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Clinical Study

The effects of exposure to microgravity and reconditioning of the lumbar multifidus and anterolateral abdominal muscles: implications for people with LBP

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ABSTRACT

BACKGROUND CONTEXT: One of the primary changes in the neuromuscular system in response to microgravity is skeletal muscle atrophy, which occurs especially in muscles that maintain posture while being upright on Earth. Reduced size of paraspinal and abdominal muscles has been documented after spaceflight. Exercises are undertaken on the International Space Station (ISS) during and following space flight to remediate these effects. Understanding the adaptations which occur in trunk muscles in response to microgravity could inform the development of specific countermeasures, which may have applications for people with conditions on Earth such as low back pain (LBP).

PURPOSE: The aim of this study was to examine the changes in muscle size and function of the lumbar multifidus (MF) and anterolateral abdominal muscles (1) in response to exposure to 6 months of microgravity on the ISS and (2) in response to a 15-day reconditioning program on Earth.

DESIGN: Prospective longitudinal series.

PATIENT SAMPLE: Data were collected from five astronauts who undertook seven long-duration missions on the ISS.

OUTCOME MEASURES: For the MF muscle, measures included cross-sectional area (CSA) and linear measures to assess voluntary isometric contractions at vertebral levels L2 to L5. For the abdominal muscles, the thickness of the transversus abdominis (TrA), obliquus internus abdominis (IO) and obliquus externus abdominis (EO) muscles at rest and on contraction were measured.

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METHODS: Ultrasound imaging of trunk muscles was conducted at four timepoints (preflight, postflight, mid-reconditioning, and post reconditioning). Data were analyzed using multilevel linear models to estimate the change in muscle parameters of interest across three time periods.

RESULTS: Beta-coefficients (estimates of the expected change in the measure across the specified time period, adjusted for the baseline measurement) indicated that the CSA of the MF muscles decreased significantly at all lumbar vertebral levels (except L2) in response to exposure to microgravity (L3=12.6%; L4=6.1%, L5=10.3%; p<.001), and CSAs at L3-L5 vertebral levels increased in the reconditioning period (p<.001). The thickness of the TrA decreased by 34.1% (p<.017), IO decreased by 15.4% (p=.04), and the combination of anterolateral abdominal muscles decreased by 16.2% (p<.001) between pre- and postflight assessment and increased (TrA<0.008; combined p=.035) during the postreconditioning period. Results showed decreased contraction of the MF muscles at the L2 (from 12.8% to 3.4%; p=.007) and L3 (from 12.2% to 5%; p=.032) vertebral levels following exposure to microgravity which increased (L2, p=.046) after the postreconditioning period. Comparison with preflight measures indicated that there were no residual changes in muscle size and function after the postreconditioning period, apart from CSA of MF at L2, which remained 15.3% larger than preflight values (p<.001).

CONCLUSIONS: In-flight exercise countermeasures mitigated, but did not completely prevent, changes in the size and function of the lumbar MF and anterolateral abdominal muscles. Many of the observed changes in size and control of the MF and abdominal muscles that occurred in response to prolonged exposure to microgravity paralleled those seen in people with LBP or exposed to prolonged bed rest on Earth. Daily individualized postflight reconditioning, which included both motor control training and weight-bearing exercises with an emphasis on retraining strength and endurance to re-establish normal postural alignment with respect to gravity, restored the decreased size and control of the MF (at the L3-L5 vertebral levels) and anterolateral abdominal muscles. Drawing parallels between changes which occur to the neuromuscular system in microgravity and which exercises best recover muscle size and function could help health professionals tailor improved interventions for terrestrial populations. Results suggested that the principles underpinning the exercises developed for astronauts following prolonged exposure to microgravity (emphasizing strength and endurance training to re-establish normal postural alignment and distribution of load with respect to gravity) can also be applied for people with chronic LBP, as the MF and anterolateral abdominal muscles were affected in similar ways in both populations. The results may also inform the development of new astronaut countermeasures targeting the MF and abdominal muscles.

