

Section 3

# **Functional Performance Evaluation**

EXTENDED DURATION ORBITER MEDICAL PROJECT

# Functional Performance Evaluation

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## INTRODUCTION

The Extended Duration Orbiter Medical Project (EDOMP) was established to address specific issues associated with optimizing the ability of crews to complete mission tasks deemed essential to entry, landing, and egress for spaceflights lasting up to 16 days. The main objectives of this functional performance evaluation were to investigate the physiological effects of long-duration spaceflight on skeletal muscle strength and endurance, as well as aerobic capacity and orthostatic function. Long-duration exposure to a microgravity environment may produce physiological alterations that affect crew ability to complete critical tasks such as extravehicular activity (EVA), intravehicular activity (IVA), and nominal or emergency egress. Ultimately, this information will be used to develop and verify countermeasures. The answers to three specific functional performance questions were sought: (1) What are the performance decrements resulting from missions of varying durations? (2) What are the physical requirements for successful entry, landing, and emergency egress from the Shuttle? and (3) What combination of preflight fitness training and in-flight countermeasures will minimize in-flight muscle performance decrements?

To answer these questions, the Exercise Countermeasures Project looked at physiological changes associated with muscle degradation as well as orthostatic intolerance. A means of ensuring motor coordination was necessary to maintain proficiency in piloting skills, EVA, and IVA tasks. In addition, it was necessary to maintain musculoskeletal strength and function to meet the rigors associated with moderate altitude bailout and with nominal or emergency egress from the landed Orbiter. Eight investigations, referred to as Detailed Supplementary Objectives (DSOs) 475, 476, 477, 606, 608, 617, 618, and 624, were conducted to study muscle degradation and the effects of exercise on exercise capacity and orthostatic function (Table 3-1).

This chapter is divided into three parts. Part 1 describes specific findings from studies of muscle strength, endurance, fiber size, and volume. Part 2 describes results from studies of how in-flight exercise

affects postflight exercise capacity and orthostatic function. Part 3 focuses on the development of new noninvasive methods for assessing body composition in astronauts and how those methods can be used to correlate measures of exercise performance and changes in body composition.

## PART 1 – SKELETAL MUSCLE ADAPTATIONS TO SPACEFLIGHT

### Purpose

Adaptation to the microgravity environment of spaceflight involves muscular deconditioning. Changes in muscle morphology and function could affect motor function and control. Decrements in motor performance could impair the successful completion of many tasks associated with EVA, IVA, and emergency or routine landing and egress. Prior to EDOMP, the scope of the deconditioning process and the extent to which it may affect performance had not been established. In particular, changes in skeletal muscle performance and morphology during extended duration Shuttle flights had not been determined.

The four studies described in Part 1 (DSOs 475, 477, 606, and 617) constituted a comprehensive investigation of skeletal muscle function and atrophy associated with the physiological adaptation to spaceflight. The associated measurements were important because: (1) a timeline for muscle function changes had not been established, (2) critical periods of muscle atrophy and deconditioning had not been identified, and (3) losses of functional levels of muscle strength and endurance had not been assessed. The results from these investigations were expected to provide the knowledge needed to support development of future preflight conditioning, in-flight countermeasures, and postflight rehabilitation activities, all of which are essential in maintaining operational effectiveness.

*Table 3-1. Investigations constituting the functional performance evaluation of the Extended Duration Orbiter Medical Project*

<i>DSO No.</i>	<i>Title</i>	<i>Investigators</i>
DSO 475	Direct assessment of muscle atrophy and biochemistry before and after short spaceflight.	VR Edgerton, ML Carter, and MC Greenisen
DSO 476	Aerobic exercise in flight and recovery of cardiovascular function after landing.	SF Siconolfi and JB Charles
DSO 477	Evaluating concentric and eccentric skeletal muscle contractions after spaceflight.	JC Hayes, BA Harris, and MC Greenisen
DSO 606	Assessing muscle size and lipid content with magnetic resonance imaging (MRI) after spaceflight.	AD LeBlanc
DSO 608	Effects of space flight on aerobic and anaerobic metabolism during exercise: The role of body composition.	SF Siconolfi and AD Moore
DSO 617	Evaluating functional muscle performance after spaceflight.	JC Hayes and MC Greenisen
DSO 618	Effects of intense in-flight exercise on postflight aerobic capacity and orthostatic function.	AD Moore and MC Greenisen
DSO 624	Cardiorespiratory responses to sub-maximal exercise before and after flight.	AD Moore and MC Greenisen

## **Background**

Scientific and technological advancements in spaceflight have necessitated the development of ways to maximize the ability of flight crews to perform during increasingly long missions. Optimizing crew capability, both during flight and upon return to a terrestrial environment, is essential for successful completion of and recovery from long missions.

NASA has established the development, construction, and operation of a permanently occupied space station in low Earth orbit as a definitive goal. Constructing an International Space Station (ISS) is expected to exacerbate the physiological stresses on flight crews, both from increasingly longer stays in space and from the physical demands associated with construction activities. In order to accomplish the objectives associated with longer spaceflights safely and efficiently, the life sciences community was charged with establishing reliable means of ensuring crew proficiency for such flights.

EDOMP was established to address the issue of how best to protect the ability of crews to complete mission tasks deemed essential to entry, landing, and egress for spaceflights lasting up to 16 days [1]. A major component of this effort was the development and verification of in-flight countermeasures to offset any physiological adaptations that could negatively affect the ability to complete those tasks. Effective countermeasures also could speed the rate of recovery after landing, i.e., the rate at which crew members return to their preflight baselines.

Microgravity exposure is known to affect neuromuscular and musculoskeletal function in ways that could affect the ability to complete critical operational tasks [2]. Maintaining adequate motor coordination and function is essential for operational success, which can be defined as being able to preserve proficiency in tasks associated with piloting, EVA, and IVA. Musculoskeletal strength and function also must be maintained to help crews meet the physical rigors associated with nominal or emergency egress.

Egress from the Orbiter, even under nominal conditions, places physical demands on the major muscle groups of the arms, legs, and torso. The current launch and entry suit (LES) weighs 51 pounds (23 kg) and must be worn during all landing and egress procedures. In addition, a parachute pack weighing an additional 26 pounds (12 kg) must be worn with the LES in the event of emergency bailouts. The excess weight could well impair operational performance during landing and egress, especially in emergencies which require lifting, pushing, pulling, jumping, climbing, and running. For example, in an expedited contingency landing, one of the crew members must deploy a 45 pound (20 kg) flight package, which includes an inflatable slide that must be lifted up against the side hatch and locked into designated slots before inflation and egress. Another somewhat less likely scenario involves exiting through the top window on the flight deck, which would require climbing out of the top window and rappelling down the side of the Orbiter [3].

Maintaining physical fitness during flight has been proposed as one way of minimizing the physiological effects of adaptation to microgravity during flight, thereby protecting the ability to function effectively upon return to a gravity environment and perhaps speeding the postflight recovery process [4]. The complexity of the adaptation process, which involves shifts in the cardiovascular, respiratory, musculoskeletal, neurosensory, and other systems, requires that baseline measures be established against which the effects of intervention can be compared. Some aspects of the musculoskeletal adaptation process are briefly described below.

Muscles become deconditioned as a result of chronic disuse. Insufficient functional loads, whether engendered by immobilization, bed rest, or spaceflight, result in atrophy, reduced strength, and reduced endurance [5-9]. Rats flown on Spacelab-3 (STS-51B) lost 36% of the mass and 30% of the cross sectional area of the soleus after only one week of spaceflight [10]. Pre-flight-to-postflight comparisons of skeletal muscle volume by magnetic resonance imaging (MRI) revealed 4 to 10% reductions in selected muscles and muscle groups from the crew of Spacelab-J (STS-47) [11]. Cosmonauts on Mir flights have shown reductions of up to 18% in lower limb and back muscle mass. The implications of these findings for performance are significant, since loss of muscle mass is directly related to movement control. If less muscle mass is available, then less tension is produced when these muscles are maximally activated. Thus, functional adjustments in performance would have to be made in order to maintain appropriate movement responses and postural control [12]. Loss of movement control has operational impacts during IVA and EVA, but also may have important implications for landing and egress tasks, especially in emergencies.

Skeletal muscle contractions involve either shortening or lengthening of muscle fibers. Muscle tensions that accelerate a lever arm and shorten the muscle fibers are defined as concentric contractions. Such contractions often are labeled "positive work." Conversely, muscle tensions that decelerate a lever arm and lengthen muscle fibers are termed eccentric contractions, or negative work. Isokinetic contractions are dynamic muscle activities, performed at a fixed angular velocity and with variable resistance, conditions that accommodate the ability of the muscle to generate force [13]. Eccentric and concentric muscular contractions contribute equally to the functional activities of daily living. Running, jumping, throwing, and maintaining postural balance all require eccentric strength and endurance. Many activities associated with EVA and IVA, routine or rapid egress, and piloting a space vehicle upon return to Earth, also involve eccentric capabilities.

Postflight isokinetic strength testing has provided an important means of quantifying musculoskeletal deconditioning. Concentric strength of Skylab crews was

tested with a Cybex isokinetic dynamometer before and after flight. Postflight tests conducted with the Skylab 2 crew, which took place 5 days after their 28-day flight, revealed losses of approximately 25% in leg extensor strength. Declines in arm strength were not as severe [9]. Moreover, these crew members likely had experienced some recovery in strength during the 5 days between landing and testing. The Skylab 3 and 4 crews also lost leg strength after their 59- and 84-day missions, respectively, but to a lesser extent than the Skylab 2 crew, presumably because of the emphasis on in-flight exercise during the two longer missions [8,9].

Evidence of microgravity-induced changes in motor performance has been reported by Russian investigators. Biomechanical analysis of ambulation patterns showed that adaptation to space flight affected the motor skills associated with walking after return to Earth [14]. Gross motor skills, as assessed by long and high jumps, were diminished after a 63-day Russian mission [14]. Skeletal muscle strength, measured with concentric isokinetic dynamometry after long (110 to 237 days) and short (7 days) flights, declined by as much as 28% in both isometric and isokinetic modes [15]. Significant changes in the torque-velocity relationship were apparent in the gastrocnemius/soleus, anterior tibialis, and ankle extensors of 12 crew members after only 7 days of flight on Salyut 6. Losses in the sural triceps ranged from 20 to 50% after missions lasting 110 to 235 days. Decrements in isokinetic strength properties of the sural triceps were similar after long or short missions [15], although loss of strength was not uniform throughout the velocity spectrum tested.

Aspects of neuromuscular function that affect contractility and the electrical efficiency of muscles also may adapt to microgravity in ways that would affect performance upon return to 1-g. However, the mechanisms underlying such space deconditioning are unclear.

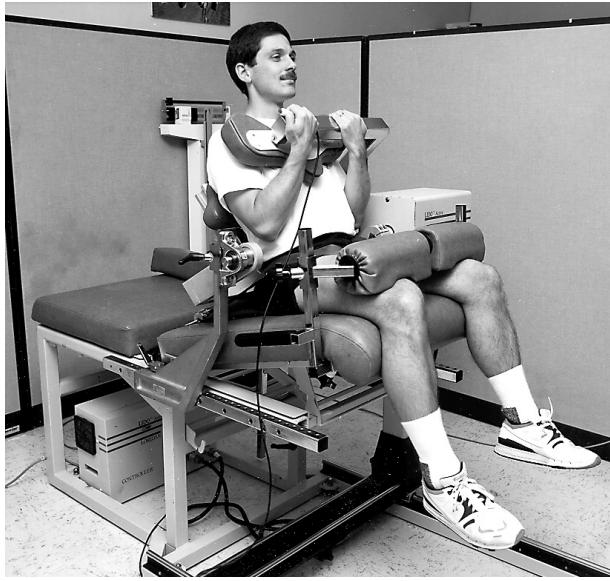
In summary, flight crews must preserve muscle strength and endurance in order to maintain their ability to carry out operational tasks during and after flight. The EDOMP provided an opportunity to quantify flight-induced changes in skeletal muscle mass and function. This information is operationally relevant to the development of future preflight, in-flight, and postflight exercise prescriptions and countermeasures because the effectiveness of proposed countermeasures cannot be evaluated without information on normal changes in skeletal muscle.

