HHS Public Access

Author manuscript

Spine (Phila Pa 1976). Author manuscript; available in PMC 2017 September 07.

Published in final edited form as:

Spine (Phila Pa 1976). 2016 December 15; 41(24): 1917–1924. doi:10.1097/BRS.0000000000001873.

Lumbar spine paraspinal muscle and intervertebral disc height changes in astronauts after long-duration spaceflight on the International Space Station

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Abstract

Study Design—Prospective case series

Objective—Evaluate lumbar paraspinal muscle (PSM) cross-sectional area and intervertebral disc (IVD) height changes induced by a 6-month space mission on the International Space Station (ISS). The long-term objective of this project is to promote spine health and prevent spinal injury during space missions as well as here on Earth.

Summary of Background—NASA crewmembers have a 4.3 times higher risk of herniated IVDs, compared to the general and military aviator populations. The highest risk occurs during the first year after a mission. Microgravity exposure during long-duration spaceflights results in ~5cm lengthening of body height, spinal pain, and skeletal deconditioning. How the PSMs and IVDs respond during spaceflight is not well described.

Methods—Six NASA crewmembers were imaged supine with a 3T MRI. Imaging was conducted pre-flight, immediately post-flight and then 33 to 67 days after landing. Functional cross-sectional area (FCSA) measurements of the PSMs were performed at the L3-4 level. FCSA was measured by grayscale thresholding within the posterior lumbar extensors to isolate lean muscle on T2-weighted scans. IVD heights were measured at the anterior, middle and posterior sections of all lumbar levels. Repeated measures ANOVA was used to determine significance at $p<0.05$, followed by post-hoc testing.

Results—Paraspinal lean muscle mass, as indicated by the FCSA, decreased from 86% of the total PSM cross-sectional area down to 72%, immediately after the mission. Recovery of 68% of

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the post-flight loss occurred over the next 6 weeks, still leaving a significantly lower lean muscle fractional content compared to pre-flight values. In contrast, lumbar IVD heights were not appreciably different at any time point.

Conclusions—The data reveal lumbar spine PSM atrophy after long-duration spaceflight. Some FCSA recovery was seen with 46 days post-flight in a terrestrial environment, but it remained incomplete compared to pre-flight levels.

Keywords

Aerospace Medicine; Atrophy; Immobilization; Intervertebral Disc; Magnetic Resonance Imaging; Paraspinal Muscles; Muscles; Back Pain; Spine; Weightlessness

Introduction

The lumbar paraspinal muscles provide postural stability, enabling gait and supporting upper extremity movements [1,2]. They are critical to function in a gravitational environment. In particular, these muscles facilitate vertebral motion, and protect articular structures, discs and ligaments from excessive strain and injury [3]. Atrophy of these muscles is evidenced by altered fat content, cross-sectional area, and higher proportions of type II fast-twitch fibers [4,5], and is strongly associated with low back pain on Earth [6,7]. However, how these muscles function and respond during space flight is not well described.

With microgravity exposure in space, several spine-related issues are observed among crewmembers [8]. The torso lengthens 4 to 6 cm, about 2 to 3 times the normal diurnal increase (1 to 2 cm) on Earth [9,10]. This reportedly occurs because of spinal unloading, flattening of spinal curvature, loss of paravertebral muscle tone and vertebral disc degeneration [11,12]. Flight medical data indicate that over half of U.S. astronauts report spine pain during their mission [13–15]. While in space, astronauts report that a lumbar flexed, “fetal tuck” position to stretch is the most effective way of alleviating back pain [14]. The back pain is described with a moderate to severe level of intensity for 14 to 28% percent of the U.S. astronauts. Shuttle crewmembers described pain lasting for 15 to 100% of their mission. The location of pain is reported most frequently in the following anatomic regions: 50% low back, 11% mid-back, 11% neck and 1% chest. Even after their return to Earth, ~40% of crewmembers report spine pain [16]. Another indication of lumbar pain is vertebral hypomobility from guarding [17], and preliminary data indicate such spinal stiffness is seen with prolonged space flight [18,19].

