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ORIGINAL ARTICLE

The effects of rehabilitation on the muscles of the trunk following prolonged bed rest

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Abstract Microgravity and inactivity due to prolonged bed rest have been shown to result in atrophy of spinal extensor muscles such as the multifidus, and either no atrophy or hypertrophy of flexor muscles such as the abdominal group and psoas muscle. These effects are long-lasting after bed rest and the potential effects of rehabilitation are unknown. This two-group intervention study aimed to investigate the effects of two rehabilitation programs on the recovery of lumbo-pelvic musculature following prolonged bed rest. 24 subjects underwent 60 days of head down tilt bed rest as part of the 2nd Berlin BedRest Study (BBR2-2). After bed rest, they underwent one of two exercise programs, trunk flexor and general strength (TFS) training or specific motor control (SMC) training. Magnetic resonance imaging of the lumbo-pelvic region was conducted at the start and end of bed rest and during the recovery period (14 and 90 days after re-ambulation). Cross-sectional areas (CSAs) of the multifidus, psoas, lumbar erector spinae and quadratus lumborum muscles were measured from L_1 to L_5. Morphological changes including disc volume, spinal length, lordosis angle and disc height were also measured. Both exercise programs restored the multifidus muscle to pre-bed-rest size, but further increases in psoas muscle size were seen in the TFS group up to 14 days after bed rest. There was no significant difference in the number of low back pain reports for the two rehabilitation groups ($p = .59$). The TFS program resulted in greater decreases in disc volume and anterior disc height. The SMC training program may be preferable to TFS training after bed rest as it restored the CSA of the multifidus muscle without generating potentially harmful compressive forces through the spine.

Keywords Bed rest · Magnetic resonance imaging · Gravity · Multifidus muscle · Psoas muscle · Rehabilitation

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Introduction

Alterations in physical activity experienced during spaceflight or prolonged bed rest have direct effects on the musculoskeletal system. Exposure to microgravity has been shown to lead to an increased incidence of low back pain (LBP) associated with abnormal lengthening of the spine [61], atrophy of spinal musculature [37], increased intervertebral disc (IVD) height and area [35, 61], and altered IVD composition. Greater than 50% of astronauts complain of LBP during space missions [61], and astronauts have an increased incidence of disc protrusion when compared to a general or an army aviation population [30]. Astronauts undergo specific training programs before and after spaceflight, to try and minimise the effects of loss of functional weight bearing, and help prevent development of conditions such as LBP. LBP is also known to be a problem for a large number of people [20], but it is difficult to perform longitudinal studies before and after onset as development of insidious LBP may take a long time. This process is accelerated in spaceflight and prolonged bed rest, and these studies therefore offer a unique opportunity to study people before and after the onset of LBP. Bed rest studies are also useful as they allow testing of countermeasures and rehabilitation procedures both during and after periods of reduced functional weight bearing.

Countermeasures and rehabilitation procedures have traditionally aimed at reversing muscle atrophy and weakness which are assumed to be the result of LBP, spaceflight and prolonged bed rest; however, this is not always the case. While some muscles do atrophy, other muscles increase in size under these conditions. For example, laboratory studies have demonstrated the effects of induced pain [27, 32] or anticipation of pain [46] on muscle function in normal subjects, and demonstrated that while some muscles become inhibited (and atrophy) [32], other muscles increase their activation in response to induced pain [27].

This situation of differential atrophy between muscles also occurs in bed rest. Studies using magnetic resonance imaging (MRI) have demonstrated greater atrophy in the spinal extensor muscles than in the flexor muscles [12, 39]. The psoas muscle, a spinal flexor, has been shown not to change significantly in size during spaceflight [36, 37] and bed rest [12, 38] with other more recent studies showing increases in psoas size during bed rest [4, 21]. Recent studies of prolonged bed rest have shown differential atrophy in the paraspinal (extensor) muscles with the multifidus muscle showing greater atrophy than the lumbar erector spinae at the lower lumbar levels [4, 21]. In comparison, the abdominal flexor muscle group has been shown to increase in size during bed rest [21].

Some of the changes in bed rest have been observed to be long-lasting in nature. It took 28 days for the psoas muscle to return to its pre-bed-rest size following re-ambulation [21] and changes in the multifidus muscle were still evident at 90 days after re-ambulation and return to normal activities [6]. Electromyographic studies have also shown the persistence of motor control changes in the lumbo-pelvic musculature up to 1 year after bed rest [7–9].

Similar changes in muscle size have been reported for people with LBP for the multifidus [12, 14, 24, 25, 36–38, 60] and psoas [14, 43, 58] muscles. This differential atrophy of the muscles during bed rest has also been linked to the development of LBP [4, 28].

The effects of prolonged bed rest on the lumbar IVDs have also been studied [4, 6, 12, 28, 35]. Similar to during spaceflight, the length of the lumbar spine has been shown to increase [4, 6, 12, 28]. This is thought to be due to discs imbibing fluid in combination with flattening of the lumbar lordosis [39]. It is important to measure these morphological changes as they may also have biomechanical consequences on the ability of the disc to distribute load [47] and have been associated with LBP incidence after bed rest [4, 28]. It has previously been shown that exercises performed for the trunk muscles may directly affect passive structures such as the disc [2], and the possible negative effects of exercises on passive structures should be considered [2, 41, 46] when developing exercise programs. This may be very relevant for people performing exercises when they have LBP associated with discal pathology, and also for astronauts when they exercise and reload their spines after being in the microgravity environment.

Prolonged bed rest has previously resulted in changes in the lumbo-pelvic muscles [6, 21] and IVDs [6]. As these changes have been shown to persist over time [6–9], rehabilitation efforts are warranted. The aim of this study was to determine the effectiveness of two commonly adopted rehabilitation programs on recovery of size of the trunk muscles and changes in morphology of the lumbar spine following prolonged bed rest.

Methods

Subjects

Twenty-four medically and psychologically healthy male subjects were recruited for the bed rest study. Full details of the study protocol have been described elsewhere [5]. In brief, four groups of six subjects underwent bed rest at a time in 2007 and 2008. Baseline data were collected for 9 days before the commencement of the bed rest phase (BDC). All subjects underwent 60 days of 6° head down tilt bed rest (HDT 1-60) and returned for assessment at 14 and 90 days following the bed rest period (recovery, R+14 and R+90). Inclusion criteria included subjects aged between 20 and 45 years, with a height of 155–195 cm. Exclusion criteria included any addictions, regular intake of medication, chronic diseases, history of psychological disease, cardiovascular disease, muscle or bone disease, metal implants, chronic LBP, spinal operations, scoliosis and low bone mass.