Keywords: Exercise therapy; Lumbar spine; Paraspinal muscles; Rehabilitation; Spaceflight; Trunk muscles; Ultrasound imaging

Introduction

Microgravity provides a unique opportunity to examine the effects of decreased axial loading on spinal structures, including muscles. One spine-related issue that has been observed among crewmembers includes lengthening of the torso by 4 to 6 cm, which is 2 to 3 times the normal diurnal increase (1−2 cm) on Earth [1,2]. The proposed explanations for this observation are flattening of the lumbar lordosis [3], accumulated swelling of unloaded discs [4], and loss of cross-sectional area (CSA) [3] and tone [5,6] of the paravertebral muscles. The effects of decreased gravity on the trunk extensor muscles may be almost immediate. A recent study that used parabolic flights to investigate the responses of spinal muscles to hypogravity demonstrated reduced neuromuscular contribution of antigravity trunk extensor muscles to control spinal posture at rest and during simulated perturbations of the trunk [7]. Results of a recent study of astronauts exposed to microgravity on the International Space Station (ISS) showed that the combined CSA of the lumbar paraspinal muscles (multifidus [MF], lumbar erector spinae, psoas, and quadratus lumborum) decreased by as much as 19% at the L3-4 vertebral level [8]. Interestingly, atrophy of the MF muscle, rather than intervertebral disc swelling, was shown to be strongly associated with flattening of the lumbar lordosis and increased stiffness (decreased intersegmental flexion-extension range of motion) of the mid lumbar spine segments after spaceflight [3].

Decreases in the CSA of the lumbar MF muscle have previously been observed in people with low back pain (LBP) and those exposed to prolonged bed rest on Earth. Acute LBP has been characterized by localized atrophy of the MF muscles, most commonly at the L5 vertebral level [9], whereas chronic LBP has been shown to be characterized by more diffuse atrophy [10]. Poor ability to contract the MF muscle has also been identified in people with both acute and chronic LBP [9,11]. A recent systematic review confirmed the association between LBP and the CSA of the MF muscles, whereby those with worse LBP had smaller muscles [12]. CSA of the MF muscles has also been shown to predict LBP [12] and disability [13]. In addition, ability to contract the MF, which can be improved by exercise interventions, was shown to be predictive of a positive outcome for people with LBP [14]. Results of prolonged bed rest studies have demonstrated that preferential atrophy of antigravity muscles occurs in response to this stimulus (for review, see Bloomfield [15]). Atrophy of the MF muscles has been shown to occur at all lumbar vertebral levels, but was fastest and occurred to the greatest extent at the L4 and L5 levels [16]. Interestingly, a prolonged bed rest study also showed that while the lordosis flattened (similar to findings from microgravity studies), the upper lumbar spine actually became more lordotic [16]. Preferential atrophy of the MF muscle in prolonged bed rest studies is thought to be related to the muscle no longer performing one of its key functions in relation to posture and axial loading. The MF controls the lumbar lordosis (and therefore distribution of axial load) [17] and plays a key role in proprioception, as the muscle is dense with muscle spindles [18]. The ability to control and be aware of the position of the lumbar lordosis is important as it allows people on Earth to optimize loading on the lumbar spine during loaded resistance exercises such as squats [19].

With respect to the effects of microgravity on other key trunk muscles, there is little information currently available regarding the abdominal muscles. On Earth, the abdominal muscles play an important mechanical role in relation to posture [20], and weightbearing has been shown to recruit the transversus abdominis (TrA) and obliquus internus abdominis (IO) muscles [21]. However, people with LBP have been shown to over contract their IO muscles in response to weightbearing tasks [22-24]. Furthermore, rather than atrophying in prolonged bed rest, which might be expected due to disuse and deconditioning, a prolonged bed rest study reported that a combined measure of the anterolateral abdominal muscles (TrA, IO and obliquus externus abdominis, EO) increased in size [25]. With respect to microgravity, an animal study, which measured the CSA of muscle fibers of the TrA muscle showed that it did not decrease in size [26]. However, both the rectus abdominis and the EO muscles did show significant signs of atrophy after extended exposure to microgravity. Results from an astronaut who spent 6 months on the ISS [27] showed that while the thickness of the TrA muscle decreased, the thickness of the IO muscle increased in response to microgravity [27]. These varying findings suggest that more research is required to better understand the effects of microgravity on the abdominal muscles.

There is evidence which suggests that exercise interventions can mitigate many of the adverse effects of microgravity on the musculoskeletal system during long-duration ISS flights [28-30]. Results of one spaceflight study showed that performing more resistance exercise was associated with less decline in the CSA of the erector spinae and MF muscles [31]. Successful restoration of decreased size of the MF and TrA muscles following return to Earth has been documented in a longitudinal case history describing reconditioning of one astronaut [27]. Further support of this concept is that an exercise program developed for people with LBP on Earth [32] has been shown to restore the (decreased) CSA of the MF muscle following exposure to prolonged bed rest [33].