## **Skeletal Muscle Performance (DSOs 477 & 617)**

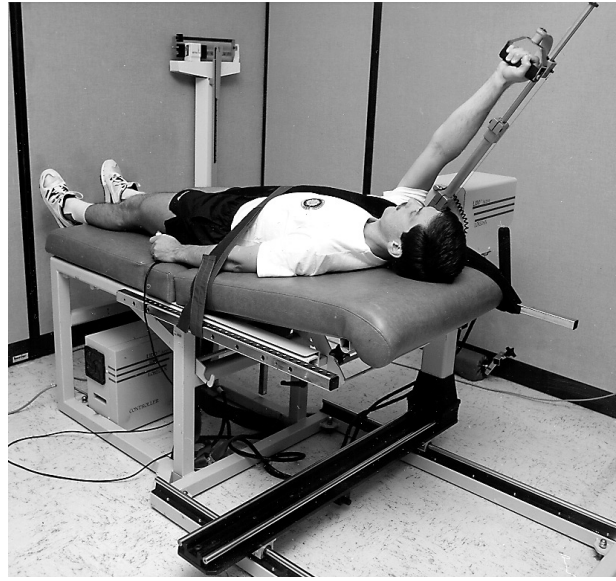
### *Specific Aim*

The specific aim of DSOs 477 and 617 was to evaluate functional changes in concentric and eccentric strength (peak torque) and endurance (fatigue index) of the trunk, upper limbs, and lower limbs of crew members before and after flight.

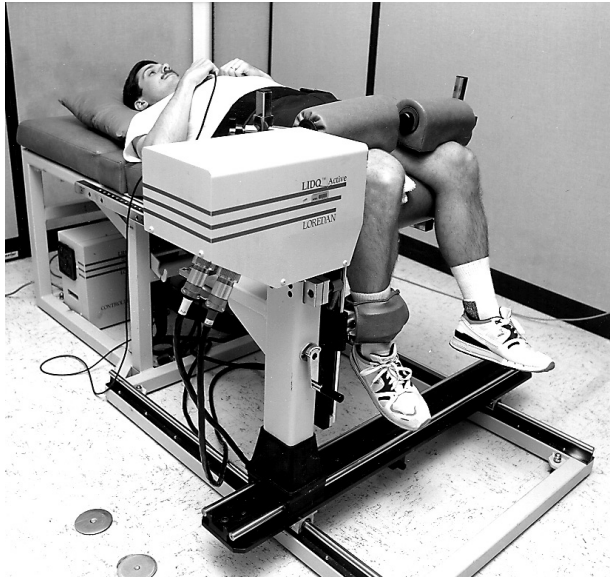




a. Trunk



b. Ankle



c. Knee



d. Shoulder

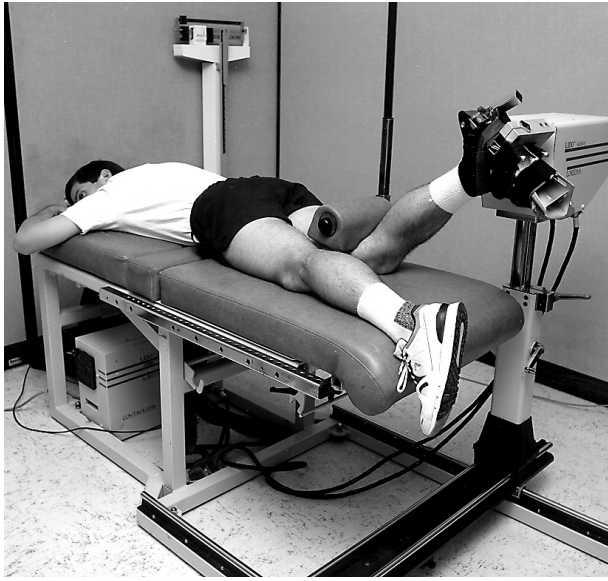
Figure 3-1. A subject undergoes strength and endurance testing with the LIDO® dynamometer.

#### Methods

Muscle function was tested before and after flight in the Exercise Physiology Laboratory at the Johnson Space Center (JSC). The landing-day tests took place at the Orbiter landing site in the Baseline Data Collection Facility (BDCF) at the Kennedy Space Center (KSC) or the Postflight Science Support Facility (PSSF) at the Dryden Flight Research Center (DFRC).

LIDO® dynamometers were used to evaluate concentric and eccentric contractions before and after flight. In all, three LIDO® Active Multi-Joint Isokinetic Rehabilitation

Systems [16] were used to assess muscle performance. Each dynamometer was upgraded by the manufacturer to increase the eccentric torque maximum to 400 ft lbs. Each test facility (JSC, KSC, and DFRC) was equipped with identical dedicated systems. Test subjects were crew members on Shuttle missions ranging from 5 to 13 days in duration. All subjects were instructed to abstain from food for 2 hours before testing, from caffeine for 4 hours before testing, and from exercise for 12 hours before testing. The dynamometers were calibrated externally and internally (electronically) before each test session. Joint



e. Elbow

Figure 3-1. Concluded.

configurations and ranges of motion were recorded for each subject and reproduced for each test session (Figure 3-1). All testing (except for the trunk) was unilateral with the dominant limb, unless otherwise contraindicated (i.e., previous injury). Concentric and eccentric strength were tested in the trunk and upper and lower limbs. Concentric endurance was tested in the knee. Verbal instructions were

1. Tread
2. Pulleys
3. Flywheel
4. Brake
5. Speed Control
6. Speedometer
7. Control
8. Tachometer  
General

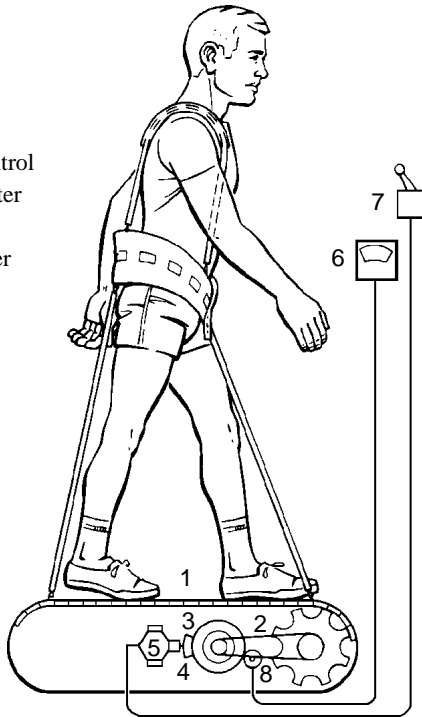


Figure 3-2. U.S. Space Shuttle treadmill.

consistent and given before each joint test. No verbal encouragement was given during the tests.

Test subjects in this study exercised during flight as part of separate investigations (DSOs 476 or 608). Those subjects ran on the original Shuttle treadmill (Figure 3-2) for various durations, intensities, and number of days in flight. Exercise protocols included continuous and interval training, with prescriptions varying from 60% to 85% of preflight maximum oxygen consumed ( $\dot{V}O_{2\max}$ ) as estimated from heart rate. However, several subjects reported difficulty in achieving or maintaining these target heart rates during flight. The speed of this passive treadmill was controlled at seven braking levels by a rapid-onset centrifugal brake. A harness and Bungee tether system was used to simulate body weight by providing forces approximately equivalent to a 1-g body mass. This nonmotorized treadmill required subjects to run at a positive percentage grade in microgravity to overcome mechanical friction.

Test subjects were familiarized with the LIDO<sup>®</sup> test protocol and procedures 30 days before flight (L-30), after which six test sessions were held. Three sessions took place before launch (L-21, L-14, and L-8 days) and three after landing (landing day, R+2, and R+7-10 days).

#### Data Reduction and Analysis

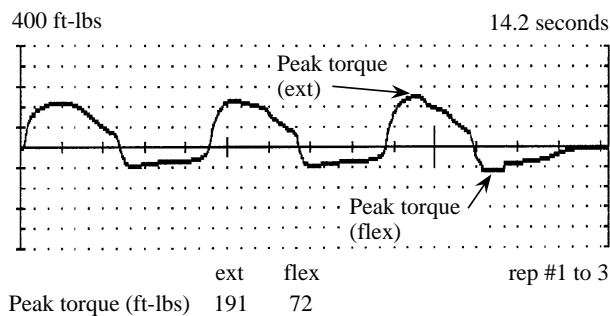
Torque and work data were reduced from the force-velocity curves (Figure 3-3). Statistical analyses of strength, endurance, and power were conducted separately for each muscle group tested. Repeated-measures analysis of variance was used to test the null hypothesis (i.e., no effect of spaceflight on mean peak responses). Peak torque, total work, and fatigue index measurements were compared among the three preflight test sessions; when no differences were found among sessions, values from the three preflight sessions were averaged and this average used to compare preflight values with those on landing day and thereafter. When the overall effect of spaceflight was significant, dependent (paired) t-tests were performed to compare the preflight response to each postflight response.

Skeletal-muscle strength was defined as the peak torque generated throughout a range of motion from 3 consecutive voluntary contractions for flexion and extension (Figures 3-3a, 3-3b).

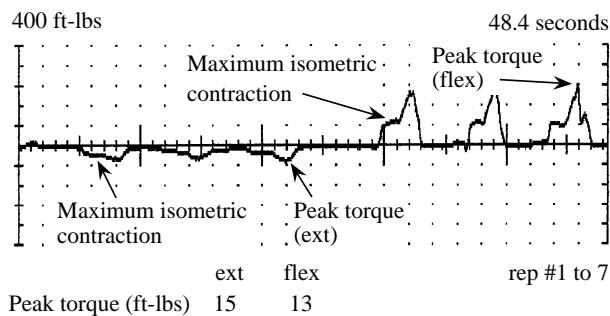
Skeletal-muscle endurance was defined as the total work generated during 25 repetitions of concentric knee exercise (Figure 3-3c), as determined from the area under the torque curve for a set of exercise. Work also was compared between the first 8 and last 8 repetitions. Endurance parameters were measured during concentric knee flexion and extension activity only.

#### Results

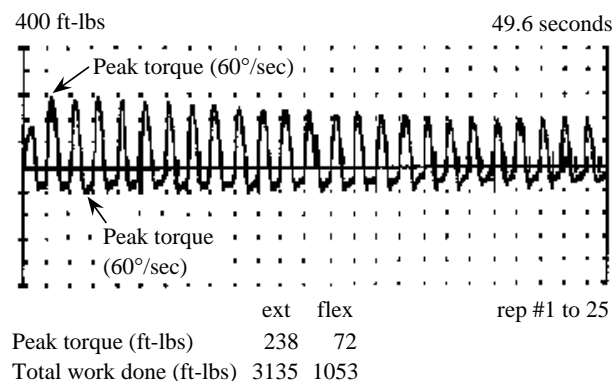
With the exception of concentric strength in the quadriceps, results from the three preflight test sessions were found to be statistically equal by univariate



a. Isokinetic concentric tests consisted of 3 maximal voluntary contractions.



b. Isokinetic eccentric tests included 3 maximal voluntary contractions with a 2-second pause between directions to allow a maximal isometric contraction to precede the onset of each eccentric action.



c. Skeletal-muscle endurance was tested during 25 repetitions of isokinetic concentric (flexion-extension) exercise of the knee.

Figure 3-3. Examples of force-velocity curves for concentric strength (3-3 a), eccentric strength (3-3 b), and concentric endurance (3-3 c) tests.

repeated-measures ANOVA for all muscle groups. Therefore, means of the three preflight sessions were compared to results on landing day (R+0) and on the seventh day after landing (R+7).