Bed rest protocol

The subjects participated in a trial designed to counterbalance the effect of prolonged bed rest. Subjects were paired as room-mates according to psychological criteria and the pairs were randomised to three different groups during bed rest. One group performed resistive exercises with whole body vibration during bed rest (RVE), one group performed resistive exercises only (RES) and one group did not perform any exercises during bed rest (control group, CTR). The study was approved by the institutional ethics committee. All subjects gave their informed written consent prior to participation in the study. Rehabilitation was not commenced until after the bed rest phase of the study was completed.

Rehabilitation protocol

Two rehabilitation approaches were delivered; a trunk flexor and general strength (TFS) program and a specific motor control (SMC) training program. The SMC program consisted of training the subjects to voluntarily contract the multifidus and deep abdominal muscles using ultrasound imaging [23–25] before progressing to functional retraining in upright positions focusing on spinal position [26, 54]. Subjects worked on maintaining normal patterns of respiration and developing endurance of the deep abdominal and back muscles. Further progression involved functional retraining, including work in a forward leaning position, sitting to standing and maintaining a semi-squat position. To further increase resistance, Thera Band exercise bands (USA) were used for both the upper and lower limbs. A Flexi-bar (Germany) was also used to train endurance of the trunk muscles. This required subjects to rhythmically perturb a flexible bar while maintaining their spinal position.

There is level I evidence [19] to support the efficacy of this exercise approach in people with LBP [22] in both restoring multifidus muscle size [24, 26] and decreasing pain and disability [17, 50, 51, 55, 59] and LBP recurrence rates. The trunk component of the TFS program involved trunk strengthening exercises performed in the supine position. These exercises involved lifting the trunk and lower limbs off the floor, and included exercises such as sit-ups, diagonal sit-ups, leg lifts (single and double) and alternating arm and leg lifts. To increase resistance Thera Band exercise bands were used. These exercises have been shown to strongly activate the trunk and hip flexor muscles [1, 13, 15, 40] in co-contraction with the lumbar extensor muscles [57], but are also associated with the generation of large compressive forces on the spine [41]. This form of floor exercise is used extensively to train the trunk muscles in both athletic programs (competitive sports and fitness) and rehabilitation [45]. In addition, subjects in the TFS program performed exercises targeting the following muscles: quadratus lumborum, hip abductors and adductors, muscles of the shoulder girdle, biceps, and triceps. They also performed stretches of the hamstring, gastrocnemius, soleus, pectoralis major and minor, biceps and triceps muscles. Exercises for both groups were progressed by increasing the number of repetitions of exercises and hold times for static endurance work.

Four subjects from each bed rest trial group ($n = 12$) were allocated to the SMC program and the TFS program. This design, stratified for the bed rest interventions, ensured that there was equal representation of the three groups during bed rest (high load resistive exercise with whole body vibration, resistive exercise alone and control, no exercise) in each post-bed-rest training group. Subjects from each rehabilitation group were seen for equal amounts of time. From R+2 to R+7, all subjects were seen in hospital daily for individual treatment sessions lasting 30 min. From R+8 to R+14, subjects were seen for two appointments of 30-min duration in a private physiotherapy practice in Berlin. They were given a formal written home program. Between R+16 and R+29, subjects were seen for 30 min in the physiotherapy practice for four appointments, and between R+31 and R+89 for three appointments. At these times, exercises were checked and progressed as able. Overall, it was planned for each subject to be seen 15 times for rehabilitation.

MRI protocol

MRI was performed prior to bed rest during the baseline data collection period (BDC, either 8 or 9 days prior to bed rest), at the end of bed rest (HDT55/56), at R+14 and R+90. To obtain the axial images used for measurement of muscle cross-sectional areas (CSAs), five groups of three axial slices (slice thickness: 4 mm; interslice distance: 4 mm; repetition time: 7,560 ms; echo time: 97 ms; field of view: 260 × 234 mm interpolated to 320 × 288 pixels) were positioned over the transverse process of each vertebral body from L_1 to L_5. Each group of slices was angulated to be parallel to the superior vertebral endplate of its vertebra (Fig. 1).

For spinal morphology, 29 sagittal images (thickness 3 mm; interslice distance: 3.3 mm; repetition time: 5,240 ms; echo time: 101 ms; field of view: 380 × 380 mm interpolated to 320 × 320 pixels) were taken to encompass the entire vertebral body and include the transverse processes of the lumbar spine in a field of view from the lower thoracic spine (typically T_{10}) to the sacrum (Fig. 2).

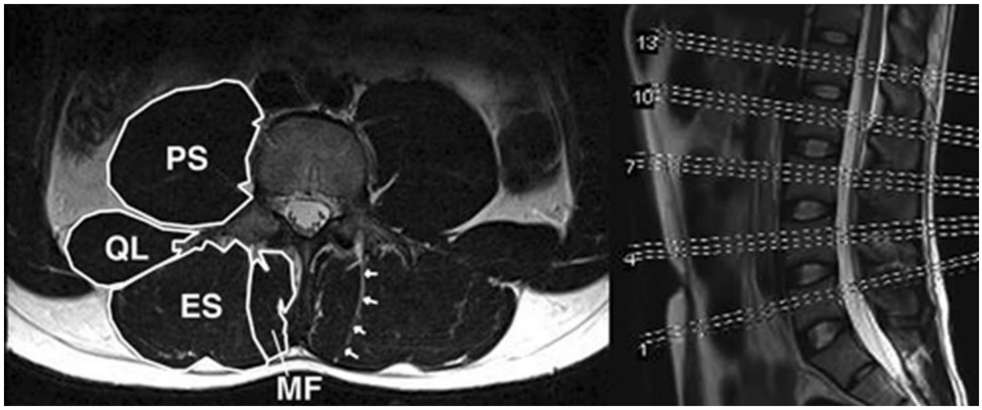

Fig. 1 Muscle cross-sectional area measurements. *Left of image* Cross-sectional area measurements were made of the psoas (*PS*), erector spinae (*ES*) and multifidus (*MF*) muscles from L_1 to L_5. Quadratus lumborum (*QL*) was measured from L_1 to L_4 as it was typically absent at L_5. *Arrows* indicate the fascial border between *MF* and *ES* which aided delineation of these two muscles. *Right of image* Positioning of images at each vertebral level

