Exercise within lower body negative pressure partially counteracts lumbar spine deconditioning associated with 28-day bed rest

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Submitted 21 December 2004; accepted in final form 7 March 2005

Cao, Peihong, Shinji Kimura, Brandon R. Macias, Toshiaki Ueno, Donald E. Watenpaugh, and Alan R. Hargens. Exercise within lower body negative pressure partially counteracts lumbar spine deconditioning associated with 28-day bed rest. J Appl Physiol 99: 39–44, 2005. First published March 10, 2005; doi:10.1152/japplphysiol.01400.2004. —Astronauts experience spine deconditioning during exposure to microgravity due to the lack of axial loads on the spine. Treadmill exercise in a lower body negative pressure (LBNP) chamber provides axial loads on the lumbar spine. We hypothesize that daily supine LBNP exercise helps counteract lumbar spine deconditioning during 28 days of microgravity simulated by bed rest. Twelve sets of healthy, identical twins underwent 6° head-down-tilt bed rest for 28 days. One subject from each set of twins was randomly assigned to the exercise (Ex) group, whereas their sibling served as a nonexercise control (Con). The Ex group exercised in supine posture within a LBNP chamber for 45 min/day, 6 days/wk. All subjects underwent magnetic resonance imaging of their lumbar spine before and at the end of bed rest. Lumbar spinal length increased 3.7 ± 0.5 mm in the Con group over 28-day bed rest, whereas, in the Ex group, lumbar spinal length increased significantly less (2.3 ± 0.4 mm, P = 0.01). All lumbar intervertebral disk heights (L5–S1, L4–5, L3–4, L2–3, and L1–2) in the Con group increased significantly over the 28-day bed rest (P < 0.05). In the Ex group, there were no significant increases in L5–S1 and L4–5 disk heights. Lumbar lordosis decreased significantly by 3.3 ± 1.2° during bed rest in the Con group (P = 0.02), but it did not decrease significantly in the Ex group. Our results suggest that supine LBNP treadmill exercise partially counteracts lumbar spine lengthening and deconditioning associated with simulated microgravity.

simulated microgravity; lumbar spine length; intervertebral disk height; spinal curvature; countermeasures

MANY ANATOMICAL AND PHYSIOLOGICAL changes occur when the human body is exposed to microgravity. These changes include cardiovascular deconditioning, loss of exercise capacity, muscle atrophy, and bone loss. Moreover, there are several reports concerning spine deconditioning during adaptation to microgravity, such as spine lengthening (4, 28, 32), intervertebral disk alterations (15), spine curvature increase (29), and back muscle atrophy (17).

Because the lumbar spine normally bears ~50% body weight (BW) during upright posture on Earth (14, 22, 23), this portion of the spine may be uniquely adapted to gravity. On Earth after overnight bed rest, lumbar length increases ~2.7 mm (15). During spaceflight, 4- to 6-cm increase of body height occurs in astronauts (4, 28, 32). Additionally, intervertebral disk volume and cross-sectional area (CSA) increase during simulated and actual microgravity (11, 15). Animal experiments document disk biochemistry and degeneration during microgravity (12, 25). Thornton and collaborators (29) found a decrease in spinal curvature with exposing to microgravity. Moreover, LeBlanc and coworkers (17) report that even short-duration spaceflight produces significant back muscular atrophy.

Due to the high cost of research during actual microgravity, bed rest is often used as an analog of microgravity to study the anatomical and physiological changes of the spine, as well as other gravity-related functions (11, 20, 24). Hutchinson and coworkers (10) document that 6° head-down tilt (HDT) bed rest increases body height. Our study used 28-day HDT bed rest to investigate lumbar spine changes during simulated microgravity.

