significantly different from pretraining.

wk of training in both groups. In view of a possible training specificity issue in the interpretation of the 1-RM strength data for the iRED3 group, the faster rate of 1-RM strength in the FW group may have been influenced by their greater familiarity with the FW testing equipment. Therefore, no conclusions about the rate of training should be drawn from the 1-RM data.

Muscle hypertrophy was evident in both the iRED3 and the FW group in response to training, yet there were subtle differences in this response. Whole body lean mass increased only in the FW group after training. Although leg muscle volume increased significantly in both groups, there was a twofold larger increase in thigh muscle volume in the FW group despite similar increases in calf muscle volume between the two groups. This greater thigh hypertrophy in the FW group may have been due to the different loading conditions during the SQ and DL exercises, exercises that targeted the hamstring and quadricep muscle groups (3). From our pilot study, the peak force during a FW squat occurred when the subject was in a low-squat position. Here, the inertial forces associated with changing direction of movement combined with static forces provided by the mass of the bar, the weights, and the subject's body mass. During an iRED squat, the lowest force occurred when the subject was in the low-squat position. At this point in the exercise ROM, the iRED cable is almost fully retracted and the stretch on the elastomer spokes of the FlexPacks is minimized. Inertial forces associated with the change in direction of movement would also be less with the iRED. A greater loading to the thigh muscles also may have occurred during the DL exercise in the FW group because of similar loading variations during the ROM of this exercise. However, only small loading differences would be expected during the HR exercise, which primarily targets the calf muscles (3). The ROM of this exercise is small and the forces are applied near the extreme end of the iRED cable extension, where forces should be more similar to the resistance with FW. EMG analysis would be required to confirm these differences in muscle activation between the two exercise devices.

Another difference between the iRED and FW training responses was that the lumbar BMD increased significantly in the FW group but not in the iRED3 group. Site-specific increases in BMD have been reported after intense resistance training programs (8,17,28). The regions of bone most commonly affected included the femur, lumbar spine, and os calcis (19). Biochemical markers suggest an increase in bone formation and a transient suppression of bone resorption during the first month of a high-intensity resistance-training program in sedentary subjects (11). Karlsson and coworkers (18) also confirmed that bone formation markers are elevated significantly in competitive weight lifters compared with controls. In the present study, blood samples were not available, and therefore bone formation could not be assessed. But because of the increase in lumbar BMD in the FW group, we expected to see a reduction in bone resorption markers in this group during training. Our failure to confirm the decreased resorption markers noted by Fujimura and coworkers (11) may have been because the decline was only a transient response; in their study, it occurred during the first month of training, and we obtained our samples after 4 months of training.

Comparison of iRED3 and iRED6 training responses. Doubling the training volume in the iRED6 group did not produce any further improvement in the training responses. Similar increases in muscle strength, increases in muscle volume, and a lack of change in BMD occurred in the iRED6 and iRED3 groups. As a general training guideline, two to five maximal effort sets performed $3\times$ wk^{-1} should be sufficient to induce an optimal training response for most muscle groups in untrained subjects (20). A greater training volume may pose a risk of overtraining. We suspect that at least part of the failure of the iRED6 group to show better training responses was related to the greater number of reduced-load training days in this group due to muscle soreness or injury. Five of six of the iRED6 subjects had reduced training loads at some point during the 16 wk of training. We cannot confirm that overtraining contributed to the greater complications in the iRED6 group. The urinary 3-methyl-histidine levels were not significantly elevated in the iRED6 group compared with any of the other groups. It is possible that the combination of the increased training volume in combination with their other habitual activities may have contributed to the unusual number of sports-related injuries in this group during our study.

Implications for spaceflight. A critical question is what is the minimal level of resistive loading required to maintain muscle and bone mass in microgravity? High-resistance loads are technically difficult to provide in microgravity. An optimal combination of high-volume but moderate-intensity resistance exercise with proper dietary or hormonal supplementation may be sufficient to maintain bone and muscle mass during spaceflight. The training intensity required to maintain musculoskeletal mass during microgravity is unknown. During spaceflight, the failure of previous resistive exercise devices to prevent changes in muscle and bone suggest that high training intensities may be required. In the Russian space program, resistance exercises have been performed using elastic "expanders" that provide a maximum resistance of approximately 60 kg at full extension (Inessa Kozlovskaya, personal communication). In the American space program, during Skylab 3 and Skylab 4 crewmembers used a bungee device (MK-1) and a spring device (MK-2) to perform resistance exercise. The MK devices provided only approximately 68 kg of loading at their extreme range of extension (27). Neither the American nor the Russian devices prevented the losses of lower body muscle or bone mass after long-duration spaceflight (21,27). However, this is not to say that the exercises were ineffective. Without a "control" group of astronauts who performed no resistive exercises, we cannot determine whether these exercises were ineffective or whether even greater changes in musculoskeletal mass would have occurred without the in-flight exercises. Although the iRED with a maximal capacity of 136 kg offers more resistance than the previous resistive exercise devices, it is still unknown whether this force will be sufficient to maintain muscle in the susceptible body regions. Although we might suspect that the iRED would not protect bone mass during spaceflight, based on its failure to improve BMD in the present study, and the indication in the literature that high levels of compressive force are required to improve BMD (8,16,23), this conclusion cannot be supported because the exact stimuli required to maintain bone in microgravity have not been defined.

An unusually high rate of injury occurred in this study, mostly in the iRED6 group. It is unclear whether this was due to an overly aggressive training program for our novice subjects, or perhaps, susceptibility to overuse was exacerbated by possible nonideal biomechanics of the iRED. Further study is required to select specific movements that may minimize musculoskeletal strain when using the iRED and to identify exercises that may be more compatible with the ascending, nonlinear force curve of the iRED.

Another serious limitation in the current flight version of the iRED is the inability to precisely select and quantify the exercise resistance. This deficiency will impede the ability to develop countermeasure prescriptions and to accurately assess the effectiveness of resistance training on ISS. The unquantified perturbations in physiological responses induced by iRED training on ISS also will complicate interpretation of results from other human spaceflight investigations.

CONCLUSIONS

We evaluated the musculoskeletal responses to 16 wk of training with the ISS iRED and compared these responses to a similar training protocol using FW. iRED training resulted in increases in muscle strength and leg muscle volume and no change in BMD. FW training on the other hand, resulted in similar increases in strength and leg mass but also increases in whole body lean mass and in lumbar spine BMD. In attempting to improve the iRED training response, we doubled the training volume, but this was not effective. However, a greater incidence of injury occurred in this iRED6 group, which may have limited the training effects.

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