Effects of resistance training, using flywheel technology, on size and function of unloaded skeletal muscle

Introduction

Physiological deconditioning poses a significant barrier to space industrialization and future attempts at the colonization of space. To meet such a challenge, the preservation of astronaut's health and physical fitness is a major concern. Over-all fitness in space crews must be maintained for optimal performance of daily in-flight tasks and extra-vehicular activities (EVA), and perhaps even more importantly, astronauts must be prepared for egress situations and re-entry to Earth. Upon landing on Mars, or on any other planet, astronauts cannot afford lengthy rehabilitation programs; they will be required to perform instant job tasks.

Novel exercise equipment and protocol development is vital in meeting future long-term objectives including the current habitat on the International Space Station (ISS) and Manned Missions to Mars. Bone and muscle loss and impaired function of skeletal muscle are among the adverse physiological effects of long-duration spaceflight. Resistance training is the most beneficial method to promote increases in bone mineral density and muscle strength and size at 1g. This method also appears to offer the most potent stimulus to prevent skeletal muscle from atrophy and deteriorated function, and skeleton to become fragile.

Our long-term goal over the last decade has been to present an effective and functional exercise countermeasures system, which could be used in space. In simulating microgravity at 1g, we introduced a new method more than ten years ago (Berg et al. 1991). By walking on crutches while using a "plateau shoe" for up to six weeks, this technique produces muscle atrophy and changes in voluntary force production similar to spaceflight. Hence, after reviewing our data from experiments on crew, who flew on the Space Shuttle Columbia, and on bedridden and unloaded subjects, results clearly show the rate of these changes are comparable. NASA's Countermeasure Task Force Working Group has recommended our model as a valid spaceflight analog for human muscle research.

It is implicit resistance exercise, as performed on Earth and using weights cannot be performed in space. We have developed a resistance exercise device that uses the inertia of rotating flywheels to provide resistance. Thus, it is gravity independent, non-electrical and requires no external power source (Berg & Tesch 1994). Because it functions in the absence of gravity, it has been proposed as an exercise countermeasures device on ISS (Tesch & Berg 1997). Several configurations using this principle have been designed and subsequently evaluated in laboratory trials, including long-duration simulated ISS confinement (Alkner et al., At Press).

We addressed several issues identified in NASA's Critical Path Roadmap for "Muscle Alterations and Atrophy". Subjects performed simulated spaceflight with or without resistance exercise using flywheel technology and, the efficacy of this exercise system to offset or ameliorate the negative effects of simulated spaceflight was assessed. We hypothesized unloading would induce a marked decrease in muscle strength and, that quadriceps muscle atrophy mainly would be responsible for this effect. Further, we hypothesized the proposed resistance exercise regimen would ameliorate and most likely eliminate the negative effects of unloading on quadriceps muscle size and voluntary knee extensor strength. Because quadriceps muscles are involved in the employed knee extensor exercise

they, but not the ankle plantar flexor muscle group, were believed to show maintained size after resistance exercise performed by unloaded subjects. Our data suggest that muscle volume is not only maintained, but in fact is augmented in response to resistance exercise of otherwise unloaded muscle. We also had the opportunity to compare muscle atrophy of the calf (mainly slow muscles) and the quadriceps muscle (a mixed muscle) in response to five wk unloading. Based on past animal research, we hypothesized the calf muscle would show greater atrophy. Furthermore, the experimental protocol allowed us to compare ankle plantar flexor atrophy in men and women. Such information is warranted since the astronaut corps of today comprises a large number of women. Although the questions addressed in this study originate from the observation that space travellers show atrophy and impaired muscle function upon return to Earth, we thought the results of the completed research would have broader applications.

References

Berg HE, GA Dudley, T Häggmark, H Ohlsén, PA Tesch. Effects of lower limb unloading on skeletal muscle mass and function in man. J. Appl. Physiol. 70:1882-1885. 1991.

Berg HE & PA Tesch. A gravity-independent ergometer to be used for resistance training in space. Aviat. Space Environ. Med. 65: 752-756. 1994

Tesch PA & HE Berg. Resistance training in space. Int. J. Sports Med. 18: (Suppl. 4) 322-324. 1997.

Alkner B, HE Berg, I Kozlovskaya, D Sayenko, PA Tesch. Effects of strength training, using a gravity-independent exercise system, performed during 110 days of simulated space station confinement. Eur J Appl Physiol. At Press.

Logistics

After moving to Little Rock to join the Department of Geriatrics at the University of Arkansas for Medical Sciences in February 1999, I established an exercise laboratory exclusively designed for this NASA funded project at the VA Medical Center in North Little Rock. Later, the entire laboratory moved to new facilities at the DWR Center on Aging at the UAMS Campus downtown Little Rock. The early phase of the first fiscal year was devoted to building and equipping this laboratory, manufacturing, purchasing and integrating hardware and software and employing and training personal and recruiting subjects. At the time of the beginning of the experiments of the actual study, the laboratory was equipped with state of the art computers and measuring and data acquisition systems allowing for assessment of multiple muscle performance functions and detailed analyses of magnetic resonance images. It also comprised exercise ergometers, using flywheel technology that monitored performance and also offered instant performance feedback.

