SPINE Volume 33, Number 5, pp E121–E131

Resistive Simulated Weightbearing Exercise With Whole Body Vibration Reduces Lumbar Spine Deconditioning in Bed-Rest

Daniel L. Belavý, PhD,*†‡ Julie A. Hides, PhD,‡|| Stephen J. Wilson, PhD,† Warren Stanton, Fernando C. Dimeo, PhD,§ Jörn Rittweger, PhD,¶ Dieter Felsenberg, PhD,* and Carolyn A. Richardson, PhD‡

Study Design. Randomized controlled trial.

Objective. Determine the effectiveness a resistive exercise countermeasure with whole-body vibration in relation to lumbo-pelvic muscle and spinal morphology changes during simulated spaceflight (bed-rest).

Summary of Background Data. Spinal lengthening, flattening of the spinal curves, increases in disc size, and muscle atrophy are commonly seen in spaceflight simulation. This may represent a risk for low back injury. Consideration of exercise countermeasures against these changes is critical for success of long-term spaceflight missions.

Methods. Twenty healthy male subjects underwent 8-weeks of bed-rest with 6-months follow-up and were randomly allocated to an inactive control or countermeasure exercise group. Magnetic resonance imaging of the lumbo-pelvic region was conducted at regular timepoints during and after bed-rest. Using uniplanar images at L4, cross-sectional areas of the multifidus, lumbar erector spinae, quadratus lumborum, psoas, anterolateral abdominal, and rectus abdominis muscles were measured. Sagittal scans were used to assess lumbar spine morphology (length, sagittal disc area and height, and intervertebral angles).

Results. The countermeasure group exhibited less multifidus muscle atrophy ($P = 0.024$) and its atrophy did not persist long-term as in the control group (up to 3-months; $P < 0.006$). Spinal lengthening ($P = 0.03$) and increases in disc area ($P = 0.041$) were also reduced. Significant partial correlations ($P < 0.001$) existed between spinal morphology and muscle cross-sectional area changes.

Conclusion. The resistive vibration exercise countermeasure reduced, but did not entirely prevent, multifidus muscle atrophy and passive spinal tissue deconditioning during bed-rest. Atrophy of the multifidus muscles was persistent long-term in the inactive subjects. Future work could consider closer attention to spinal posture during exercise and optimizing exercise dose.

Key words: microgravity, spaceflight, Berlin Bed-Rest Study, multifidus muscle, magnetic resonance imaging, back pain, intervertebral disc, abdominal, erector spinae. **Spine 2008;33:E121–E131**

With space agencies and governments striving for manned missions to Mars, an important research question is the development of appropriate countermeasures to maintain the differing body systems to function on landing. The lumbar spine forms an important part of the antigravity kinetic chain of the human body, stretching from foot to head. Injury to the lumbar spine with subsequent disability, such as due to a disc prolapse, on landing could threaten mission success. The focus of countermeasure development to date, however, has been predominately been on the leg and thigh musculature,[1–6] with only very recent works considering the lumbar spine.[7,8]

A number of studies have used magnetic resonance imaging (MRI) to investigate the lumbar spine in spaceflight and simulation (*e.g.*, bed-rest[9]). MRI studies of the morphology of lumbar spine disc and joint structures during bed-rest have found increased disc height, loss of lumbar lordosis, spinal lengthening, and increased spinal compressibility.[7,8] Studies of the lumbo-pelvic (LP) muscle systems have found atrophy of the spinal extensor musculature, with no change in the psoas muscle.[7,10,11] More detailed work,[12] however, found that spinal extensor muscle atrophy was predominately localized to the multifidus (MF) muscle, a muscle important for spinal stabilization,[13,14] with increased cross-sectional area (CSA) observed in the abdominal muscles. This pattern of change in disc and joint structures, suggestive of viscoelastic changes in passive tissues, combined with deconditioning of the muscular systems important in joint stabilization, could contribute to an increased risk of spinal injury after spaceflight. It is therefore highly rele-

From the *Zentrum für Muskel- und Knochenforschung, Charité Campus Benjamin Franklin, Hindenburgdamm, Berlin, Germany; †School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Australia; ‡Division of Physiotherapy, School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia; §Department of Sports Medicine, Charité Universitätsmedizin Berlin, Hindenburgdamm, Berlin, Germany; ¶Institute for Biophysical and Clinical Research into Human Movement, Manchester Metropolitan University, Hassall Rd, Alsager, Cheshire, England; and ||Mater Misericordiae Health Services Brisbane Limited, South Brisbane, Queensland, Australia.

Acknowledgment date: September 6, 2007. Revision date: October 11, 2007. Acceptance date: October 29, 2007.

The manuscript submitted does not contain information about medical device(s)/drug(s).

Institutional funds were received in support of this work. No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

The Berlin Bed-Rest Study was supported by grant 14431/02/NL/SH2 from the European Space Agency. The Berlin Bed-Rest Study was also sponsored by the Charité Campus Benjamin Franklin, DLR (German AeroSpace), MSD Sharp and Dohme, Lilly Germany, Servier Germany, Hoffmann-LaRoche, Siemens, Novartis, Danone and Seca. Daniel L. Belavý was supported by a postdoctoral fellowship from the Alexander von Humboldt Foundation.

Address correspondence and reprint requests to Daniel L. Belavý, Zentrum für Muskel- und Knochenforschung, Charité Campus Benjamin Franklin, Hindenburgdamm 30, 12200 Berlin, Germany; E-mail: belavy@gmail.com

Figure 1. Countermeasure exercise during bed-rest. Subjects were required to perform leg exercises against a resistive force transmitted *via* belts at the waist and shoulders and *via* handgrips. Vibratory stimuli in the legs are generated by rotation of the suspended platform around a vertically oriented axis. Axial loading of the spine occurs *via* the shoulder straps.

vant to consider exercise countermeasure development to ameliorate these changes.

An intuitive approach to spaceflight countermeasure development would suggest the use of resistive exercise. Similar to physical activity under Earth's gravitational field, resistive exercise with exercises simulating antigravity weightbearing requires greater activity in the extensor musculature. Recently, however, vibration exercise has received greater attention in exercise and rehabilitation. A number of studies have shown vibration exercise to facilitate neuromuscular performance,[15–19] but particularly at the low back, facilitate LP proprioception[16] and be beneficial in the treatment of low back pain.[20] Vibration exercise is thought to stimulate muscle activity *via* the muscle spindle system.[21,22] Vibratory stimuli, although attenuated, are transmitted to the lumbar spine.[23] It has been suggested that vibration, in combination with resistive exercise could also have positive effects on muscle atrophy and bone loss in bed-rest as a ground based model for spaceflight.[24]

The aim of this study was to consider the efficacy of a resistive vibration exercise countermeasure during bed-rest on MRI measures of passive lumbar spinal structures (spinal morphology; measured as lumbar disc area and height, lordosis angle, and spinal length) and the active muscle system of the lumbar spine (as measured by CSA of the LP muscles) during bed-rest.

Materials and Methods

Bed-Rest Protocol

The "Berlin Bed-Rest Study" was undertaken at the Charité Campus Benjamin Franklin Hospital in Berlin, Germany, from February 2003 to June 2005. Twenty male subjects underwent 8-weeks of strict bed-rest with a subsequent 6-month follow-up recovery period. The bed-rest protocol, and inclusion and exclusion criteria, is discussed in detail elsewhere.[24] In brief, however, subjects were randomly allocated to either a group that remained inactive (controls, CTRL) or a group that underwent a whole body resistive vibration exercise countermeasure program (RVE group) using the Galileo Space exercise device (Novotec Medical, Pforzheim, Germany). One subject (RVE group) became claustrophobic in the MRI scanner and the desired imaging could not be performed. This study is therefore based on the remaining 9 RVE [age: 31.4 (3.2) years, height: 182 (9) cm, weight: 78.4 (12.5) kg] and 10 CTRL [age: 33.4 (6.6) years, height: 185 (7) cm, weight: 79.4 (9.7) kg] subjects.

