Comparison of a space shuttle flight (STS-78) and bed rest on human muscle function

SCOTT W. TRAPPE,1 TODD A. TRAPPE,1 GARY A. LEE,1 JEFFERY J. WIDRICK,2 DAVID L. COSTILL,1 AND ROBERT H. FITTS2
1Human Performance Laboratory, Ball State University, Muncie, Indiana 47306; and 2Biology Department, Marquette University, Milwaukee, Wisconsin 53201

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Trappe, Scott W., Todd A. Trappe, Gary A. Lee, Jeffery J. Widrick, David L. Costill, and Robert H. Fitts. Comparison of a space shuttle flight (STS-78) and bed rest on human muscle function. J Appl Physiol 91: 57–64, 2001.—The purpose of this investigation was to assess muscle fiber size, composition, and in vivo contractile characteristics of the calf muscle of four male crew members during a 17-day spaceflight (SF; Life and Microgravity Sciences Spacelab Shuttle Transport System-78 mission) and eight men during a 17-day bed rest (BR). The protocols and timelines of these two investigations were identical, therefore allowing for direct comparisons between SF and the BR. The subjects’ age, height, and weight were 43 ± 2 yr, 183 ± 4 cm, and 86 ± 3 kg for SF and 43 ± 2 yr, 182 ± 3 cm, and 82 ± 4 kg for BR, respectively. Calf muscle strength was examined before SF and BR; on days 2, 8, and 12 during SF and BR; and on days 2 and 8 of recovery. Muscle biopsies were obtained before and within 3 h after SF (gastrocnemius and soleus) and BR (soleus) before reloading. Maximal isometric calf strength and the force-velocity characteristics were unchanged with SF or BR. Additionally, neither SF nor BR had any effect on fiber composition or fiber size of the calf muscles studied. In summary, no changes in calf muscle strength and morphology were observed after the 17-day SF and BR. Because muscle strength is lost during unloading, both during spaceflight and on the ground, these data suggest that the testing sequence employed during the SF and BR may have served as a resistance training countermeasure to attenuate whole muscle strength loss.

spaceflight; skeletal muscle; weightlessness; unloading; Shuttle Transport System-78

Information regarding the functional and morphological changes in human skeletal muscle after spaceflight is limited (14), and the results are difficult to interpret because the crew members engaged in physical training during the flights. Nevertheless, marked decreases in muscle strength and size have been reported after spaceflight. Astronauts aboard Skylab (28, 56, and 84 days) averaged a 5–26% decline in whole muscle strength of the knee extensors and flexors (29). Soviet cosmonauts also experienced a significant decline in ankle extensor strength after short- (7 days) and long-duration (110–237 days) exposure to weightlessness (17, 20). The decline in muscular strength observed in Skylab astronauts and Russian cosmonauts occurred despite in-flight countermeasures (e.g., cycle ergometry, lower body negative pressure). The reduction in muscular strength appears to be accompanied by a decline in whole muscle size. Using magnetic resonance imaging technology, LeBlanc et al. (21) reported a 6–8% atrophy in the major leg muscles after an 8-day space shuttle flight. These data demonstrate that the skeletal muscle of humans becomes weaker and smaller as a result of short- and long-duration space travel.

Most of the information on unloaded muscle function in humans has been obtained from ground-based simulation of weightlessness [i.e., bed rest, unilateral lower limb suspension (ULLS)]. Collectively, these studies have shown that muscle strength is reduced by ~12% within 2 wk of unloading, increasing to ~30% after 4 mo (1, 7). These studies have shown changes in muscle that appear to mimic those observed with 0 G (6, 21). However, studies providing information that directly compares skeletal muscle characteristics during spaceflight and ground-based analogs (i.e., bed rest) of simulated weightlessness have not been conducted. Information directly comparing these two models would be beneficial for future studies examining human muscle function and for the design of effective skeletal muscle countermeasure protocols for extended spaceflights and stays on the International Space Station (4).