The aim of this study was to examine the changes in muscle size and function of the lumbar MF and anterolateral abdominal muscles across three time periods: (1) Time in-flight on the ISS (Preflight to Return day (R)+1 to determine changes associated with exposure to microgravity), (2) Reconditioning time (R+1 day to R+15 days, with an additional midpoint measure at R+8 days to determine changes associated with performing daily reconditioning exercises), and (3) Total time (Preflight to R+15 days to determine if muscle values measured after reconditioning returned to preflight values).

Methods

Participants

The participants in this case study were five (four male, one female) astronauts who undertook, in total, seven long-duration missions (6 months) to the ISS. There were data available from seven missions (but only five astronauts) as two male astronauts undertook two missions. The astronauts provided informed consent regarding the use of their data, and approval was granted by the Medical Board of the European Space Agency (ESA).

Assessment of the multifidus and abdominal muscles

Repeated measures of the MF, TrA, IO, and EO muscles were conducted on Earth preflight, and R+1, R+8, and R+15. Ultrasound imaging was used to assess the MF muscle [34,35] and anterolateral abdominal muscles [36]. The ultrasound imaging apparatus used (GE LOGIQ *e*, GE Healthcare, Wuxi, China) was equipped with a 5-MHz convex array transducer. For collection of images of the MF muscle, the astronaut was positioned in a prone position. Bilateral transverse images of the MF muscle were obtained in a transverse plane (Fig. 1a), except in the case of larger muscles where left and right sides were imaged separately. To assess the ability of the astronaut to contract the MF muscle, the muscle was imaged in a parasagittal section at rest and on contraction using a split screen, to best allow visualization of the muscle contracting. Subjects were instructed to take a relaxed breath in and out, pause breathing and then try to ‘‘swell’’ or gently contract the muscle. The participants were also instructed not to move their spine or pelvis when they contracted the muscle, as the type of muscle contraction required was a slow, gentle, sustained isometric contraction [11]. The relationship between the change in thickness of the MF muscle associated with contraction of the muscle, as assessed by ultrasound imaging, has been validated by comparison with activity of the MF muscle, measured by fine wire electromyography [37]. For