Table 3-2. DSO 477 mean skeletal muscle strength performance on landing vs. preflight (n=17)

\*Pre > R+0 (p<0.05)

Muscle Group	Test Mode	
	Concentric	Eccentric
Back	-23 (± 4)*	-14 (± 4)*
Abdomen	-10 (± 2)*	-8 (± 2)*
Quadriceps	-12 (± 3)*	-7 (± 3)
Hamstrings	-6 (± 3)	-1 (± 0)
Tibialis Anterior	-8 (± 4)	-1 (± 2)
Gastroc/Soleus	1 (± 3)	2 (± 4)
Deltoids	1 (± 5)	-2 (± 2)
Pects/Lats	0 (± 5)	-6 (± 2)*
Biceps	6 (± 6)	1 (± 2)
Triceps	0 (± 2)	8 (± 6)

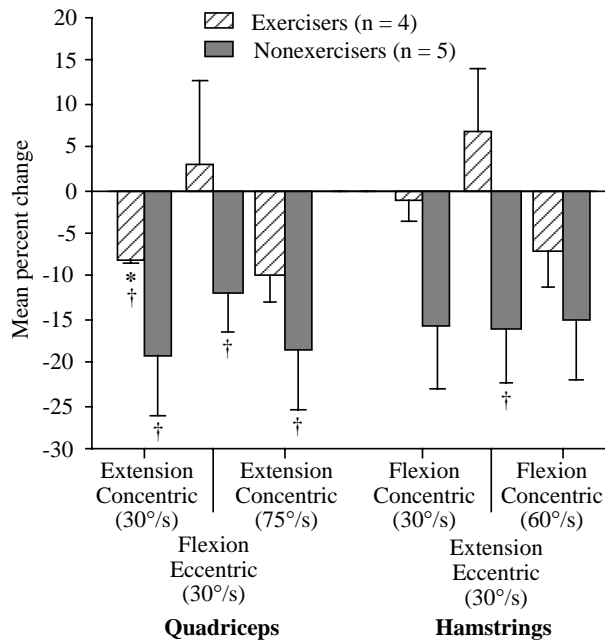
**Strength:** On landing day, significant decreases in concentric and eccentric strength were shown in the back and abdomen relative to the preflight means (Table 3-2). Concentric back extension and eccentric dorsiflexion were still significantly less than preflight values on R+7. Recovery (i.e., an increase in peak torque from R+0 to R+7) was demonstrated for the eccentric abdomen and the concentric and eccentric back extensors.

**Endurance:** Most of the decrease in total work by the quadriceps on R+0 probably reflects significant loss in the first third of the exercise bout (-11%). The declines in peak torque at the faster endurance-test velocities are consistent with changes seen at the slower angular velocity used during the strength tests. Torque for the quadriceps at 75°/s was 15% less than preflight values, but for the hamstrings was 12% less than the preflight mean at 60°/s. Endurance data showed little difference between preflight and R+7 tests, suggesting that crew members had returned to baseline by one week after landing.

**In-Flight Treadmill Exercise:** Subjects who exercised during flight (as part of a separate study) tended to have slightly higher preflight peak torques than those who did not exercise during flight. At landing day, no significant differences were found between exercisers and nonexercisers, except for concentric strength of the quadriceps (Figure 3-4a, 3-4b). Exercisers had greater concentric leg extension strength on landing day than did nonexercisers (224.0 vs. 131.0 ± 61.9 ft-lbs, respectively).

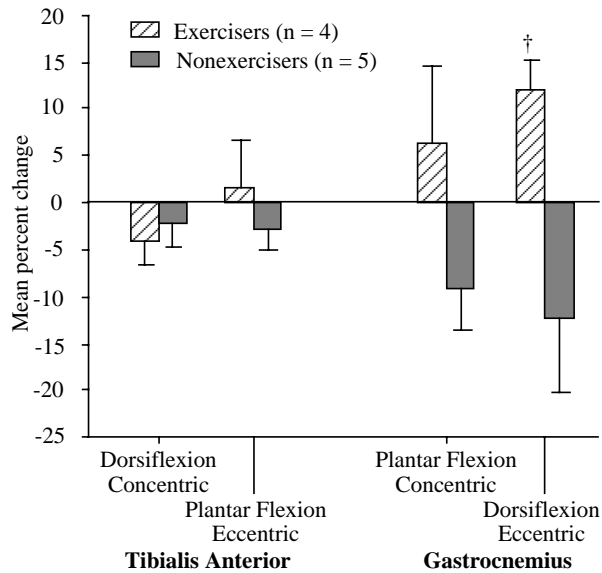
Subjects who exercised during flight had significant (p<0.05) losses within 5 hours of landing in concentric and eccentric strength of the abdomen, eccentric strength of the gastrocnemius/soleus, and concentric strength of the quadriceps (30°/sec), relative to the respective preflight values. No aspect of endurance changed for this group.





a. Percent changes in upper leg strength following space flight

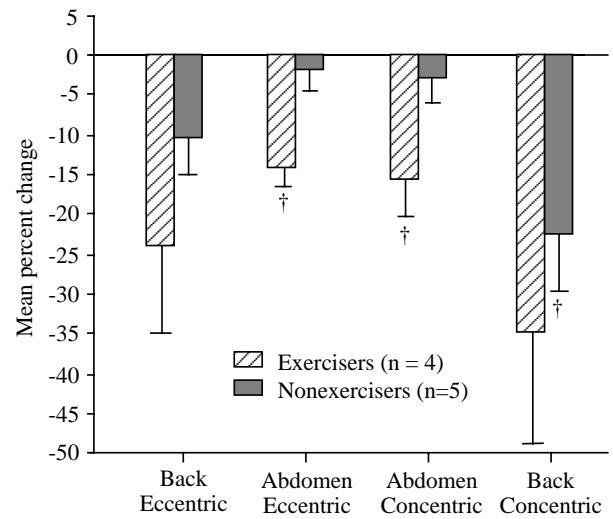
\*Nonexercisers change > exercisers on R+0  
 †Preflight > R+0 ( $p < 0.05$ )



b. Percent change in lower leg strength following space flight; exercisers vs. nonexercisers

†Pre < R+0 ( $p < 0.05$ )

Subjects who did not exercise in flight also had significant ( $p < 0.05$ ) losses within 5 hours of landing in concentric strength of the back, concentric and eccentric strength of the quadriceps (30°/sec), and eccentric strength of the hamstrings, relative to the respective preflight values. Nonexercisers also had significantly less



c. Percent change in trunk strength following space flight; exercisers vs. nonexercisers

†Pre > R+0 ( $p < 0.05$ )

Figure 3-4. Changes in strength of the knee (3-4 a), lower leg (3-4 b), and trunk (3-4 c) on landing day in those who exercised on a treadmill during flight versus those who did not.

concentric strength of the quadriceps at 75°/sec, and lower total work extension, work first-third flexion, and work last-third extension, immediately after landing, than before flight. These results indicate that muscles are less able to maintain endurance and resist fatigue after spaceflight, and that exercise may avert decrements in these aspects of endurance.

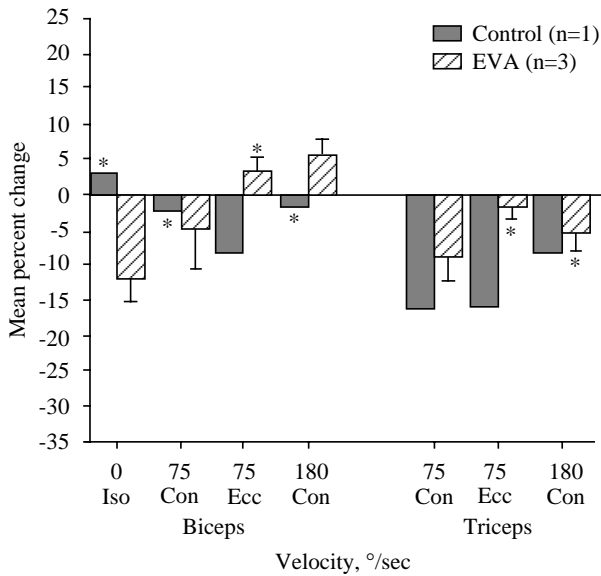
Although the in-flight exercise group had lost more strength at landing, when the changes were expressed as percentages (Figure 3-4c), preflight strength in trunk flexion and extension was substantially greater in the exercising group. These results imply that treadmill exercise did not prevent decrements in trunk strength after 9-11 days of spaceflight, and that preservation of muscle integrity may be limited to only those muscles exercised.

**EVA:** Early attempts to evaluate the effect of EVA on strength in the elbow (Figure 3-5a) and wrist (Figure 3-5b) over several functional velocities demonstrated some significant losses (>10%) in arm-musculature strength. Although these losses imply a tendency toward deconditioning and fatigue, they could not be verified statistically. Therefore, the effects of EVA on performance require further study.

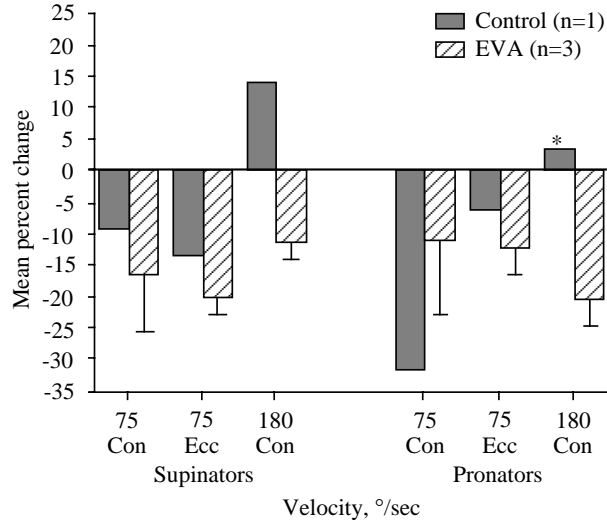
#### Estimates of Risk

Loss of muscle mass is associated with loss of muscle function. Less efficient ambulation is the major consequence, as the lower limb muscles are most at risk. Loss of the ability to ambulate effectively would delay





a. Percent change in elbow strength; EVA vs. control  
\*Preflight variability > percent change



b. Percent change in wrist supination and pronation strength; EVA vs. control  
\*Preflight variability > percent change

Figure 3-5. DSO 617 changes in elbow (3-5 a) and wrist (3-5 b) strength after space flight in crew members who conducted EVA during flight versus one who did not.

the crew member's return to normal status and would negatively affect the crew member's ability to vacate an Earth-landing vehicle in the event of an emergency egress. Loss of muscle mass during long-duration spaceflight may affect the ability to carry out in-flight operational tasks such as EVA. Additionally, skeletal muscle damage could contribute to decreases in functional ability, as well as predispose a crew member to a higher risk of injury while performing nominal operational tasks.

Because no risk-of-injury analogs had been identified for space deconditioning, rehabilitation clinical standards for injured or postoperative individuals were used to assess musculoskeletal risk. With this model, the predicted percentage of the astronaut population at increased risk for back injury exceeded 40%, and about 20% were at risk for upper and lower leg injury. Because these predictions were based on a single muscle group, this analysis represents a fairly conservative estimate of musculoskeletal injury risk in astronauts after landing. Space-induced changes in skeletal muscle occur systematically, affecting many major muscle groups simultaneously. Loss of muscle performance and volume, coupled with changes in neuromuscular function and potential muscle damage, increases the risk of musculoskeletal injury immediately after landing. Additionally, the requirement of wearing the 51-lb. (23 kg) LES during landing may further compromise the safety of some crew members by increasing the musculoskeletal demands of routine egress.

Most of the crew members tested returned to near-baseline status by 7 to 10 days after landing. Thus, many

of the losses described above were transitory after relatively short flights, and the risk of injury decreased rapidly as the crew members readapted to the Earth environment. However, the time course of reconditioning after spaceflight has yet to be defined for long duration flights (i.e., aboard Mir or the International Space Station) or for those flights that incorporate operational countermeasures.

### Skeletal Muscle Biopsies (DSO 475)

#### Specific Aim

The specific aim of this investigation was to define the morphologic and biochemical effects of spaceflight on skeletal muscle fibers.

#### Methods

Biopsies were conducted once before flight (L->21 days) and again on landing day (R+0). Preflight biopsies were conducted at the JSC Occupational Health Clinic. R+0 biopsies were conducted at the Orbiter landing site either in the BDCF at KSC or the PSSF at DFRC.

Subjects were eight crew members, three from a 5-day mission and five from an 11-day mission. Biopsies were taken with a 6 mm biopsy needle equipped with a suction device. Other materials included Betadine (a topical antiseptic/microbiocide), alcohol wipes, #11 scalpel, 23 gauge hypodermic needle, 3 ml syringe, and 2% xylocaine. Liquid nitrogen and freon were used to freeze and store samples.