We studied four crew members before, during, and after the 17-day Life and Microgravity Spacelab (LMS) Space Transport System-78 (STS-78) mission, which contained 14 human life science experiments, 6 of which examined skeletal muscle responses to spaceflight. We also studied eight subjects during a 17-day bed rest, which mimicked the protocols and time line that was flown aboard the LMS space shuttle mission. Thus we were able to make direct comparisons between the spaceflight (spaceflight + exercise + working in space) and bed-rest (bed rest + exercise) models on whole muscle function. It must be pointed out that

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this comparison is made on the basis of the fact that countermeasure programs are mandatory as part of the space shuttle program and that the STS-78 mission was dedicated to the study of life sciences, which incorporated human physiology testing. Thus these comparisons are not of spaceflight per se but rather of the conditions that crew members were subjected to while in space for the STS-78 mission.

This study examined the strength, fiber composition, and enzymatic characteristics of the calf muscle group in response to 17 days of spaceflight and bed rest. The calf muscle was chosen because it is believed to be one of the skeletal muscles most affected by microgravity unloading because of its postural role in an 1-G environment (23, 28). Electromyographic (EMG) analysis of single-muscle-fiber physiology of the calf muscles from these same subjects is presented elsewhere (28, 33, 34).

METHODS

Subjects. The spaceflight and bed-rest experiments evaluated four and eight male subjects, respectively. Subject characteristics are shown in Table 1. All subjects were informed of the risks and benefits associated with the research and gave their written consent in accordance with the Institutional Review Boards at Ball State University, Marquette University, and National Aeronautics and Space Administration (NASA).

Experiment overview. The space shuttle Columbia (flight designation LMS STS-78) lifted off June 20, 1996, and landed on July 7, 1996, concluding a 17-day (16 days, 22 h, and 48 min) mission. The testing protocols of all the experiments (a total of 14 human experiments were conducted) were integrated, and the scheduled time line of the mission was followed. The bed-rest study (24 h/day 6° head-down tilt) was performed at the Human Research Facility at the NASA Ames Research Center. One subject did not complete testing during the final bed-rest testing point (days 13 and 14 of bed rest) because of a fever and nausea. He was able to complete the postbiopsy and all recovery testing. A detailed description of the other human experiments and nutritional status of the subjects is presented elsewhere (3, 30).

Testing time line. The testing time lines for the spaceflight and bed-rest protocols were nearly identical between the two experiments. Before any calf strength testing, the crew members and bed-rest subjects performed several orientation sessions with the torque velocity dynamometer (TVD; described below) preceding the pretesting to familiarize them with our protocol and testing procedures.

Preflight testing included four separate sessions spaced out over 90 days before the launch (90, 60, 30, and 15 days). In-flight measurements of calf muscle contractile characteristics were conducted on flight day (FD) 2 or 3 (FD2/3), 8 or 9 (FD8/9), and 12 or 13 (FD12/13). Because of the mission time line, some crew members performed the TVD protocol on FD2, whereas other crew members performed the protocol on FD3 (the same scenario occurred on FD8/9 and FD12/13). These 2-day testing sessions were considered together as one testing session. Postflight (recovery) TVD testing sessions were conducted on days 2 and 8 after return. The bed-rest calf muscle testing sessions were identical with the exception of the pre-bed-rest measurements that consisted of two evaluations separated by 2 wk.

TVD. As a result of limitations in using flight hardware for the bed-rest experiments, a ground-based TVD was constructed and used for muscle strength evaluations during the bed-rest protocols (32). The device was similar in function and operation to the spaceflight TVD. Our laboratory has previously used the ground-based TVD in other experiments with reliable results (31, 32). The coefficient of variation for the pretesting sessions (n = 4) was 5% for both the spaceflight and bed-rest subjects. The bed-rest model was calibrated before each testing session, whereas the flight unit was calibrated by the manufacturer and was not able to be further calibrated by individual investigators involved with the flight (STS-78). Subject position and instructions during testing were similar during both the spaceflight and bed-rest protocols and is described below.

During testing, the subject was in the supine position through the use of a platform-seat configuration. A five-point buckle harness was used to secure the upper body along with shoulder stabilizer bars to prevent extraneous movement. The lower leg was immobilized at 160° with the foot secured to the footplate using Velcro straps. These straps were adjusted rather tightly to properly secure the foot to the footplate and to minimize heel lift (<2 cm). Circulation to the foot area was diminished somewhat, so the straps were periodically loosened to restore blood flow.