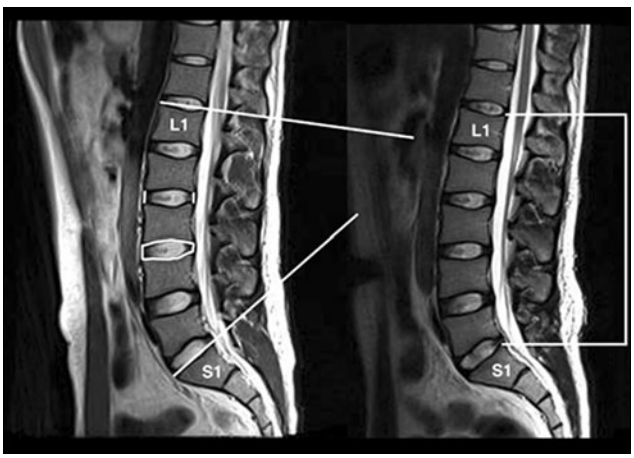

Fig. 2 Measurements of spinal morphology. *Left* End of 60 days bed rest; *right* end of rehabilitation phase (90 days after end of bed rest) in the same subject. Disc volume was interpolated from sagittal plane disc area measurements of each lumbar intervertebral disc (shown at $L_{3/4}$ on *left side of image*). Anterior and posterior disc height was also measured (shown between $L_{2/3}$ at *left*). The lumbar lordosis angle was calculated between *lines* drawn at the superior endplate of L_1 and S_1. Spinal length (*right*) was measured between the dorsorostral corner of S_1 and L_1

Image measurements

To ensure measurer blinding to study timepoint, each data set was assigned a random number (http://www.random.org). ImageJ 1.38x (http://rsb.info.nih.gov/ij/) was used for MR image analyses which were conducted by the same operator. The following measures of spinal morphology were conducted in every image where the required anatomical landmarks could be delineated (Fig. 2):

1. Spinal length: the length of a line drawn from between the dorsorostral corners of S_1 and L_1 and its angle were measured. The vertical distance (spinal length) between the dorsorostral corner of S_1 and L_1 was then calculated via simple trigonometry.
2. Disc volume of each disc from $L_{1/2}$ to L_5S_1 was interpolated from all sagittal plane CSA measures.
3. Anterior and posterior disc heights were measured from between the ventrocaudal and ventrorostral corners (anterior disc height) and dorsocaudal and dorsorostral corners (posterior disc height) of the vertebral bodies from $L_{1/2}$ to L_5S_1.
4. Lumbar lordosis was measured between lines drawn parallel to the superior endplates L_1 and S_1. The lumbar curvature was calculated such that positive values denoted a “lordosis”.

Bilateral CSA measurements of the lumbar multifidus (MF), erector spinae (ES), quadratus lumborum (QL) and psoas (PS) muscles were conducted (Fig. 1). To accurately delineate MF and the more laterally placed longissimus muscle, the fascial border [10] separating these two muscles was used as an anatomical landmark. The CSA measures for the three MR images at each vertebral level were averaged and then left and right sides were averaged prior to further analysis.

Questionnaires

Subjects completed a habitual physical activity questionnaire [3], prior to bed rest and at the end of the rehabilitation period (either 90 or 180 days after bed rest). Furthermore, from day 2 to day 7 after bed rest (R+2 to R+7) and when subjects returned to the bed rest facility 14, 30 and 90 days (R+14, R+30, R+90) after bed rest, they were asked to fill out a LBP questionnaire. Subjects were asked to report whether LBP was present, mark its location on a body chart and its intensity on a Visual Analogue Scale (VAS) [16]. Incidence of LBP was defined as any report of pain or discomfort between the first lumbar vertebrae and the coccyx.

Statistical analyses

Linear mixed-effects models [52] were used to assess each of the spinal morphology variables with factors of group (TFS, SMC), study date (HDT55/56, R+14, R+90), a group × study date interaction and linear co-variates of baseline (BDC) subject age, height and weight. Random effects for each subject were permitted and were necessary allowances for heterogeneity of variance (such as due to group or study date). For disc volume and height, the additional factors of vertebral level ($L_{1/2}$, $L_{2/3}$, $L_{3/4}$, $L_{4/5}$, L_5/S_1), all appropriate interactions and random effects were used. An α of 0.05 was taken for statistical significance. For the muscle CSA data, separate models were constructed for each muscle and vertebral level, and a similar approach was used as per spinal morphology. Additional analyses examined the effect of subject training group during bed rest on recovery after bed rest [i.e. interaction of countermeasure group (RVE, RE or CTR) with rehabilitation group (SMC, TFS)]. The "R" statistical environment (version 2.6.1, http://www.r-project.org) was used for all analyses. Activity questionnaire data were also evaluated in a similar fashion.

For analysis of LBP incidence, Chi-square analyses were used to evaluate differences between groups in the total number of reports of LBP compared to the total number of times the questionnaire was completed from R+2 to R+90.

Results

Subjects

One subject from the TFS group finished bed rest early due to medical reasons and was therefore excluded from the rehabilitation study. Two subjects (1 from the SMC and 1 from the TFS group) failed to return for testing at R+90. The mean (SD) age, height and weight for the subjects in the two groups was as follows—TFS: 30.9 (8.5) years, 177.9 (5.5) cm and 77 (7.9) kg; SMC: 34.1 (7.2) years, 183.4 (5.8) cm and 81.6 (9.2) kg. Total habitual physical activity from questionnaires (no units) before bed rest was 9.1 (1.6) [mean (SD)] in the SMC group and 9.3 (0.9) in the TFS group (no difference between groups before bed rest; $p = .80$). At the end of the rehabilitation period, total physical activity scores were not significantly different ($p > .27$) to baseline values [SMC: 9.1 (1.3), TFS: 9.4 (1.0)]. Compliance rates for attendance at the rehabilitation sessions were similar for both groups with a compliance rate of 77.1% for the SMC group and 80.7% for the TFS group.

As analysis of muscle CSA (PS: $p > 0.079$, ES: $p > 0.18$, QL: $p > .072$, MF: $p > .059$) and spinal morphology data (disc volume: $p > .33$, anterior disc height: $p > .033$, posterior disc height: $p > .39$, lordosis: $p = .49$, spinal length: $p = .63$) provided limited evidence of an interaction between training group during bed rest (RVE, RE or CTR) on the effect of rehabilitation group after bed rest (SMC, TFS), the variable of training group during bed rest was removed from the further analyses presented here.