Awards from the Swedish National Space Board (SNSB) did in part support this project. Anneli Ekberg, M.D., a full-time on-site collaborator on this project, was paid through SNSB grants administered by the Huddinge University Hospital of the Karolinska Institute, Sweden. The effort by undersigned and Jay Trieschmann, MA, research assistant, on this project was one hundred percent. Two faculty members (Drs. Evans and Trappe) were in part funded through this grant. Several local small businesses were subcontracted to manufacture e.g., shoe gear and exercise ergometers and electronics.

Materials and Methods

Volunteers, matching the astronaut corps with regard to gender, age and body stature, were recruited from the Little Rock area through fliers and displays and advertisements and campaigns in local newspapers, radio and television. During this selection process a total of more than 200 persons were interviewed. After additional interviews and physical exams, thirty-one subjects (twenty men, eleven women) were assigned to the study. Each subject completed several orientations sessions over two weeks prior to any intervention. Three groups of ten or eleven (seven men and three women; the UL group contained four women) subjects each, performed five weeks of either unilateral lower limb suspension (UL), unilateral lower limb suspension and concurrent resistance exercise (ULRE) or resistance exercise (RE) only. Group RE was ambulatory. Subjects assigned to crutch walking, reported to the laboratory at least three times per week to ensure compliance. Resistance exercise (ULRE and RE) was performed two or three times weekly (unilateral coupled concentric and eccentric actions; four sets of seven repetitions) using an exercise configuration designed for the knee extension. Force, power and work of each repetition were monitored in each training session. Neuro-muscular function was assessed by means of a battery of performance tasks, that measures force and surface electromyography (EMG) during different exercises and types of muscle actions, and emphasizes use of the knee extensor muscle group. These tests were carried out on several occasions before and after intervention. Magnetic resonance imaging was employed to assess muscle cross-sectional area and volume of individual knee- and ankle plantar flexor muscles pre and post intervention and five weeks following completion of any regime.

All subjects did comply with the prescribed protocols. Subjects were re-examined after five weeks of either free ambulating or a supervised resistive exercise program. The entire series of experiments were completed in the summer of 2001. Final data analyses are to be completed.

Results

Muscle hypertrophy following five wk resistance training using a non-gravity dependent loading principle

The efficacy of the flywheel system was validated in a five wk training study using a knee extensor exercise configuration (**fig 1**).

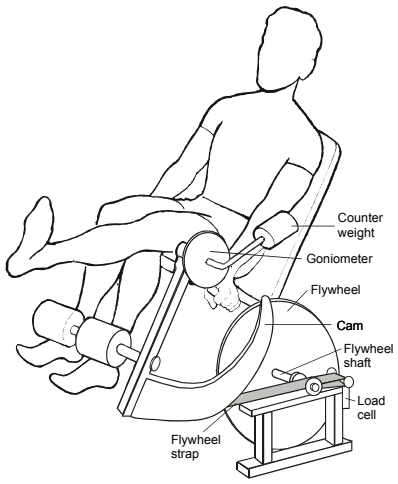


Figure 1
Knee extensor exercise device utilizing the flywheel principle and used for resistance training and strength testing.

Ten middle-aged men and women performed four sets of seven maximal, unilateral (left limb) knee extensions two or three times weekly. Knee extensor force and electromyographic (EMG) activity of the three superficial quadriceps muscles were measured before and after this intervention. Also, with use of magnetic resonance (MR) imaging, volume of individual knee extensor and ankle plantar flexor muscles was assessed. Over the twelve training sessions, the average concentric (CON) and eccentric (ECC) force generated during exercise (**fig 2**) increased 11% ($p<0.05$).

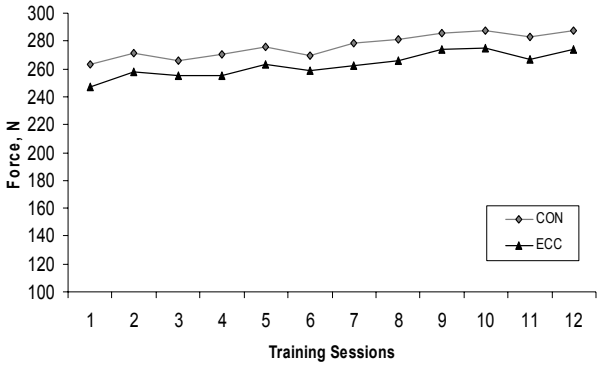


Figure 2
Performance during the twelve exercise sessions. Average force in a 30° window (5° above min knee joint angle) is shown where diamond and triangle symbols represent concentric (CON) and eccentric (ECC) force, respectively. Values are group mean.