An upper and lower shin pad rested against the anterior surface of the lower leg, which was secured to the faceplate of the TVD to prevent movement of the leg-restraint system. There were no straps or braces that crossed over the calf muscles, which would cause compression. The spaceflight (Laboratory for Biomechanics, Zurich, Switzerland) and ground-based (Cybex II, NY, NY) dynamometers were mounted in a metal box with the shaft of the dynamometer protruding through the faceplate and attaching to the leg-restraint device. The shaft of the dynamometer was aligned with the axis of rotation about the ankle. The length of the leg-restraint lever was adjusted to accommodate different limb lengths. Both of these devices could be arranged for both right and left lower leg testing.

Because the technique utilized during contraction of the calf was an important aspect, the subjects performed three 30-min training sessions. The instinct for the subject was to push against the footplate, causing the leg to straighten and the knee to drop (thus the knee angle becomes larger). In the training sessions, the subjects were taught to concentrate on rotating about the ankle such that the knee pushed upward into the apparatus, stabilizing the knee and maintaining knee angle and leg position throughout the full range of motion.

Calf muscle strength protocol. The spaceflight and bed rest both tested the strength of the right calf muscles. The calf muscle strength protocol consisted of three parts: 1) maximal isometric strength at ankle angles of 80, 90, and 100° (with 90° a neutral position); 2) force-velocity measurements at 0.52, 1.05, 2.09, 3.14, 4.19, and 5.24 rad/s; and 3) a fatigue test consisting of 30 maximal contractions at 3.14 rad/s. With rest periods included, the total test time was ~30 min. At each isometric ankle angle, the subjects performed two 50%
efforts for warm-up followed by one maximal effort lasting 5 s. At each isokinetic test velocity, a series of four warm-up contractions at ~50% effort were performed to familiarize the subjects with the test velocity and movement. After this warm-up, subjects were asked to perform four maximal plantar flexion contractions at the corresponding angular velocity. Dorsiflexion movements were performed by the TVD; thus they were passive for the subject. These contractions occurred with ~1 s between repetitions. In addition, no preload was applied to the muscle. A 2-min rest period occurred between each test velocity. Peak torque at a given velocity was taken as the highest value obtained for each of the four contractions. After a 5-min rest period, subjects performed a fatigue test that consisted of 30 maximal contractions at 3.14 rad/s without interruption. A contraction was performed at a rate of ~1/s until all 30 had been completed. Subjects were instructed to perform this test all out from the beginning to avoid any pacing that might occur with this test.

Muscle biopsy and analysis. The crew members’ muscle biopsy samples were obtained from the gastrocnemius (lateral head) and soleus muscles 45 days before launch and within 3 h after landing. Postflight, the crew members were escorted in wheelchairs until the muscle samples were obtained to help prevent muscle damage as a result of reloading (15). The bed-rest subjects were biopsied 2 wk before bed rest and on day 17 before reambulation. Because of time constraints and the number of subjects studied during the bed-rest experiment, muscle biopsies were only obtained from the soleus muscle.

For histochemical analysis, the muscle sample was oriented longitudinally in embedding medium, frozen in isopentane cooled to liquid N2 temperature, and stored in liquid N2. Additionally, a portion of the muscle tissue for enzymatic analysis was frozen in liquid N2 and stored at ~80°C. The remaining muscle tissue was used for single-muscle-fiber physiology and biochemistry studies that are presented elsewhere (28, 33, 34).

Transverse sections (10 μm) for histochemical analysis were cut on a cryostat (Tissue-Tek II, Miles Laboratory, Elkhart, IN) at −20°C. Fiber-type distribution was determined in sections stained for adenosine triphosphatase activity at pH 9.4 after preincubation at pH 4.30 and 4.55 (26). An average of 734 ± 205 (range 411–1,097) fibers per subject were classified as type I, type IIa, or type IIb according to the nomenclature of Brooke and Kaiser (11). Muscle fiber areas were determined from NADH-tetrazolium reductase stains (to minimize fiber shrinkage due to dehydration). Sections were projected and magnified with a minimum of 50 type I and 50 type II muscle fibers randomly selected from an artifact-free region. Manual planimetry was then completed on these fibers using a public domain software (National Institutes of Health Image program v1.60) on a computer (Macintosh Centris 650). Type II fiber areas were calculated without regard for subtypes because most samples contained very few or no type IIB muscle fibers.