Spinal morphology

Disc volume, anterior and posterior disc height, lordosis angle and lumbar spine length changed from the end of bed rest up until the end of the rehabilitation phase ($F \geq 9.3$, $p \leq .0005$). At the end of bed rest, disc volume and height and spinal length were all larger and the lumbar lordosis was smaller (Table 1). In the recovery phase, all of these variables returned towards their baseline levels; however,

Table 1 Effect of rehabilitation on spinal morphology after prolonged bed rest

	Study date			
	BDC	HDT55/56	R+14	R+90
Spinal length (L1–S1, mm)				
SMC	180.2 (2.3)	184.4 (2.3)^{c}	181.7 (2.3)^{‡b}	182.0 (2.3)^{‡b}
TFS	170.9 (2.0)	175.4 (2.1)^{c}	171.9 (2.0)^{‡c}	172.9 (2.0)^{‡c}
Lumbar lordosis (L1–S1, degrees)				
SMC	50.4 (2.0)	48.6 (1.9)^{a}	49.5 (1.9)	49.9 (1.9)‡
TFS	47.0 (1.3)	46.5 (1.3)	46.2 (1.4)	47.0 (1.3)
Posterior disc height (average $L_{1/2}$–L_5S_1, mm)				
SMC	6.4 (0.2)	6.9 (0.2)^{c}	6.4 (0.2)‡	6.6 (0.2)^{‡b}
TFS	6.6 (0.3)	7.2 (0.3)^{c}	6.7 (0.3)‡	7.0 (0.3)^{‡c}
Anterior disc height (average $L_{1/2}$–L_5S_1, mm)				
SMC	11.8 (0.3)	12.2 (0.3)^{c}	12.1 (0.3)^{*b}	12.2 (0.3)^{c}
TFS	10.9 (0.5)	11.6 (0.5)^{c}	10.9 (0.5)‡	11.3 (0.5)^{c}
Disc volume (average $L_{1/2}$–L_5S_1, cm^3)				
SMC	26.3 (1.0)	28.1 (1.0)^{c}	27.5 (1.0)^{‡c}	28.1 (1.0)^{c}
TFS	26.9 (1.8)	28.5 (1.8)^{c}	26.6 (1.8)‡	27.7 (1.8)^{‡c}

Values are mean (standard error). Analysis suggested that the change in volume and height of each of the lumbar discs was similar during bed rest and recovery and in response to rehabilitation ($p > .14$); therefore, data for disc volume and anterior and posterior disc height represent averages across the five lumbar vertebral levels. Values have been adjusted for subject age, height and weight

R+14 and R+90 14 and 90 days after bed rest, respectively, *SMC* specific motor control, *TFS* trunk flexor and general strength

$^{*}p < .05$, $^{†}p < .01$, $^{‡}p < .001$ indicate significance of difference to end-bed-rest (HDT55/56) value. $^{a}p < .05$, $^{b}p < .01$, $^{c}p < .001$ indicate significance of difference to baseline (BDC) value

90 days after bed rest (R+90), disc volume [mean (SE); 4.8 (0.7)% greater on average than before bed rest], posterior disc height [4.3 (1.1)%], anterior disc height [3.6 (0.8)%], as well as spinal length [1.1 (0.2)%] remained significantly greater than at baseline (Table 1).

The type of rehabilitation impacted upon the changes in disc volume and anterior disc height after bed rest ($F \geq 9.2$, $p \leq .0002$) with greater reductions in disc volume seen in the TFS group at R+14 [−6.1 (0.6)% compared to the end of bed rest; mean (SEM)] and R+90 [−2.7 (0.6)%] than in the SMC group [R+14: −2.4 (0.9)%, R+90: +0.3 (0.7)% compared to the end of bed rest]. Also, anterior disc height decreased more in the TFS group, and this effect was most apparent at R+14 [−5.9 (0.7)% compared to the end of bed rest vs. −1.6 (0.7)% in the SMC group; R+90: −1.3 (0.7) vs. −0.7 (0.8)% in the SMC group]. The change in posterior disc height, lordosis angle and lumbar spine length during the rehabilitation phase after bed rest was similar in both the TFS and SMC groups ($F \leq 1.5$, $p \geq .24$; Table 1). Vertebral level ($L_{1/2}$ to L_5S_1) had no influence on the changes in disc height or volume over the course of the study or on the impact of the rehabilitation ($F \leq 1.6$, $p \geq .14$).

Muscle CSA

With the exception of the quadratus lumborum muscle at L_1 and L_2 ($F \leq 2.4$, $p \geq .10$), the CSA of all muscles changed at all vertebral levels in the period from the end of bed rest (HDT55/56) up to 90 days later (R+90; $F \geq 6.6$, $p \leq .0022$). For the psoas muscle, results from the ANOVA suggested a different response between the two rehabilitation groups at all vertebral levels ($F > 4.6$, $p \leq .0117$). Psoas muscle CSA was marginally increased in the TFS group at all vertebral levels at R+14 (Table 2), while the SMC group showed decreases in CSA of the psoas muscle at all vertebral levels at this time point. At R+90, CSA of the psoas muscle had decreased further in both rehabilitation groups (Table 2). At R+90, with the exception of L_5 in the TFS group, CSA of the psoas muscle was still greater than pre-bed-rest values in both subject groups, and this effect was significant at L_3 and L_5 in the