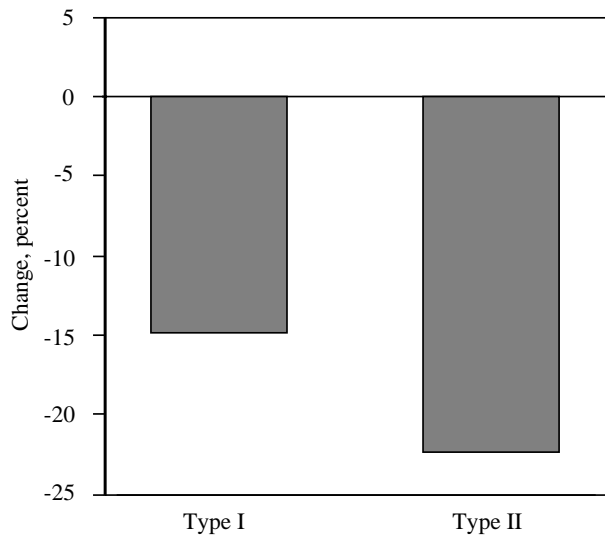


Figure 3-6 Preflight vs. postflight, percent change by skeletal muscle fiber type of the vastus lateralis (n=8).

Samples were obtained from the mid-portion of the vastus lateralis, using the needle as follows: The sample site was identified as being 40% of the distance from the lateral condyle of the distal femur to the femoral trochanter. The site was prepared by shaving and cleaning with Betadine. The site was anesthetized by subcutaneous injections of 2% xylocaine, followed by in-depth injections just below the muscle fascial plane. Once anesthetized, the muscle fascial plane was pierced with a scalpel. The biopsy needle was inserted and suction applied for tissue extraction. Samples were withdrawn, the site was cleaned, and butterfly adhesive bandages were applied to the incision. The samples were quick-frozen in liquid nitrogen and maintained at -70°C. Samples

were split, packaged, and transported for analysis to the University of California/Los Angeles (UCLA), Washington State University, and the Karolinska Institute in Stockholm.

#### Data Reduction and Analysis

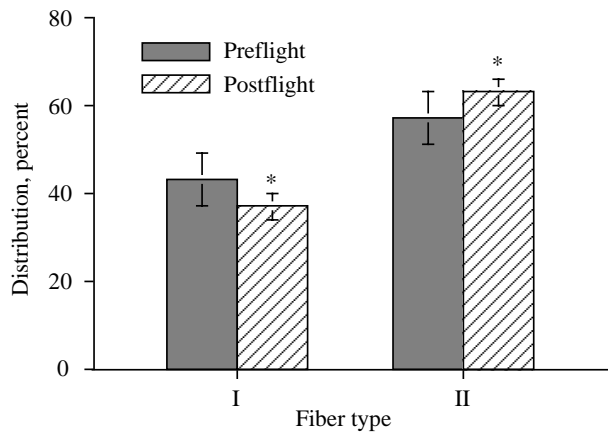
A one-tailed paired t-test was used to identify significant differences ( $p < 0.05$ ) between the mean values of fiber cross-sectional area (CSA), fiber distribution, and number of capillaries of all crew members before flight compared to the mean value for all crew members after flight.

#### Results

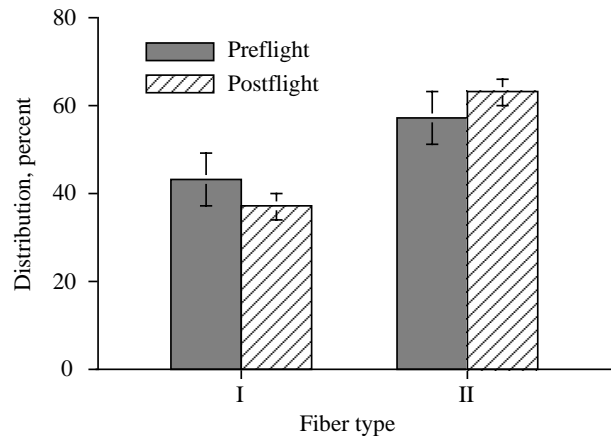
Of all the variables measured, the one with the greatest implications from a physiological standpoint was CSA of the muscle fibers. The CSA of slow-twitch (Type I) fibers after flight was 15% less than before; the CSA of fast-twitch (Type II) fibers was 22% less after flight than before (Figure 3-6). However, these mean values do not reflect the considerable variation among the eight astronauts tested. At least some of this variation probably resulted from differences in the types and amounts of preflight and in-flight countermeasures (exercise or LBNP) in the group.

The relative proportions of Type I and II fibers were different after the 11-day mission than before (Figure 3-7a); the fiber distribution also seemed to follow the same trend after the 5-day mission (i.e., more Type II and less Type I fibers after than before), but the sample size was too small to reach statistical significance (Figure 3-7b).

The number of capillaries per fiber was significantly reduced after 11 days of flight (Figure 3-8). However, since the mean fiber size was also reduced, the number of capillaries per unit of CSA of skeletal-muscle tissue was unchanged.



a. Fiber type distribution following 11 days of space flight (n=5). \* $p < 0.05$



b. Fiber-type distribution following 5 days of space flight (n=3).

Figure 3-7. Changes in the distribution of Type I and Type II muscle fibers in the vastus lateralis on landing day after 11 days (3-7 a) or 5 days (3-7 b) of space flight.

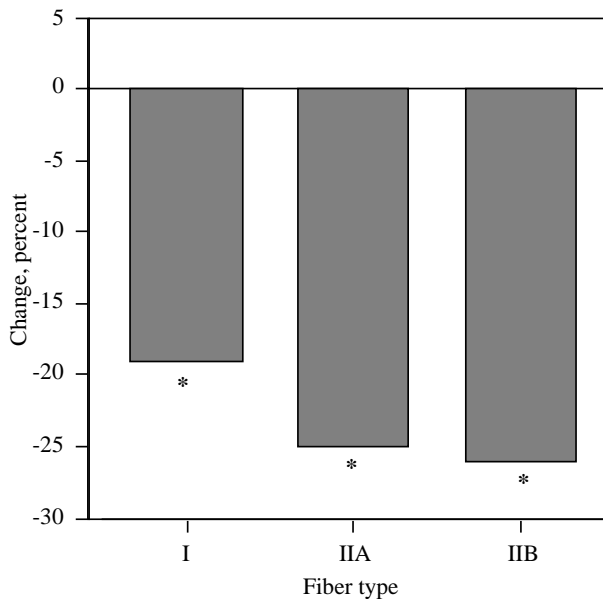


Figure 3-8. Percent change of mean number of capillaries per fiber type following 11 days of space flight (n=5). \* $p < 0.03$ .

### Quantifying Skeletal Muscle Size by Magnetic Resonance Imaging (MRI) (DSO 606)

#### Specific Aim

The purpose of this investigation was to noninvasively quantify changes in size, water, and lipid composition in antigravity (leg) muscles after spaceflight.

#### Methods

Eight Space Shuttle crew members, five from a 7-day flight and three from a 9-day flight, participated as test subjects. The subjects underwent one preflight and two postflight tests on days L-30 or L-16 days and on R+2 and R+7 days. Testing involved obtaining an MRI scan of the leg (soleus and gastrocnemius) at The University of Texas-Houston Health Science Center, Hermann Hospital. Equipment consisted of: (1) a General Electric Signa whole-body MRI scanner, operated at 1.5 Tesla, with spectroscopy accessory, (2) a 2T MR imager/spectrometer with a 25 cm clear horizontal bore magnet, and (3) an HP 4193A Vector impedance bridge for the RF coil design.

Test subjects were positioned supine inside the magnetic bore for approximately one hour. A 15 cm cage resonator was used for radio frequency transmission and signal reception. Multi-slice axial images of the leg were obtained to identify and locate various muscle groups. Image-guided localized proton spectroscopy of individual muscle groups used stimulated echo (STE) sequence. Spectral analysis was obtained with an echo time of 15 ms and mixing time of 7.8 ms. All MR studies were performed on the soleus and gastrocnemius

muscles. Water and lipid peak areas were computed to quantify concentrations. The proton sample was obtained from a standard placed within the field of view. Concentrations of tissue water and lipid in the soleus and gastrocnemius were expressed relative to a standard sample placed in the field of view. Changes in water and lipid content were measured, in addition to CSA, to distinguish changes in fluid versus tissue volumes. Multiple slices were measured by computerized planimetry.

#### Data Reduction and Analysis

The time in milliseconds required for protons to reach a resting state after maximal excitation is the relaxation time. Two types of relaxation time (T1 and T2) were used to detect changes in the water and lipid content of tissue. Skeletal-muscle volume was assessed in terms of CSA. Thirty to forty 3 to 5 mm slices were acquired in 256 x 128 or 256 x 246 matrices. Multiple slices were measured by computerized planimetry.

#### Results

CSA and volume of the total leg compartment, soleus, and gastrocnemius were evaluated to assess skeletal muscle atrophy. The volumes of all three compartments were significantly smaller ( $p < 0.05$ ) after both the 7- and 9-day Shuttle flights, relative to preflight, with 5.8% lost in the soleus, 4.0% lost in the gastrocnemius, and 4.3% lost in the total compartment. These decreases represent true skeletal muscle tissue atrophy, not fluid shift. No recovery was apparent by 7 days after landing (data not shown).

## PART 2 – THE EFFECT OF IN-FLIGHT EXERCISE ON POSTFLIGHT EXERCISE CAPACITY AND ORTHOSTATIC FUNCTION

### Purpose

Exposure to the microgravity environment of spaceflight causes loss of the gravity-induced hydrostatic pressure gradients normally present in the body, thus allowing blood volume to move away from the lower extremities and toward the upper body [17]. Changes in orthostatic function observed immediately after spaceflight have been attributed to orthostatic intolerance [18]. Four investigations (DSOs 476, 608, 618, and 624) were conducted to study the effects of exercise on aerobic capacity and orthostatic function before, during, and after spaceflight.

Both bed rest and microgravity induce cardiovascular deconditioning and affect exercise capacity [19-21]. Less tolerance of orthostatic stress on the day of return from spaceflight has been shown to be common and has been attributed mostly to reduced blood plasma volume and depressed baroreflex response.

Findings from the Apollo era (n=27) demonstrated that oxygen consumption, at work loads that elicited heart rates (HR) of 160 beats per minute, was reduced by an average of 19.2% on the first day after flight, and that this decrease was largely mitigated 24 hours later [20, 21]. The relative contributions of postflight change in vascular volume versus classical “aerobic deconditioning” were unclear. However, it is known that regular aerobic exercise during bed rest can maintain both vascular volume and aerobic capacity [22, 23]. Three investigations were conducted (DSOs 476, 608 and 624) to document the degree of exercise deconditioning after flight and to investigate the use of aerobic exercise during flight to reduce the severity of postflight deconditioning (Table 3-1).

Intense exercise has been shown to expand plasma volume 24 hours thereafter [24, 25]. Intense exercise near the end of a bed-rest study also has been shown to reverse the depression of the vagally mediated baroreflex function [26]. A maximal or near-maximal exercise bout before return from spaceflight could minimize the effects of renewed exposure to gravity on the cardiovascular system [19, 27]. These findings prompted an investigation (DSO 618) of the acute effects of exercise on aerobic capacity and orthostatic function.

## Background

Aspects of the four EDOMP investigations of how in-flight exercise affects postflight exercise capacity and orthostatic function are compared in Table 3-3. The original intent of DSO 476, which began before EDOMP, was to examine the effect of aerobic exercise performed during flight on cardiac echocardiographic measurements of left-ventricular end-diastolic volume at rest. Exercise capacity was measured two days after landing. Because EDOMP focused on the ability to carry out landing and egress, DSO 608, in which exercise capacity was to be measured on landing day, was conducted to replace DSO 476. The preflight and postflight exercise tests were similar for the two investigations, but DSO 608 included a body-composition component.