Oxidative and glycolytic enzymes were determined from a 10- to 20-mg portion of the muscle specimen. Citrate synthase activity was determined through the reduction of DTNB by the release of CoA-SH in the cleaving of acetyl-CoA (12). Phosphorylase activity was determined fluorometrically from the production of NADPH, and β-hydroxyacyl-CoA dehydrogenase was determined using a kinetic assay measuring the rate of disappearance of NADH (12). Because limitations in tissue sample size from the bed-rest subjects, β-hydroxyacyl-CoA dehydrogenase was not analyzed.

Calculations and statistical analysis. For all strength measurements, data were collected at 500 Hz. From these data, peak torque, for any given measurement, was taken as the highest recorded value. Any record showing an artifact or torque spike was discarded and not used for analysis. During the maximal isokinetic contraction, the record with the greatest value was used. In addition, the angle-specific torque at 90° was recorded for all contractions. Because of inadvertent torque spikes using the spaceflight TVD, the fatigue data were inconsistent and not used in the analysis.

Individual data for the spaceflight (crew members A–D) and bed rest (subjects 1–8) are presented along with the means ± SD. It should be noted that the muscular results from these experiments reflect those of space travel (which includes a heavy daily work schedule) and simulated weightlessness (bed rest), which mimicked the time line of the spaceflight.

RESULTS

Figure 1 illustrates the force-velocity relationship comparing the pre- to post-spaceflight (preflight plotted with FD13/14) and bed-rest (pre-bed rest plotted with days 13 and 14 of bed rest) testing. Because of technical difficulties with the TVD baseplate during the in
flight space shuttle testing, the strength measurements on FD2/3 and FD8/9 were considerably lower than all other testing sessions. The baseplate (which was used to support, stabilize, and secure the upper body) utilized Velcro to secure it to the floor of the space shuttle. The Velcro remained secure during all ground-based testing. However, once in orbit, the Velcro proved to be insufficient to properly secure the baseplate to the floor of the Spacelab. As a result the crew members were lifting and “floating” while in the TVD unit. The resulting outcome was torque values that were ~50% lower compared with preflight values. This was an ongoing problem that was fixed (different security attachment of baseplate for all crew members after the FD8/9 testing session). Because the isometric values from FD12/13 were unchanged compared with preflight values, we concluded that the technical difficulties with the TVD were responsible for the subpar performance of muscular strength. Furthermore, we observed no change in isometric strength at 80, 90, or 100° of ankle plantar flexion before, during, or after the mission or bed rest (Table 2). On the final testing session, day 8 of recovery, all four crew members and all eight bed-rest subjects had similar isometric strength compared with the preflight testing values. No differences were observed in the force-velocity relationship during or after spaceflight or bed rest and in the pre- to postflight relationship shown in Fig. 1. Figure 1 is representative of all testing sessions, excluding the sessions involving technical difficulties.

Muscle fiber composition of the soleus and gastrocnemius, as determined by myosin ATPase histochemistry staining, were similar before and after 17 days of spaceflight (Table 3) and bed rest (Table 4). Both the spaceflight and the bed-rest subjects’ soleus muscle samples were predominantly slow-twitch (type I) muscle fibers (mean = 84%), with minimal to zero type IIb muscle fibers observed.

Table 5 shows the muscle fiber area (µm) preflight and postflight and the percent change in size of the gastrocnemius and soleus muscle fiber types. There was considerable variation in fiber areas among the four crew members pre- to postflight. However, no statistical differences in single-fiber size (type I and II) was noted in the gastrocnemius or the soleus muscles of the crew members.