Even with an exercise protocol in place during prolonged space missions, significantly decreased muscle size is seen at multiple sites in the body, including the lumbar paraspinals [20]. The exercise protocols have evolved over time, but traditionally they have not specifically focused on core strengthening [21]. LeBlanc and co-workers describe an exponential recovery of pre-flight muscle size after Mir missions, and the recovery is complete within 30 to 60 days. These measurements were made by manually tracing the outline of muscle cross-sections seen on 1.5T MR images of 16 crew members. It is unknown if fatty replacement, fluid redistribution, or actual lean muscle mass changes occur, such as observed in patients or ground-based bed rest simulations of microgravity [22,23].

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Lastly, a concerning risk of intervertebral disc herniation is seen post-flight. The incidence of herniated nucleus pulposus is reported as 4.3 times higher in the U.S. astronaut corps compared to matched aviator control populations on Earth [11]. The highest risk period for disc herniation appears in the first year after return to Earth, with the majority reported within the first month of landing. It is unknown how medical staff surveillance of the astronauts versus control populations, and different behavioral decisions regarding medical care seeking and reporting by crewmembers before versus after a mission might play into the observations. However, it does strongly suggest that structural changes in the spine associated with space adaptation result in deleterious effects occurring with the re-introduction of the gravity environment. Moreover, the consequence of disc herniation may impact an astronaut's ability to return to work on Earth or conduct work upon arriving at a planetary destination such as Mars after a long space flight.

The immediate purpose of this research is to evaluate lumbar paraspinal muscle (PSM) cross-sectional area (CSA) and intervertebral disc (IVD) heights following a 6-month International Space Station (ISS) mission and a 33 to 67 day post-flight recovery period. The goals are to understand the factors involved in lumbar spine strength and back pain in crewmembers during a long mission and after increased g-loads of landing and re-adaptation to Earth. This could provide helpful physiological information to support a manned mission to Mars. On Earth, this information could help our understanding of spinal atrophy and degeneration due to inactivity, and potential issues involved with backpack use of military personnel, and first-responders.

Materials and Methods

Institutional Research Board approval was obtained from the National Aeronautics and Space Administration (NASA) and the University of California, San Diego. Six ISS crewmembers volunteered for the study, 1female and 5 males. The range of crewmember ages spanned 46–55 years, height 168–183 cm, and body mass 60–93 kg. The mission duration on the ISS ranged from 117–213 days. This project represents four years of active data collection, through 2016.

Supine lumbar spine magnetic resonance imaging (MRI) scans were conducted pre-flight, immediate post-flight and at least 30 days post-flight recovery after an ISS mission (Figure 1). Imaging took about 80 minutes, and was performed in the morning, using a Siemens Magnetom Verio 3T system at a University of Texas Medical Branch facility outside Houston, TX. Pre-flight imaging was performed on average 214 days prior to launch. While on the ISS, the astronauts engaged in 2–3 hours of daily exercise with a treadmill, stationary cycle and resistive strength training of the large muscle groups [21,24–26]. After landing in Kazakhstan, the "Immediate" post-flight imaging was performed within 1–2 days, in Houston. Landing details are described elsewhere [27]. The astronauts completed typical post-flight astronaut strength, conditioning and rehabilitation (ASCR) exercise and activities [26], including a brief trip back to Russia, and return to Houston, TX where they were imaged again. These "Recovery" period images were performed an average of 46 days (range 33–67 days) after landing. The imaging time points are summarized in Table 1.