Horizontal bed-rest was employed, though subjects were permitted to be positioned in up to 30 degrees head-up tilt for recreational activities during daylight hours (such as watching television). Subjects performed all hygiene in the supine position and were discouraged from moving excessively or unnecessarily. Force sensors placed in the bed supports and video surveillance permitted monitoring of subjects' activities. The institutional ethics committee approved this study and subjects gave their informed written consent.

Countermeasure Exercise

RVE subjects underwent 2 exercise sessions daily (morning and afternoon) of approximately 5 to 10 minutes each during bed-rest. A detailed description of the exercise protocol has been

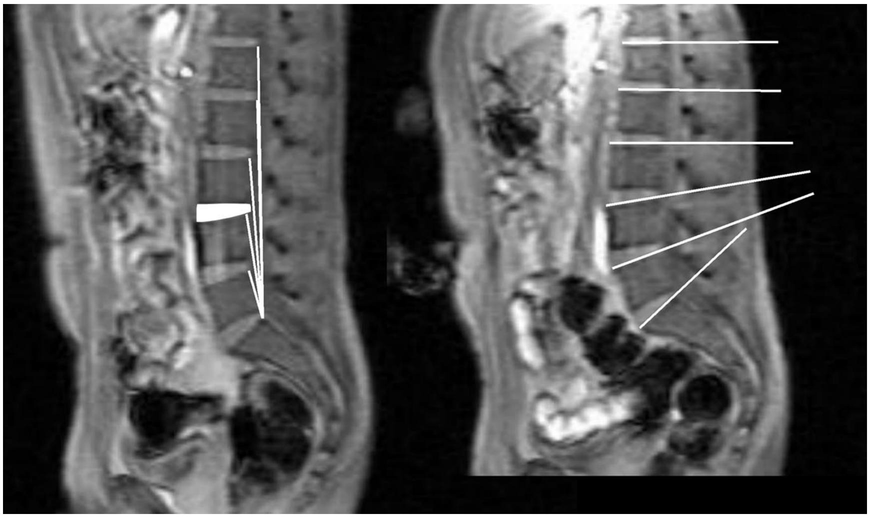

Figure 2. Measurements of spinal morphology. Spinal length (left) was measured between each lumbar vertebra. Sagittal plane disc area of each lumbar intervertebral disc was also measured. Disc height was calculated as the height of a rectangle fitted to the area region of interest. Intervertebral angle was calculated between lines drawn at the superior border of each vertebra (right). Figure at left during bed-rest, postbed-rest at right in the same subject. Note the shortening of the spine after bed-rest, decrease in disc size, and accentuation of the spinal curvature.

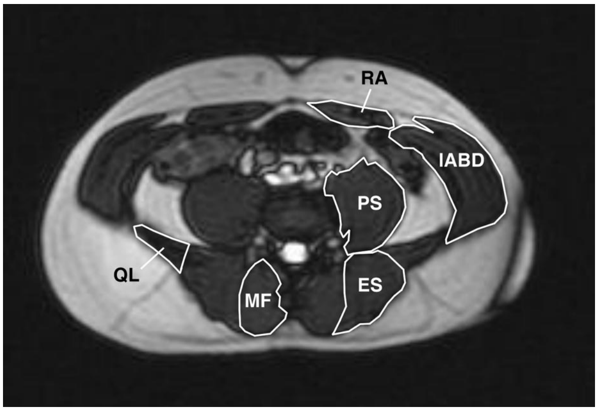

Figure 3. Lumbar muscle cross-sectional area measurements. RA indicates rectus abdominis muscle; IABD, anterolateral abdominal muscles (external oblique, internal oblique, and transversus abdominis muscles); QL, quadratus lumborum; PS, psoas muscle; MF, multifidus muscle; LES, lumbar erector spinae.

published elsewhere.[24] In brief, while the subjects were placed in supine position (Figure 1), they placed their feet on a suspended vibrating platform (frequency range: 19–26 Hz, amplitude = approximately 3.5–4 mm). An axial force (between 1.2 and 1.8 times body weight) was placed through the subjects' trunk and spine *via* elastic shoulder straps. A belt was also attached around the pelvis and hand-grips attached to the frame from which the vibrating platform was suspended. Morning and afternoon exercise sessions were performed. The exercises performed were: squats (from 90 degrees of knee flexion to near full extension), heel raises (with the knees in near extension, heels raised into ankle plantarflexion) and toe raises (with the knees in near extension, forefoot raised into ankle dorsiflexion) against the platform. Each exercise was performed for more than 60 seconds. In morning sessions, subjects also performed 10 repetitions of "explosive kicks" (explosive pushes against the vibrating platform from near full knee and hip flexion) at intervals of 10 seconds. Vibration frequency was increased if the subject could perform an exercise for more than 100 seconds. During afternoon sessions, subjects exercised at only 60% to 80% of the static force used in the morning sessions.

Table 2. Baseline Lumbo-Pelvic Muscle Cross-Sectional Area at the Fourth Lumbar Vertebra

	Subject-Group	
Muscle	CTRL	RVE
Lumbar erector spinae	16.1 (0.6)	16.5 (0.7)
Multifidus	8.4 (0.3)	8.5 (0.4)
Antero-lateral abdominals	27.6 (1.4)	27.5 (1.4)
Psoas	16.2 (0.8)	18.2 (1.1)
Quadratus lumborum	7.0 (0.2)	7.3 (0.4)
Rectus abdominis	7.3 (0.4)	6.5 (0.3)

Values are mean (SD) cross-sectional area in cm^2.
CTRL indicates inactive control group; RVE, resistive vibration exercise group.

MRI Protocol

Baseline MR scanning was conducted on the first day of bed-rest (BR1) and then at 2-week intervals (BR14, BR28, BR42, and BR56) through to the end of the bed-rest period. During the follow-up (recovery, R+) period, scanning was conducted on the 4th day of follow-up (R + 4), and then at regular intervals (R + 14, R + 28, R + 90) through to 180 days after the bed-rest period (R + 180).

Subjects were positioned on the scanning bed in supine with their knees and hips supported in slight flexion by a pillow. Sagittal (for spinal morphology measurements) and transverse MR images (LP muscle CSA measurements) were acquired using a 1.5 Tesla Magnetom Vision system (Siemens, Erlangen, Germany). Sagittal spinal scans were acquired from the first lumbar (L1) vertebra to sacrum (3 slices, TruFisp sequence, thickness = 10 mm; interslice distance = 10 mm, TR = 25.0, TE = 6.0 milliseconds, FA = 30 degrees, image matrix of 128 × 128 interpolated to 256 × 256). Ten transverse scans centered at the L4 vertebra were subsequently acquired (fast gradient recalled echo sequence, thickness = 8 mm; interslice distance = 0.5 mm, TR = 4.8, TE = 2.3 milliseconds, FA = 70 degrees, image matrix of 128 × 128 interpolated to 256 × 256). Transverse scans of the LP muscles required 23 seconds, which was within the breathe-hold tolerance of all subjects. Images were stored for offline analysis.