### Table 2. Maximal isometric torque at ankle angles of 80, 90, and 100° (with 90° a neutral position) before and after a 17-day spaceflight and bed rest

<table>
<thead>
<tr>
<th>Crew Member</th>
<th>Pre-Bed Rest</th>
<th>Post-Bed Rest</th>
<th>Pre-Bed Rest</th>
<th>Post-Bed Rest</th>
</tr>
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<td>84</td>
<td>86</td>
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<td>41</td>
<td>29</td>
<td>16</td>
<td>13</td>
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<td>12</td>
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<td>0</td>
<td>1</td>
</tr>
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<td></td>
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<tr>
<td>Type I</td>
<td>73</td>
<td>67</td>
<td>81</td>
<td>86</td>
</tr>
<tr>
<td>Type IIa</td>
<td>17</td>
<td>31</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>Type IIb</td>
<td>10</td>
<td>3</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
</tr>
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<td>72</td>
<td>66</td>
<td>82</td>
<td>78</td>
</tr>
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<td>2</td>
<td>7</td>
</tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>56</td>
<td>63</td>
<td>92</td>
<td>96</td>
</tr>
<tr>
<td>Type IIa</td>
<td>23</td>
<td>28</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Type IIb</td>
<td>21</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>62 ± 12</td>
<td>62 ± 7</td>
<td>85 ± 5</td>
<td>86 ± 8</td>
</tr>
<tr>
<td>Type IIa</td>
<td>23 ± 13</td>
<td>29 ± 1</td>
<td>10 ± 7</td>
<td>12 ± 7</td>
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<tr>
<td>Type IIb</td>
<td>15 ± 5</td>
<td>9 ± 7</td>
<td>5 ± 8</td>
<td>2 ± 3</td>
</tr>
</tbody>
</table>

Values are given as %. Mean values are ± SD.

Similar to the spaceflight subjects, the bed-rest subjects showed no changes in single-fiber size of the soleus type I muscle fibers (Table 6). Whereas there were no differences in mean single-fiber size in this study, there was considerable subject variability in the change in soleus fiber area in both the spaceflight (range = +5.8 to −20.5%) and bed rest (range = +22.1 to −33.1%) subjects.

The gastrocnemius and soleus enzyme activities for citrate synthase, phosphorylase, and β-hydroxyacyl-CoA dehydrogenase are shown in Table 7. All three muscle enzymes were unchanged pre- to postflight. Similar to spaceflight, bed rest had no significant effect on the oxidative enzyme citrate synthase or the glycolytic enzyme phosphorylase (Table 8).

### Table 4. Muscle fiber composition of the soleus muscles before and after 17 days of bed rest

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>Type I</th>
<th>Type II</th>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
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<td>100</td>
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<tr>
<td>2</td>
<td>92</td>
<td>8</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>89</td>
<td>11</td>
<td>97</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>66</td>
<td>34</td>
<td>78</td>
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</tr>
<tr>
<td>7</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
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<tr>
<td>8</td>
<td>91</td>
<td>9</td>
<td>83</td>
<td>17</td>
</tr>
</tbody>
</table>

Mean: 84 ± 11 16 ± 11 88 ± 9 12 ± 9

Values are given as a %. Mean values are ± SD. For subject 7, a histochemical analysis was not determined (ND). No type IIb fibers were observed in any of the biopsies.
and after 17 days of bed rest

Table 6. Fiber area of the soleus type I fibers before and after a 17-day spaceflight

<table>
<thead>
<tr>
<th>Crew Member</th>
<th>Gastrocnemius</th>
<th>Soleus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre, µm²</td>
<td>Post, µm²</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>6,193</td>
<td>5,949</td>
</tr>
<tr>
<td>Type IIa</td>
<td>6,842</td>
<td>7,509</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>7,729</td>
<td>5,354</td>
</tr>
<tr>
<td>Type IIa</td>
<td>10,180</td>
<td>5,737</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type I</td>
<td>5,247</td>
<td>6,645</td>
</tr>
<tr>
<td>Type IIa</td>
<td>6,241</td>
<td>6,690</td>
</tr>
<tr>
<td>D</td>
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</tr>
<tr>
<td>Type I</td>
<td>5,528</td>
<td>4,340</td>
</tr>
<tr>
<td>Type IIa</td>
<td>6,691</td>
<td>5,772</td>
</tr>
<tr>
<td>Mean</td>
<td>6,174 ± 1,110</td>
<td>5,572 ± 976</td>
</tr>
</tbody>
</table>

Mean values of the individual percent are ± SD. Because of the limited number of fibers, the fiber area of the soleus type II fibers was not determined (ND). %Δ, percent change.