As the duration of manned spaceflights becomes longer, it is necessary for astronauts to have an effective method to counteract spinal deconditioning. Several exercise protocols and devices are used during spaceflight, such as Mini Gym, Penguin suit, and the bungee cord harness system. However, these devices are uncomfortable or lack sufficient loads to maintain preflight musculoskeletal mass. The optimal protocol and equipment for exercise in space are still unresolved (5). Over the past 10 yr, we have developed a lower body negative pressure (LBNP) treadmill exercise system that provides both cardiovascular and musculoskeletal responses equivalent to upright exercise in gravity (3, 9, 21, 31). This exercise system also ameliorates some of the negative effects of weightlessness on exercise capacity and bone metabolism (26, 31). The present study evaluates the possible benefits of supine LBNP treadmill exercise partially counteracting lumbar spine lengthening and deconditioning associated with simulated microgravity.

METHODS

The University of California San Diego and National Aeronautics and Space Administration Ames Research Center and Johnson Space Center Institutional Review Boards approved this study, and all subjects gave informed, written consent before participation. Twelve
sets of healthy, identical twins (14 women and 10 men) participated in this study. They exhibited the following characteristics (means ± SD): age = 26 ± 4 yr, range 22–37 yr; weight = 61.7 ± 12.4 kg, range 43.7–84.1 kg; and height = 168.7 ± 10.7 cm, range 152.4 – 190.5 cm. All subjects had no previous history of back pain, back surgery, or contraindications for magnetic resonance imaging (MRI).

One subject from each set of twins was randomly assigned to an exercise (Ex) group, while their sibling served as a nonexercise, control (Con) group. All subjects remained at strict 6° HDT bed rest for 28 days, except during LBNP exercise and shower, when they were in the horizontal supine position. The subjects of the Ex group exercised in a LBNP chamber, whereas those of the Con group did not exercise. The same exercise device and protocol used in the present study were described in detail in a previous report (31). In brief, the subject was placed supine into a LBNP chamber and sealed with a flexible, neoprene waist seal (Fig. 1). LBNP (50–55 mmHg) produced footward or ground reaction force (GRF) equivalent to one BW on the subject. The shoulder straps connected to the elastic waist seal generated additional axial loads on the spine during treadmill exercise (Fig. 1). Subjects performed an interval exercise protocol for 40 min (40–80% peak oxygen consumption), followed by a 5-min period of nonexercise LBNP, 6 days/wk.

All subjects underwent MRI (1.5-T system, MAGNETOM Symphony, Siemens, Munich, Germany) in supine psoas-relaxed position before bed rest (Pre-BR) and at the end of bed rest (Post-BR). The parameters of MRI scanning 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.

MR images were analyzed by using a personal computer with software Image J 1.30V (Wayne Rasband, National Institutes of Health). Midsagittal MRI views were used to measure the entire lumbar spinal length, individual lumbar intervertebral disk heights, lumbar lordosis, and individual lumbar intervertebral angles. A transverse MRI view at L3–4 intervertebral disk level was used to measure the CSAs of the psoas and erector muscles. 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. Disk height was obtained from the average of anterior and posterior disk heights, according to the method of Dabbs and Dabbs (6) (Fig. 2A). Lumbar lordosis was defined as the angle between the upper surfaces of L1 and S1 vertebral body, according to Andersson and coworkers’ method (2) (Fig. 2B). The intervertebral angle was measured as the angle between the upper surfaces of L1 and S1 vertebral body and the next vertebral body. For example, the intervertebral L4 angle was measured as the angle between the upper surface of L4 vertebral body and the upper surface of L5 vertebral body. Positive values indicated lordosis, whereas negative values indicated kyphosis. The CSAs of the psoas and erector muscles were measured as the total muscle area on both sides of the spine at the L3–4 intervertebral disk level. Due to imperfect MR images at L3–4 disk level of one set of male and one set of female twins, their muscle CSAs were not used in data analysis.

Each spine parameter was measured twice, and the two results were averaged. If there was a difference between the two results of >10%, additional measurements were made and averaged. Repeated-measures ANOVA was performed to determine statistical significance using software SPSS 9.0 (SPSS, Chicago, IL). If ANOVA results were statistically significant, the individual groups were tested by using paired t-tests. Data are expressed as means ± SE. Significance was set at P < 0.05.