Likewise, maximal isometric strength (MVC) at 90 and 120° knee angle (**fig 3**) increased ($p<0.05$) 11% and 12% respectively, after training. Neither individual quadriceps muscle showed a change ($p>0.05$) in maximal integrated EMG (iEMG) activity.

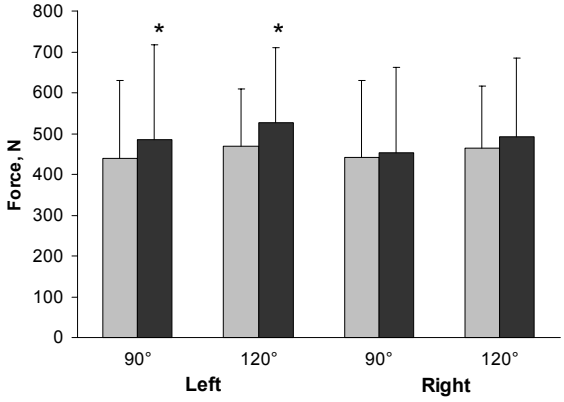
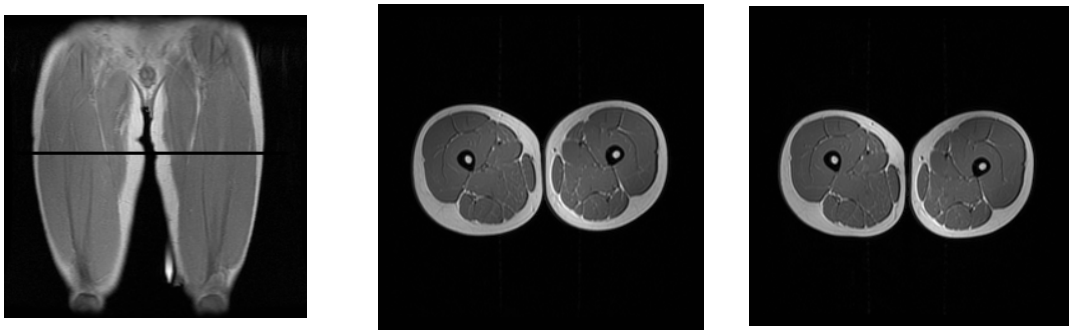


Figure 3
Maximal voluntary isometric force (MVC) at 90 and 120° knee angle pre (gray bars) and post (black bars) resistance training. Left is trained limb; right is non-trained limb. * denotes difference from pre test.

Quadriceps muscle volume increased 6.1% ($p<0.05$). Although the magnitude of response varied, all individual quadriceps muscles showed increased ($p<0.05$)

volume after training (**fig 4**; **Table 1**). As expected, ankle plantar flexor volume of the trained limb was unchanged (p>0.05). Likewise, MVC, CON and ECC force, iEMG and knee extensor and plantar flexor muscle volume were unaltered (p>0.05) in the non-trained limb. The preliminary results of this study show the present resistance exercise regimen produces marked muscle hypertrophy and important increases in maximal voluntary strength and, in these regards, appears equally effective as resistance exercise paradigms using gravity-dependent weights.



Pre **Post**

Figure 4
Coronal (far left) and axial (pre and post training) magnetic resonance images (MRI) of the thigh. Horizontal line of coronal image depicts level where the pictured images were obtained.

Muscle/ Muscle group	Left Pre	Left Post	Right Pre	Right Post
VL	420±110	446±119 *	368±102	362±102
VI	361±80	374±85 *	370±89	366±87
VM	267±75	288±81 *	293±71	292±75
RF	113±35	123±41 *	115±26	111±26
Quadriceps	1161±285	1232±310 *	1145±273	1132±275
Plantar Flexors	448±87	437±79	448±88	443±88

Table 1
Volume (ml) of individual muscles and muscle groups pre and post five weeks of resistance exercise. Left is trained limb; right is non-trained limb. Values are mean ± SD. VL = m. vastus lateralis; VI = m. vastus intermedius; VM = m. vastus medialis; RF = m. rectus femoris. Differences between pre and post values are denoted where * p<0.05.

Plantar flexor muscle atrophy in men and women in response to five wk simulated spaceflight

Among muscles responsible for weight-bearing function, it appears the ankle plantar flexor muscle group show the most severe atrophy in response to unloading. Unfortunately, little is known as to whether men and women are equally susceptible to such muscle wasting. However, this information is warranted because today NASA's astronaut corps (classes of 1998 and 2000) includes about 20% women.