DISCUSSION

The aim of the present investigations was to document the changes in calf muscle strength, fiber composition, and enzyme activity during exposure to 17 days of spaceflight and bed rest and to compare the results between these two studies. Because the two projects’ time lines were nearly identical, this is the first direct comparison between spaceflight and bed rest on human skeletal muscle strength and fiber composition. In addition, data regarding these muscles (i.e., the calf muscles) in humans after simulated weightlessness are relatively limited (16, 19, 22), and, to our knowledge, these muscles have not been studied in response to spaceflight. The primary finding from these studies was that no significant changes were observed in the functional characteristics of the calf muscles during exposure to 17 days of real (spaceflight) or simulated (bed rest) weightlessness. These findings were most likely influenced by the exercise paradigms performed as part of this spaceflight mission (STS-78) and bed-rest experiments.

Table 5. Fiber area for the gastrocnemius and soleus muscles before and after a 17-day spaceflight

<table>
<thead>
<tr>
<th>Crew Member</th>
<th>Gastrocnemius</th>
<th>Soleus</th>
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<tbody>
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</tbody>
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Mean values of the individual percent are ± SD. Because of the limited number of fibers, the fiber area of the soleus type II fibers was not determined (ND). %Δ, percent change.

In the present studies, calf muscle strength on the final measurement period during spaceflight and bed rest (days 13 and 14) was unchanged (P > 0.05) over a range of isokinetic velocities (0–5.24 rad/s). Similarly, Narici et al. (25) found no changes in maximal voluntary contraction during spaceflight or bed rest from the opposite leg (left) of the same subjects (25). However, maximal voluntary contraction increased in the recovery phase with a decrease in tetanic force, indicating incomplete motor unit activation or changes in antagonist and synergistic muscle activation (25). In contrast, Gogia et al. (16) and Leblanc et al. (22) have reported large, significant decreases in calf muscle strength after 35 and 119 days of bed rest, respectively.

Studies examining the quadriceps muscles (ULLS) have shown a 12–21% decline in knee-extension strength over 16–42 days (1, 8, 13, 27). Discrepancies among the present studies and the published data regarding loss of calf and quadriceps muscle strength with unloading can most likely be explained by the physiological testing completed during the integrated testing protocols. Recently, Bamman et al. conducted a 14-day bed-rest study in which subjects performed resistance exercise every other day on the quadriceps (5) and calf (6) muscle groups. During the training sessions, subjects performed concentric and eccentric muscle contractions (5 sets, 6–10 repetitions) at ~80% of maximum. This protocol was sufficient to maintain whole muscle dynamic strength. These data indicate that resistance-type exercise can alleviate the decrement in skeletal muscle strength with bed rest.

The subjects in the studies by Bamman et al. (5, 6) performed ~210–350 contractions at ~80% of maximum during the course of the 14-day bed-rest study. The spaceflight crew members and bed-rest subjects in the present studies performed ~525 contractions over the 3 testing sessions during the 17-day mission. Of the 525 contractions, ~50% of these were at an intensity of
muscle before and after 17 days of bed rest

Table 8. Selected enzyme activities for the soleus muscles before and after a 17-day space flight

<table>
<thead>
<tr>
<th>Crew Member</th>
<th>Citrate synthase</th>
<th>Phosphorylase</th>
<th>β-OAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>10.73</td>
<td>5.30</td>
<td>13.51</td>
</tr>
<tr>
<td>Post</td>
<td>12.94</td>
<td>4.92</td>
<td>16.89</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>9.26</td>
<td>4.42</td>
<td>12.52</td>
</tr>
<tr>
<td>Post</td>
<td>8.97</td>
<td>5.14</td>
<td>11.23</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>8.38</td>
<td>4.34</td>
<td>9.74</td>
</tr>
<tr>
<td>Post</td>
<td>8.38</td>
<td>4.75</td>
<td>10.83</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>8.53</td>
<td>5.66</td>
<td>10.43</td>
</tr>
<tr>
<td>Post</td>
<td>9.41</td>
<td>6.00</td>
<td>11.72</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>9.23 ± 1.07</td>
<td>4.93 ± 0.65</td>
<td>11.55 ± 1.76</td>
</tr>
<tr>
<td>Post</td>
<td>9.93 ± 2.05</td>
<td>5.20 ± 0.56</td>
<td>12.67 ± 2.84</td>
</tr>
</tbody>
</table>

Values are given as mol·h⁻¹·kg dry wt⁻¹. Mean values are ± SD. β-OAC, β-hydroxyacyl-CoA dehydrogenase.