Manifesting equipment and recruiting subjects for DSOs 476 and 608 proved to be challenging for several reasons. First, the preflight and postflight tests involved maximal exercise, during which subjects were monitored continuously with electrocardiography (ECG). Second, the tests were designed to be conducted with a treadmill, for the reason that emergency egress would require crew members to walk or run away from the Shuttle. After occasional reports of delayed muscular soreness after the R+0 test, which was severe in one case, the exercise test device for DSO 608 was changed from treadmill to cycle ergometer so that tests would be given on the same type of device provided for exercise during flight. Yet another challenge was the relatively long period on landing day needed for all of the DSO 608 activities. Finally, DSO 608 was

Table 3-3. Measurements from all subjects on all test days

<i>Experiment</i>	<i>First Postflight Test on</i>	<i>Exercise to Maximum?</i>	<i>Testing to Modality</i>
DSO 476	R+2	Yes	Treadmill
DSO 608	R+0	Yes	Mixed*
DSO 618	R+0	Yes	Cycle
DSO 624	R+0	No	Cycle

\*Originally treadmill: later changed to match the device used for exercise during flight.

modified after its initiation to allow several in-flight exercise prescriptions and modalities to be studied.

DSO 624, which was limited to sub-maximal exercise, was proposed as an alternative to DSO 608 with the objective of increasing crew participation. DSO 624 involved preflight and postflight sub-maximal tests on a cycle ergometer. Workloads were calculated to elicit 85% of each participant’s age-predicted maximum HR. Subjects participating in DSO 624 were not assigned specific in-flight exercise prescriptions, but logged all in-flight exercise and monitored their heart rates during that exercise.

DSO 618 was designed to study how a single bout of intense exercise, performed 24 hours before landing, affected postflight orthostatic function and aerobic capacity. Maximal exercise testing was required before, during, and after flight. DSO 618 also required a long data collection session on landing day. Results from 10 subjects were collected to assess the efficacy of this potential countermeasure.

## Exercise In Flight and the Effects on Exercise Capacity at Landing (DSOs 476 & 608)

### *Specific Aim*

The specific aim of DSOs 476 and 608 was to document exercise capacity, measured as peak oxygen consumption ( $\dot{V}O_{2\text{peak}}$ ), after spaceflight in crew members who exercised during flight compared to those who did not.

### *Methods*

*Exercise Tests:* All exercise tests, except for those performed on landing day, were conducted at the Exercise Physiology Laboratory at JSC. Landing day tests were conducted in either in the BDCF at KSC or the PSSF at DFRC. All exercise tests were similar for the two studies (DSOs 476 and 608) except as noted. Forty-two astronauts (38 men and 4 women, ages  $40.3 \pm 4.8$  y, weight  $74.7 \pm 9.6$  kg) participated in the exercise portion of the two studies. Each subject completed one or two



graded exercise tests to volitional fatigue 10 to 30 days before and 0 to 10 days after spaceflight. Subjects in DSO 476 (n=24) were tested on R+2 or R+3. Subjects in DSO 608 were tested on R+0.

HR and rhythm were monitored continuously during exercise tests with a Q-5000 ECG (Quinton Instruments, Seattle, WA). Blood pressure was recorded at rest and during the last minute of each exercise stage. Volume of oxygen consumed ( $\dot{V}O_2$ ) and volume of carbon dioxide output ( $\dot{V}CO_2$ ) were analyzed continuously during exercise tests held at JSC with a Q-Plex system (Quinton Instruments, Seattle, WA), modified and interfaced with a mass spectrometer (MGA-1100, Marquette Electronics, St. Louis, MO). The Q-Plex provided the ventilatory measurements and computational software, and the MGA-1100 provided measures of the composition of expired gases. Tests on landing day were conducted with a standard Q-Plex system that used zirconium oxide and infrared sensors to measure expired gas composition. Verification tests of both systems showed no differences in metabolic measurements obtained with the two systems. The metabolic gas analysis systems were calibrated before and after each test with a calibrated syringe and calibration gases that were certified as accurate to  $\pm 0.03\%$ .

Thirty-two astronauts completed graded exercise tests on a treadmill. The remaining 10 performed cycle-ergometer tests before and after flight. Thirteen of the treadmill subjects (DSO 476) completed tests that included five sub-maximal steady-state exercise stages of 3 minutes each at 4.0, 4.5, 5.0, 6.0, and 7.0 mph, followed by grade increases of 2.5% each minute until the subject reported volitional fatigue. Tests for the remaining 19 treadmill subjects included three sub-maximal steady-state exercise stages of 3 minutes each at 5.0, 6.0, and 7.0 mph, followed by grade increases of 3.0% each minute until the subject reported volitional fatigue. This shorter protocol was adopted to reduce the amount of time needed for landing day tests. Because preliminary analyses revealed greater decreases in treadmill determined aerobic capacity in the crew members who used the cycle ergometer during flight, and because of the muscular soreness experienced during postflight treadmill exercise as mentioned earlier, cycle ergometry tests were used for the remaining subjects. The cycle ergometer test included three sub-maximal steady-state exercise stages of 3 minutes each at 100, 125 and 150 watts (w) at 60 rpm, followed by increases of 25w each minute until the subject reported volitional fatigue. These subjects also exercised during flight on the cycle ergometer.

*In-flight Exercise:* Most of the subjects who participated in exercise tests also completed one of three prescribed exercise protocols (continuous, interval, or high interval) during spaceflight. The continuous protocol consisted of three stages, lasting 8 to 10 minutes each, at heart rates (HR) elicited by 60, 70, and 80% of the subject's preflight  $\dot{V}O_{2\text{peak}}$ . This protocol was conducted on

the treadmill only. The interval protocol consisted of five stages of work at a HR corresponding to 65% of the preflight  $\dot{V}O_{2\text{peak}}$  for 4 minutes followed by 2 minutes at a HR corresponding to 50%  $\dot{V}O_{2\text{peak}}$ . Subjects completed this protocol on the treadmill, rower, or cycle ergometer. The high interval protocol was a modification of the interval protocol. This protocol had five stages, each consisting of 4 minutes of high and 2 minutes of low exercise. The first two high/low stages were at HRs corresponding to 65 to 50% of the preflight  $\dot{V}O_{2\text{peak}}$ . The next two stages were at HRs corresponding to 75 to 50% of preflight  $\dot{V}O_{2\text{peak}}$ . The last stage was at the HR elicited by 85% of preflight  $\dot{V}O_{2\text{peak}}$ . All protocols began and ended with a 3-minute warm-up and cool-down period. One cycle-ergometer subject performed a continuous exercise protocol of his own design, but averaged 70 to 80% of the  $\dot{V}O_{2\text{peak}}$  estimated by HR for all sessions. A Polar Vantage XL heart rate monitor (Polar CIC, Inc., Port Washington, NY) recorded HRs and provided real-time visual feedback to the exercising astronauts.

The amount of in-flight exercise was quantified as follows. HR was used as an indicator of exercise intensity. The duration of exercise performed for each session was recorded, as was the number of times that the crew member exercised. "Exercise volume" was calculated as the product of exercise intensity (% of  $HR_{\text{max}}$ ), minutes exercised per session (time), and number of exercise sessions per week.

### *Results*

The amount of exercise performed by the participants both before and during flight varied greatly (Table 3-4). Participants who used the cycle ergometer during flight tended to be on longer missions. Preflight-to-postflight changes in aerobic capacity (quantified by  $\dot{V}O_{2\text{peak}}$ ) are illustrated in Figure 3-9. Subjects who did not exercise and subjects who used the in-flight cycle-ergometer protocols had significant ( $p < 0.05$ ) reductions in aerobic capacity. Those subjects who exercised with the treadmill or rower showed no significant change from preflight aerobic capacity. Flight duration and the extent of decline in  $\dot{V}O_{2\text{peak}}$  were not correlated.

## **Sub-Maximal Exercise In Flight and Cardiac Performance at Landing (DSO 624)**

### *Specific Aim*

The purpose of DSO 624 was to evaluate the usefulness of sub-maximal aerobic exercise during flight in reducing the severity of postflight deconditioning, as assessed by heart rate and  $\dot{V}O_2$  measurements during postflight exercise.

### *Methods*

*Exercise Tests:* Thirty-nine Shuttle crew members (35 men and 4 women), assigned to missions lasting 8 to 16 days, were subjects for this study. Two subjects

Table 3-4. Flight duration and “exercise volume” (%HR<sub>max</sub> × min/week) for DSOs 476 and 608 (mean ± S.D.)

Exercise Modality	Flight Duration, days	“Exercise Vol” Before Flight	“Exercise Vol” During Flight	“Exercise Vol” During/Before
No exercise	10	8.7 ± 1.9	NA	NA
Cycle	16	12.1* ± 3.2	20,737 ± 19,429	20,127 ± 20,206
Rower or treadmill	9	7 ± 1.7	17,799 ± 8,097	12,665 ± 6,688
Treadmill, continuous	7	8.6 ± 1.1	15,858 ± 6,993	16,893 ± 6,848

Cycle significantly ( $p < 0.05$ ) longer flights than other groups.

Note: The crew member who completed his own continuous cycle protocol during flight was included in the cycle group: one member of the no-exercise group was evaluated before and after flight on a cycle ergometer and was added to the No Ex group.

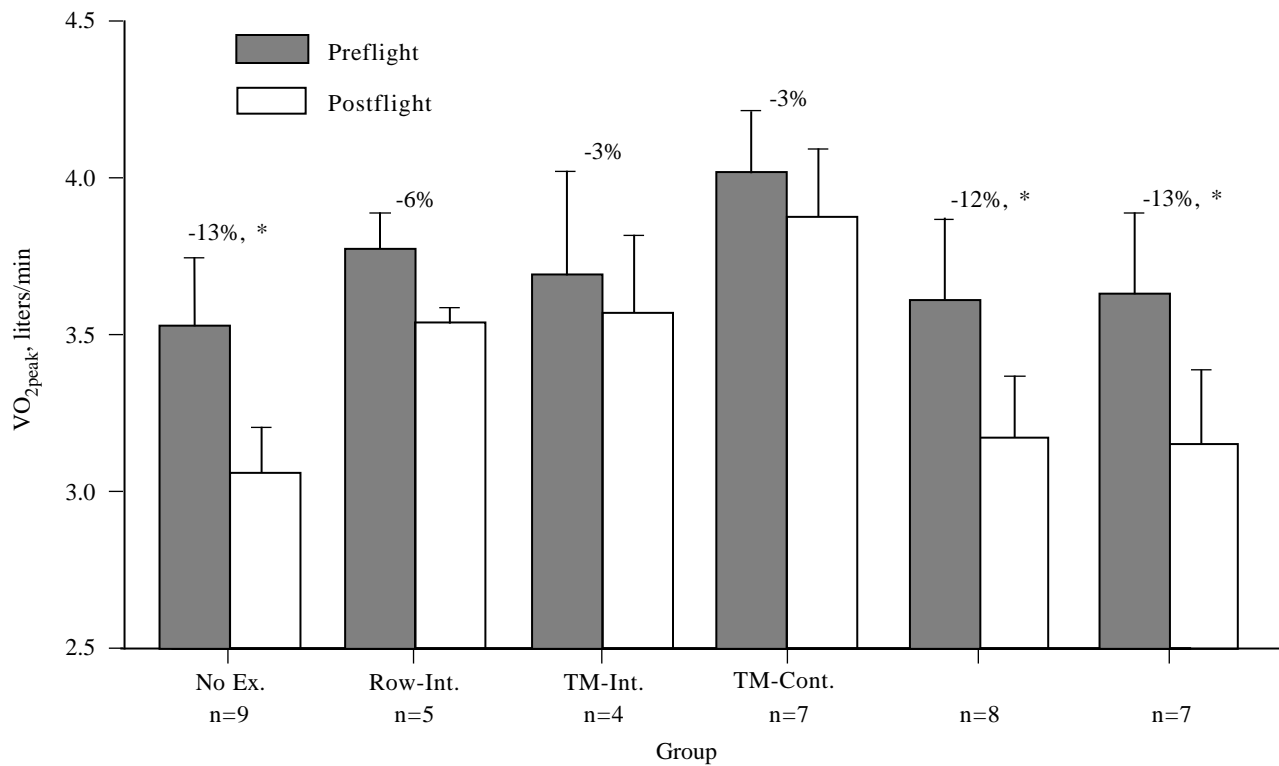


Figure 3-9. Preflight-to-postflight changes in  $\dot{V}O_{2peak}$  for 40 participants in DSOs 476 and 608. Subjects are categorized by type of exercise device used and protocol performed during flight: No Ex = nonexercisers; Row = rower; TM = treadmill; Cycle = cycle/ergometer; Int = interval; Cont = continuous; Hi Int = high intensity.