In an effort to address this issue we examined 21 middle-aged men (n=14; 30-56 yrs, 65-95 kg, 170-191 cm) and women (n=7; 35-51 yrs, 59-90 kg, 163-173 cm) and compared changes in ankle plantar

flexor muscle volume following five wk of unilateral lower limb unloading (**fig 6**; se below). In brief, subjects unloaded their left leg by wearing a shoe with an elevated sole on the right foot to prevent ground contact, while walking on crutches. Muscle volume was assessed by means of magnetic resonance imaging. Ankle plantar flexor muscle cross-sectional area (CSA) was assessed by drawing a straight line between the anterior boundaries of the lateral and medial aspects of m. gastrocnemius and subsequently encircle the area that contained the soleus and gastrocnemius muscles. This approach allowed accurate measurements of the major portion (>80%) of m. soleus and the entire m. gastrocnemius. CSA of all images beginning with the first one where both tibia and fibula appeared and ending with the most distal image containing both heads of m. gastrocnemius was measured. Plantar flexor muscle volume was determined by multiplying the CSA of each image by thickness (10 mm) and number (12-15) of interleaved, serial images.

Prior to unloading, muscle volume (right + left leg) averaged (range) 559 (330-833) ml in men. It averaged 378 (239-514) ml in women. There was no difference in volume between right and left legs before unloading. Unloading produced an 11% decrease ($p<0.05$) in muscle volume in both men and women. The volume of the right leg showed no change in men (+1%; $p>0.05$) or women (-1%; $p>0.05$). Thus, men and women showed a very similar rate of muscle atrophy in response to unloading (**fig 5**).

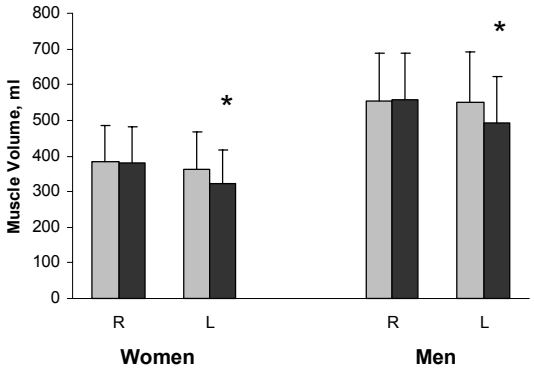


Figure 5
Plantar flexor muscle volume pre (gray bars) and post (black bars) unloading for men and women, respectively. Left is unloaded limb; right is weight-bearing limb. * denotes difference from pre test.

These data suggest atrophy of plantar flexor muscles occurs at a very similar rate in middle-aged men and women subjected to five wk muscle unloading. Although it seems likely, it remains to be proven if these data also apply to long-duration spaceflight.

A resistance training regimen promoting muscle hypertrophy of unloaded muscle

In an effort to simulate the effects of spaceflight on weight-bearing muscles, twenty-one middle-aged men and women were subjected to unilateral lower limb unloading for five wk (**fig 6**), as described above.

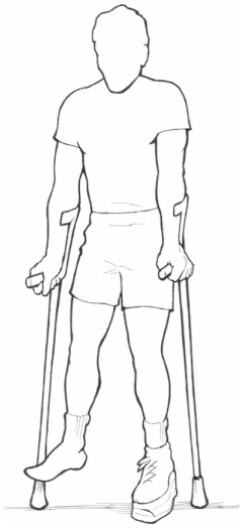


Figure 6
Cartoon showing individual subjected to unilateral lower limb unloading.

Eleven subjects (UL) refrained from any physical activity, whereas ten of these subjects, performed unilateral knee extensor resistance exercise (ULRE) two or three times weekly using the exercise regimen described above. Muscle strength was measured, using the knee extensor device, before and after UL and ULRE and by means of MR imaging, volume of individual knee extensor and ankle plantar flexor muscles was assessed before and after these interventions (**fig 7**).