Table 1. Baseline (First Day of Bed-Rest) Spinal Morphology in Each Subject-Group

	Spinal Morphology Variable			
Vertebral Level	Spinal Length (mm)	Sagittal Disc Area (mm^2)	Disc Height (mm)	Intervertebral Lordosis Angle (°)
CTRL				
L1	174.1 (3.1)	187.3 (18.5)	9.5 (2.0)	0.1 (1.3)
L2	138.1 (7.1)	240.1 (56.7)	9.6 (2.4)	0.8 (2.1)
L3	103.1 (7.2)	331.2 (70.0)	11.0 (2.0)	4.2 (1.7)
L4	67.7 (4.2)	339.7 (88.9)	14.8 (3.1)	11.9 (2.4)
L5	32.3 (1.8)	335.3 (70.1)	24.8 (3.1)	23.2 (3.5)
RVE				
L1	171.2 (11.4)	191.3 (49.6)	8.9 (2.2)	−0.3 (1.1)
L2	138.2 (8.5)	249.2 (50.0)	9.6 (2.4)	1.5 (1.7)
L3	103.9 (5.5)	301.5 (51.3)	10.3 (1.6)	5.1 (2.7)
L4	68.1 (3.5)	336.6 (68.6)	15.6 (3.2)	11.7 (4.1)
L5	32.2 (1.8)	310.9 (66.6)	25.3 (5.8)	25.1 (4.2)

Values are mean (SD).
Spinal length, L1 refers to distance between L1 and S1 vertebral bodies; Disc area and height, L1 refers to intervertebral disc between L1 and L2; Intervertebral lordosis angle, L1 refers to lordosis between L1 and L2 vertebrae; CTRL, inactive control group; RVE, resistive vibration exercise group.

Image Measurements

For measurements of spinal morphology, if a true sagittal image was not obtained, up to 3 off-center images were analyzed and the results averaged. Similarly, if the transverse images were not placed at the center of the L4 vertebral body, 2 slices superior and inferior to the target position were chosen and measurements were averaged. ImageJ (Ver. 1.36b, http://rsb.info.nih.gov/ij/) was used for MR image analysis. To ensure

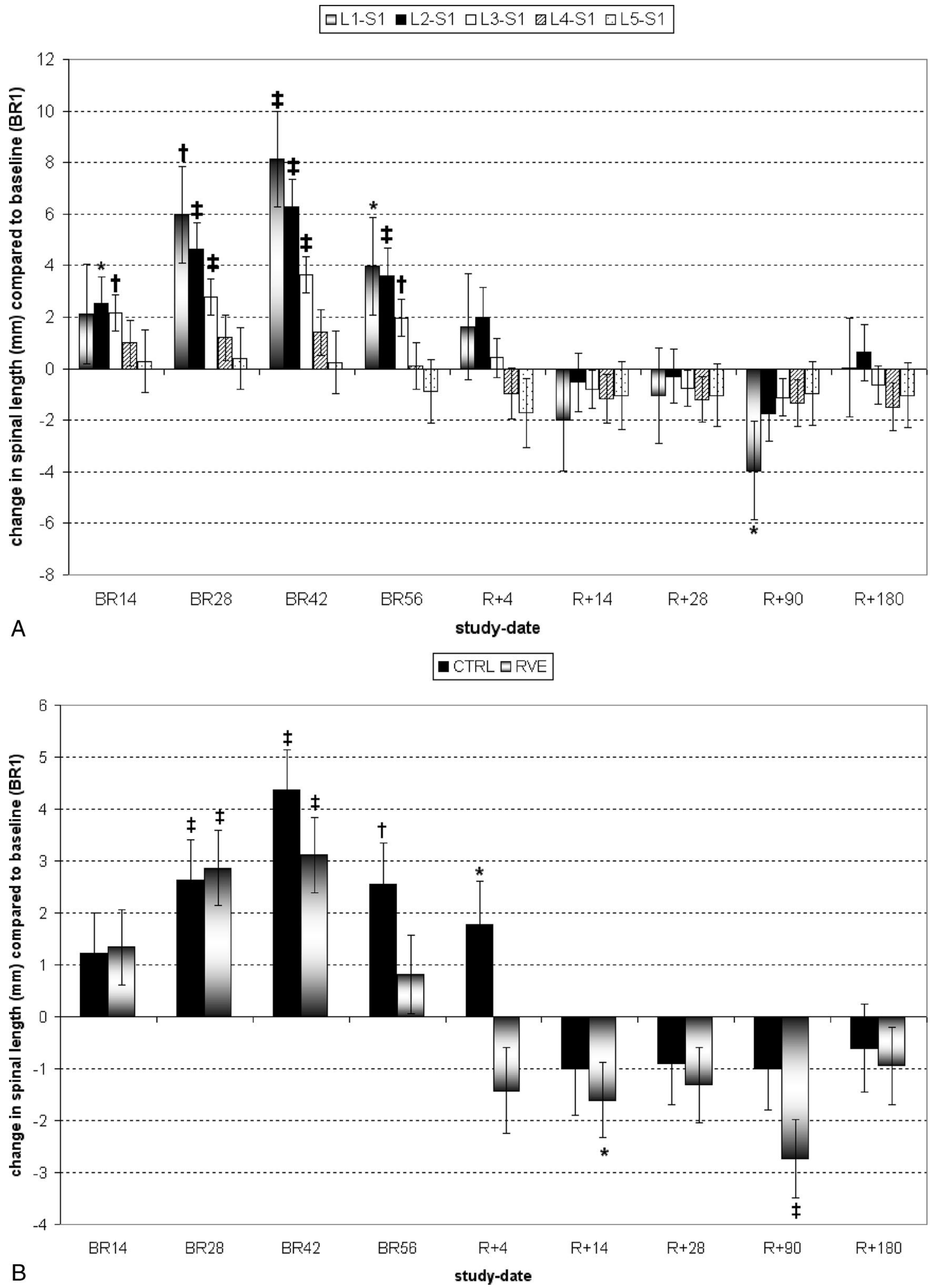

Figure 4. **A, B** Change over study-date in lumbar spinal length measured (**A,**) at each vertebral level and (**B,**) the different responses of the 2 groups. Error bars represent standard error of the mean difference to baseline (BR1) values. L1–S1 implies distance between first lumbar and first sacral vertebrae. BR indicates day of bed-rest; R+, day of recovery; CTRL, inactive control group; RVE, resistive vibration exercise group. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

measurer blinding to study time-point and subject group, each image was assigned a random number (www.random.org).

The following measurements of spinal morphology were made on each sagittal plane image (Figure 2):

1. Lumbar spinal length: distance between the dorsorostral corners of S1 and the L1, L2, L3, L4, and L5 vertebral bodies.
2. Sagittal disc area: from L1 through to S1.
3. Disc height: as the height of a rectangle fitted to the region of interest in area measurements (L1–S1).
4. Intervertebral angles: between each adjacent vertebra L1 through to S1.

Bilateral CSA measurements of the following LP muscles were conducted on each transverse plane image (Figure 3): lumbar MF, lumbar erector spinae (LES; iliocostalis lumborum pars lumborum and longissimus thoracis pars lumborum), quadratus lumborum (QL), psoas (Ps), rectus abdominis (RA), and anterolateral abdominal muscles (lABD; external oblique, internal oblique, transversus abdominis). To accurately delineate MF and the more laterally placed longissimus muscle, the fascial border[25] (obscured by the lines in Figure 3) separating these 2 muscles was used. Left- and right-sided measurements were averaged before statistical analysis. The same operator conducted all MR image analyses.

Data Processing and Statistical Analyses

Subject age, height, and weight were included in all analyses. Linear mixed-effects models[26] in the "R" statistical environment (version 2.4.1, www.r-project.org) with subsequent analysis of variance were used to examine changes in each of the spinal morphology variables (spinal length, sagittal disc area, disc height, and intervertebral angles) and CSA of each of the LP muscles. In analyses of spinal morphology, factors of intervertebral level, subject-group, study-date, and up to a 3-way interaction between these variables were included.