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Functional cross-sectional area (FCSA) measurements of the lumbar paraspinal muscles were obtained using the T2-weighted MRI scans. We elected to focus on the L3/4 vertebral level, based on the relative ease of identifying muscle boundaries as compared to lower vertebral levels. The FCSA measurements involved an image-analysis thresholding technique to estimate lean muscle mass. The technique details are reported elsewhere [1,28–31]. Briefly, the lumbar paraspinal muscles (multifidus, erector spinae, quadratus lumborum, and psoas) were identified and analyzed using Fiji imaging software (National Institutes of Health) [32], Figure 2A. Total paraspinal muscle CSA was defined as the sum total of the CSAs obtained from the eight PSM (combining right and left). Functional PSM CSA was measured using gray-scale thresholding to analyze those regions of the muscle cross-sections corresponding to dark, lean muscle mass. The analysis was conducted by one individual (R.H.). Our control studies showed that repeat measurements done by an individual as well as by several individuals were reliable and reproducible, with an intraclass correlation coefficient of 0.99, consistent with the literature [28,29]. Statistical analysis was conducted using one-way, repeated measures ANOVA to establish significance, defined as $p<0.05$, followed by post-hoc testing with the Newman-Keuls multiple comparison test [33] with alpha = 0.05, using GraphPad Prism (version 5.04, GraphPad Software, Inc., La Jolla, CA) software.

Lastly, lumbar IVD heights were measured at the anterior, middle and posterior sections from the L1-2 to L5-S1 disc levels (Figure 2B). The fast spin echo T2 images were obtained at the midsaggital plane [34], with slice thickness 4mm, field of view 200, 192×320 image matrix, voxel size 1×0.6×4mm, and NEX 2. For each subject, the disc height at a given lumbar intervertebral level was defined as the average of measurements made in the anterior, middle and posterior locations along the disc, modified from the Dabbs method [35]. Change in the average disc height was calculated at post-flight (Post-Preflight), recovery (Recovery-Postflight), and overall change from pre-flight to recovery (Recovery-Preflight). This measurement has an uncertainty with inter- and intra-observer standard deviations of 0.2 and 0.3mm, respectively [36]. Our group has used the technique to measure changes in lumbar IVD heights with Earth-bound subjects in unloaded bedrest [34], and loaded backpack studies [36,37].

Results

Lumbar paraspinal FCSA decreased by 19% on average from a pre-flight value of 8737 mm^2 ± 1758 mm^2 (avg ± sd) down to a post-flight value of 7049 mm^2 ± 1822 mm^2. Later, there was a change in FCSA up to a recovery value of 8195 mm^2 ± 1900 mm^2. ANOVA testing indicates a significant difference in FCSA measured at the three time points, with F ratio 23.39, R^2 0.82 and $p=0.0002$. Post hoc testing indicates the FCSA changed significantly from pre- to post-flight, and from post-flight to post-flight recovery. The FCSA data at the recovery time point were less than the pre-flight values, representing a 68% recovery of the post-flight loss, a difference not significantly different as determined by post hoc testing. In comparison, the total lumbar paraspinal CSA (that encompass the unthresholded manual outlines, and therefore includes both lean muscle and non-lean muscle components) followed a similar trend at the three time points, but with non-significant changes (F ratio 1.44, R^2 0.22, $p=0.2832$) , Table 2.

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Expressed as a percent of the total lumbar CSA, the relative proportion of lumbar lean muscle FCSA decreased from pre-flight to post-flight by 14 percentage points from 86% ± 5% down to 72 ± 7% . The fraction of lumbar muscle FCSA recovered nine percentage points over the next six weeks to an average of 81% ± 4%. ANOVA testing indicates a significant difference in percent FCSA measured at the three time points, with F ratio 22.25, R^2 0.82, and p=0.0002. Post hoc testing indicates the FCSA changed significantly from pre- to post-flight, and from post-flight to post-flight recovery. This resulted in a significantly lower lean muscle fractional content at recovery compared to the pre-flight values (Figure 3).

Among the six crewmembers studied, average disc height did not change in the lumbar spine. There was no consistent pattern before and after the mission (Table 3). There was considerable disc height variability from crewmember to crewmember, over various lumbar spine levels, and along anterior-middle-posterior locations of the disc.

Discussion

This study showed reductions in total cross-sectional area with long-duration space flight, but even more dramatic reductions in functional cross-sectional area, a proxy for lean muscle mass. At six weeks post-mission, the FCSA and CSA trended toward pre-flight levels. After the mission, the lumbar paraspinal extensors recovered 68% of the loss after ~46 days back on Earth. These ISS data are comparable to previous long-duration Mir data obtained ~20 years ago [20], where intrinsic back muscle total cross sectional area decreased to 84% of pre-flight values, and psoas cross-sectional area decreased to 96%. However direct comparisons to that study are difficult to make due to several factors.