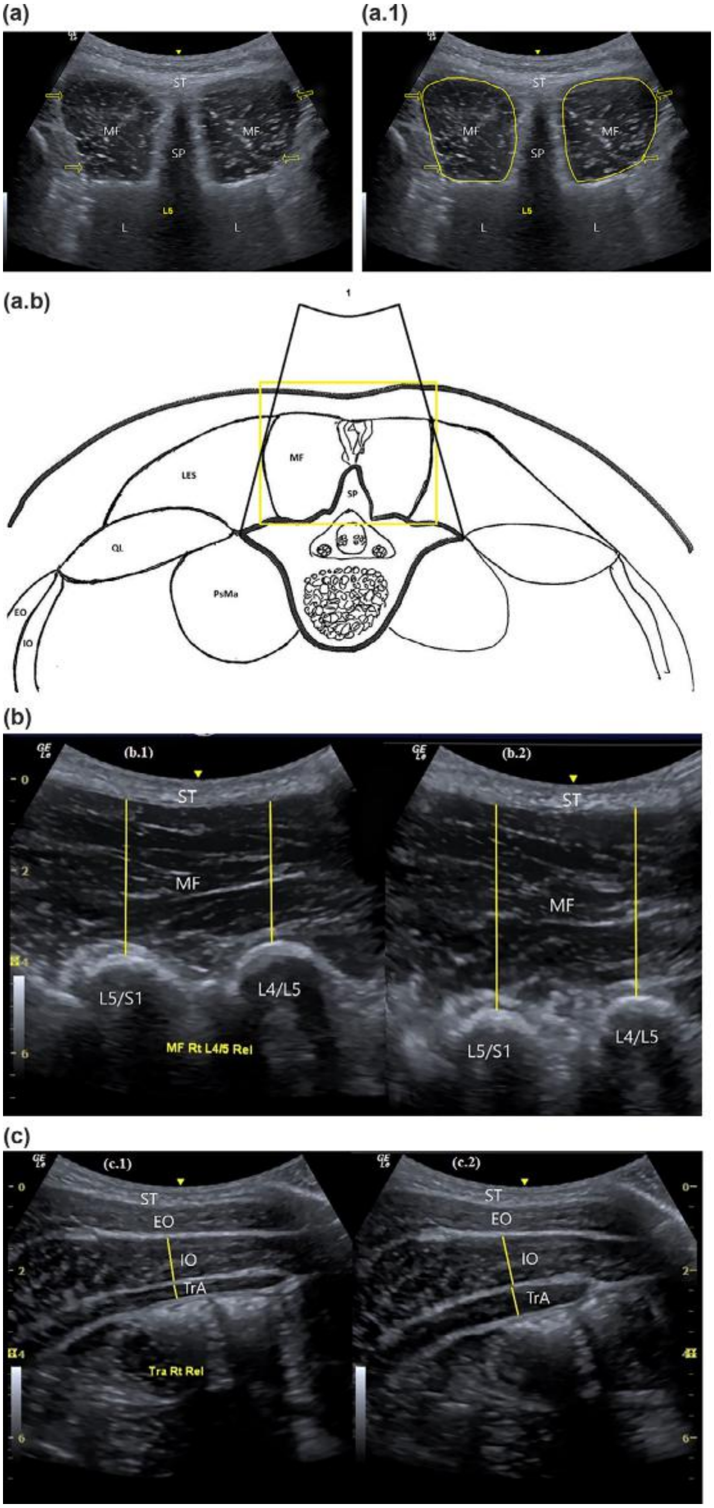

Fig. 1. (a) Bilateral transverse ultrasound image of the multifidus, (a.1) with the borders of the multifidus outlined to demonstrate segmentation. ST, subcutaneous tissue; SP, acoustic shadow of spinous process; MF, multifidus muscle; L5, vertebral level; L, acoustic shadow of the lamina. (a.b) Schematic representation of transducer placement to obtain ultrasound image of multifidus muscle at the L5 vertebral level, and surrounding anatomical structures. MF, multifidus muscles; SP, spinous process; LES, lumbar erector spinae muscle; QL, quadratus lumborum muscles; PsMa, psoas major muscles; EO, obliquus externus abdominis muscle; IO, obliquus internus abdominis muscle; 1, placement of ultrasound transducer; box, bilateral MF muscle. (b) Parasagittal ultrasound images of multifidus muscle thickness, using a split screen, measured from the top of the zygapophyseal joint to the thoracolumbar fascia in relaxed (b.1) and contracted (b.2) states. L4/L5 and L5/S1 indicate zygapophyseal joints. MF, multifidus muscles; ST, subcutaneous tissue. (c) Transverse ultrasound image of the muscles of the anterolateral abdominal wall, in relaxed and contracted states, using a split screen. Lines indicate thickness measures of the TrA and IO muscles in the relaxed (c.1) and contracted (c.2) states. EO, obliquus externus abdominis; IO, obliquus internus abdominis; TrA, transversus abdominis muscle; ST, subcutaneous tissue.

low level voluntary isometric contractions of the muscle (less than 34% of maximal voluntary isometric contraction), muscle thickness change assessed by ultrasound imaging were reported to be highly correlated with EMG activity of the lumbar MF muscle [37]. It has been proposed that the ability to perform this MF muscle test reflects the proprioceptive role of the muscles, as the muscle is rich in muscle spindles [18], and therefore, the MF muscle plays an important role in facilitating accurate spine positioning [38].

Ultrasound images of the anterolateral abdominal muscles (TrA, IO, and EO) were captured in a supine position. The subject was instructed to relax the abdominal wall, and a transverse image was obtained along a line midway between the inferior angle of the rib cage and the iliac crest for the right side [36]. To assess the ability of the astronauts to voluntarily contract the abdominal muscles, they were instructed to "Take a relaxed breath in and out, hold the breath, and then draw in the lower abdomen without moving the spine" [36]. This muscle test has been used to identify whether patients can contract their TrA muscle independently of the oblique abdominal muscles, as the muscles have different functional roles and there is evidence that the TrA muscle is controlled independently [39].