Table 2 Changes in psoas and multifidus muscle cross-sectional area

Study date	Vertebral level				
	L_1	L_2	L_3	L_4	L_5
Psoas: specific motor control (SMC) training					
BDC	225.4 (38.0)	690.7 (35.8)	1,245.5 (51.0)	1,738.6 (72.9)	1,919.1 (123.5)
HDT55/56	254.2 (38.0)^{c}	786.9 (36.1)^{c}	1,374.2 (50.1)^{c}	1,886.1 (71.5)^{c}	2,033.3 (122.9)^{c}
R+14	237.9 (37.8)†	760.5 (35.1)$^{\dagger c}$	1,355.0 (49.6)^{*c}	1,877.8 (70.7)^{c}	2,013.8 (122.2)^{c}
R+90	225.4 (37.8)‡	691.4 (37.3)‡	1,288.3 (51.8)$^{\ddagger a}$	1,780.1 (72.0)‡	1,969.4 (122.1)$^{\dagger a}$
Psoas: trunk flexor and general strength (TFS)					
BDC	254.9 (41.4)	754.6 (44.8)	1,293.4 (26.4)	1,811.3 (36.4)	1,892.0 (49.9)
HDT55/56	286.1 (41.3)^{c}	833.2 (44.0)^{c}	1,384.8 (21.5)^{c}	1,892.8 (27.1)^{b}	1,928.2 (45.2)
R+14	295.2 (41.0)^{c}	840.0 (43.8)^{c}	1,413.7 (21.1)^{*c}	1,951.5 (26.8)$^{\ddagger c}$	1,980.1 (44.9)$^{\ddagger c}$
R+90	284.0 (41.6)^{b}	767.3 (44.6)‡	1,309.0 (21.9)‡	1,823.4 (28.9)‡	1,881.3 (49.5)
Multifidus: specific motor control (SMC) training					
BDC	260.1 (13.5)	347.8 (19.3)	487.0 (28.0)	730.3 (39.8)	938.2 (37.4)
HDT55/56	250.9 (13.5)^{b}	330.0 (19.4)^{c}	475.1 (28.2)	671.6 (39.8)^{b}	829.3 (33.8)^{c}
R+14	262.1 (13.6)†	344.4 (19.3)†	477.2 (27.6)	717.7 (37.9)†	887.3 (32.9)$^{\ddagger b}$
R+90	260.2 (14.0)*	350.6 (19.2)‡	486.3 (27.9)	723.9 (38.1)‡	906.1 (35.0)‡
Multifidus: trunk flexor and general strength (TFS)					
BDC	258.2 (18.4)	350.2 (22.8)	492.6 (29.4)	705.6 (39.9)	868.3 (45.6)
HDT55/56	247.8 (18.6)	346.2 (22.4)	471.5 (29.1)	644.4 (40.2)^{c}	804.6 (44.2)^{c}
R+14	265.4 (18.2)‡	360.9 (22.3)†	521.0 (28.6)$^{\ddagger b}$	709.9 (38.9)‡	868.0 (44.5)‡
R+90	268.3 (18.3)$^{\ddagger a}$	353.9 (22.7)	513.3 (28.5)$^{\ddagger a}$	718.7 (39.9)‡	894.4 (44.1)‡

Values are mean (standard error) in mm^2. Values have been adjusted for subject age, height and weight. ANOVA suggested a difference between the two rehabilitation groups after bed rest at all vertebral levels in psoas ($p < .12$) but only at L_3 in multifidus ($p = .0008$, otherwise $p > .24$)

R+14 and R+90 14 and 90 days after bed rest, respectively

$^{*}p < .05$, $^{\dagger}p < .01$, $^{\ddagger}p < .001$ indicate significance of difference to end-bed-rest (HDT55/56) value. $^{a}p < .05$, $^{b}p < .01$, $^{c}p < .001$ indicate significance of difference to baseline (BDC) value

SMC group ($p \leq .032$; Table 2) and at L_1 in the TFS group ($p = .002$; Table 2).

The CSA of the multifidus muscle increased in both groups during the rehabilitation phase and there was a different response between the two rehabilitation groups only at one vertebral level, L_3 ($F = 7.8$, $p = .0008$; otherwise: $F < 1.4$, $p > .24$; Table 2). A greater increase in the CSA of the multifidus muscle was seen at the L_3 vertebral level in the TFS group at both R+14 and R+90. At R+90, the CSA of the multifidus muscle was not significantly less ($p > .13$) than pre-bed-rest levels, though in the TFS group the CSA of this muscle was greater than pre-bed-rest levels at R+90 at L_1 and L_3 ($p \leq .042$).

The CSA of the erector spinae muscle also increased in both rehabilitation groups after bed rest (Table 3). Ninety days after bed rest, the CSA of the erector spinae muscle was marginally (non-significantly) greater than pre-bed-rest values in the TFS group, whereas the SMC group showed marginally smaller values for this muscle at all vertebral levels except L_5, and this effect reached significance at L_2 ($p = .046$). The results of the ANOVA showed that these marginal differences between groups were not significant ($F < 2.4$, $p \geq .10$).

The CSA of the quadratus lumborum muscle also increased after bed rest (Table 3). Ninety days after bed rest, the CSA of this muscle was significantly less than pre-bed-rest levels in the SMC group at L_2, L_3 and L_4, whereas this was not the case in the TFS group (Table 3), but results of the ANOVA suggested the response in the two rehabilitation groups to be similar for this muscle ($F \leq 2.0$, $p \geq .14$).

LBP

Subjects in both the TFS and SMC groups reported LBP during the rehabilitation period. From R+2 to R+7, 5/12 (42%) of the subjects in the SMC group reported LBP, versus 6/11 (55%) in the TFS group. In the period subsequent to this (from R+14 to R+90), an additional two subjects in each group reported LBP. The SMC group reported pain on a total of 14 times (of 107 times of questionnaire completion between R+2 and R+90; 13%) and the TFS group reported LBP 17 times (of 98

Table 3 Changes in erector spinae and quadratus lumborum muscle cross-sectional area

Study date	Vertebral level				
	L_1	L_2	L_3	L_4	L_5
Erector spinae: specific motor control (SMC) training					
BDC	1,988.0 (54.6)	2,224.7 (66.6)	2,154.5 (88.0)	1,803.4 (105.5)	1,266.9 (91.3)
HDT55/56	1,759.5 (52.0)^{c}	2,026.8 (64.6)^{c}	1,980.7 (86.8)^{c}	1,685.6 (104.3)^{c}	1,211.3 (91.3)^{a}
R+14	1,887.2 (50.9)^{‡c}	2,150.9 (63.4)^{‡b}	2,100.8 (86.3)^{‡a}	1,763.5 (103.3)‡	1,225.8 (89.8)^{a}
R+90	1,939.1 (52.0)‡	2,175.4 (64.3)^{‡a}	2,134.1 (86.9)‡	1,779.9 (105.0)‡	1,299.5 (91.5)‡
Erector spinae: trunk flexor strengthening (TFS)					
BDC	1,902.3 (62.2)	2,045.5 (68.2)	1,904.9 (74.1)	1,604.0 (64.9)	1,137.8 (95.4)
HDT55/56	1,726.5 (62.1)^{c}	1,891.8 (66.2)^{c}	1,814.4 (74.0)^{c}	1,539.4 (65.7)^{a}	1,072.0 (91.8)^{a}
R+14	1,887.3 (59.2)‡	2,003.5 (65.8)‡	1,885.4 (71.9)‡	1,612.1 (63.5)†	1,130.9 (93.8)*
R+90	1,929.0 (61.9)‡	2,046.5 (67.2)‡	1,909.1 (72.8)‡	1,615.4 (63.5)†	1,156.6 (100.2)
Quadratus lumborum: specific motor control (SMC) training					
BDC	200.2 (33.2)	413.1 (26.4)	584.5 (26.3)	833.5 (31.2)	–
HDT55/56	195.8 (33.2)	397.2 (26.2)^{b}	559.7 (25.9)^{b}	778.6 (31.0)^{c}	–
R+14	195.6 (33.2)	408.7 (26.3)*	576.5 (26.1)†	814.4 (30.3)‡	–
R+90	196.4 (33.2)	394.1 (26.4)b	562.3 (26.1)^{b}	795.8 (31.7)^{b}	–
Quadratus lumborum: trunk flexor strengthening (TFS)					
BDC	199.0 (32.0)	388.8 (18.7)	625.8 (33.2)	774.8 (37.2)	–
HDT55/56	194.1 (32.0)	383.6 (18.7)	580.4 (31.6)^{c}	735.9 (37.6)^{a}	–
R+14	200.8 (31.8)	386.2 (18.1)	614.0 (31.8)‡	779.2 (35.4)†	–
R+90	207.3 (32.1)*	380.9 (19.1)	604.6 (32.8)*	771.3 (35.8)*	–