We had six crewmembers, whereas LeBlanc and co-workers report on 16 crewmembers. We used one 3 Tesla MRI scanner in Houston operated by a single team of technicians, whereas LeBlanc et al. used three 1.5 Tesla scanners at two centers (Moscow, Russia and Houston, TX). During the missions, different exercise countermeasures were utilized on board more recent ISS compared to previous Mir flights [38]. On Mir specifically, there were no significant resistance exercises for strength. LeBlanc and co-workers report slightly more temporal variability for scan times after landing. For example, five of the six crewmembers were scanned between day 1–2 after landing in the present study, whereas their first postflight measurements occurred on landing day itself or up to four days after landing. We focused on the L3/4 lumbar level, whereas LeBlanc and co-workers made muscle volume calculations using an unspecified region of the lumbar spine. We elected not to measure the lower lumbar levels due to the greater difficulty in identifying clear muscle boundaries in a region that typically has a greater degree of fatty atrophy/intermuscular fascial connections (e.g. lumbar intermuscular aponeurosis, lumbosacral ligaments) in the multifidi/erector spinae muscles, and a fanning/thinning of the psoas and erector spinae muscles as they traverse normally away from the lumbar spine [39]. Lastly, we evaluated both total and functional cross-sectional area measurements. This provides insight into lean-muscle mass changes separated from the effects of water retention or fatty replacement.

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In contrast to paraspinal muscle data, individual disc height changes in the lumbar spine were small and demonstrated no consistent changes across time points. Specifically, disc height increases were not seen in a significant or consistent fashion postflight. We continue to review this data in several additional ways, including total lumbar disc height (measured by summing disc heights from every level) and total lumbar length between the L1 and the L5 vertebral bodies [40], and also by making comparisons with lumbar lordosis measurements, MRI T2 water mapping techniques [41] in the discs [19], and a separate data set we collected on the subjects using upright standing MRI data [36]. So far, our data are compatible to previous lumbar disc height and lumbar length measurements after short-duration space flight [40], and preliminary data from in-flight ultrasound studies of cervical and lumbar disc heights, which also do not indicate significant disc height increases or swelling [42].

These measurements run counter to previous hypotheses about the effects of micro-gravity on disc swelling [11,43], and suggest that the torso lengthening observed in crewmembers [12,44] may be due to factors other than swelling of the intervertebral discs. Specifically, postural straightening (i.e. a flattening of spinal lumbar lordosis and thoracic kyphosis into a 'neutral body posture' in microgravity) is an important factor [12,19]. However our sample size is presently small for the study of IVD heights, and we have no in-flight images. Further spine analysis with additional crewmembers and in-flight ultrasound imaging will be forthcoming.

Back pain is a part of life. About two-thirds of the adult population will experience low back pain and a specific pathologic anatomical diagnosis is made in only ~15% of cases [45]. Given that, what are the implications of lowered paraspinal muscle functional cross-sectional area? Back pain patients do demonstrate reduced paraspinal muscle cross-sectional area [7]. However, the positive predictive value of cross-sectional area on the development of future low back pain is controversial, and it has not yet been established as a strong independent risk factor [46,47]. This may be similar to other reported low back pain risk factors (such as physical demands at work, job satisfaction, bodily vibration, smoking, alcohol consumption, lumbar flexibility, etc.), where reliable predictive conclusions from the literature are difficult to make for any one person due to the many intercorrelated and confounding parameters, and the fact low back pain is common even in people without such risks. Back weakness is one known risk factor for low back pain [45,48] and our laboratory is analyzing Biering-Sorensen back extension endurance data to help characterize a structure-function relationship among the crewmembers. Even so, muscle endurance and strength depend not only on cross-sectional area, but also on many other factors such as muscle contractility, metabolism, and fiber type atrophy [49,50], as well as neuromuscular recruitment, coordination, and fatigue mechanisms [51,52], pain and psychosocial factors [53].