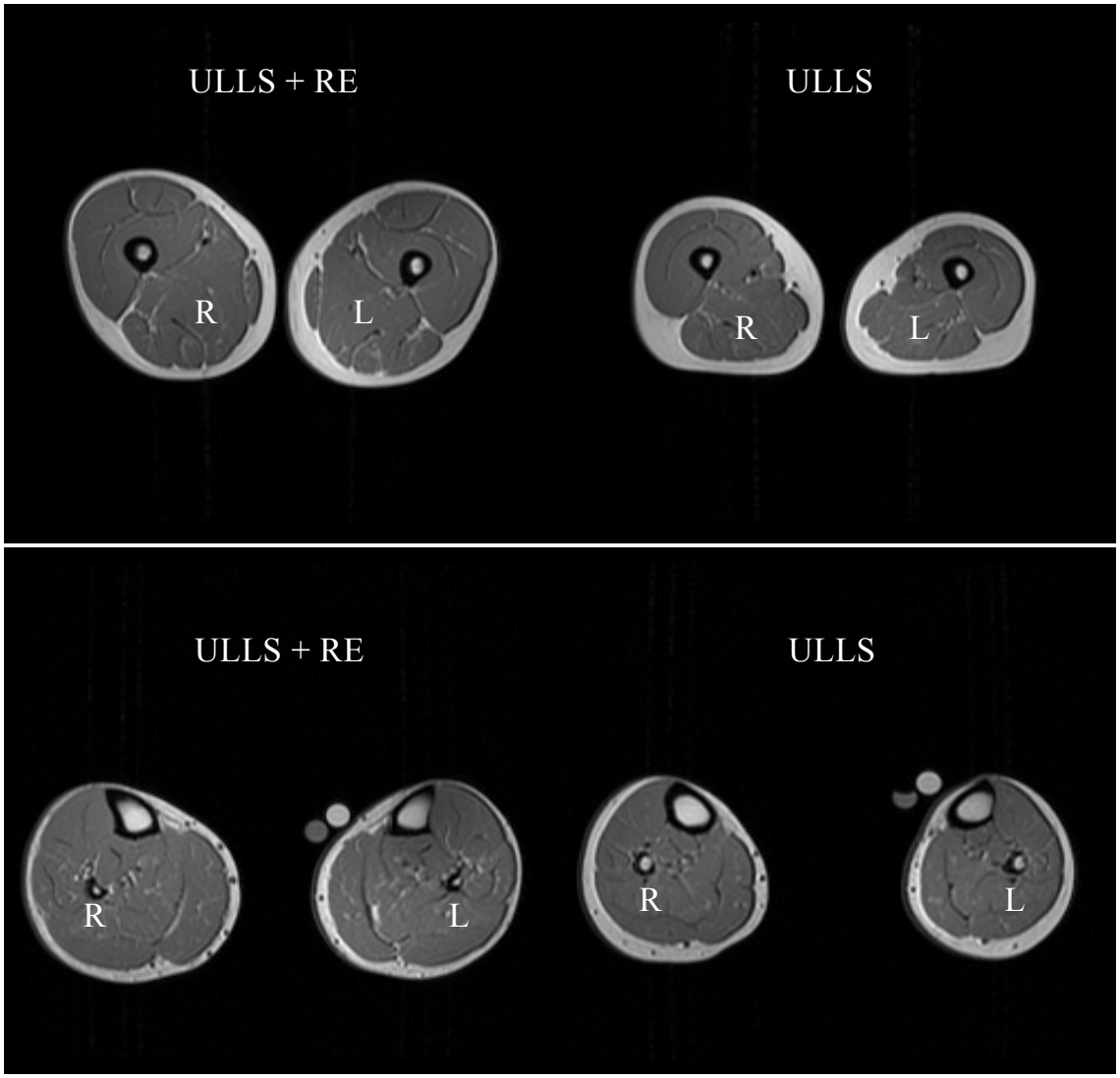


Figure 7
Images were obtained after five weeks of lower limb unloading only (ULLS) or with concurrent resistive exercise (ULLS+RE). Subject A (left hand) who performed knee extensor training of the unloaded muscle (left; L) showed no quadriceps atrophy (upper panel; images were obtained mid-thigh; slice 27 of 46). In contrast, the left ankle extensor muscles showed atrophy (lower panel; image is obtained mid-calf; slice 17 of 29). Subject B (right hand), subjected to unilateral lower limb suspension showed marked atrophy of both the quadriceps muscles (slice 27 of 47) and calf (slice 22 of 32). Field of view is 32 (calf) and 48 (thigh), respectively.

UL produced a 9 % decrease ($p<0.05$) in quadriceps muscle volume (average CSA). It increased (8%; $p<0.05$) following ULRE as a result of about 16 min of maximal contractile activity over the five wk course (**fig 8**).

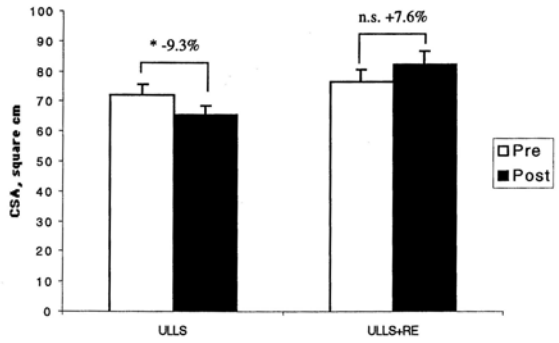


Figure 8
Muscle (quadriceps femoris) average cross-sectional area (CSA) in the ULLS and ULLS+RE groups before and after 5 weeks of ULLS. *$p<0.05$ from pre-ULLS

Maximal isometric strength decreased 26% ($p<0.05$) in response to UL. Group ULRE showed a non-significant 7% decrease ($p>0.05$) in strength on day 1 of ambulation (**fig 9**).