Values are mean (standard error) in mm^2. Quadratus lumborum typically not present at L_5. Values have been adjusted for subject age, height and weight. ANOVA did not suggest a different response between the two rehabilitation groups after bed rest for either muscle ($p \geq .10$)

R+14 and R+90 14 and 90 days after bed rest, respectively

$^{*}p < .05$, $^{†}p < .01$, $^{‡}p < .001$ indicate significance of difference to end-bed-rest (HDT55/56) value. $^{a}p < .05$, $^{b}p < .01$, $^{c}p < .001$ indicate significance of difference to baseline (BDC) value questionnaire completions; 17%), though these differences were not significant ($\chi^2 = .29$, $p = .59$).

Discussion

The 2nd Berlin BedRest Study has provided a unique set of circumstances to investigate the effects of two different rehabilitation programs. The advantage of this study was that a homogenous group of healthy male individuals was exposed to a controlled environment known to induce predictable changes in lumbo-pelvic muscles. Both rehabilitation programs used in this study are currently widely used in the community for people with and without LBP [45].

Both rehabilitation programs adopted were successful in restoring the CSA of the multifidus muscle. This is important as decreases in the CSA of the multifidus muscle have been documented not only in those who have undergone bed rest studies [4, 6, 21], and these changes have been linked to LBP incidence after bed rest [4]. Data from astronauts [36, 37] suggest that similar changes in multifidus may occur in microgravity as well as in individuals with acute and chronic LBP [14, 24, 26, 31, 44]. While the mechanism of muscle atrophy may not be the same in these different populations, findings were promising in that they showed that rehabilitation of the multifidus muscle was successful for both groups by R+14. Changes were greatest during the period of intensive rehabilitation between R+2 and R+14, with no significant improvements seen between R+14 and R+90 (when subjects were seen less regularly and were performing predominantly home exercise programs). As the TFS training targeted the trunk flexor muscles, the improvement in CSA of the multifidus muscle in this group is most likely due to co-contraction of the abdominal muscles with the multifidus and erector spinae muscles during the exercises performed. This phenomenon has been shown in EMG studies of exercises such as the sit-up [57], and underlies the common belief that doing exercises such as sit-ups will simultaneously strengthen the back muscles. A possible explanation for the greater increase in multifidus CSA at the L3 vertebral level in the TFS group compared to the SMC group may relate to the location of the vertebral level (middle of the lumbar spine) being loaded by exercises which lift the trunk (maximal effect upper to mid-lumbar spine) and lift the lower limbs (maximal effect lower lumbar spine to mid-lumbar spine), though the overall higher loads developed during TFS group training may have also played a role. With regard to the SMC training, similar improvements in multifidus muscle CSA have been seen in subjects with acute LBP [24] and athletes with LBP [26] who underwent a similar training program.

For the psoas muscle, which increased in size during bed rest, there was a different result for the two rehabilitation groups. The TFS training resulted in an initial increase in the CSA of the psoas muscles from the end of bed rest up until R+14, with decreases after that period. This was not seen in the SMC group.

The increase in the psoas muscle size which was demonstrated in the TFS group was likely due to its action as a powerful hip and lumbar spine flexor. In this capacity, the psoas is capable of exerting substantial loads on the lumbar spine due to its attachment to the vertebral column [11]. For this reason, researchers have advised that increasing psoas action by spine and hip flexion could have detrimental effects on the lumbar spine by increasing compressive forces. It has, therefore, been suggested that, when performing abdominal exercises in the supine position, exercises should focus on spine flexion alone [2, 33] rather than spine and hip flexion [2, 46]. Researchers have further advocated performing trunk flexion exercises with the hips and knees bent to (1) reduce tension in the psoas muscle [29], (2) reduce involvement of the hip flexors [18] and (3) to reduce the torque produced [48]. However, others have shown that using this position decreased compressive forces [29], while another study showed that it made no difference to the induced compressive forces on the spine [2].

When considering the effects of the psoas and multifidus muscles working together in normal function, Quint et al. [53] proposed that theses muscles co-contract to increase the overall stiffness of the lumbar spinal segments. Using fixed levels of simulated muscle forces in the multifidus and psoas muscles, these researchers demonstrated this to be the case for axial torque and lateral bending, but such co-contraction acted to *destabilise* the lumbar segments in flexion. Thus, the situation of an imbalance between the hypertrophied psoas muscle, which induces a flexion force on the spine, and the atrophied multifidus muscle may be detrimental to the lumbar spine. Interestingly, increased psoas muscle size has also been documented in athletes with LBP when compared with athletes without LBP [43, 58].

This result would support the theory that it may be preferable to use SMC and functional retraining rather than floor-based programs following bed rest. The results of increasing the size of the multifidus muscle without concurrent increase in psoas muscle size may be due to the focus on obtaining and maintaining an "s" curve (thoracic kyphosis and lumbar lordosis) in SMC training with axial loading of the spine. This principle of exercise which has been demonstrated to be effective in the rehabilitation of LBP, and now for bed rest subjects, may also apply to training programs used for astronauts.

The other main consideration of the exercises used is the potential effect on the IVD and vertebrae. Exercises in the supine position which involve lifting the trunk or lifting the legs are often prescribed with caution in those with LBP due to the potential for increased intradiscal pressure [2, 41, 46]. Evidence of this concern has been confirmed in patients with osteoporosis where a greater percentage of further wedge or compression fractures have occurred in subjects performing flexion exercises such as sit-ups [56]. The results from the current study showed that the forces induced by the TFS program were large enough to induce changes in the anterior disc height and disc volume. While this may seem a desirable effect, it happened rapidly (by R+14), and other works [4, 28] have found a link between IVD changes during bed rest and LBP subsequent to bed rest. The incidence of LBP after bed rest was marginally (non-significantly) higher in the TFS group and hence a gradual return to more normal disc morphology may be preferable from a safety perspective.