Astronaut exercise programs currently emphasize the maintenance of bone mineral density, aerobic/anerobic capacity, and muscle strength/power (focused on the large muscles of the proximal hips and shoulders) and endurance [21]. Pre-flight, the exercise program involves a mix of cardio aerobic training, functional training for activities performed in daily life, resistive weight-training (e.g. squats and deadlifts), and familiarization of in-flight exercises. In-mission there is treadmill training, cycle ergometer and resistive training (squats, deadlifts, bench/shoulder press, rows). Post-flight there is cardio, resistive weight-training, and functional exercise focused on balance, proprioception, agility, coordination and

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power [26]. These routinized exercise programs are closely monitored by NASA Astronaut Strength, Conditioning and Rehabiliation (ASCR) and medical staff. With such a steady-state, maintenance program in place pre-flight, we do not believe significant lumbar deconditioning or strengthening occurs between the pre-flight images and the flight itself. However, we are unable to substantiate this belief because mission logistics preclude testing close to the actual launch date.

Our lumbar spine data identify a specific departure from the terrestrial, baseline anatomy of astronauts. It further suggests an exercise countermeasure is needed to focus on the lumbar paraspinal muscles. Low load, lumbar core stabilization exercises are efficacious for back pain patients [54], deconditioned [1,55] and healthy [56] adults on Earth, specifically improving paraspinal muscle CSA atrophy and strength [4,57–59], as well as acute [60,61] and chronic [57,62,63] low back pain. Such core-strengthening exercises specifically involve isometric exercises or lumbar extensor training. Another promising exercise countermeasure for low back pain is yoga [64], which might be particularly effective in addressing spaceflight-associated lumbar stiffness and hypomobility [15,19,65]. Existing exercise interventions in microgravity that target other muscle groups are effective in addressing atrophy [38]. Whether new exercise countermeasures can prevent inflight paraspinal muscle atrophy, improve spinal pain and function, shorten recovery time and how such exercise might be performed in a micro-gravity environment with available exercise equipment need further study.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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

National Aeronautics and Space Administration (NASA) grants NNX10AM18G and NNX13AM89G, a National Space Biomedical Research Institute grant NASA NCC 9-58 and Environmental and Exercise Section Gravitational Physiology Predoctoral Award, and American Physiological Society Excellence in Professional Student Research Travel Award funds were received in support of this work.

Relevant financial activities outside the submitted work: board membership, payment for lectures.

We thank Marilyn Johnson, Stephanie Miller, Laura Sarmiento and Stephanie Vallarino, and Drs. S. Chiang, D. Hughes and R. Riascos-Castaneda for their work towards the success of this project. We thank the International Space Station crew members for their research participation.

