LBNP treadmill exercise maintains spine function and muscle strength in identical twins during 28-day simulated microgravity

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Macias BR, Cao P, Watenpaugh DE, Hargens AR. LBNP treadmill exercise maintains spine function and muscle strength in identical twins during 28-day simulated microgravity. J Appl Physiol 102: 2274–2278, 2007. First published March 29, 2007; doi:10.1152/japplphysiol.00541.2006.—The purpose of this study was to determine whether lower body negative pressure (LBNP) treadmill exercise maintains lumbar intervertebral properties, curvature, and back muscle strength after 28 days of 6° head-down tilt (HDT) bed rest (BR). We hypothesize that LBNP treadmill exercise will maintain lumbar spine compressibility, lumbar lordosis and back muscle strength after 28 days of 6° HDT bed rest. Fifteen healthy identical twin pairs (14 women and 16 men) participated in this study. One identical twin was randomly assigned to the nonexercise control (Con) group, and their sibling was assigned to the exercise (Ex) group. The lumbar spine was significantly more compressible Post-BR compared with Pre-BR in the Con (P = 0.01). Lumbar spine compressibility Post-BR was not significantly different compared with Pre-BR in the Ex group (P = 0.89). In both the Con and Ex groups, there were no significant changes Post-BR in lumbar lordosis compared with Pre-BR. Back muscle strength significantly decreased in the Con group Post-BR (P = 0.002), whereas in the Ex group back muscle strength was not significantly different from Pre-BR values. A significant increase in lumbar spine compressibility in the Con group suggests that spinal deconditioning to gravity occurs during 28-day bed rest. Changes in the mechanical properties of the lumbar spine may be an early indicator of lumbar intervertebral disk degeneration. Supine LBNP treadmill exercise provides axial loads to the lumbar spine and may prevent lumbar spine deconditioning associated with HDT bed rest.

spaceflight; bed rest; back strength; lower body negative pressure; lumbar compressibility

The vertebral bodies and flexible intervertebral disks are very important, weight-bearing tissues that have adapted to gravitational stress (14). The absence of gravitational axial loads on the body during exposure to microgravity may disrupt normal spine physiology. During longer spaceflight missions, deconditioning of the intervertebral disks and spinal muscles may pose a serious risk with reexposure to upright posture in a gravitational environment. However, there are few studies in humans to examine intervertebral disk mechanics and lumbar muscle strength during microgravity. Currently, the type of exercise equipment needed to prevent spinal deconditioning during spaceflight is unresolved (7, 8).

During upright activity, gravity and back musculature provide axial compressive loads to the spine, allowing for diurnal changes in body height (19, 30, 32). Axial loads decrease body height, primarily by decreasing spine length (19, 28) and increasing lumbar lordosis (2). The body loses ~15–20 mm in height (1% of total body height) following normal upright daytime activity (19, 30). It is the swelling pressure of the hydrophilic proteoglycans that enables the intervertebral disk to retain fluid when under high mechanical compression. During unloading, high concentrations of negatively charged proteoglycan macromolecules and their associated fixed-charge density cause the nucleus pulposus to swell, allowing fluid to move across the vertebral end plates and annulus and into the nucleus pulposus (24). Because the intervertebral disk is avascular, the diurnal loading cycle is an important physiological mechanism that maintains the mechanical and metabolic properties of the intervertebral disks (1, 4).

Without a diurnal loading cycle in microgravity or simulated microgravity, astronauts may be at serious risk when returning to a gravitational environment because the integrity of the intervertebral disk may not be able to support the compressive loads (16). Understanding the compressive properties of the lumbar spine and intervertebral disks in response to a controlled axial load may provide valuable information about the response of the spine to gravity or microgravity. During 6° head-down tilt (HDT) bed rest, simulated microgravity, the gravitational load along the axis of the body is reduced and the spine lengthens (6). Previous studies have found increases in spine length (5, 29) and intervertebral disk height (22) associated with spinal deconditioning. In addition, animal models document changes in intervertebral disk proteoglycan content and the collagen-to-proteoglycan ratio, which suggest alterations in biochemical processes during simulated (17) and actual (26) microgravity.