\*Postflight < Preflight ( $p < 0.05$ ).

participated twice, on separate missions. All exercise tests took place on an upright cycle ergometer. The upright, as opposed to supine, position was selected because of the operational nature of EDOMP. Even though an orthostatic component of postflight deconditioning could exaggerate HR during postflight exercise, gravitational effects on the cardiovascular responses to exercise also would be present during contingency egress.

Exercise tests were conducted twice before flight (L-30 and L-10 days) and again on landing day. The L-30 test was designated a familiarization trial, and L-10 data were used for subsequent preflight-to-postflight comparisons. Tests consisted of exercise that increased by 50 w every 3 minutes until the subject completed the first workload that elicited a HR 85% of his or her age-predicted maximum HR. At the end of a stage, if the participant’s HR

was  $\leq 5$  beats per minute of their 85% age-predicted maximum HR, the workload was increased 25 w for the final stage. HR was recorded every 15 seconds during the test with a Polar Vantage XL heart rate monitor (Polar CIC, Inc., Port Washington, NY). Metabolic gases were analyzed continuously with the same systems described above for DSOs 476 and 608. Oxygen consumption ( $\dot{V}O_2$ ) attained during the last minute of the final exercise stage was used as an index of cardiovascular exercise performance to compare preflight and postflight results.

**In-flight Exercise:** Subjects in DSO 624 were not given specific in-flight exercise prescriptions, but all exercised on the cycle ergometer during flight. Subjects wore the Polar HR monitor during exercise, and recorded the number and duration of exercise sessions. The HR monitor recorded and stored HR once every 15 seconds during exercise in up to eight data files. These data were retrieved and down-loaded onto a personal computer after landing. One mission did include both the cycle ergometer and the EDO treadmill, but only one DSO 624 subject performed two exercise sessions on the treadmill. In-flight exercise was quantified on the basis of exercise frequency, intensity (HR as % of age-predicted maximum), and duration of the in-flight exercise sessions.

### Results

Heart rate and  $\dot{V}O_2$  responses for the 25 subjects who achieved 50, 100, and 150 w work rates before and after flight are presented in Figure 3-10. Not all subjects completed these three levels of exercise, because several terminated exercise sessions on landing day at 125 w. Both the  $\dot{V}O_2$  and HR results confirmed that cardiovascular stress, as indicated by elevated HR, was increased during the postflight activity. The elevation in HR response resulted in the test being terminated at a lower work rate on landing day relative to preflight tests. Subjects who exercised three or more times per week during flight, at a HR  $>70\%$  of their age-predicted maximum HR and for more than 20 minutes per session, experienced smaller decrements in  $\dot{V}O_2$  at test termination on landing day than did subjects who exercised less frequently or at lower intensities (Figure 3-11). Again, no correlation was found between amount of decline in  $\dot{V}O_2$  and flight duration.

### Effects of Intense Exercise Before Landing on Aerobic Capacity and Orthostatic Function at Landing (DSO 618)

#### Specific Aim

This investigation was designed to study the influence of a single bout of maximal exercise, conducted 24 hours before landing, on aerobic capacity and orthostatic function at landing. Aerobic capacity was assessed from peak oxygen consumption during cycle ergometer tests, and orthostatic function from HR and blood pressure (BP) responses to a stand test.

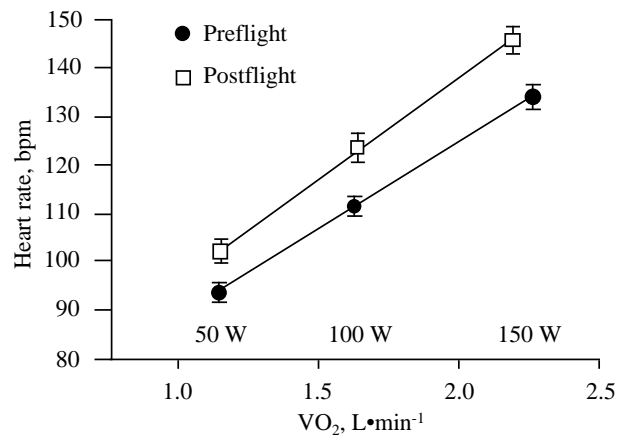
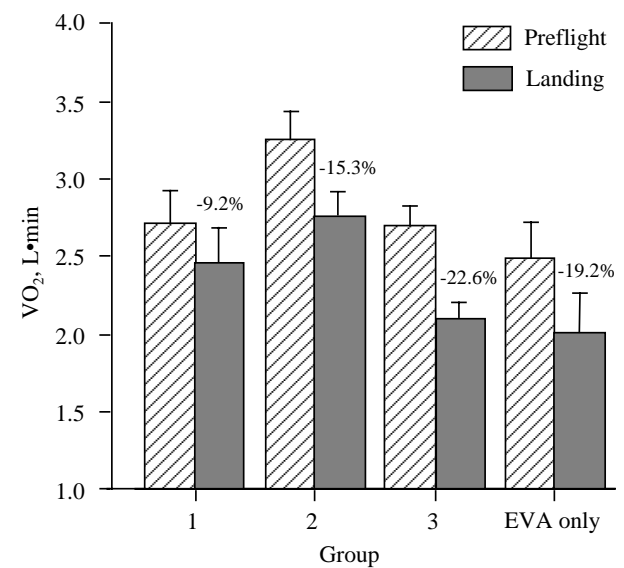


Figure 3-10. DSO 624 subjects ( $n=25$ ) who performed identical work rates before and after flight demonstrated increased cardiovascular stress by an increased HR, with no change in  $\dot{V}O_2$ , within each exercise stage on landing day.



Group 1 ( $n=11$ ): Exercised  $>3x/week$ . HR  $>70\%$  age-predicted,  $\geq 20$  min/session (“regular” exercise group)

Group 2 ( $n=10$ ): Exercised  $>3x/week$ . HR  $<70\%$  age-predicted,  $\geq 20$  min/session (“low intensity” exercise group)

Group 3 ( $n=14$ ): Exercised  $<3x/week$ . HR and min/session variable (“minimal” exercise group)

EVA Only ( $n=4$ ): Subjects performed EVAs. Minimal other exercise performed during flight (Hubble mission)

Figure 3-11. In-flight exercise patterns appear to influence the degree of oxygen consumption change at the termination workload (85% age-predicted HR max) following flight.

## Methods

*Subjects:* Ten Shuttle crew members (9 men and 1 woman), assigned to missions lasting 8 to 14 days, were the subjects for DSO 618. Six of the subjects, designated the countermeasure (CM) group, were instructed to perform a maximal exercise session 18 to 24 hours before the scheduled landing time of their flight. The other four subjects acted as controls. Each subject was to perform a test of orthostatic function (stand test) and a test to measure  $\dot{V}O_{2\text{ peak}}$  before and after flight.

Although 10 subjects participated in the study, mission constraints dictated that data from fewer subjects could be used. One CM participant performed the in-flight exercise session to volitional fatigue 24 hours before scheduled landing time, but landing was postponed for an additional 24 hours and the subject could not repeat the exercise. Thus, the landing-day data collected from this subject could not be used for preflight-to-postflight comparisons. Another CM participant was not allowed to perform the stand test or the exercise tests on landing day because that participant had exceeded the maximum 18-hour duty day limit [28] by that time. Two other participants, one CM and one control, performed the stand test on landing day, but did not perform the exercise test, in one case because of duty day constraints and in the other because of extreme fatigue. Thus, the final data set for DSO 618 allowed comparison of eight subjects (four control and four CM) for orthostatic function and only six subjects (two control and four CM) for aerobic capacity measures.

*Orthostatic-Function (Stand) Test:* Stand tests were conducted twice before flight, at about L-20 and L-10 days, and once 1.5 to 3.0 hours after landing. The L-30 test was designated a familiarization trial, and L-10 data were used for subsequent preflight-to-postflight comparisons. Preflight tests were conducted in the morning, 2 to 4 hours after subjects had consumed a light breakfast. Subjects were asked not to consume alcohol, caffeine, or cold medications, and to avoid smoking or strenuous exercise for 24 hours before testing. The exception to this rule was the exercise session by the CM group before landing. All subjects completed a NASA-required fluid loading protocol [29] about 2 hours before landing, during which approximately eight salt tablets were consumed with approximately 912 ml of water (actual amount was based on subject's weight). Subjects were asked to not consume additional fluids after the fluid load until after the stand test.

For the stand test, subjects rested supine for 6 minutes, after which two assistants helped them move quickly into a standing position. Subjects were instructed to let the technicians move them rather than making active movements themselves. Subjects stayed still once they reached the standing position, with feet approximately 25 cm apart, and remained in that position for 10 minutes. HR and rhythm were monitored continuously

with a defibrillator monitor (Lifepak8™, Physiocontrol, Inc., Redmond, WA) throughout the test. HR was recorded during the last 15 seconds of each minute. BP was recorded every 60 seconds from the left arm, at the level of the heart, with a calibrated aneroid sphygmomanometer. Mean HR and BP during the last 3 minutes in each posture were computed and used for subsequent analyses.

*Preflight and Postflight Exercise Tests:* All subjects performed two exercise tests on a Monarch cycle ergometer during the month before flight, and one test on landing day. Subjects were asked to maintain a 75 revolutions per minute (rpm) rotation rate, beginning at 50 w and increasing by 50 w increments every 3 minutes until they either could not maintain the cycling cadence or indicated that they could not continue the test. When the test was completed, subjects continued to pedal at 50 w for at least 5 minutes. During these tests, HR and rhythm were monitored continuously with a Q-5000 ECG (Quinton Instruments, Seattle, WA). Blood pressure was recorded while the subjects were seated at rest, and during the last minute of each exercise stage. Metabolic gases ( $\dot{V}O_2$  and  $\dot{V}CO_2$ ) were analyzed continuously during the exercise tests as described above for DSOs 476 and 608. The " $\dot{V}O_{2\text{ peak}}$ " was considered to be the highest value attained during any 60-second period during the test.

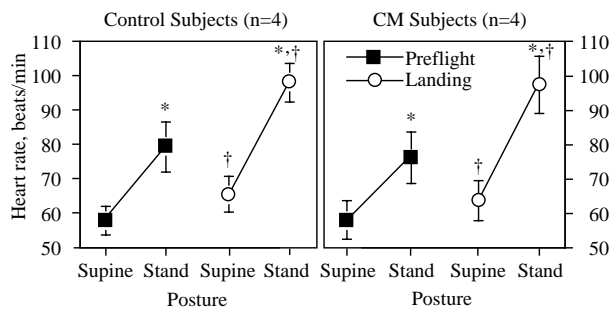
*In-flight Exercise Constraints and Tests:* All in-flight exercise was performed on a cycle ergometer designed for use in microgravity. The ergometer was calibrated before flight and verified as unchanged after each flight. Because a NASA flight rule required that exercise take place on all missions lasting more than 10 days, all subjects were allowed to exercise in flight. However, because of the potential for confounding the experiment, the investigators limited that exercise as follows: (1) intensity of < 60% of the maximum work rate attained before flight, (2) duration of no more than 20 minutes per session, and (3) frequency of no more than 3 times in a 7-day period. Subjects recorded HR during exercise with the Polar HR monitor. No exercise, other than the maximum session by the CM subjects, was allowed during the last 48 hours of flight.

The maximum session for the CM subjects was similar to the exercise test and was conducted 18 to 24 hours before scheduled landing. In order to ensure high-quality data and voice transfer, subjects contacted the Mission Control Center in Houston before beginning the exercise and again before beginning the stage that corresponded to their peak preflight exercise level. The ECG was monitored via the Shuttle's bioinstrumentation system. Heart rates and rhythms were monitored in the Mission Control Center. Metabolic gas data were not collected during flight.