RESULTS

Lumbar spine lengthened in both Ex and Con groups over 28-day bed rest. However, the increase of lumbar length in the Ex group was significantly less than that in the Con group (P = 0.01, Fig. 3). Lumbar spine lengths were 183.0 ± 3.7 (SE) mm in the Con group Pre-BR and 186.7 ± 3.8 mm Post-BR, an increase of 3.7 ± 0.5 mm (2.0 ± 0.3% of the total lumbar length) (P < 0.001). In the Ex group, lumbar spinal lengths were 183.3 ± 4.0 and 185.6 ± 3.9 mm Pre-BR and Post-BR,
respectively, an increase of $2.3 \pm 0.4$ mm ($1.3 \pm 0.2\%$ of the total lumbar length) ($P < 0.001$).

All of the lumbar intervertebral disk heights increased significantly over 28 days of bed rest ($P < 0.05$) in the Con group (Fig. 4). The increases of the five disk heights were $0.9 \pm 0.2$ mm ($11.1 \pm 2.0\%$ of the disk height) at L5–S1, $1.4 \pm 0.1$ mm ($15.7 \pm 1.6\%$) at L4–5, $1.0 \pm 0.2$ mm ($11.5 \pm 2.2\%$) at L3–4, $0.9 \pm 0.2$ mm ($11.2 \pm 2.7\%$) at L2–3, and $0.8 \pm 0.1$ mm ($11.6 \pm 1.9\%$) at L1–2. In contrast, in the Ex group, there were no significant increases in disks L5–S1 and L4–5 over 28 days of bed rest. Although the other three intervertebral disks in the Ex group significantly increased in heights over 28 days of bed rest, they tended to be lower than those in the Con group. The increases were $0.5 \pm 0.2$ mm ($5.9 \pm 2.5\%$ of the disk height) at L3–4, $0.6 \pm 0.2$ mm ($8.0 \pm 2.6\%$) at L2–3, and $0.7 \pm 0.2$ mm ($9.85 \pm 3.1\%$) at L1–2, respectively.

In the Con group, lumbar lordosis (L1–S1) were $51.1 \pm 3.6^\circ$ Pre-BR and $47.8 \pm 3.5^\circ$ Post-BR (Fig. 5), a significant decrease of $3.3 \pm 1.2^\circ$ ($P = 0.02$). In the Ex group, lumbar lordosis (L1–S1) were $52.0 \pm 3.1^\circ$ Pre-BR and $50.1 \pm 2.9^\circ$ Post-BR. The decrease of $1.9 \pm 1.1^\circ$ was not significant ($P = 0.11$).

The L3–4 intervertebral angle decreased significantly in the Con group from $9.9 \pm 1.3$ to $7.2 \pm 1.4^\circ$ over 28-day bed rest ($P = 0.001$) (Fig. 6). In the Ex group, the L3–4 intervertebral angle also significantly decreased from $9.6 \pm 0.9$ to $7.9 \pm 0.8^\circ$ over 28-day bed rest ($P = 0.004$). There were no significant changes in the other four intervertebral angles over 28 days of bed rest. Moreover, there were no significant differences in all intervertebral angles between the Con and Ex groups over 28-day bed rest.

The CSAs of erector muscles at L3–4 intervertebral disk level were $5,378 \pm 701$ mm$^2$ in the Con group Pre-BR and $4,910 \pm 602$ mm$^2$ Post-BR, a decrease of $468 \pm 112$ mm$^2$.
(7.7 ± 1.3% of the CSA) (P < 0.01). In the Ex group, the CSAs of erector at L3–4 disk level were 5,167 ± 615 and 4,795 ± 555 mm², respectively, a decrease of 372 ± 69 mm² (6.8 ± 0.7% of the CSAs of erector) (P < 0.01). There were no significant differences between the Con and Ex groups. The CSAs of psoas muscles at L3–4 disk level were 2,300 ± 286 mm² in the Con group Pre-BR and 2,335 ± 303 mm² Post-BR. In the Ex group, the CSAs of psoas muscles at L3–4 disk level were 2,215 ± 271 and 2,227 ± 264 mm², respectively. No significant changes in CSAs of psoas muscles were found in either the Con or Ex group over 28-day bed rest.