Maintaining lumbar muscle strength is also important to prevent back-related injuries during spaceflight and on reexposure to a gravitational environment. Lumbar musculature effects vertebral motion during posture and spinal movement to protect the articular structures, disks, and ligaments from excessive bending strains and injury (3, 11). Magnetic resonance imaging (MRI) analyses after a 115-day space mission demonstrated 3–10% reductions in lower back muscle volumes (21, 28). In addition, after 17 wk of 6° HDT bed rest, the volume of intrinsic lower back muscles decreased rapidly with an average loss of 9% (20).

Over the past 10 yr, our laboratory has developed a lower body negative pressure (LBNP) treadmill exercise system. Supine LBNP treadmill exercise maintains exercise capacity (31), retards increased bone resorption (27), and prevents lumbar lengthening in bed rest studies (6). The purpose of this study was to determine whether supine LBNP treadmill exer-
cise maintains lumbar spine compressive properties, curvature, and back muscle strength after 28-days of 6° HDT bed rest. We hypothesize that supine LBNP treadmill exercise maintains lumbar spine compressibility, lumbar lordosis, and lumbar muscle strength after 28 days of 6° HDT bed rest.

METHODS

The University of California San Diego (UCSD) and National Aeronautics and Space Administration Institutional Review Boards approved this study and all subjects gave informed written consent prior to participation. Fifteen healthy identical twin pairs (14 women and 16 men) participated in this study. The twin pairs were confirmed to be monozygotic using a standard DNA marker verification technique (Affiliated Genetics, Salt Lake City, UT). The subject’s age, height, and weight were 26 yr (SD 4) (range 22–37 yr) 61.7 kg (SD 12.4) (range 43.7–84.1 kg), and 168.7 cm (SD 10.7) (range 152.4–190.5 cm), respectively. The subjects were given a physical and questionnaire to ensure they were in good health and without previous history of back pain, back surgery, or contraindications for MRI.

Subjects were admitted to the UCSD General Clinical Research Center 6 days before 6° HDT bed rest for familiarization and pre-bed rest (Pre-BR) testing. Subjects then remained in 6° HDT bed rest for 30-days, followed by 3 days of post bed rest (Post-BR) testing. One subject from each set of twins was randomly assigned to the LBNP exercise (Ex) group, while their sibling served as a nonexercise, control (Con). The LBNP exercise device has been described in detail in previous studies (Fig. 1) (6, 13, 27, 31). In brief, the subject was placed supine into the LBNP exercise chamber and sealed with a flexible neoprene waist seal. Supine LBNP from 50 to 55 mmHg was applied to produce a static force equivalent to one body weight (BW) in the head-to-foot direction. In addition to the pressure differential applied across the entire surface of the body, the spine is loaded with shoulder straps that connect to the waist seal and provide additional axial load (6, 31). The Ex group performed a variable intensity exercise protocol for 40 min (40–80% peak oxygen consumption), followed by a 5-min period of noneexercise LBNP, 6 days/wk for 30 days.

Five sets of male and seven sets of female identical twins completed a spine MRI test to determine intervertebral disk compressibility. Subjects underwent MRI (1.5-T system, Magnetom Symphony, Siemens, Germany) 1 day before bed rest (Pre-BR) and on day 28 of bed rest (Post-BR). On the day of the MRI Pre-BR test, the subjects maintained normal daily upright activity and were in upright position 1 h before data collection. The subjects donned a compression vest, they were positioned in the supine MRI, and the vest was connected to the compression device (DynaWell, DynaMed, Stockholm, Sweden) without axial load. Parameters for MRI of the lumbar spine were as follows: fast spin-echo pulse sequence, T1 weighted; repetition/time/echo time = 450/15 ms; field of view, 512 × 512 image matrix; slice thickness, 4 mm; and space between slices, 4.4 mm. Then, MR images were collected without axial load. Next, while the subject remained in the same position in the MRI their lumbar spine was loaded axially using the compression device to a force equivalent to 50% BW. This compression device loads the spine and simulates the 50% BW portion (not including loads from muscles) of the load on the spine in upright posture (23). The load was allowed to equilibrate for 5 min, after which time the load was readjusted to 50% BW and magnetic resonance (MR) images were acquired over the next 10 min. The 50% BW load was calculated using the BW from the day before 6° HDT bed rest. This same 50% BW load was used for the Post-BR MRI test.