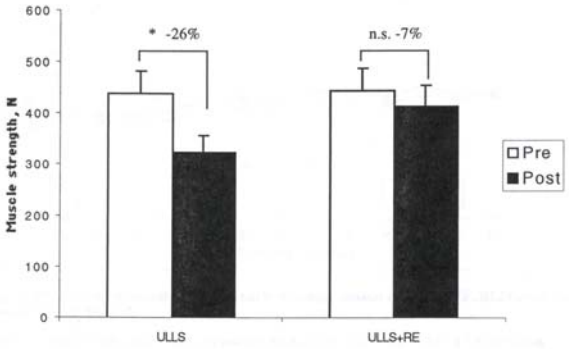


Figure 9
Isometric muscle strength in the ULLS and ULLS+RE groups before and after 5 weeks of ULLS. *$p<0.05$ from pre-ULLS

Further, training produced an increase ($p<0.05$) in concentric and eccentric performance across the 12 exercise sessions (**fig 10**) at a rate similar to that demonstrated in ambulatory subjects performing the same exercise protocol (see above).

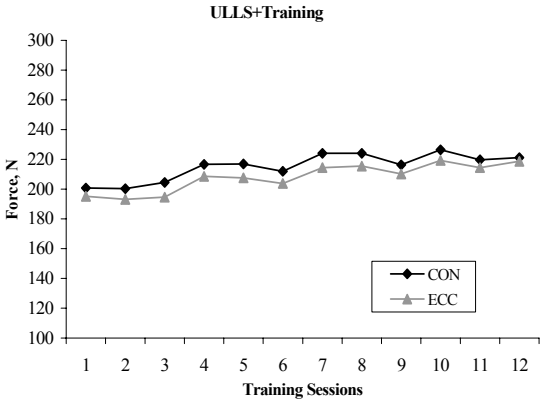


Figure 10
Training progress during ULLS combined with training on the knee extension apparatus using flywheel technology

Ankle plantar flexor muscle volume of the unloaded limb decreased ($p<0.05$) in both groups (11% in UL and 10% in ULRE). Muscles of the right weight-bearing limb/leg showed no changes ($p>0.05$) in muscle volume. This study provides evidence resistance exercise not only prevents muscle atrophy, but is in fact capable of promoting hypertrophy of chronically unloaded muscle. In light of these findings we are confident the flywheel exercise concept could serve as an effective in-flight countermeasure.

Discussion

This study was designed in an effort to validate the efficacy of the flywheel exercise system to counteract muscle and strength loss induced by five wk of simulated spaceflight. Previously other laboratories have produced evidences inferring resistance exercise paradigms can offset such effects during short-term spaceflight simulation. Unfortunately, these studies employed exercise systems that are dependent on gravity. We used a system that utilizes the inertia of rotating flywheels to produce resistance during concentric and eccentric actions and showed that the marked 9% loss in muscle volume induced by five wk unloading was eliminated. In fact, our data demonstrated that resistance training of unloaded muscle produced hypertrophy, that was of the same order of magnitude or even greater, than that found in an ambulatory individuals, who performed an identical exercise task. This is a remarkable finding and suggests rate of skeletal muscle hypertrophy is not limited by unloading. This is not to say neuromuscular adaptations follow the same course. Albeit muscle strength was maintained in subjects who performed resistance training while being unloaded, it appears the increase in muscle protein content was not entirely translated and reflected in improved muscle function, at least not in the acute state (the first days of ambulation).

NASA's Critical Path Roadmap (CPR) for "Muscle Alterations and Atrophy" identifies muscle loss and associated changes in muscle function and motor performance as potential risks consequent to prolonged exposure to microgravity. We had subjects perform five wk simulated spaceflight and showed a marked decrease in knee extensor muscle strength. Quadriceps muscle atrophy mainly was responsible for this effect; yet neural factors (and/or changes within the contractile apparatus) must have been involved as well, as the voluntary strength loss was much greater than the decrease in muscle volume.

We hypothesized the proposed resistance exercise regimen would ameliorate and most likely eliminate the negative effects of unloading on quadriceps muscle size and voluntary knee extensor strength. The CPR proposes exercise regimes, among other interventions, could potentially offset the identified risk factors. The results of our study suggest voluntary strength and work/power are maintained. This particular study did not address issues related to endurance or motor performance. Our studies so far (up to seven wk of unloading) suggest muscle phenotype of the quadriceps is not altered. The results of this study concord in that neither unloading, training nor unloading plus training induced a shift in myosin heavy chain composition. Hence, we are not convinced altered muscle phenotype is a major concern or a significant risk factor in space travellers, as proposed in the CPR.