DISCUSSION

Referring back to our initial hypothesis, we find that daily supine LBNP treadmill exercise maintains normal diurnal lumbar spine length change and partially diminishes the lumbar spine deconditioning associated with 28-day bed rest. LBNP exercise helps to 1) reduce lumbar lengthening, 2) counteract intervertebral lumbar disk thickening, and 3) prevent the loss of lumbar lordosis associated with 28-day microgravity simulated by HDT bed rest.

The LBNP exercise protocol provides 60–65% BW axial loads on lumbar spine during supine exercise. With a pressure differential of 50–55 mmHg between the inside and outside LBNP chamber, the subject is exposed to one BW footward force or GRF. We believe the GRF over the body is composed of three components (Fig. 1). The first component is the suction force produced by the elastic waist seal around the hip due to negative pressure on the seal. The second component is the axial force over the whole body produced by negative pressure on the subject, which is equivalent to the CSA of the body’s waist multiplied by the negative pressure. The third is the force generated by the shoulder straps that connect to the seal. The latter two components provide axial loads on lumbar spine. In our study, the negative pressure in the chamber was 50–55 mmHg. The waist areas of subjects were 400–500 cm². While exercising, the shoulder straps provide 10–15% BW force on the shoulder. Therefore, we calculate the overall axial loads on lumbar spine to be 60–65% BW.

On Earth, the lumbar spine is exposed to 50% BW axial loads during upright posture (14, 22, 23) for 12–16 h/day. LeBlanc and coworkers (15) find that the lumbar spine lengthens 2.7 mm after overnight bed rest. Kimura and collaborators (14) report that lumbar spinal length is reduced by 2.5 mm (1.3% of total lumbar spinal length) with 50% BW loads compared with a no-load condition. Our LBNP exercise system provides 60–65% BW axial loads over the lumbar spine. It is noteworthy that the loading time of our exercise protocol (45 min/day) is much less than the normal diurnal loading time associated with upright seated and standing postures (~16 h/day), and the lumbar axial loads of our exercise system are more than the normal upright loads of 50% BW on Earth. Our study finds that, in the Ex group, the lumbar spinal lengthening is 2.3 mm (1.3% of the total lumbar length), which is similar with the normal diurnal lumbar lengthening.

Lengthening of the whole spine may induce back pain during the first few days of spaceflight (27, 32). This conclusion is based on the assumption that the spine lengthening stretches the spinal cord, disk anulus, intervertebral muscles, spinal ligaments, and facet joint capsules. Our data indicate that daily supine LBNP exercise helps prevent abnormal lumbar lengthening during bed rest. These results suggest that the
LBNP exercise may decrease the back pain in actual microgravity, although we have no such pain data from our HDT bed-rest simulation.

During the chronic unloading of long-term spaceflight, intervertebral disk expansion is potentially a significant problem for astronauts (8, 11, 15). The intervertebral disk is the largest avascular structure in the human body, and the disk’s cellular metabolism depends on the fluid flux into and out of the disk (30). On Earth, the diurnal change of posture and spine movement (flexion/extension) alters compressive loads on disks, moving fluid into and out of the disk. During upright posture or spinal flexion, the intervertebral disk is compressed (8). Fluid is driven out of the nucleus pulposus, and metabolic waste products are expelled. In the supine position or spinal extension, the intervertebral disk is unloaded, causing fluid influx into the nucleus pulposus and facilitating transport of nutrients into the disk. During long-term bed rest or spaceflight, owing to lack of loading force along the vertical body axis, the intervertebral disk probably expands until a new equilibrium is attained whereby swelling pressure within the disk matches external loads (8). The diurnal cycle to expel wastes and imbibe nutrients may thus be seriously deficient (1, 8). This might inhibit the metabolism of nucleus pulposus cells and, consequently, produce early degenerative changes in intervertebral disks. Some animal data showed that proteoglycans decreased, and the collagen-to-proteoglycan ratio of intervertebral disks increased in space-flown animals (12, 25). No such biochemical and cytological studies are available for human intervertebral disks during microgravity or long-term bed rest, although some studies show that disk height, CSA, and volume all increase (11, 15). Supine LBNP treadmill exercise provides axial loads on lumbar intervertebral disk to simulate upright loading cycles. Gait biomechanics impose some dynamic cyclical loads on the spine to simulate loads of daily activity on intervertebral disks during upright exercise on Earth. Such loads help maintain normal disk metabolism, structure, and function. Our data indicate that the exercise system prevents L3–S1 and L4–L5 disk heightening and diminishes heightening of the other disks. From a scientific viewpoint, it may be worthwhile to include another experimental group with LBNP alone (no treadmill exercise). However, such a group does not provide the same loads on the lumbar spine compared with our dynamic LBNP treadmill exercise group (Fig. 1). Moreover, it is difficult to add another group of 12 subjects of the same genotype for comparison to our LBNP Ex and Con groups. We had great difficulty recruiting identical twins. Recruiting identical triplets would be even more difficult to undertake for a study of three groups with the same genotype.