To examine the relationship between spinal morphology and LP muscle CSA, partial correlation analyses (controlling for study-date and subject age, height, and weight) were performed. The summary spinal morphology variables spinal length L1–S1, average disc area, average disc height, lumbar lordosis L1–S1, and LP muscle CSA were included in these analyses.

In analysis of LP muscle CSA, to control for the potential influence of changes in spinal morphology, spinal length L1–S1, average disc area, average disc height, lumbar lordosis L1–S1 were included in the linear mixed-effects models. Factors of subject-group and study-date including their 2-way interaction were included.

An α of 0.05 was taken for statistical significance. For the spinal morphology and LP muscle CSA data, as multiple imaging sessions were undertaken on the same subjects, we looked for consistent significant differences across time points. For correlation analyses, however, an α of 0.01 was used.

Results

Tables 1 and 2 list, respectively, the baseline (BR1) values of the spinal morphology variables (spinal length, disc area, disc height, and intervertebral angle) and LP muscle CSA values in each subject-group. No baseline differences existed between groups for any of the spinal

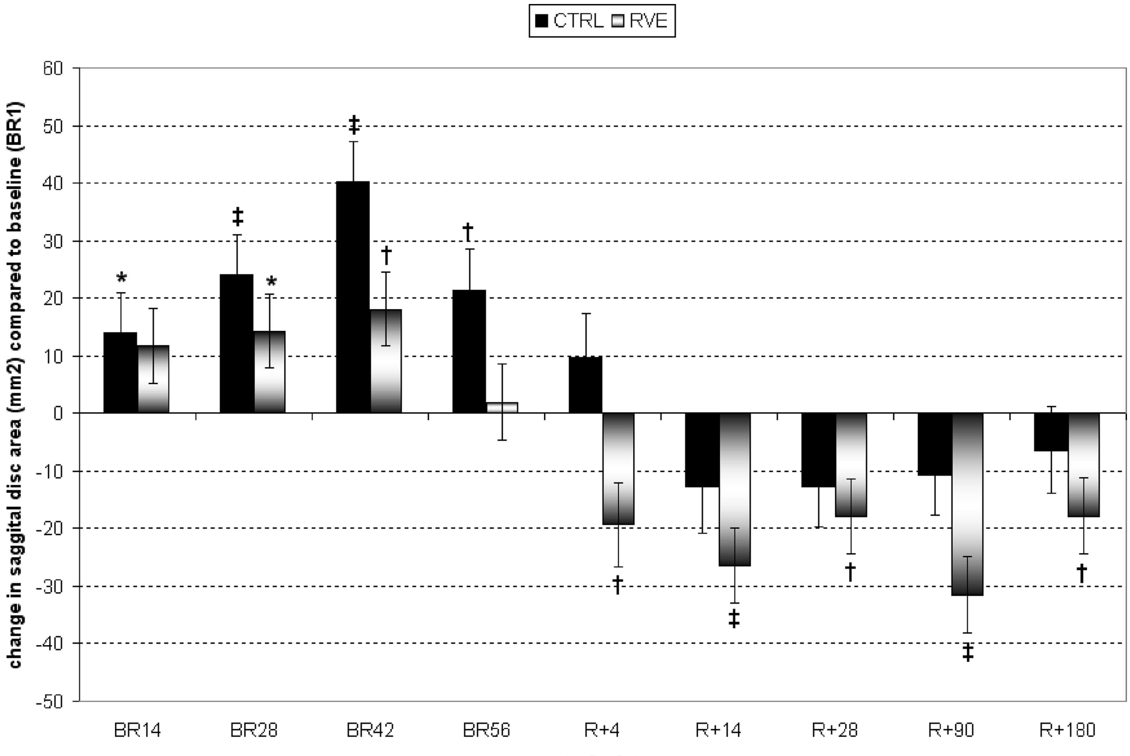

Figure 5. Sagittal plane lumbar disc area during bed-rest and recovery. No significant differences between vertebral levels, therefore values are pooled. Error bars represent standard error of the mean difference to baseline (BR1) values. BR indicates day of bed-rest; R+, day of recovery; CTRL, inactive control group; RVE, resistive vibration exercise group. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

morphology variables (P all >0.20), but the RVE subjects showed larger psoas muscle CSA at baseline (t = 3.5, P = 0.0005). This was not the case for the other LP muscles (P all >0.21).

Spinal Morphology

Analysis of changes in spinal length showed, as expected differences between vertebral levels (F = 5329.6, P < 0.0001; Table 1). Strong effects existed for changes over