We compared muscle atrophy of the ankle plantar flexor and the knee extensor muscles in response to five wk unloading. Our data suggest no major difference with regard to rate of atrophy in these two postural muscles. Finally, we were able to generate novel information on potential gender differences in ankle plantar flexor atrophy. Our data suggest men and women show very similar rate of muscle loss in response to five wk unloading. These two issues are both of concern in regards to design of in-flight exercise prescriptions and have important operational implications. Based on our results, we believe equal and major emphasis should be placed on plantar flexor and knee extensor resistance exercise. Similarly, since it appears men and women are equally vulnerable to muscle loss, exercise prescriptions should have the same focus regardless of gender.

Although the questions addressed in this study originate from the observation that space travellers show atrophy and

impaired muscle function upon return to Earth, the results of the completed research has broader applications. Enhanced knowledge how unloaded skeletal muscle responds to a resistive exercise paradigm should be useful in the process of designing techniques to counteract the negative effects of aging, bed rest or muscle disease.

Spin-off and continued related research

We took advantage of this extensive and unique study protocol and, after approval by the local IRB, obtained muscle biopsies from m. vastus lateralis and m. soleus pre and post the three different interventions. Several research groups have then shared muscle tissue in an effort to study more specific muscle adaptations. For example, we assessed skeletal muscle protein content and myosin heavy chain composition in muscle samples taken before and after unloading with and without resistance exercise. Preliminary results suggest, despite very similar rate of muscle loss, the soleus muscle but not the vasti muscle, show a decrease in the content of specific proteins. There was no change in muscle phenotype following any of the protocols employed. Further, in collaboration with Dr. Baldwin, University of California, we analyse different markers (including IGF-1), thought to control or be associated with muscle atrophy and hypertrophy (data not reported here).

Through interaction with other research groups at UAMS, Dr. James Fluckey employed the flywheel system and developed a rat experimental model. He and associate researchers then used the system in rats subjected to hind limb suspension to examine its efficacy as a countermeasure to bone and muscle loss. His initial results (Fluckey et al 2002) show bone loss is offset and muscle atrophy ameliorated in hind limb suspended rats performing flywheel exercise. These results are encouraging and suggest this innovative animal model could be used for more mechanistic studies of skeletal muscle and bone adaptations in space flown rats performing resistance exercise.

It should be recalled the exercise configuration we employed in this study emphasize isolated knee extensor use to ensure well-controlled experiments. The flywheel principle has been employed in other multi-exercise configurations aimed at being used on the ISS.

Presentations

•Tesch PA. Resistance training using fly-wheel technology ameliorates muscle atrophy induced by five wk lowerlimb unloading. 13th Annual IAA meeting and Human in Space Symposium, Santorini, Greece, May 22-25, 2000

•Tesch PA. Rationale for resistance exercise in space. In Symposium "Mission to Mars", 11th International Conference on the Biochemistry of Exercise, Molecular Aspects of Physical Activity and Aging, Little Rock, AR, June 4-7, 2000

•Trieschmann JT. A resistance-training regimen promoting hypertrophy of unloaded muscle, 11th International Conference on the Biochemistry of Exercise, Molecular Aspects of Physical Activity and Aging, Little Rock, AR, June 4-7, 2000

•Tesch PA. Resistance training using flywheel technology promotes hypertrophy of unloaded muscle, Bioastronautics Investigators' Workshop, Galveston, TX, Jan 17-19, 2001

•Tesch PA. Effect of resistance exercise on function and size of human skeletal muscle subjected to unloading. 22nd Annual International Gravitational Physiology Meeting, Budapest, Hungary, April 22-27, 2001

•Ekberg A. Effects of five week lower limb unloading and resistance exercise on calf and individual quadriceps muscle size. 22nd Annual International Gravitational

Physiology Meeting, Budapest, Hungary, April 22-27, 2001

•Tesch PA. Resistance exercise using fly-wheel technology promotes hypertrophy of unloaded muscle. Emerging technologies for the new millenium. Aerospace Medical Association 72nd Annual Scientific Meeting, Reno, NE, May 6-10, 2001

•Tesch PA. Effect of in-flight resistive exercise using fly-wheel technology on muscle size and function. Conference and exhibit on International Space Station Utilization, Cape Canaveral, FL., Oct 15-17, 2001

•Carrithers JA. Skeletal muscle protein content following 5 weeks of unloading with or without resistance exercise countermeasures. 23nd Annual International Gravitational Physiology Meeting, Stockholm, Sweden, June 2-7, 2002

•Trappe TA. The influence of 5 weeks of ULLS and resistance exercise on vastus lateralis and soleus myosin heavy chain distribution. 23nd Annual International Gravitational Physiology Meeting, Stockholm, Sweden, June 2-7, 2002

•Tesch PA. Resistance exercise prescriptions for space. In symposium: Physiological basis for countermeasures and applications. 23nd Annual International Gravitational Physiology Meeting, Stockholm, Sweden, June 2-7, 2002

•Tesch PA. Plantar flexor muscle atrophy in men and women in response to five wk simulated spaceflight. "Living in Space", 14th Annual IAA meeting and Human in Space Symposium, Banff, Alberta, Canada, May 18-22, 2003.