Spinal curvature is diminished with the loss of axial spinal loads. For example, Thornton et al. (29) report that the decrease of spinal curvature in space is due to the lack of axial loads. During ground-based MRI studies of gravity effects on the spine, Lee and coworkers (18) found that spinal curvature decreased with reduced axial loading. The spinal curvature and intervertebral disk health are interrelated. Farfan and colleagues (7) note an association between decreased lumbar curve and increased disk degeneration. In a study of osteoporotic patients by Itoi (13), decreased curvature was associated with increased low back pain. Our results indicate that lumbar lordosis is reduced after 28-day HDT bed rest in the Con group. In LBNP Ex group, no significant lordosis change occurs over 28-day HDT bed rest. This finding suggests that LBNP exercise may help ameliorate the negative effects of spaceflight on spinal curvature. Lumbar lordosis is the sum of the lumbar intervertebral angles from L1 to L5. Our study shows that the individual lumbar intervertebral angles tend to decrease after 28-day bed rest, although not significantly (except for L3–4) in Con and Ex groups. We think this is because such changes are simply too small relative to the sensitivity of our MR images.

Most astronauts experience muscle atrophy in microgravity (17). It is shown that 4–5 wk of bed rest produce ~10% loss in muscle mass in the lower limbs (16). LeBlanc and coworkers (17) find that back muscle volume decreases by 10% after 8-day shuttle flight. Our study shows that, at L3–4 disk level over 28-day HDT bed rest, erector muscle CSA decreases by 7.7 and 6.8% in the Con and Ex group, respectively. We find no significant difference in the erector muscle atrophy between Con and Ex groups, suggesting that supine LBNP treadmill exercise had no significant effect on spinal back muscle atrophy during 28-day bed rest.

The limitations of the present study should be noted. For example, HDT bed rest does not completely unload the lumbar spine compared with actual microgravity. Because of the nature of bed rest in 6° HDT, the gravity vector is still present. Thus the weight of the lower body provides an axial load on the lumbar spine during HDT bed rest. This may explain why, in the Con group, the spinal lengthening during bed rest is less than the lengthening during spaceflight (4, 27, 28). Another limitation of this study is that LBNP exercise cannot simulate daytime spinal movements such as spinal flexion and extension, which are important to maintain intervertebral disk metabolism. In our Earth-based LBNP exercise protocol, a back support is needed to bear the BW that limits spinal movement during exercise. Therefore, LBNP exercise in microgravity may yield more movement on the spine because the back support is unnecessary in microgravity. Additionally, the heightening of individual intervertebral disks is small, and, therefore, it is more appropriate to focus on the total lumbar spinal length increase.

In summary, supine LBNP treadmill exercise provides axial loads on the lumbar spine and helps counteract some of the lumbar deconditioning of HDT bed rest observed in Con subjects. Therefore, this countermeasure has the potential to assist astronauts in maintaining normal spine structure and function during spaceflight.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the enthusiastic participation of our outstanding twins and the staff working at University of California-San Diego General Clinic Research Center (UCSD GCRC).

GRANTS

This study was supported by National Aeronautics and Space Administration Grant NAG9–1425 and National Institutes of Health Grant M01RR-00827 to the UCSD GCRC.

REFERENCES

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J Appl Physiol • VOL 99 • JULY 2005 • www.jap.org