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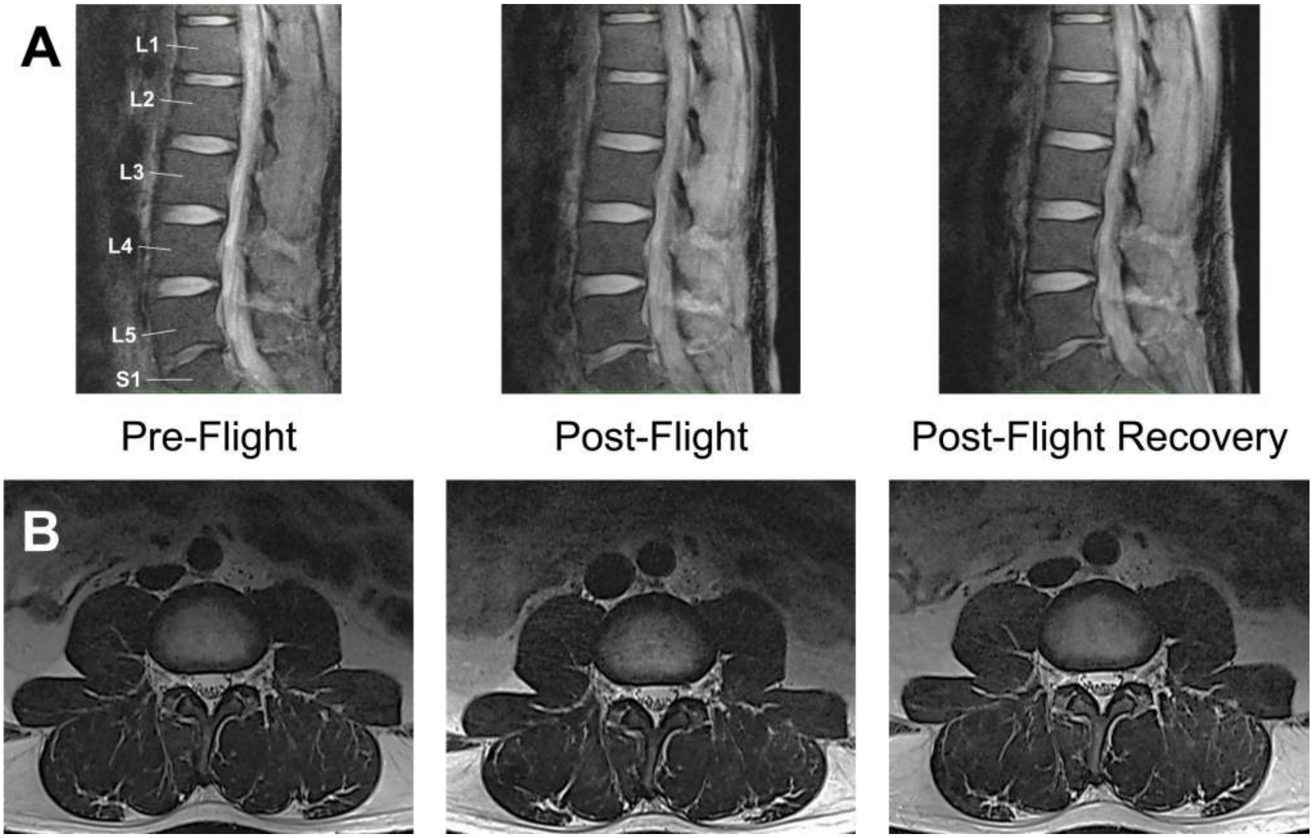

Figure 1.

Characteristic pre-, post- flight and recovery lumbar spine MR images, A) L1-S1 sagittal and B) L3/4 axial T2 sequences.

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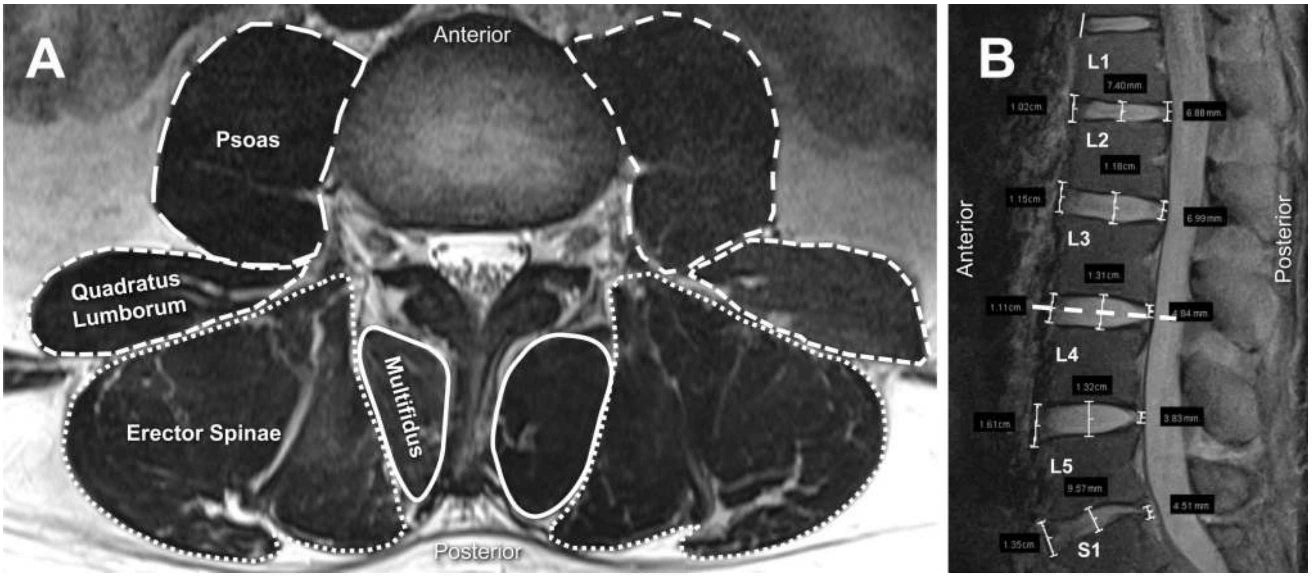