Abstracts

•Tesch PA. Rationale for resistance exercise in space. In Symposium "Mission to Mars", 11th International Conference on the Biochemistry of Exercise, Molecular Aspects of Physical Activity and Aging, Little Rock, AR, June 4-7, 2000

•Trieschmann JT, A Ekberg, PA Tesch. A resistance-training regimen promoting hypertrophy of unloaded muscle, 11th International Conference on the Biochemistry of Exercise, Molecular Aspects of Physical Activity and Aging, Little Rock, AR, June 4-7, 2000

•Tesch PA, A Ekberg, JT Trieschmann. Resistance training using flywheel technology promotes hypertrophy of unloaded muscle. Proceedings. Bioastronautics Investigators' Workshop, Galveston, TX, Jan 17-19, 2001

•Tesch PA, A Ekberg, JT Trieschmann. Effect of resistance exercise on function and size of human skeletal muscle subjected to unloading. Proceedings. 22nd Annual International Gravitational Physiology Meeting, Budapest, Hungary, April 22-27, 2001

•Ekberg A, JT Trieschmann, PA Tesch. Effects of five week lower limb unloading and resistance exercise on calf and individual quadriceps muscle size. Proceedings. 22nd Annual International Gravitational Physiology Meeting, Budapest, Hungary, April 22-27, 2001

•Tesch PA, JT Trieschmann, A Ekberg. Resistance exercise using fly-wheel technology promotes hypertrophy of unloaded muscle. Aviat Space Environ Med 72(3), p.262, 2001

•Tesch PA. Resistance exercise prescriptions for space. Proceedings. 23nd Annual International Gravitational Physiology Meeting, Stockholm, Sweden, June 2-7, 2002

•Trappe TA, JA Carrithers, A Ekberg, J Trieschmann, PA Tesch. The influence of 5 weeks of ULLS and resistance exercise on vastus lateralis and soleus myosin heavy chain distribution. Proceedings. 23nd Annual International Gravitational Physiology Meeting, Stockholm, Sweden, June 2-7, 2002

•Carrithers JA, PA Tesch, JT Trieschmann, A Ekberg, TA Trappe. Skeletal muscle protein content following 5 weeks of unloading with or without resistance exercise countermeasures. 23nd Annual

International Gravitational Physiology Meeting, Stockholm, Sweden, June 2-7, 2002

•Tesch PA, JT Trieschmann, A Ekberg. Plantar flexor muscle atrophy in men and women in response to five wk simulated spaceflight. Proceedings. Living in Space, Banff, Alberta, Canada, May 18-22, 2003.

Publications

•Trieschmann JT, A Ekberg, PA Tesch. A resistance training regimen promoting muscle hypertrophy of unloaded muscle. J Aging Phys Activity. 8(3):278-279. 2000.

•Fluckey JD, E Dupont-Versteegden, DC Montague, M Knox, PA Tesch, CA Peterson, D Gaddy-Kurten. A rat resistance exercise regimen attenuates losses of musculoskeletal mass during hindlimb suspension. Acta Physiol Scand. 176:293-300. 2002.

•Trappe TA, J Carrithers, A Ekberg, JT Trieschmann, PA Tesch. The influence of 5 weeks of ULLS and resistance exercise on vastus lateralis and soleus myosin heavy chain distribution. J. Grav. Physiol. 9:127-128. 2002.

•Carrithers J, PA Tesch, JT Trieschmann, A Ekberg, TA Trappe. Skeletal muscle protein content following 5 weeks of unloading with or without resistance exercise countermeasures. J. Grav. Physiol. 9: 155-156. 2002.

•Tesch PA, A Ekberg D Lindquist, JT Trieschmann. Muscle hypertrophy following five wk resistance training a non-gravity dependent loading principle. Acta Physiol Scand. Accepted for Publication.

•Tesch PA, JT Trieschmann, A Ekberg. A resistance training regimen promoting hypertrophy of unloaded muscle. J Appl Physiol. In Review.

Other Information and Materials

Newsprint coverage:

Arkansas Democrat-Gazette (Linda Caillouet) Volunteers help study on astronauts' training. Weight program in space could maintain muscles. October 23, 1999

UAMS Today. News from the University of Arkansas for Medical Sciences. "UAMS Researchers boost NASA research", December 8, 2000

Television coverage:

KATV-ABC News (Rachael Oesch) NASA study. November 4, 1999

KARK-NBC News (Betsy Pilgrim) NASA study. December 6, 1999

KATV-ABC News (Cary Martin) Diet and Exercise in Space. June 10, 2000

Undergraduate/graduate students

Jay Trieschmann (undergraduate)
Lena Jonsson (undergraduate)
Anneli Ekberg (graduate)
John Carrithers (graduate)