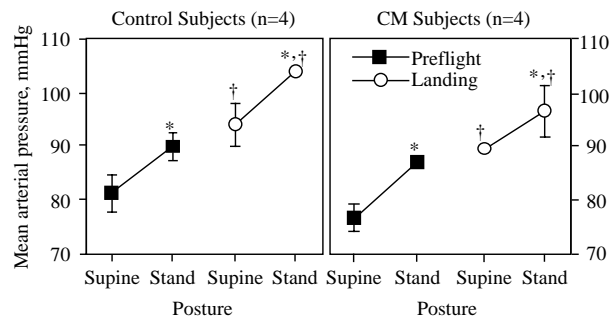
## Results

*Orthostatic Function:* Stand-test results revealed no systematic differences between the CM (n=4) and control (n=4) subjects. Both groups demonstrated





a. Stand test heart rates in the DSO 618 subject groups. \*Standing HR was significantly greater than supine HR ( $p < 0.01$ ); †landing HR > preflight HR ( $p < 0.01$ )



b. Stand test mean arterial pressures in DSO 618 subject groups. \*Standing HR was significantly > supine HR ( $p < 0.01$ ); †landing HR > preflight HR ( $p < 0.01$ )

Figure 3-12. Heart rate and arterial pressure responses to preflight and landing day Stand tests.

approximately equivalent HR responses to standing after flight (Figure 3-12a). The BP responses also changed after flight, but no differences were evident between groups. Mean arterial BP was elevated, compared to preflight values, on landing day in both the horizontal and standing positions (Figure 3-12b) for both groups. None of the subjects in either group exhibited symptoms of orthostatic intolerance, such as dizziness or presyncope, on landing day.

**Intense In-flight Exercise and Postflight Aerobic Capacity:** Aerobic capacity declined 18% in the CM subjects versus 21% in the two control subjects who performed exercise tests on landing day (Figure 3-13). The HR responses for those participants who performed an exercise test before and during flight (the full set of CM subjects) are illustrated in Figure 3-15. HR response to exercise during flight was not statistically ( $p = 0.12$ ) different than that recorded before flight (Figure 3-14).

### Discussion

DSOs 476, 608, and 624 were steps in assessing the efficacy of exercise countermeasures with regard to preserving aerobic capacity for egress on landing day. Tasks associated with landing and egress also required maintaining orthostatic function. The remaining study, DSO 618, was an evaluation of a potential exercise countermeasure to improve orthostatic function and exercise capacity on landing day.

**Aerobic Capacity:** The results demonstrate clearly that performing minimal or no exercise countermeasures during flight negatively affects the ability to perform aerobic exercise on landing day. The postflight  $\dot{V}O_{2\text{peak}}$  dropped 13% in the control (no exercise) group for DSO 608, and 18 to 21% for subjects in DSO 618. Moreover,

those DSO 624 participants who performed only minimal exercise during flight had the largest drop in  $\dot{V}O_2$  (22.6%) of any subject group at the test termination HR.

These results also indicate that regular aerobic training attenuates microgravity effects on aerobic performance after flight. Treadmill exercise during flight was associated with only a 3% reduction in  $\dot{V}O_{2\text{peak}}$ , and rowing during flight resulted in a 6% reduction after flight. Cycle ergometer exercise was associated with a 12 to 13% reduction in aerobic capacity after flight, which was equivalent to the drop seen for DSOs 476 and 608 control subjects. However, these results also include the confounding factor of the time at which postflight testing

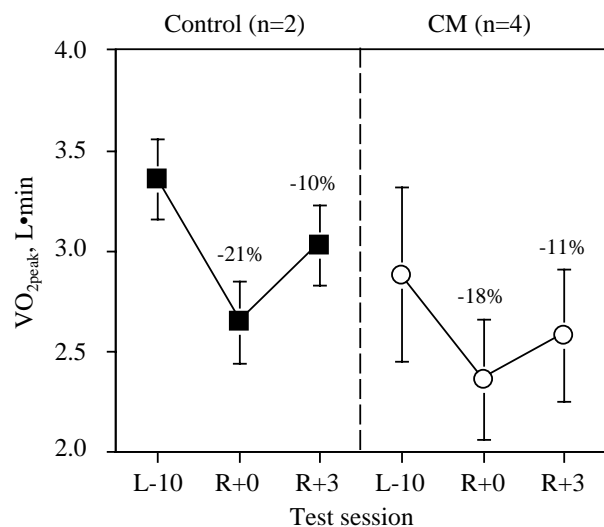


Figure 3-13. Aerobic Capacity of DSO 618 Subjects.

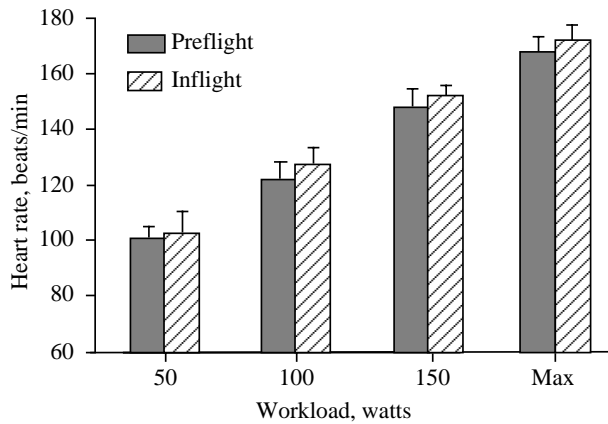


Figure 3-14. Pre- and in-flight heart rate responses of DSO 618 subjects ( $n=6$ ). Although HR increased with work rate ( $p<0.01$ ), there were no statistical differences between the pre- vs. in-flight values ( $p=0.12$ ).

took place (on R+0 or on R+2 or R+3). Subgroups that were tested on landing day (R+0) for DSOs 476 and 608 were as follows:

- No Exercise, 44% (four of nine subjects)
- Treadmill or Rower Interval Subjects, 22% (two of nine)
- Treadmill Continuous Subjects, 0% (zero of seven)
- Cycle Ergometer subjects, 67% (10 of 15)

The preservation of  $\dot{V}O_{2\text{ peak}}$  among the treadmill or rower group may not have been as marked if more subjects had been tested on R+0. This hypothesis is supported by the results from DSO 618, which showed  $\dot{V}O_{2\text{ peak}}$  to be reduced on R+3, but to a lesser extent than on R+0 (from a 20% to a 10% reduction). To date, no consensus of opinion has been reached as to the optimal exercise device, or protocol, for maintaining aerobic capacity.

The results from DSO 624 also verify the benefit of in-flight exercise. Subjects who exercised regularly, that is, more than three times a week, for more than 20 minutes, at an intensity eliciting greater than 70% of their age-predicted HR maximum, experienced smaller declines in  $\dot{V}O_2$  measured immediately after flight than did those subjects who performed less exercise. Subjects who exercised regularly, but at lower intensities, experienced greater reductions in their termination  $\dot{V}O_2$  on landing day. Finally, those subjects who exercised the least during flight showed the largest reduction in test-termination  $\dot{V}O_2$ . Thus, exercise intensity has been shown to be an important factor to consider in developing exercise prescriptions.

*Intense Exercise and Orthostatic Function:* The crew members tested with the intense exercise countermeasure did not seem to be protected against orthostatic intolerance after flight. This finding contrasts with results from other investigations [28, 29] because of the lack of difference in orthostatic tolerance between the control and experimental groups.

DSO 618 was useful in exposing potential difficulties associated with an end-of-mission countermeasure. For example, the subject whose mission was delayed for 24 hours could not unpack the exercise and monitoring hardware to repeat the exercise session. This situation would be even more difficult if several crew members were scheduled for repeat exercise sessions. Another useful finding was that the HR response to exercise on the cycle ergometer during flight was similar to preflight values. Some astronauts, mostly those from flights on which the original Shuttle treadmill was flown, have commented on the difficulty in achieving sufficient HR during flight. The results from DSO 618 indicate that such difficulty was related more to the exercise device than to any physiological changes associated with microgravity exposure.

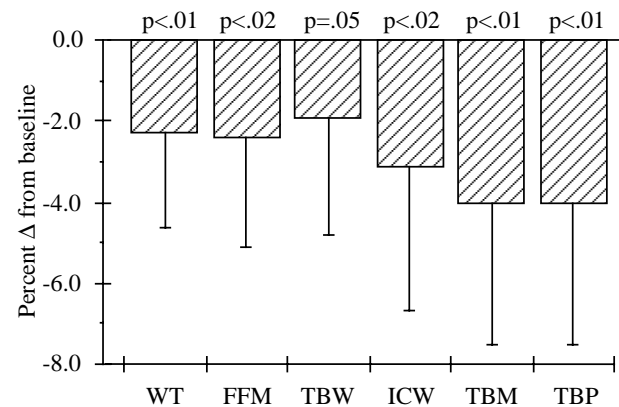


Figure 3-15. Changes in body weight (WT), fat-free mass (FFM), total body water (TBW), intracellular water (ICW), total body mineral (TBM), and total body protein (TBP) in 10 astronauts after 7- to 16-day flights. Variables were measured or derived from underwater weighing and the BERS model.

## PART 3 – CHANGES IN BODY COMPOSITION IN SPACE AND THE EFFECTS ON EXERCISE PERFORMANCE

### Purpose

Spaceflight is thought to affect aspects of body composition such as total body protein [11, 32-36], mineral and bone mineral content [37-41], and various body-water compartments [42-45]. To some extent, changes in compositional variables reflect the process by which humans adapt to the spaceflight environment, but can also result from inadequate nutrition, exercise, or fluid intake. Changes in these variables may well limit the safe duration of human space exploration through their putative effects on muscle performance, orthostatic tolerance, and crew safety.

A simple, reliable way of monitoring changes in protein, bone mineral, and fluid volumes before and after spaceflight would allow flight surgeons, crew medical officers, and investigators to monitor crew health and the effectiveness of nutrition, exercise, and fluid countermeasures. One of the goals of DSO 608 was to develop such a method.

### Background

One of the EDOMP goals was to integrate measures of body composition with measures of performance so that they could be used to evaluate the efficacy of countermeasures. Accordingly, simple, reliable techniques were developed that could be used during spaceflight to measure the four basic components of body composition: fat, water, protein, and mineral. A new body-composition model, the bioelectrical response spectrography or BERS model, was also developed to noninvasively measure blood and plasma volume [46-51]. The new methods were evaluated by measuring changes in body composition during spaceflight and by relating changes in protein and fluid volume to the performance variable  $\dot{V}O_{2\text{peak}}$ .

Development of a body-composition measurement technique for use in space took place in several steps. The first step was to select an appropriate body-compositional model from existing equations used to estimate amounts of fat, water, protein, and mineral. The results generated by the selected model were then compared with those generated by standard techniques such as dilution of isotopically labeled water, dual X-ray absorptiometry, and underwater weighing. This comparison verified that total body mineral, bone mineral content, and total body protein could be assessed from total body water and body density with a three-compartment model (fat, water, and dry lean mass), and that this approach was suitably simple for use in spaceflight.

The next step in completing the new model was to find ways of measuring body mass, body volume, and total body water during spaceflight. Body mass has been measured during flight since Skylab [52], and new methods that involve smaller and more accurate instruments are currently being evaluated on the Shuttle by other investigators. Therefore, we focused our attention on ways of easily and noninvasively assessing body volume and total body water in space.

To measure body volume, a series of air-displacement volumeters were developed [50]. To measure total body water, a new circuit model was developed that relied on BERS [53-61]; this model was used to estimate blood and plasma volumes. These important components of total body water typically are measured from dilution of radio-labeled albumin ( $^{125}\text{I}$ ) or red blood cells ( $^{51}\text{Cr}$ ) [62-64], carbon monoxide [65], or inert dyes such as Evans blue [66]. The usefulness of these techniques for spaceflight is limited by the need for multiple blood samples, the time needed for tracers to equilibrate within the vascular compartment, and the potential risks from use of radiolabeled compounds. Preliminary results (data not shown) suggest that BERS could serve as a good noninvasive alternative to these techniques for assessing vascular volumes. The new body-composition method was used to measure changes in crew member body composition before and after spaceflight. Additionally, potential changes in protein and fluid volume were related to changes in  $\dot{V}O_{2\text{peak}}$ .

### Changes in Body Composition After EDO Flights

#### *Specific Aim*

The purpose of this investigation, a component of DSO 608, was to use the new body-composition method to assess weight, total body water, extracellular water, intracellular water, fat, fat-free mass, total body mineral, and total body protein in astronauts after 7- to 16-day flights.