Table 7. Selected enzyme activities for the gastrocnemius and soleus muscles before and after a 17-day space flight

<table>
<thead>
<tr>
<th>Crew Member</th>
<th>Citrate synthase</th>
<th>Phosphorylase</th>
<th>β-OAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre</td>
<td>9.00</td>
<td>5.00</td>
<td>13.00</td>
</tr>
<tr>
<td>Post</td>
<td>12.00</td>
<td>4.00</td>
<td>16.00</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre</td>
<td>9.26</td>
<td>4.42</td>
<td>12.52</td>
</tr>
<tr>
<td>Post</td>
<td>8.97</td>
<td>5.14</td>
<td>11.23</td>
</tr>
</tbody>
</table>

Values are given as mol·h⁻¹·kg dry wt⁻¹. Mean values are ± SD. β-OAC, β-hydroxyacyl-CoA dehydrogenase.

80–100% of their best effort. Thus the possibility exists that the testing protocols used in this investigation, which were employed to document the time course of change in muscle function, may have served as an exercise countermeasure to preserve whole muscle function after a relatively short-term stay (17 days) in space or bed.

When comparing the results of the present 17-day studies with other ground-based (bed rest and ULLS) studies of similar duration, it is apparent that, when no exercise is performed, a decrease in muscle strength is observed (1, 7, 8, 10). However, these studies have shown that neural activation (EMG) is relatively unchanged with short-term unweighting (5, 10). Thus unspecific tissue factors (such as changes at the cell level) other than neural activation must impair muscle function with short-term unloading (5, 10). Thus the possibility exists that neural activation (EMG) is relatively unchanged with short-term unweighting (5, 10). However, these studies have shown that neural activation (EMG) is relatively unchanged with short-term unweighting (5, 10). Thus unspecific tissue factors (such as changes at the cell level) other than neural activation must impair muscle function with short-term unloading. This is further verified by the data of McCall et al. (24), who reported no alteration in the EMG activity of the calf muscles after the 17-day bed-rest investigation on the same subjects.

On average, we observed ~7–10% decrease in type I and II muscle fiber types after spaceflight (gastrocnemius and soleus) and bed rest (soleus). However, there was considerable individual variation in the direction and magnitude of change in muscle fiber size. Two of the spaceflight crew members' (B and D) fiber size appeared to be more affected than the other crew members, whereas another (crew member C) showed an increase in fiber size after 17 days aboard the space shuttle. The bed-rest subjects also demonstrated a large variability in fiber-size change with the 17-day protocol. In six of the eight subjects, type I fiber atrophy occurred (range ~2 to ~33%), whereas the remaining two (subjects 1 and 4) showed an increase (~5% and ~19%). For comparison, single-muscle-fiber diameters measured at a specific sarcomere length (2.5 μm) from the same muscle biopsy samples of the same subjects yielded similar results (33, 34). Crew members B (~19%) and D (~8%) were more affected than the others, whereas bed-rest subjects 1 and 4 showed no change and an increase (~5%) in fiber size, respectively. No notable difference in fiber atrophy among the type I and II fiber-type populations was observed. These data suggest that single-fiber size alterations were highly individualized among the crew members and bed-rest subjects. This is in agreement with previous studies on human muscle morphology with spaceflight (14).

When comparing the fiber size results with other studies, it is difficult to ascertain the degree of muscle fiber atrophy with exposure to microgravity. After an 11-day spaceflight, type I, IIA, and IIB fibers from the vastus lateralis were significantly reduced by 16–36% (14). These authors also reported that the type IIA/IIB fibers decreased in size more than the type I muscle fibers. These significant reductions in fiber size occurred despite aerobic running and lower body negative pressure countermeasures. In contrast, ground-
based simulations employing bed rest and ULLS with no countermeasures found no significant change in muscle fiber size (vastus lateralis, gastrocnemius, and soleus) after up to 4 wk of muscle unloading (1, 8). However, studies beyond 4 wk have shown a significant decrease in type I and II muscle fibers from the vastus lateralis and soleus (9, 18, 19). These data support the contention that both duration and the microgravity analog used to examine the change in muscle fiber size impact the skeletal muscle response to unloading. It should be noted that differences in daily work schedules, physical activity performed, and the stress response to actual spaceflight most likely contribute to the differences observed among the present and previous studies.