While the tissues of the lumbar spine may be more susceptible to damage following bed rest [4, 28, 34] and spaceflight [30], this does not mean that these subjects should never perform higher load exercises, as the spine is exposed to high loads in everyday activities such as lifting [42], and even coughing and sneezing [49], due to forces created by the trunk muscles themselves. It may be sensible to commence training for bed rest subjects and astronauts using an approach such as SMC, with progression later on to higher load activities, when the spinal morphology has returned to normal. Another feature of appropriate exercise may be the use of weight bearing (closed chain) exercises which activate antigravity extensor muscles and apply axial loading to the skeleton and soft tissues [54].

The main limitation of this study was the small subject sample size, which is common to all bed rest studies due to their complex nature and expense. Despite the small sample size, significant changes were seen in the muscles of the lumbo-pelvic region in terms of muscle atrophy, muscle hypertrophy and response to rehabilitation. Although it was not possible to include a control group for the rehabilitation phase of the study due to small numbers, results from the 1st Berlin BedRest Study [6–9, 21] (where subjects did not receive rehabilitation after bed rest) showed that changes in the multifidus muscle were long-lasting without rehabilitation.

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References

1. Alon G, McCombe SA, Koutsantonis S, Stumphauzer LJ, Burgwin KC, Parent MM, Bosworth RA (1987) Comparison of the effects of electrical stimulation and exercise on abdominal musculature. J Orthop Sports Phys Ther 8:567–573
2. Axler CT, McGill SM (1997) Low back loads over a variety of abdominal exercises: searching for the safest abdominal challenge. Med Sci Sports Exerc 29:804–811
3. Baecke JA, Burema J, Frijters JE (1982) A short questionnaire for the measurement of habitual physical activity in epidemiological studies. Am J Clin Nutr 36:936–942
4. Belavý DL, Armbrecht G, Richardson CA, Felsenberg D, Hides JA (2010) Muscle atrophy and changes in spinal morphology: is the lumbar spine vulnerable after prolonged bed-rest? Spine (in press)
5. Belavý DL, Bock O, Börst H, Armbrecht G, Gast U, Degner C, Beller G, Heer M, de Haan A, Stegeman DF, Ceretteli P, Blottner D, Rittweger J, Gelfi C, Kornak U, Felsenberg D. (2010) The 2nd Berlin BedRest Study: protocol and implementation. J Musculoskel Neuronal Interact (in press)
6. Belavý DL, Hides JA, Wilson SJ, Stanton W, Dimeo FC, Rittweger J, Felsenberg D, Richardson CA (2008) Resistive simulated weight bearing exercise with whole body vibration reduces lumbar spine deconditioning in bed-rest. Spine 33:E121–E131
7. Belavý DL, Ng JK, Wilson SJ, Armbrecht G, Stegeman DF, Rittweger J, Felsenberg D, Richardson CA (2009) Influence of prolonged bed-rest on spectral and temporal electromyographic motor control characteristics of the superficial lumbo-pelvic musculature. J Electromyogr Kinesiol. doi:10.1016/j.jelekin.2009.1003.1006
8. Belavý DL, Richardson CA, Wilson SJ, Felsenberg D, Rittweger J (2007) Tonic to phasic shift of lumbo-pelvic muscle activity during 8-weeks of bed-rest and 6-months follow-up. J Appl Physiol 103:48–54
9. Belavý DL, Richardson CA, Wilson SJ, Rittweger J, Felsenberg D (2007) Superficial lumbo-pelvic muscle overactivity and decreased co-contraction after 8-weeks of bed-rest. Spine 32:E23–E29
10. Bogduk N (1997) Clinical anatomy of the lumbar spine and sacrum, 3rd edn. Churchill Livingstone, London
11. Bogduk N, Pearcy M, Hadfield G (1992) Anatomy and biomechanics of psoas major. Clin Biomech 7:109–119
12. Cao P, Kimura S, Macias BR et al (2005) Exercise within lower body negative pressure partially counteracts lumbar spine deconditioning associated with 28-day bed rest. J Appl Physiol 99:39–44
13. Carman BJ, Blanton PL, Biggs NL (1972) Electromyographic study of the anterolateral abdominal musculature utilizing indwelling electrodes. Am J Phys Med 51:113–129
14. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, Cuyper HJ (2000) CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. Eur Spine J 9:266–272