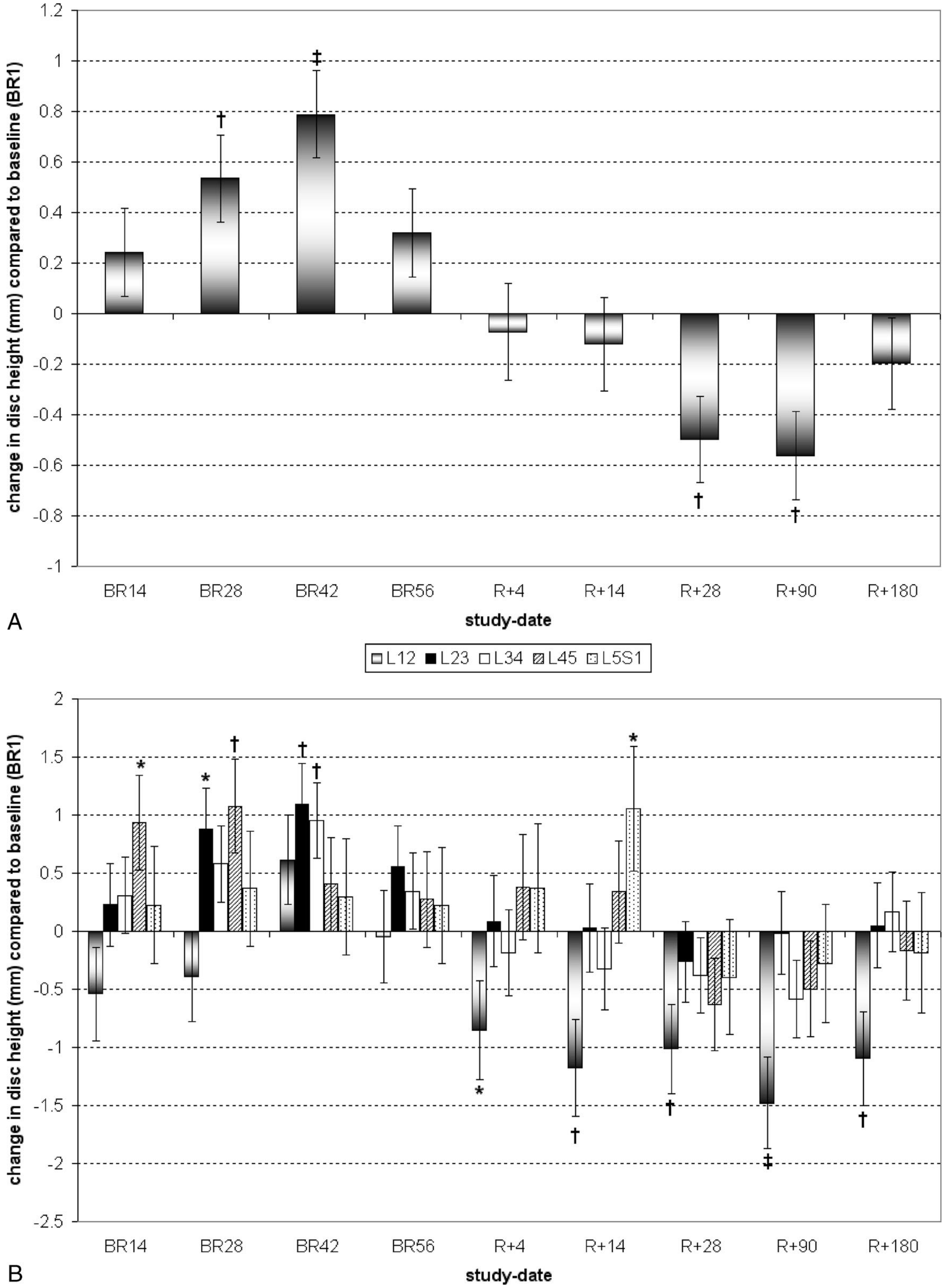

Figure 6. **A, B** Lumbar disc height during bed-rest and recovery (**A,**) pooled and (**B,**) separated for each vertebral level. No significant differences between subject-groups, therefore values are pooled. Error bars represent standard error of the mean difference to baseline (BR1) values. BR indicates day of bed-rest; R+, day of recovery; L12, intervertebral disc between first and second lumbar vertebrae; L5S1, intervertebral disc between 5th lumbar vertebra and sacrum. *P < 0.05; †P < 0.01; ‡P < 0.001.

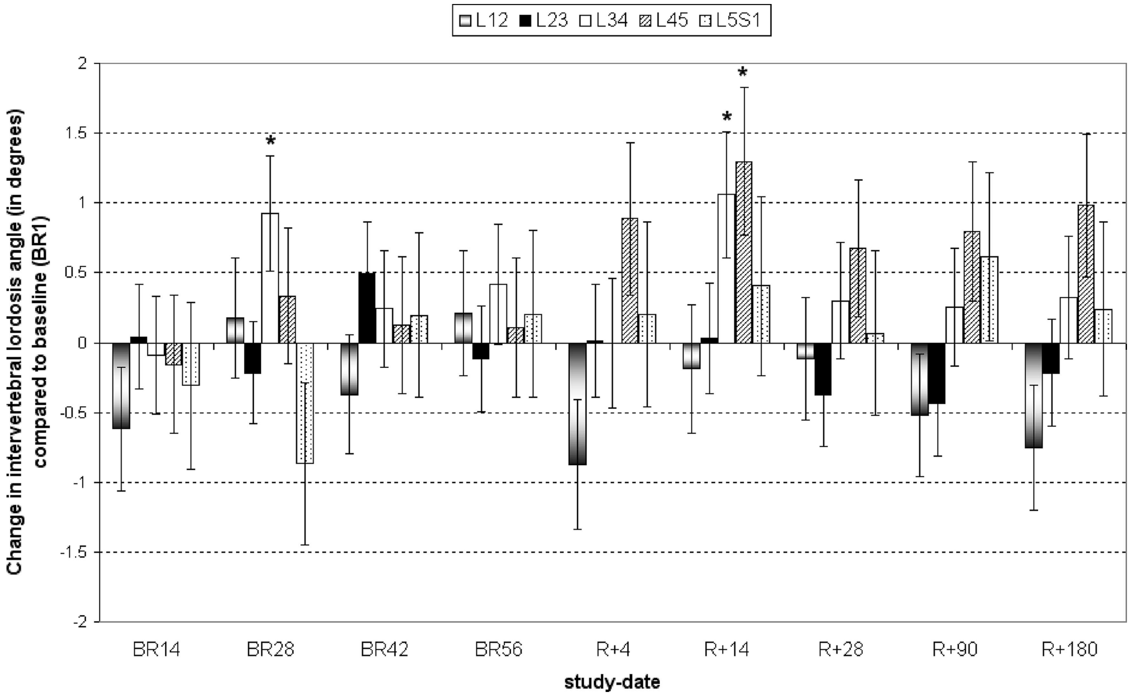

Figure 7. Lumbar intervertebral angles during bed-rest and recovery. No significant differences between subject-groups, therefore values are pooled. Error bars represent standard error of the mean difference to baseline (BR1) values. BR indicates day of bed-rest; R+, day of recovery; L12, intervertebral angle between 1st and 2nd lumbar vertebra. *$P < 0.05$.

study-date ($F = 28.3$, $P < 0.0001$) with the length changes varying for each of the vertebral levels ($F = 3.0$, $P < 0.0001$; Figure 4A). Analysis suggested the 2 subject groups responded differently over time (group × study-date: $F = 2.1$, $P = 0.030$; Figure 4B), but this effect did not extend to the different vertebral levels (F all <0.4, P all >0.597). Generally, spinal length increases during bed-rest, particularly between the L1–S1 vertebrae, which encompasses all the lumbar intervertebral discs. After bed-rest, the spine shortens and remains consis-

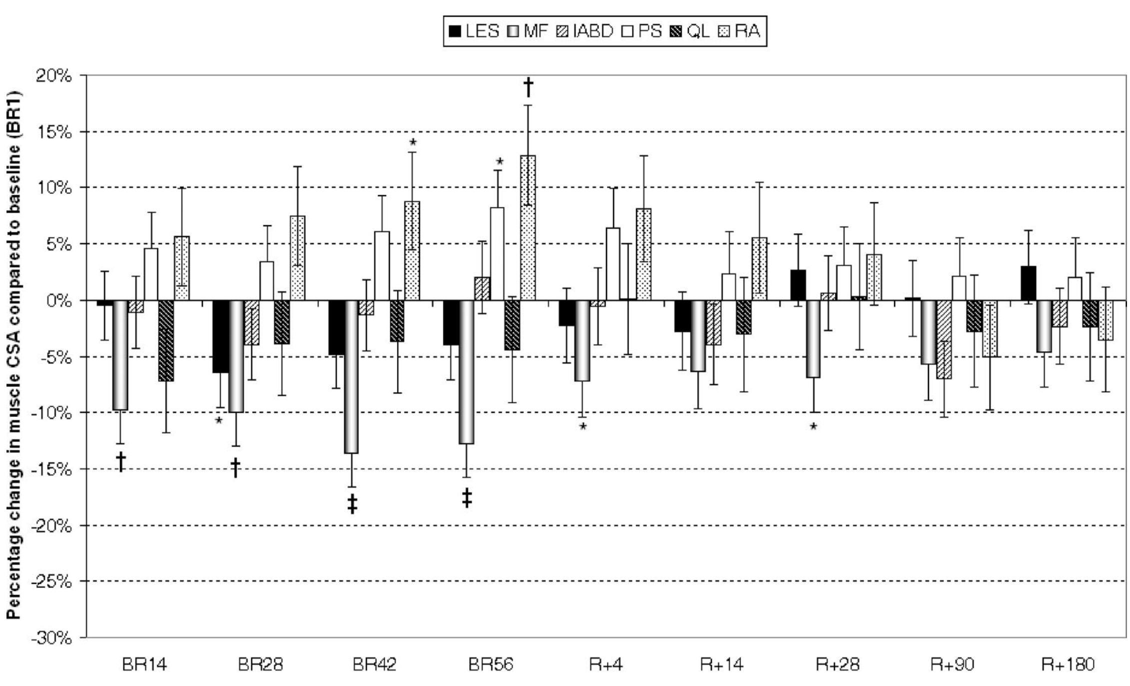

Figure 8. Change in lumbo-pelvic muscle CSA during and after 8-weeks of bed-rest. Error bars represent standard error of the mean difference to baseline (BR1) values. Values are pooled across both training groups; see Figure 9 for results where analysis suggested a difference in response between the 2 groups. BR indicates day of bed-rest; R+, day of recovery; LES, lumbar erector spinae; MF, multifidus; IABD, lateral abdominals; PS, psoas; QL, quadratus lumborum; RA, rectus abdominis. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

tently shorter (albeit nonsignificantly) than at baseline (BR1). In the RVE group, lengthening of the spine is generally less severe.