Figure 2.

Characteristic location of A) lumbar paraspinal muscles identified for FCSA lean muscle area measurement on axial images at the L3-L4 level, and B) IVD height measurement on sagittal images (Anterior, Middle, and Posterior).

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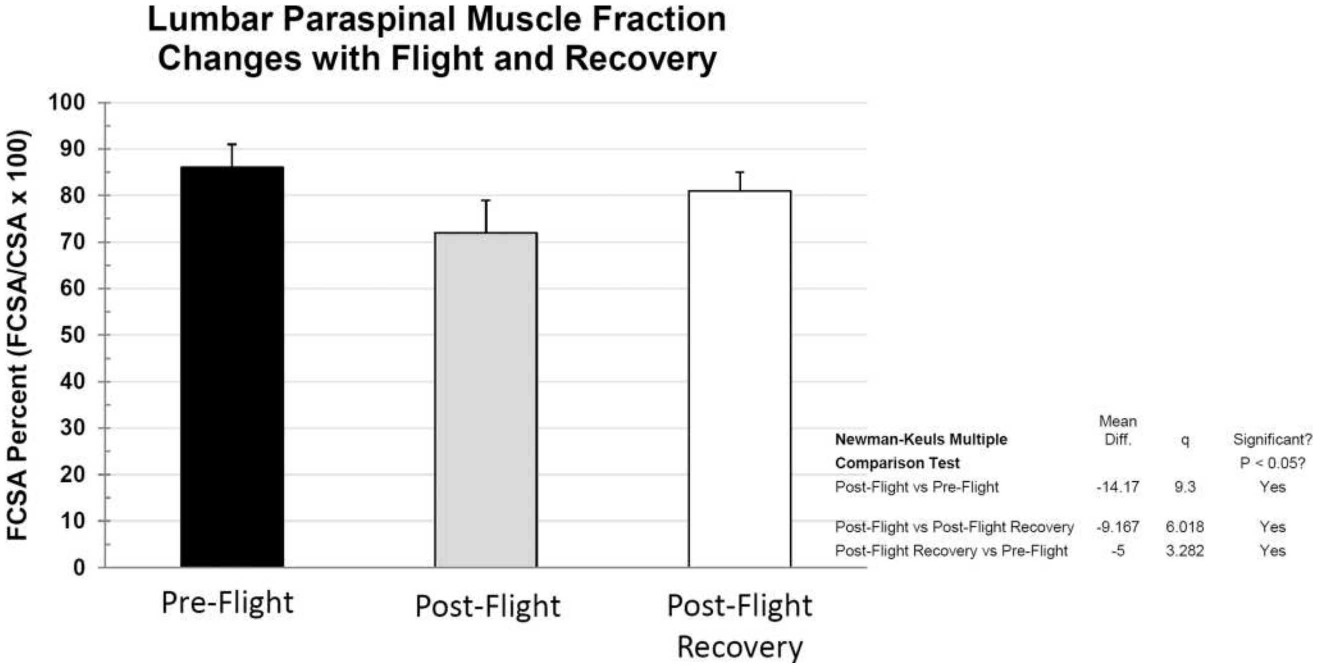

Newman-Keuls Multiple Comparison Test	Mean Diff.	q	Significant? P < 0.05?
Post-Flight vs Pre-Flight	-14.17	9.3	Yes
Post-Flight vs Post-Flight Recovery	-9.167	6.018	Yes
Post-Flight Recovery vs Pre-Flight	-5	3.282	Yes

Figure 3.