Pre- to postspaceflight muscle biopsy samples from the spaceflight and bed-rest subjects revealed minor to no alterations in fiber-type distribution as determined by myosin ATPase staining. These findings are in agreement with ground-based studies (1, 8) and in disagreement with the only other spaceflight experiment to examine fiber-type composition in humans (14). Again, these findings are difficult to directly compare because of differences in duration, activity, stress, and methodological considerations. A recent study by Anderson et al. (2) examined muscle fiber composition using ATPase staining, immunocytochemistry, and myosin heavy chain expression in humans before and after 37 days of bed rest (with no activity during bed rest). They reported no significant alteration in fiber composition at the protein level but did find that the mRNA for certain myosin heavy chain isoforms were altered with bed rest. Thus changes at the level of the gene may be occurring with muscle unloading that are not detected at the level of the muscle protein. From these data, it can be concluded that the ground-based studies and the present spaceflight and bed-rest studies do not induce significant alterations in fiber composition (as determined by ATPase histochemical methods) of human skeletal muscle with short to moderate exposure to weightlessness.

Data relating changes in enzyme activity and unloading of the leg muscles are limited. Generally, the glycolytic enzymes are unaffected with unloading, whereas oxidative enzymes decrease or remain unchanged (8, 14, 19). In the present spaceflight and bed-rest studies, no changes were observed in the glycolytic (phosphofructokinase) or oxidative (citrate synthase and β-hydroxyacyl-CoA dehydrogenase) enzyme activities. Previous data indicate that enzyme activity appears to be altered when the exposure to unloading is 4 wk or greater (8, 19). Thus the present 17-day protocol may have been too short to significantly alter the enzyme profile of the calf muscles.

In the single-muscle-fiber analysis of these same subjects, we found a decrease in peak isometric tension (P<sub>0</sub>) (P < 0.05) and an increase in unloaded shortening velocity (V<sub>0</sub>) (P < 0.05) in the type I fibers after spaceflight and bed rest (33, 34). The increase in V<sub>0</sub> after the 17-day “unloading” either reduced or prevented the decline in fiber absolute peak power. No differences in myosin light chain composition were observed that could help explain these changes in P<sub>0</sub> and V<sub>0</sub>. However, electron microscopic analysis indicated that the reduction in tension (P<sub>0</sub>) and elevated V<sub>0</sub> may be related to the reduction of thin-filament density after unloading (28, 33).

When examining the whole muscle and single-cell experiments from the present spaceflight and bed-rest studies, an apparent paradox exists. No changes were observed in whole muscle function; however, significant alterations were observed in single-cell function. Several possibilities exist to help explain the difference in whole muscle and single cell findings. First, it is possible that there was a learning effect with the subjects, motivational factors, or changes in recruitment strategies. However, all subjects’ calf muscles were tested several times with similar results before initiation of the study. In addition, EMG data from the same leg muscles of the same subjects indicated no alteration in neural activation (24). Another possibility is that the whole muscle testing device and whole muscle testing in general were not sensitive enough to detect the changes at the cell level. These data indicate that there were significant changes at the cell level that were not detected at the whole muscle level.

In summary, no significant changes in whole muscle function, muscle fiber size, and enzyme activity of the calf muscles (gastrocnemius and soleus) were found as a result of the 17-day spaceflight (STS-78) and bed rest. However, the muscle testing that was employed periodically during these investigations may have partially served as a countermeasure to preserve muscle strength. Although no direct conclusions can be made on the effect that spaceflight or bed rest had on muscle function (due to mission time line and exercise interventions), it can be concluded that the muscle characteristics evaluated in this 17-day investigation were similar between the spaceflight and bed-rest studies.

Special thanks to all of the crew members and the bed-rest subjects for their commitment throughout the study. We also greatly appreciate the assistance of the NASA staff and technicians at Johnson Space Center and the staff of the Human Research Facility at the NASA Ames Research Center, especially Dee O’Hara and Dr. Sara Arnaud.

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