Changes in disc area and height parallel those of the spinal length changes. Differences existed between intervertebral levels in sagittal disc area and height ($F = 56.5$, $P < 0.0001$ and $F = 225.5$, $P < 0.0001$ respectively; Table 1). Strong effects existed for changes in disc area and height over the course of the study (study-date: $F = 29.4$, $P < 0.0001$ and $F = 14.7$, $P < 0.0001$ respectively; Figures 5 and 6A). Similar to spinal length, a weak effect existed for differences between groups for disc area (group × study-date: $F = 2.0$, $P = 0.041$; Figure 6) but this was not the case for disc height ($F = 1.1$, $P = 0.358$). Analysis suggested, similar to spinal length, that disc height changes over time varied across each vertebral level, but this was nonsignificant (study-date × level: $F = 1.4$, $P = 0.065$). No variation in disc area appeared to occur between vertebral levels ($F = 0.5$, $P = 0.994$). No statistical evidence existed for further interactions between subject-group and the other factors of study-date or level for either disc area or disc height (F all $<.6$, P all >0.68). Generally, both disc area and disc height increased during bed-rest, reduced afterwards and, similar to spinal length, remained less than at baseline (BR1) for the remainder of the follow-up period (Figures 5 and 6A). The RVE group showed less severe increases in disc area during bed-rest (Figure 5). The central lumbar (L23, L34, L45) discs showed the greatest increases in height during bed-rest (Figure 6B) but interestingly, the L12 vertebral disc was the most reduced, compared with baseline, after bed-rest. With better image resolution and perhaps greater subject numbers it would be possible to better resolve the differential responses of each of the invertebral discs to bed-rest.

Lordosis angle was different at each intervertebral level ($F = 561.5$, $P < 0.0001$; Table 1). Although no systematic effect was apparent over study-date ($F = 0.5$, $P = 0.994$), the response of each intervertebral angle appeared to differ over time (study-date × level: $F = 1.5$, $P = 0.02$; Figure 7). No differences existed between the 2 subject-groups, however (F all <0.8, P all >0.51). Inspection of Figure 7 suggests that increases in lordosis were largely restricted to the lower lumbar levels after the subjects reambulated in the recovery phase.

LP Muscle CSA

Spinal morphology data were included in the statistical models to control for their effect on muscle CSA. From these analyses, the LES, MF, and RA muscles showed effects for changes in CSA over time (study-date: $F = 2.3$, $P = 0.021$, $F = 3.9$, $P = 0.0003$ and $F = 3.5$, $P = 0.0008$, respectively). The other muscles (lABD, Ps, and QL) did not (F all <1.7, P all >0.097). In MF and Ps, analysis suggested that the RVE group responded differently over time (study-date × group: $F = 2.3$, $P = 0.024$ and $F = 2.8$, $P = 0.005$, respectively), but in the other muscles, no

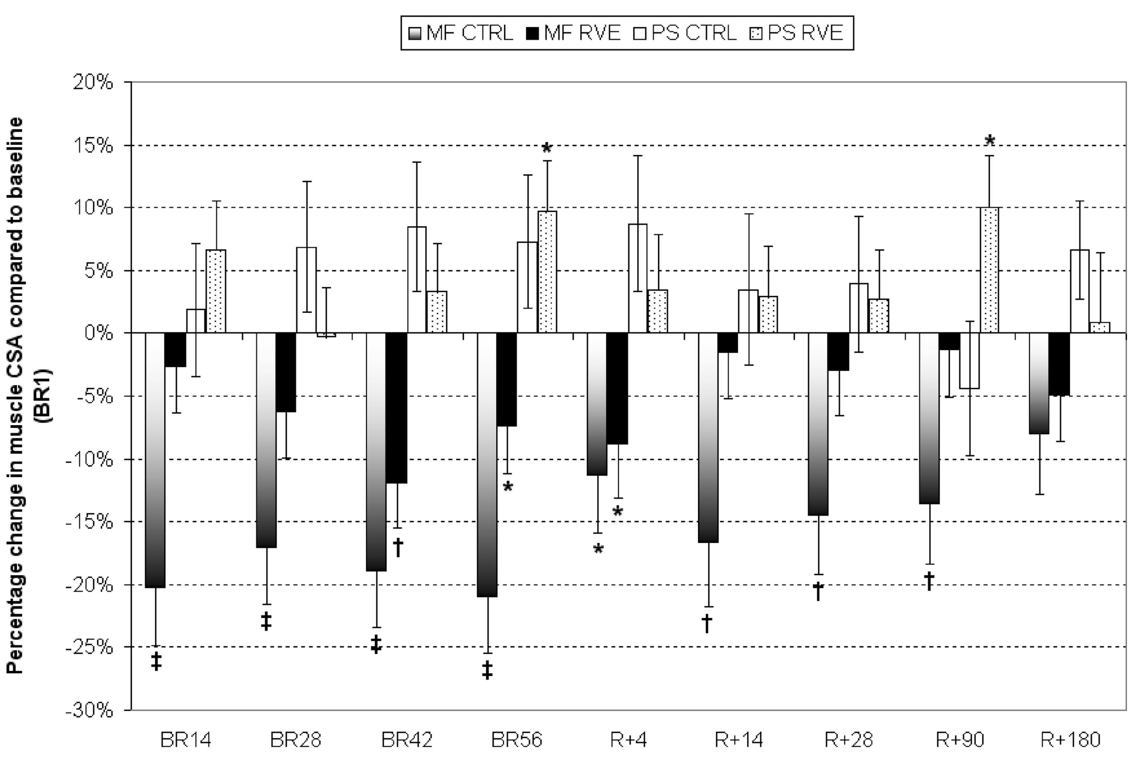

Figure 9. Differential response of the multifidus and psoas muscles in the inactive and exercise groups. Error bars represent standard error of the mean difference to baseline (BR1) values. BR indicates day of bed-rest; R+, day of recovery; MF, multifidus; PS, psoas; CTRL, inactive control group; RVE, resistive vibration exercise group. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