FCSA as a percentage of total CSA in the lumbar paraspinal muscles, n=6 crewmembers.

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Table 1

Imaging schedule of crewmembers

Subject #	Preflight MRI days before launch	Post-flight MRI days after landing	Post-flight Recovery MRI days after landing
1	−132	+2	+41
2	−246	+2	+37
3	−245	+1	+33
4	−224	+2	+34
5	−222	+1	+63
6	−30	+4	+67

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Table 2

Lumbar Paraspinal Muscle cross-sectional area data

	Lumbar Cross Sectional Area (CSA)			CSA normalized to pre-flight baseline		
Subject #	**Pre- (mm^2)**	**Post- (mm2)**	**Post-Rec (mm2)**	**Pre-**	**Post-**	**Post-Rec**
1	10175	10811	10372	1	1.06	1.02
2	6573	5326	5766	1	0.81	0.88
3	10371	10174	11026	1	0.98	1.06
4	11425	11309	11499	1	0.99	1.01
5	10119	9936	10118	1	0.98	1.00
6	12069	11060	11659	1	0.92	0.97
Average	10122	9769	10073		0.96	0.99
Std dev	1905	2239	2195		0.09	0.06
	Lumbar Functional Cross Sectional Area (FCSA)			**fCSA normalized to pre-flight baseline**		
Subject #	**Pre- (mm^2)**	**Post- (mm2)**	**Post-Rec (mm2)**	**Pre-**	**Post-**	**Post-Rec**
1	9497	7559	8577	1	0.80	0.90
2	5371	3464	4399	1	0.64	0.82
3	8855	8435	9517	1	0.95	1.07
4	10338	8217	9283	1	0.79	0.90
5	8647	7484	8535	1	0.87	0.99
6	9716	7135	8859	1	0.73	0.91
Average	8737	7049	8195		0.80	0.93
Std dev	1758	1822	1900		0.11	0.09
	Lumbar FCSA Percent (FCSA/CSA × 100)			**Lumbar FCSA Percent normalized to pre-flight baseline**		
Subject #	**Pre- (%)**	**Post- (%)**	**Post-Rec (%)**	**Pre-**	**Post-**	**Post-Rec**
1	93	70	83	1	0.75	0.89
2	82	65	76	1	0.80	0.93
3	85	83	86	1	0.97	1.01
4	90	73	81	1	0.80	0.89
5	85	75	84	1	0.88	0.99

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	Lumbar Cross Sectional Area (CSA)			CSA normalized to pre-flight		
Subject #	**Pre- (mm^2)**	**Post- (mm2)**	**Post-Rec (mm2)**	**baseline Pre-**	**Post-**	**Post-Rec**
6	81	65	76	1	0.80	0.94
Average	86	72	81		0.83	0.94
Std dev	5	7	4		0.08	0.05

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Table 3

Change in lumbar disc heights (average change ± sd), in mm. Changes at post-flight (Post-Preflight), Recovery (Recovery-Postflight), and Overall change from pre-flight to recovery (Recovery-Preflight).

	Post-Preflight	Recovery-Postflight	Recovery-Preflight
L1-L2	−0.1 ± 1.2	0.0 ± 1.0	−0.1 ± 0.6
L2-L3	0.0 ± 0.4	−0.1 ± 0.5	−0.1 ± 0.5
L3-L4	−0.8 ± 1.5	0.1 ± 0.9	−0.7 ± 1.0
L4-L5	−0.3 ± 0.5	0.2 ± 0.9	−0.2 ± 1.0
L5-S1	0.1 ± 1.0	−0.3 ± 0.9	−0.3 ± 0.6