MR images were analyzed using a personal computer with software Image J 1.30V (Wayne Rasband, National Institutes of Health, Bethesda, MD). Midsagittal MR images were used to measure the entire lumbar spinal length, individual lumbar intervertebral disk heights, and lumbar lordosis. The midsagittal plane was determined by using the spinous processes as a confirmatory landmark. Lumbar spinal length was defined as the distance between the horizontal line drawn at the anterosuperior corner of the L1 vertebral body and the horizontal line drawn at the anterosuperior corner of the S1 vertebral body (6). Disk height was obtained from the average of anterior and posterior disk heights according to the Dabbs and Dabbs method (6, 9). We define spinal compressibility as the difference in lumbar spinal length with 50% BW axial load to no axial load:

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\text{Spinal compressibility (mm)} = \frac{\text{lumbar spine length with 50% BW axial load}}{\text{– lumbar spine length with no axial load}} 
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We define intervertebral disk compressibility as the difference in intervertebral disk height with 50% BW axial load to no axial load. The 50% BW is the body weight portion of the load on the spine without load from muscles (15). Lumbar lordosis was defined as the angle between the upper surfaces of L1 and S1 vertebral body (2). Distances and angles were measured twice by a technician, and the two results were averaged. If there was a difference between the two results of >10%, additional measurements were preformed and averaged.

Lumbar strength. Eight sets of male and seven sets of female identical twins completed a lumbar strength test. The testing occurred at the UCSD OrthoMed facility Pre-BR (6 days before HDT bed rest) and Post-BR (2 days after HDT bed rest). Voluntary maximum isometric lumbar extension strength was evaluated using a lumbar extension dynamometer (MedX, Ocala, FL), at seven positions of lumbar flexion (0, 12, 24, 36, 48, 60, and 72°), using standard procedures (12). Before the test, a dynamic warm-up exercise was performed. The dynamic exercise involved 10 full-range repetitions of lumbar extension with a resistance of 54 N·m (40 ft-lb). Subsequently, a three-angle submaximal isometric test was administered for instruction and practice. A 30-s rest period was provided after each maximal isometric contraction before testing at the next angle. Each volunteer was reminded of the instructions before the test at each of the seven angles of lumbar flexion. Lumbar strength was quantified as

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\text{GRF} = F_{\text{seal}} + F_1 + F_2 
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**Fig. 1.** View from the side of the supine lower body negative pressure (LBNP) treadmill exercise device. The subject was placed supine into the LBNP chamber, which contains a vertically oriented treadmill. The ground reaction force (GRF) is composed of 3 components: 1) the suction force (F_{\text{seal}}) produced by the elastic waist seal around the hip; 2) the axial force (F_1) over the whole body produced by negative pressure on subject’s lower body (primary loading force); and 3) the loading force (F_2) generated by the shoulder straps, which connect to the seal. A_w, cross-sectional area of the subject’s body at waist level; A_x, cross-sectional area of the waist seal only. GRF = F_{\text{seal}} + F_1 + F_2, where F_1 = LBNP×A_w and F_{\text{seal}} = LBNP×A_x.
the mean peak torque for all seven angles of lumbar flexion, expressed in newton-meters. Repeated-measures analysis of variance was performed to determine statistical significance using software SPSS 9.0 (SPSS, Chicago, IL). If the main effects (group, Pre-BR/Post-BR) were statistically significant, the individual groups were tested using paired t-tests. Data are expressed as means ± SE. Significance was set at \( P < 0.05 \).