15. Demont RG, Lephart SM, Giraldo JL, Giannantonio FP, Yuktanandana P, Fu FH (1999) Comparison of two abdominal training devices with an abdominal crunch using strength and EMG measurements. J Sports Med Phys Fitness 39:253–258
16. Downie WW, Leatham PA, Rhind VM, Wright V, Branco JA, Anderson JA (1978) Studies with pain rating scales. Ann Rheum Dis 37:378–381
17. Goldby LJ, Moore AP, Doust J, Trew ME (2006) A randomized controlled trial investigating the efficiency of musculoskeletal physiotherapy on chronic low back disorder. Spine 31:1083–1093
18. Gutin B, Lipetz S (1972) An electromyographic investigation of the rectus abdominis in exercises. Res Q 42:256–263
19. Hauggaard A, Persson A (2007) Specific spinal stabilisation exercises in patients with low back pain—a systematic review. Phys Ther Rev 12:233–248
20. Hicks GS, Duddleston DN, Russell LD et al (2002) Low back pain. Am J Med Sci 324:207–211
21. Hides JA, Belavý DL, Stanton W, Wilson SJ, Rittweger J, Felsenberg Richardson C (2007) MRI assessment of trunk muscles during prolonged bed rest. Spine 32:1687–1692
22. Hides JA, Jull GA, Richardson CA (2001) Long-term effects of specific stabilizing exercises for first episode low back pain. Spine 26:E243–E248
23. Hides JA, Richardson CA, Hodges PW (2004) Local segmental control. In: Richardson C, Hodges PW, Hides J (eds) Therapeutic exercise for lumbo-pelvic stabilization: a motor control approach for the treatment and prevention of low back pain, 2nd edn. Churchill Livingstone, Edinburgh, pp 185–220
24. Hides JA, Richardson CA, Jull GA (1996) Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. Spine 21:2763–2769
25. Hides JA, Richardson CA, Jull GA (1998) Use of real-time ultrasound imaging for feedback in rehabilitation. Man Ther 3:125–131
26. Hides JA, Stanton W, McMahon S, Sims K, Richardson C (2008) The effect of stabilization training on multifidus muscle size among young elite cricketers. JOSPT 38:101–108
27. Hodges PW, Moseley GL, Gabrielsson AH, Gandevia SC (2003) Acute experimental pain changes postural recruitment of the trunk muscles in pain-free humans. Exp Brain Res 151:262–271
28. Holguin N, Muir J, Rubin C, Judex S (2009) Short applications of very low-magnitude vibrations attenuate expansion of the intervertebral disc during extended bed rest. Spine J 9:470–477
29. Johnson C, Reid JG (1991) Lumbar compressive and shear forces during various trunk curl up exercises. Clin Biomech 6:97–104
30. Johnston SL, Wear ML, Hamm PB (1998) Increased incidence of herniated nucleus pulposus among astronauts and other selected populations (abstract). Aviat Space Environ Med 69:220
31. Kader D, Wardlaw D, Smith F (2000) Correlation between the MRI changes in the lumbar multifidus muscles and leg pain. Clin Radiol 55:145–149
32. Kiesel KB, Uhl TL, Underwood FB, Nitz A (2007) Rehabilitative ultrasound measurement of select trunk muscle activation during induced pain. Man Ther (in press)
33. Knudson D (1996) A review of exercise and fitness tests for abdominal muscle. Sports Med Update 11(4–5):25–30
34. Krølner B, Toft B (1983) Vertebral bone loss: an unheeded side effect of therapeutic bed rest. Clin Sci (Lond) 64:537–540
35. Le Blanc AD, Evans HJ, Schneider VS et al (1994) Changes in intervertebral disc cross-sectional area with bed rest and space flight. Spine 19:812–817
36. Le Blanc A, Lin C, Shackelford L et al (2000) Muscle volume, MRI relaxation times (T2), and body composition after spaceflight. J Appl Physiol 89:2158–2164
37. Le Blanc A, Rowe R, Schneider V et al (1995) Regional muscle loss after short duration spaceflight. Aviat Space Environ Med 66:1151–1154
38. Le Blanc AD, Schneider VS, Evans HJ, Pientok C, Rowe R, Spector E (1992) Regional changes in muscle mass following 17 weeks of bed rest. J Appl Physiol 73:2172–2178
39. Lee SU, Hargens AR, Fredericson M, Lang PK (2003) Lumbar spine disc heights and curvature: upright posture vs. supine compression harness. Aviat Space Environ Med 74:512–516
40. Lipetz S, Gutin B (1970) An electromyographic study of four abdominal exercises. Med Sci Sports 2:35–38
41. McGill SM (1995) The mechanics of torso flexion: situps and standing dynamic flexion manoeuvres. Clin Biomech (Bristol, Avon) 10:184–192
42. McGill SM, Norman RW (1986) Partitioning of the L4–L5 dynamic moment into disc, ligamentous, and muscular components during lifting. Spine 11:666–678
43. McGregor AH, Anderton L, Gedroyc WM (2002) The trunk muscles of elite oarsmen. Br J Sports Med 36:214–221
44. Mengiardi B, Schmid MR, Boos N et al (2006) Fat content of lumbar paraspinal muscles in patients with chronic low back pain and in asymptomatic volunteers: quantification with MR spectroscopy. Radiology 240:786–792
45. Monfort-Pañego M, Vera-García FJ, Sánchez-Zuriaga D, Sarti-Martínez MA (2009) Electromyographic studies in abdominal exercises: a literature synthesis. J Manip Physiol Ther 32:232–244
46. Nachemson A, Elfström G (1970) Intravital dynamic pressure measurements in lumbar discs. A study of common movements, maneuvers and exercises. Scand J Rehabil Med Suppl 1:1–40
47. Natarajan RN, Andersson GB (1999) The influence of lumbar disc height and cross-sectional area on the mechanical response of the disc to physiologic loading. Spine 24:1873–1881
48. Neeves N, Barlow D (1975) Torque work and power differences in bent-knee and straight leg sit-ups in women. Med Sci Sports Exerc 7:77
49. Neumann P, Gill V (2002) Pelvic floor and abdominal muscle interaction: EMG activity and intra-abdominal pressure. Int Urogynecol J 13:125–132
50. Niemistö L, Lahtinen-Soupanki T, Rissanen P, Lindgren K-A, Sarna S, Hurri H (2003) A randomized trial of combined manipulation, stabilization exercises, and physician consultation compared to physician consultation alone for chronic low back pain. Spine 28:2185–2191
51. O'Sullivan PB, Twomey LT, Allison GT (1997) Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. Spine 22:1959–1967
52. Pinheiro JC, Bates DM (2000) Mixed-effects models in S and S-PLUS. Springer, Berlin
53. Quint U, Wilke HJ, Shirazi-Adl A, Parnianpour M, Löer F, Claes LE (1998) Importance of the intersegmental trunk muscles for the stability of the lumbar spine. A biomechanical study in vitro. Spine 23:1937–1945
54. Richardson CA, Hides JA (2004) Closed chain segmental control. In: Richardson CA, Hodges PW, Hides JA (eds) Therapeutic exercise for lumbo-pelvic stabilisation: a motor control approach for the treatment and prevention of low back pain, 2nd edn. Churchill Livingstone, Edinburgh, pp 221–232
55. Shaughnessy M, Caulfield B (2004) A pilot study to investigate the effect of lumbar stabilization exercise training on functional ability and quality of life in patients with chronic low back pain. Int J Rehabil Res 27:297–301
56. Sinaki M, Mikkelson BA (1984) Postmenopausal spinal osteoporosis: flexion versus extension exercises. Arch Phys Med Rehabil 65:593–596

57. Soderberg GL, Barr JO (1983) Muscular function in chronic low back dysfunction. Spine 8:79–85
58. Stewart S, Stanton WR, Wilson SJ, Hides JA (2009) Consistency in size and asymmetry of the psoas major muscle among footballers. BJSM. doi:10.1136/bjsm.2009.058909
59. Stuge B, Laerum E, Kirkesola G, Vollestad N (2004) The efficacy of a treatment program focusing on specific stabilizing exercises for pelvic girdle pain after pregnancy: a randomized controlled trial. Spine 29:351–359
60. Wallwork TL, Stanton W, Freke M, Hides JA (2009) The effect of chronic low back pain on size and contraction of the lumbar multifidus muscle. Man Ther 14:496–500
61. Wing PC, Tsang IK, Susak L et al (1991) Back pain and spinal changes in microgravity. Orthop Clin N Am 22:255–262