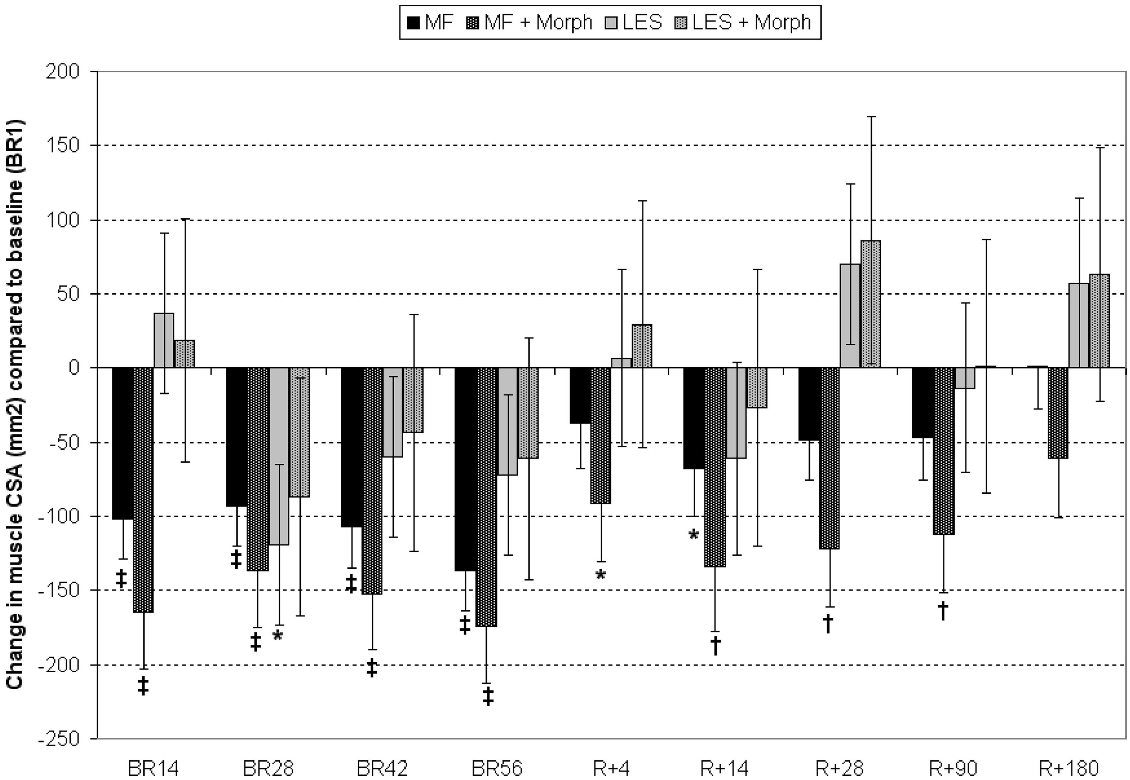

Figure 10. Influence of changes in spinal morphology on estimates of paraspinal muscle cross-sectional area decreases in the inactive (CTRL) subjects. Error bars represent standard error of the mean difference to baseline (BR1) values. BR indicates day of bed-rest; R+, day of recovery; MF, multifidus; LES, lumbar erector spinae. +Morph indicates results where changes in spinal morphology were included in the statistical models. Note the tendency to underestimate MF muscle CSA reductions and overestimate LES muscle CSA changes during and after bed-rest. *$P < 0.05$; †$P < 0.01$; ‡$P < 0.001$.

evidence existed for a differential response (F all <3.1, P all >0.106).

Changes in LP muscle CSA over study-date is displayed in Figure 8. MF shows the strongest decreases in CSA, which was persistent into the recovery phase (see also Figure 9). LES CSA decreased during bed-rest, but this effect was marginal. Little change was seen in the QL and lABD muscles. Ps and RA CSA increased during bed-rest but this was only significant late in the bed-rest phase.

The differential response of the 2 subject-groups is displayed in Figure 9. It can be quite clearly seen in the CTRL group that more atrophy of the MF muscle occurs than in the RVE group and, interestingly, with control of changes in spinal length, that this atrophy is actually persistent up to 3-months after bed-rest (see also Figure 10). At 6-months after bed-rest, while MF CSA is reduced, this is not significant ($P = 0.101$). Persistent MF CSA reduction in the recovery phase is much less apparent in the RVE group. In Ps, although analysis suggested a differential response in the 2 groups, no consistent pattern can be seen in Figure 9. Although Ps CSA increased during bed-rest, the differences between the 2 groups may represent a type I error.

Correlation Analyses

Table 3 shows the results of partial correlation analyses between spinal morphology variables. As could be expected, spinal length correlated strongly with disc area and but less so with disc height. Interestingly, the size of the lumbar lordosis depended more on disc height, but bore no relation to overall spinal length or disc area.

Table 4 describes the relationship between spinal morphology and LP muscle CSA. Interestingly, MF and

Table 3. Partial Correlations Among Spinal Length, Disc Area, Disc Height, and Lumbar Lordosis

Spinal Morphology Variable	Average Sagittal Disc Area	Average Disc Height	Lordosis Angle (L1–S1)
Spinal length (L1–S1)	0.52*	0.22*	−0.03
Sagittal disc area		0.58*	−0.03
Disc height			0.63*

Values are Pearson's correlation co-efficient (controlled for effects of study-date and subject age, height, and weight).
L1–S1 implies distance or angle between 1st lumbar vertebra and sacrum.
*$P < 0.001$.

Table 4. Partial Correlations Between Spinal Morphology and Lumbo-Pelvic Muscle Cross-Sectional Area

	Spinal Morphology Variable			
Muscle	Spinal Length (L1–S1)	Average Sagittal Disc Area	Average Disc Height	Lordosis Angle (L1–S1)
Lumbar erector spinae	0.23‡	0.24‡	0.10	−0.06
Multifidus	−0.15	−0.13	0.25‡	0.43‡
Lateral abdominals	0.06	0.02	−0.27‡	−0.4‡
Psoas	0.03	−0.11	−0.27‡	−0.36‡
Quadratus lumborum	−0.02	−0.01	−0.13	−0.12
Rectus abdominis	−0.04	0.05	0.03	−0.14†

Values are Pearson's correlation co-efficient (controlled for effects of study-date and subject age, height, and weight).
L1–S1 implies distance or angle between 1st lumbar vertebra and sacrum.
‡$P < 0.001$.
†$P < 0.01$.

LES CSA exhibit contrasting relationships to the spinal morphology variables. MF CSA increases with increased lordosis angle and disc height and shows a marginal ($P = 0.012$) correlation to decrease in CSA with increased spinal length. LES, in contrast, increases in CSA with increasing spinal length and disc area but is unaffected by lordosis angle or disc height. Figure 10 illustrates the differential impact of spinal morphology on the MF and LES muscle CSA and the tendency of changes in spinal morphology to mask persistent MF muscle atrophy. In the abdominal muscles, generally a decrease in CSA with flatting of the spine (negative correlation with lordosis) and reductions in disc height.

■ Discussion

This study has a number of interesting findings. Firstly, the resistive vibration exercise countermeasure implemented limited the extent of lumbar MF muscle atrophy and atrophy of this muscle did not persist long-term as in the control group. Furthermore, spinal lengthening and increases in disc area were reduced in the exercise group. Another interesting finding was that, changes in spinal morphology influenced muscle CSA changes, which has not been considered or reported in prior works on spinal muscle atrophy during spaceflight simulation.

A number of mechanisms may be involved in the positive effect of the countermeasure. Spinal compression, both from external loading and activity of the spinal musculature,[27] is important in maintaining intervertebral disc morphology.[28] The MF muscle is important in controlling the lumbar lordosis[27,29] and maintaining lumbar spine stiffness.[13,14] Hence, the spinal loading during exercise (simulating loading under gravity) could provide an important stimulus for this muscle. The combination with whole-body vibration could have an additional effect, given that vibration is thought to act over the muscle spindle system[21,22] and that the medial spinal muscles exhibit a greater proportion of muscle spindles.[30,31] Whole-body vibration exercise has been shown to improve lumbar spine proprioception.[16] Further work is required, however, to differentiate the effects of vibration and resistive exercise. Importantly, the countermeasure did not entirely prevent muscle atrophy. Further work should be conducted to determine the optimal exercise dose and also provide better controls of spinal posture during exercise.

The current study provides further evidence that resistive vibration exercise has positive effects on the spine. Prior work has also found that vibration exercise has a positive effect in chronic low back pain.[20] One mechanism of this may be the reversal of the spinal muscle atrophy seen in chronic low back pain,[32] or perhaps increased proprioceptive input.[16] Care should be taken, however, in applying the exercise protocols implemented here in patients with low back pain as bed-rest subjects represent a unique group where higher spinal loads may be required and can be tolerated.