RESULTS

The lumbar spine was significantly more compressible Post-BR compared with Pre-BR in the Con group (\( P = 0.01 \)). In Con group, Pre-BR, lumbar length decreased \(-1.7 \pm 0.4\) mm (Mean ± SE, 0.9% of the total lumbar length) with 50% BW axial load, whereas Post-BR, lumbar length decreased \(-2.7 \pm 0.4\) mm (1.4% of the total lumbar length) with 50% BW axial load (Fig. 2). Lumbar spine compressibility Post-BR was not significantly different compared with Pre-BR in the Ex group (\( P = 0.89 \)). In Ex group, Pre-BR, lumbar length decreased \(-1.8 \pm 0.2\) mm (1.0% of the total lumbar length) with 50% BW axial load, whereas Post-BR, the lumbar length decreased \(-1.6 \pm 0.4\) mm (0.8% of the total lumbar length) with 50% BW axial load.

The compressibility of individual lumbar intervertebral disks, Pre-BR, with 50% BW axial loads ranged between \(-0.2\) and \(-0.5\) mm in Con group, whereas Post-BR, the compressibility of lumbar intervertebral disks with 50% BW axial loads ranged between \(-0.3\) and \(-1.1\) mm. However, for individual lumbar intervertebral disks, there were no significant changes in disk compressibility with 50% BW axial load in Con and Ex group Post-BR.

In both the Con and Ex groups, there were no significant changes Post-BR in lumbar lordosis compared with Pre-BR. In Con group, Pre-BR lumbar lordosis increased \(3.5^\circ \pm 2.0^\circ\) (6.8% of total lumbar curvature) with 50% BW axial loads, whereas Post-BR, lumbar lordosis increased \(3.5^\circ \pm 0.7^\circ\) (7.3% of total lumbar curvature) (Fig. 3). In Ex group, Pre-BR, lumbar lordosis increased \(3.8^\circ \pm 1.7^\circ\) (7.3% of total lumbar curvature), whereas Post-BR, lumbar lordosis increased \(2.7^\circ \pm 1.6^\circ\) (5.4% of total lumbar curvature) (Fig. 3).

Mean lumbar muscle strength at each flexion angle decreased significantly in the Con group Post-BR (Fig. 4). In the Con group, mean lumbar muscle strength of all flexion angles Post-BR of 143 ± 16 N·m was significantly less compared with the Pre-BR value of 175 ± 19 N·m (15% loss). In the Ex group mean lumbar muscle strength at flexion angles above \(24^\circ\) was not significantly different from Pre-BR (Fig. 5). In Ex group, mean lumbar muscle strength of all flexion angles Post-BR of 169 ± 14 N·m was not significantly different from the Pre-BR value 178 ± 17 N·m.

DISCUSSION

We hypothesized that supine LBNP treadmill exercise maintains lumbar spine compressibility, lumbar lordosis, and lumbar muscle strength after 28-days of 6° HDT bed rest. Our results demonstrate that 1) lumbar compressibility significantly increases in Con group, whereas LBNP treadmill exercise maintains lumbar compressibility in Ex group after 28-day HDT bed rest; 2) lumbar lordosis did not change significantly with 50% BW axial load after bed rest in both Con and Ex groups; and 3) lumbar muscle strength decreases in the Con group, whereas LBNP treadmill exercise maintains lumbar strength in the Ex group, after bed rest. A significant increase in lumbar spine compressibility and decrease in lumbar muscle strength in the Con group suggests that spinal deconditioning occurs during 28-day bed rest. These results concerning spine function and muscle strength are new and important extensions of our laboratory’s previous studies of spinal length and curvature (6).

Spinal lengthening may decrease stability and increase the risk of disk injury when returning to a gravitational environment (21). The compressibility of individual intervertebral disks, Pre-BR, with 50% BW axial load in Con and Ex group Post-BR.
disks is not large enough to detect significant differences between Pre-BR and Post-BR, primarily because of limited MRI resolution. However, when the changes are summed among the lumbar disks, a significant change is detected. Longer compression times may enable researchers to detect differences in compressibility of individual intervertebral disks. However, using the compression device for longer durations at 50% BW is problematic because of subject discomfort from the spinal compression harness. A previous study found that when the spine is loaded, spinal length decreases for 3–4 h (19). Nevertheless, 15 min (total test time) of 50% BW load using the compression device allows for detectable differences in lumbar spine compressibility before and after 28 days of bed rest (18).