#### *Methods*

Previous measurements of changes in body composition after spaceflight have been limited to weight, total body water, and extracellular water (ECW). These variables, plus changes in intracellular water (ICW), fat, percent fat, fat-free mass, total body mineral, and protein were examined in 10 astronauts before and 2 days after flights that lasted 7 to 16 days. All measures were derived from body weight, body water, and body density. Body density was calculated from underwater weights with correction for residual lung volume. Body fluids were estimated with a previously validated, multi-frequency bioelectrical response spectrograph model [49]. The change in each variable was analyzed with dependent t-ratios.

#### *Results*

Changes in body weight, fat-free mass, total body water, intracellular water, total body mineral, and total

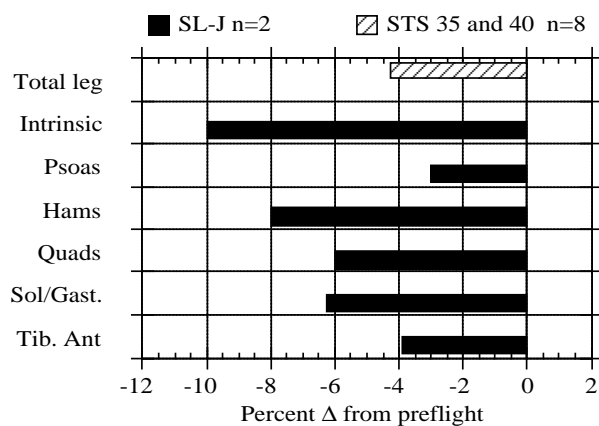


Figure 3-16. Percent decreases in muscle volumes, measured by magnetic resonance imaging, from three EDO Shuttle missions.

body protein, illustrated as percent change from preflight values, are shown in Figure 3-15. No physiologically significant changes were present in body fat or ECW. The decrease in body weight was due primarily to loss of fat-free mass. All three components of fat-free mass (water, protein, and mineral) were reduced after flight. The decrease in water was due primarily to loss of ICW, which in turn may have been a response to decreases in protein and nonosseous (~17% of the total body mineral) mineral levels within the muscles and other tissues. Since the results from Skylab showed postflight changes in serum osmolality [67], and probably no postflight change in ECW osmolality, we assume that reduction of cellular protein (and glycogen) and mineral would cause a decrease in intracellular water in order to maintain normal osmotic pressure gradients between the cells and interstitial fluids.

Decreases in cellular protein (decreased muscle volume) after Shuttle flights (Figure 3-16) have been reported previously [11, 68]. The average decrease in muscle volume was 6%, and the average decrease in total body protein was 4% (Figure 3-16). We conclude that decreases in total body protein and mineral after spaceflight contributed to the loss of water from cells and that the combination of these reductions resulted in decreased fat-free mass. These decreases may affect physical and metabolic performance or health of astronauts during or after spaceflight.

### Changes in Protein and Fluid Volumes and the Effects on Performance

#### Specific Aim

Muscle atrophy, measured by various means, after spaceflight [32-36] has been linked with postflight declines in aerobic capacity ( $\dot{V}O_{2\text{peak}}$ , in  $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) [46]. However, no one has reported how decreases in

muscle mass might affect specific aspects of performance. Therefore, we sought to determine whether post-flight decreases in performance ( $\dot{V}O_{2\text{peak}}$ ) were associated with decreases in protein, water, or both.

#### Methods

Eight astronauts who completed flights of 7 to 16 days were the subjects for this study.  $\dot{V}O_{2\text{peak}}$  was measured during a graded treadmill test to volitional fatigue [46]. Subjects also underwent underwater weighing, residual-volume, and body-mass measurements, which were used to calculate body density, and BERS, which was used to calculate body fluid volumes. Astronaut subjects completed the testing about 10 days before flight and again 0 to 2 days after flight. Body-composition analysis always preceded measures of aerobic capacity on the same day. Total body protein was calculated from body density and water [47].

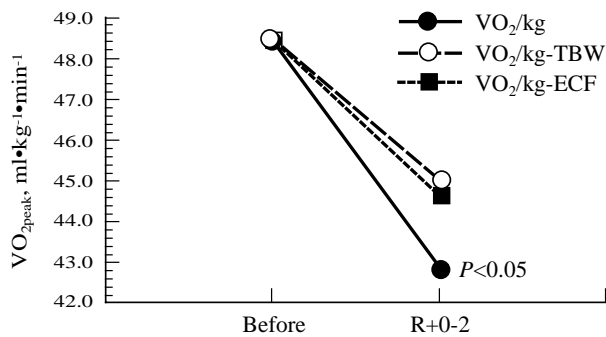
To statistically remove the effect of the covariate (body-composition variables) from the performance response, an analysis of covariance was computed with the aerobic capacity data, using total body water, extracellular fluid, total body protein, or the sum of total body water plus protein as the covariates. Any significant decrease in aerobic capacity observed after the removal of the covariate would indicate that another mechanism was contributing to the loss of performance.

#### Results

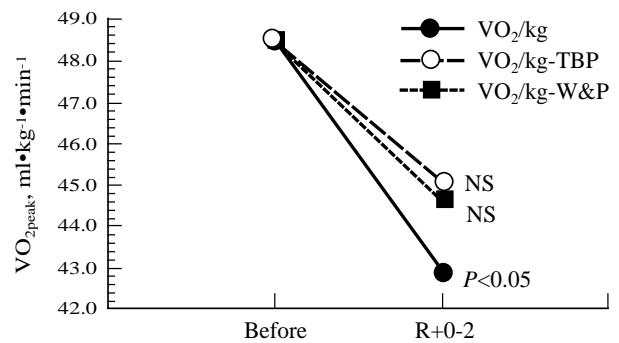
Aerobic capacity declined by 12% ( $p<0.05$ ), total body water by 2% ( $p<0.05$ ), and protein by 4% ( $p<0.05$ ). A 1.5% decrease in extracellular fluid was not significant. Removing the effects of the decrease in extracellular fluid and total body water reduced the decrease in aerobic capacity from ~12% to 9.5% and 8.6%, respectively (Figure 3-17a). These adjusted postflight aerobic performance values were still significantly lower than preflight measures. This finding probably reflects the fact that 8 of the 10 subjects were evaluated 2 days after landing, when fluid volumes had returned to near-preflight levels [42,43].

In contrast, removing the effects of the decrease in total body protein (TBP) significantly reduced the decrease in aerobic capacity from 12% to 7.4% (Figure 3-17b). Removing the effects of both total body protein and total body water (W&P) also significantly reduced the decrease in aerobic capacity from 12% to 8.0% (Figure 17a). Adding water-plus-protein as a covariate was no better than protein alone in reducing the decrease in aerobic capacity. The decrease in protein probably resulted from a reduction in muscle mass, since the observed 4% decrease was similar to the decrease in muscle volume (4-6%) measured by magnetic resonance imaging [11, 68]. The smaller muscle mass would contribute to a decrease in performance.





a. Decreases in aerobic capacity ( $\dot{V}O_{2peak}$ ) without (solid line, closed circles) and with covariate adjustments for total body water (dashed line, open circles) or extracellular fluid (dotted line, closed boxes). Removing the effects of loss of fluid did not significantly reduce the observed decreases in performance.



b. Decreases in aerobic capacity ( $\dot{V}O_{2peak}$ ) without (solid line, closed circles) and with covariate adjustments for total body protein (TBP: dashed line, open circles) or the sum of total body protein and water (W&P: dotted line, closed boxes). Removing the effects of protein significantly reduced the observed decreases in performance. However, adding water to protein did not improve this finding.

Figure 3-17. Influence of fluid volumes and protein on aerobic capacity ( $\dot{V}O_{2peak}$ ) before and after space flight.

### Conclusion

We conclude that the decreases in aerobic performance were due at least in part to a reduction in TBP, and that the protein loss probably represents a reduction of muscle mass. This study also highlights the importance of measuring changes in body composition in order to better understand changes in other physiological systems.

## SUMMARY AND RECOMMENDATIONS

### Skeletal Muscle Performance

Exposure to microgravity, even for 5 days or less, evokes changes in skeletal muscle performance and morphology. These changes, being part of the microgravity-induced deconditioning process, may have negative implications for completing critical operational tasks. NASA seeks to minimize the consequences of this deconditioning by providing countermeasures that optimize in-flight physical performance, ensure suitable return to a terrestrial environment, and ensure nominal postflight recovery.

The test battery described to monitor skeletal muscle performance is an efficient and objective way of validating preflight, in-flight, and postflight exercise countermeasures. Such countermeasures include preflight training protocols, in-flight exercise hardware such as the treadmill, rower, cycle, resistive exercise device, and other equipment, and postflight rehabilitation regimens. This test battery includes clinical tests such as MRI to

evaluate changes in muscle volume; biochemical markers, such as creatine kinase and myoglobin, to assess muscle damage; and isokinetic muscle-function tests to determine overall muscle performance. This test battery is an important step in assessing crew health and in validating countermeasure interventions.

### Exercise Capacity and Orthostatic Function

The results from DSOs 476, 608, 618, and 624 offer insight into the development of countermeasures against declines in aerobic capacity and orthostatic function on landing day. Conclusions and recommendations for future study are given below.

Exercise intensity, frequency, and duration are all important factors to consider in prescribing activities to maintain aerobic exercise capacity after flight. We recommend that crew members exercise at least three times a week, for more than 20 minutes per session, at work rates high enough to elicit 70% or more of their maximum HR. Preflight maximum exercise testing also is recommended for determining maximum HR and work rates, which will be vital in developing exercise prescriptions tailored to individuals. Age-predicted maximum HR is too conservative and shows too much variation. Interval protocols, if used, can be prescribed more accurately from work rates rather than from HR.

The modality for in-flight exercise may be important as well. Findings from DSO 608 are too limited in this regard to generate firm recommendations. Additional landing day data should be collected as to how well

aerobic exercise capacity is maintained after in-flight use of the cycle ergometer versus the treadmill versus the rower.

Crew reports of inability to reach target HR came mostly from crew members who used the original treadmill. Considerable attention has been focused on a new treadmill designed for the International Space Station (ISS). Speeds, length of the running surface, and loads on the subject from an improved restraint system have been evaluated carefully so that this device can deliver appropriate work rates.

Maximal exercise performed on the treadmill on landing day was associated with delayed onset muscle soreness. Maximal exercise tests on cycle ergometers have not produced these effects. Maximal testing is considered necessary for accurate assessment of aerobic capacity. However, values estimated from sub-maximal tests are acceptable for operational programs. If maximal testing is used on or near landing day, the cycle ergometer should be used to minimize the risk of muscle injury.

Data regarding use of maximal exercise at the end of flight to counter loss of orthostatic function on landing day were equivocal. However, the number of subjects tested was small, and the effects of fluid loading plus return of subjects to the test facility in the seated position may have confounded these findings.

In the future, if an end-of-mission countermeasure is proposed, we recommend that studies be conducted regarding the length of time after administration that the countermeasure remains effective. This will aid NASA by determining when a repeat session is absolutely necessary in the event of a landing delay. The decision on acceptable weather for landing is usually made less than 24 hours, and on many flights is postponed until minutes, before the deorbit burn is scheduled. An established plan of action is critical regarding the need for, and practicality of, repeating the countermeasure.

The time course for recovery of aerobic capacity after spaceflight has not been well documented. This information will be necessary to plan effective postflight rehabilitation protocols for longer missions, such as those planned for the ISS.

### **Body Composition and Exercise**

Spaceflight is thought to affect aspects of human body composition such as protein, mineral, and various compartments of body water. Changes in these variables can reflect the adaptation process, but they also can reflect inadequate nutrition, exercise, or fluid intake. We developed a simple, reliable way of monitoring changes in protein, bone mineral, and fluid volumes before and after spaceflight.

Changes in body composition after spaceflight revealed that decreases in TBP and mineral contributed

to the loss of water from tissue. The combination of these reductions resulted in decreased fat-free mass. These decreases may affect physical and metabolic performance or health of astronauts during or after spaceflight.

An analysis of changes in body composition and their relation to  $\dot{V}O_{2\text{peak}}$  revealed that decreases in aerobic performance were due at least in part to a reduction in TBP and that the protein loss probably represented a reduction of muscle mass. This study also highlighted the importance of measuring changes in body composition in order to better understand changes in other physiological systems.

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