A particularly interesting finding of the current study was that changes in spinal morphology can influence muscle CSA measurements and mask the extent of muscle atrophy during bed-rest. The MF and LES muscle groups showed differential responses to alterations of spinal morphology during and after bed-rest and this should be considered in future works. The results of the current study also extend findings that the MF muscle is particularly sensitive in inactivity[12] and shows that, once changes in spinal morphology are accounted for, MF muscle atrophy is long-standing despite return to normal activity, as is seen in patients with low back pain.[33]

In conclusion, the current study found that a resistive vibration exercise countermeasure reduced atrophy in the lumbar MF muscle and reduced lengthening of the spine and sagittal disc area increases during bed-rest. This study also found that changes in spinal length, disc size, and lumbar lordosis can influence measurements of LP muscle CSA during and after bed-rest and mask persistent long-term atrophy of the spinal muscles after bed-rest.

■ Key Points

- Exercise countermeasures against lumbar spine deconditioning in long-term spaceflight have received little attention in published work to date.

• A resistive vibration exercise countermeasure reduced lumbar multifidus muscle atrophy and extent of spinal lengthening and disc area increases during prolonged bed-rest.
• In inactive subjects, multifidus muscle atrophy persisted up to 3-months after bed-rest, this was not the case in the countermeasure subjects.
• Changes in spinal morphology during bed-rest can influence lumbo-pelvic muscle cross-sectional area measurements.

Acknowledgments

The authors thank the staff of ward 18A at the Charité Campus Benjamin Franklin Hospital, Berlin, Germany; Boris Calakic, Petra Helbig, Christian Kainz, and Gerhard Wolynski of the MR scanning center for their 2-year involvement; the subjects who participated in the study and Mr Benny Elmann-Larsen of the European Space Agency. Dr Michael Giehl is also thanked for his assistance with the MR image database.

References

1. Convertino VA. Neuromuscular aspects in development of exercise countermeasures. *Physiologist* 1991;34:S125–S128.
2. Koryak YA. Contractile characteristics of the triceps surae muscle in healthy males during 120-days head-down tilt (HDT) and countermeasures. *J Gravit Physiol* 1994;1:P141–P143.
3. Suzuki Y, Murakami T, Haruna Y, et al. Effects of 10 and 20 days bed rest on leg muscle mass and strength in young subjects. *Acta Physiol Scand Suppl* 1994;616:5–18.
4. Alkner BA, Tesch PA. Knee extensor and plantar flexor muscle size and function following 90 days of bed rest with or without resistance exercise. *Eur J Appl Physiol* 2004;93:294–305.
5. Akima H, Kubo K, Imai M, et al. Inactivity and muscle: effect of resistance training during bed rest on muscle size in the lower limb. *Acta Physiol Scand* 2001;172:269–78.
6. Mulder ER, Stegeman DF, Gerrits KH, et al. Strength, size and activation of knee extensors followed during 8 weeks of horizontal bed rest and the influence of a countermeasure. *Eur J Appl Physiol* 2006;97:706–15.
7. Cao P, Kimura S, Macias BR, et al. Exercise within lower body negative pressure partially counteracts lumbar spine deconditioning associated with 28-day bed rest. *J Appl Physiol* 2005;99:39–44.
8. Macias BR, Cao P, Watenpaugh DE, et al. LBNP treadmill exercise maintains spine function and muscle strength in identical twins during 28-days simulated microgravity. *J Appl Physiol* 2007;102:2274–8.
9. Booth FW, Gollnick PD. Effects of disuse on the structure and function of skeletal muscle. *Med Sci Sports Exerc* 1983;15:415–20.
10. Le Blanc A, Rowe R, Schneider V, et al. Regional muscle loss after short duration spaceflight. *Aviat Space Environ Med* 1995;66:1151–4.
11. Le Blanc A, Lin C, Shackelford L, et al. Muscle volume, MRI relaxation times (T2), and body composition after spaceflight. *J Appl Physiol* 2000;89:2158–64.
12. Hides JA, Belavý DL, Stanton W, et al. MRI assessment of trunk muscles during prolonged bed rest. *Spine* 2007;32:1687–92.
13. Kiefer A, Shirazi-Adl A, Parnianpour M. Synergy of the human spine in neutral postures. *Eur Spine J* 1998;7:471–9.
14. Wilke HJ, Wolf S, Claes LE, et al. Stability increase of the lumbar spine with different muscle groups—a biomechanical in-vitro study. *Spine* 1995;20:192–8.
15. Torvinen S, Sievanen H, Jarvinen TAH, et al. Effect of 4-min vertical whole body vibration on muscle performance and body balance: a randomized cross-over study. *Int J Sports Med* 2002;23:374–9.
16. Fontana TL, Richardson CA, Stanton WR. The effect of weight-bearing exercise with low frequency, whole body vibration on lumbosacral proprioception: a pilot study on normal subjects. *Aust J Physiother* 2005;51:259–63.
17. Delecluse C, Roelants M, Verschueren S. Strength increase after whole-body vibration compared with resistance training. *Med Sci Sports Exerc* 2003;35:1033–41.
18. Issurin VB, Liebermann DG, Tenenbaum G. Effect of vibratory stimulation training on maximal force and flexibility. *J Sports Sci* 1994;12:561–6.
19. Torvinen S, Kannus P, Sievanen H, et al. Effect of four-month vertical whole body vibration on performance and balance. *Med Sci Sports Exerc* 2002;34:1523–8.
20. Rittweger J, Just K, Kautzsch K, et al. Treatment of chronic lower back pain with lumbar extension and whole-body vibration exercise—a randomized controlled trial. *Spine* 2002;27:1829–34.
21. Ribot-Ciscar E, Butler JE, Thomas CK. Facilitation of triceps brachii muscle contraction by tendon vibration after chronic cervical spinal cord injury. *J Appl Physiol* 2003;94:2358–67.
22. Roll JP, Vedel JP, Ribot E. Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. *Exp Brain Res* 1989;76:213–22.
23. Rubin C, Pope M, Fritton JC, et al. Transmissibility of 15-hertz to 35-hertz vibrations to the human hip and lumbar spine: determining the physiologic feasibility of delivering low-level anabolic mechanical stimuli to skeletal regions at greatest risk of fracture because of osteoporosis. *Spine* 2003;28:2621–7.
24. Rittweger J, Belavy DL, Hunek P, et al. The Berlin bed-rest study: maintenance of a highly demanding resistive vibration exercise program during 56 days of strict bed-rest. *Int J Sports Med* 2006;27:553–9.
25. Bogduk N. *Clinical Anatomy of the Lumbar Spine and Sacrum*. 3rd ed. London: Churchill Livingstone; 1997.
26. Pinheiro JC, Bates DM. *Mixed-Effects Models in S and S-PLUS*. 1st ed. Berlin: Springer; 2000.
27. Macintosh JE, Bogduk N. The biomechanics of the lumbar multifidus. *Clin Biomech* 1986;1:205–31.
28. Adams MA, Hutton WC. The effects of posture on the fluid content of lumbar intervertebral discs. *Spine* 1983;8:665–71.
29. Kiefer A, Shirazi-Adl A, Parnianpour M. Stability of the human spine in neutral postures. *Eur Spine J* 1997;6:45–53.
30. Nitz AJ, Peck D. Comparison of muscle spindle concentrations in large and small human epaxial muscles acting in parallel combinations. *Am Surg* 1986;52:273–7.
31. Peck D, Buxton DF, Nitz A. A comparison of spindle concentrations in large and small muscles acting in parallel combinations. *J Morphol* 1984;180:243–52.
32. Danneels LA, Vanderstraeten GG, Cambier DC, et al. CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. *Eur Spine J* 2000;9:266–72.
33. Hides JA, Richardson CA, Jull GA. Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. *Spine* 1996;21:2763–9.