Forty-five minutes of supine LBNP treadmill exercise per day loads the spine and maintains lumbar disk compressibility. When supine and standing on the treadmill with the LBNP level adjusted to generate 1 BW, we estimate that LBNP treadmill exercise device provides ~60–65% BW axial load to the lumbar spine (6). Our laboratory’s previous studies documented that supine LBNP treadmill exercise prevents lumbar lengthening, increased lumbar intervertebral disk heights, and decreased lumbar lordosis after 28-day bed rest (6). The cyclical loading of the spine during treadmill exercise may help maintain intervertebral disk structure and function during long-term microgravity exposure. However, our ground-based studies probably do not fully apply to actual microgravity. Moreover, higher lumbar disk compressibility and spinal muscle weakness are only two components of spinal deconditioning with simulated microgravity. Importantly, however, based on our laboratory’s previous report (6) and the present paper, supine LBNP treadmill exercise does counteract four components of spinal deconditioning: lumbar lengthening, decreased lumbar lordosis, increased disk compressibility, and decreased back muscle strength.

LBNP treadmill exercise provides sufficient loads to back musculature to maintain back strength. The decrease in back muscle strength at 0, 12, and 24° may indicate that LBNP treadmill exercise only counteracts back muscle deconditioning for muscles activated at angles 36, 48, 60, and 72°. Previous studies found minimal decrements in back muscle volume after 17 wk of bed rest (20). Our back muscle strength data agree with the trend seen by Cao and coworkers (6) for erector muscle cross-sectional area to decrease more in control compared with exercise subjects after 28 days of bed rest. Volume and cross-sectional area of back musculature as assessed by MRI may not be sufficient to determine the status of back musculature. However, our tests using a muscle strength dynamometer provide direct information on back muscle strength.

Diurnal changes in lumbar length range from 3.2 to 8.8 mm (22) or an ~10% change in lumbar intervertebral disk height (25). There are other factors that influence intradisk pressure and spinal length such as muscle contraction or movement of the upper body. Wilke and coworkers (32) found that supine intradisk pressure was 0.11 MPa, intradisk pressure increased from 0.1 to 0.24 MPa during the night, and standing increased intradisk pressure to 0.50 MPa. However, it is unlikely that these other loads can maintain the normal diurnal loading cycle during microgravity exposure.

We did not directly measure histological or cytological changes of intervertebral disks. However, an increase in intervertebral disk compressibility suggests a change in mechanical properties of the lumbar spine. For example, an intervertebral disk that has become deconditioned with age has lower proteoglycan content, has less hydration, and is more compressible compared with a young healthy disk (1). In addition, when old and degenerated disks are loaded, less fluid exits the disk compared with a young individual’s disk (1). Diurnal body height loss is 2% of total body height in 5 yr olds, 1% in 20 yr olds, and 0.5% in 80 yr olds (10). Future animal studies may help explain how histologic and cytological changes affect disk compressibility.

Normal spine curvature is important to maintain spine physiology because it affects spine length. When standing lumbar curvature is about 60° or ~37% greater compared with sitting (~22°) (2). Our data show that with 50% BW axial load, lumbar lordosis increases only 3.5°. This small change in lumbar lordosis compared with upright standing and sitting postures suggests the decrease in lumbar length with 50% BW axial load is primarily attributed to the decrease in lumbar intervertebral disk heights as opposed to lumbar lordosis.

Disruptions in diurnal spine length variations during and after spaceflight may contribute to abnormal spinal physiology. In the present paper, we found that supine LBNP treadmill exercise provides axial loads to the lumbar spine and helps maintain two components of spinal function during 28-days HDT bed rest, namely lumbar disk compressibility and back muscle strength.

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REFERENCES