Ultrasound images were stored and later measured on the GE LOGIQ e equipment after all data collection was completed. To measure the CSA of the MF muscle, the outline of the muscle was traced (Fig. 1a.1). This image was captured as per schematic (Fig. 1a.b). The landmarks used to identify the borders of the MF muscle were the shadow of the tip of the spinous process (medial border), the echogenic lamina (inferiorly), the thoracolumbar fascia (superiorly), and the fascia between the MF muscle and the lumbar erector spinae (longissimus thoracis pars lumborum) muscle (laterally) [34]. Thickness measures of the MF, EO, IO, and TrA muscles were conducted for both rest and contracted conditions (Fig. 1b, c). For the MF muscle, thickness was measured from the top of the zygapophyseal joint to the thoracolumbar fascia (Fig. 1b). For the anterolateral muscles, each muscle was measured between the superior and inferior hyperechoic muscle fasciae. For measurements of slide of the anterior abdominal fascia, the distance from the medial edge of the TrA muscle to the medial edge of the ultrasound image was measured at rest. This starting position was then superimposed on the contracted image, and the distance from this point to the medial edge of the contracted TrA muscle was measured. Measurement of stored images was conducted by an investigator who was blinded to the identity of the participant and timepoint. The assessor demonstrated high intrarater reliability ($ICC_{1,1}$ range of 0.83−0.99) and interrater reliability ($ICC_{2,1}$ range of 0.88−0.99) for measurement of the MF, TrA, and IO muscles. Intrarater reliability of the measures of the MF muscle at rest for the four vertebral levels assessed ranged from 0.87 to 0.97, and for the contracted values ranged from 0.83 to 0.96. For the measures of CSA of the MF muscle at four vertebral levels, ICCs ranged from 0.84 to 0.99. Intrarater reliability of the measures of the anterolateral abdominal muscles at rest ranged from 0.83 to 0.98, and for the contracted values ranged from 0.97 to 0.98. The mean ICC (95% confidence interval; standard error of measurement) was 0.95 (0.83−0.93; 0.15) for intrarater reliability and 0.95 (0.87−0.98; 0.27) for interrater reliability, which was established by comparison with an expert.

Pre- and in-flight exercise on the ISS

During preflight training, astronauts were familiarized with the Advanced Resistive Exercise Device (ARED), which is an exercise countermeasure on the ISS (Fig. 2). These sessions focused on optimizing spinal posture during exercise on the device while on Earth, as maintaining a good spinal position in microgravity can be challenging due to the reduced awareness secondary to decreased proprioceptive feedback in the absence of gravitational load and muscle activation. On the ISS, astronauts performed 2 hours of training each day with the aim of mitigating the known negative effects of microgravity on the neuromusculoskeletal system. A comprehensive and individualized training program using a cycle ergometer (CEVIS, cycle ergometer with vibration isolation system), treadmill (Fig. 3), and the ARED (Fig. 4) was undertaken by each astronaut, with the goals of maintaining muscular and cardiovascular endurance, muscle strength, and providing axial loading of skeletal structures [28,29]. On a given flight day, the exercise

Fig. 2. Familiarization with the Advanced Resistive Exercise Device (ARED) on Earth before spaceflight (squatting). These sessions focus on optimizing spinal posture during exercise. Photo credit: © ESA/NASA.

Fig. 3. Exercising on the International Space Station using the treadmill. Note the vertical loading imposed by the harness on the treadmill. Photo credit: © ESA/NASA.

Fig. 4. Exercising (performing a deadlift) on the Advanced Resistive Exercise Device (ARED) on the International Space Station. Photo credit: © ESA/NASA.

regime hours consisted of (1) ARED exercises plus either use of the cycle ergometer (CEVIS) or the treadmill. The ARED plus treadmill combination was used more often on the missions than the ARED plus CEVIS combination. The exact ratio of treadmill vs CEVIS use can vary from mission to mission. The members of the flight crew are not entirely free to modify their exercise programs, but adaptions to the training regime to accommodate crew preferences are normal procedure. The time between exercise sessions is not always consistent and depends on many external factors.

Astronauts on the ISS were monitored by the ESA physiotherapist and sports scientist back on Earth via a privatized audio and space to ground video-downlink connection when performing ARED exercises, and were provided with real-time feedback on their execution to optimize the performance of the exercises [28,40].

Postflight reconditioning

The principles and philosophy underpinning the reconditioning program used at ESA, which embraces physiotherapy and sports science, have been described elsewhere [28,29]. In brief, the first phase of reconditioning comprised of 21 days of daily 2-hour exercise sessions. The initial period of reconditioning puts an emphasis on physiotherapy up until R+15, with a transition to a sports science focus from R+15 to R+21, however in some cases sports science can commence alongside physiotherapy earlier than this. The exercise components of the reconditioning program included both motor control training and weight-bearing exercises with an emphasis on retraining strength and endurance to re-establish normal postural alignment with respect to gravity. Motor control training in this context refers to motor, sensory, and central processes involved in control of posture and movement [41]. The exercises were progressively incorporated into gym training (aimed at full recovery of all athletic activities) and also included sensorimotor and co-ordination training. The reconditioning program also focused on functional retraining, supporting a quick adoption of various physical activities. Many of the exercises were designed so that the astronaut could include them into their normal daily lives (self-management approach). By the end of the reconditioning phase, the exercise training protocol was of similar intensity and complexity to that performed preflight.

Statistical analyses

The mean CSA values for the MF muscle were calculated for each participant at the L2, L3, L4, and L5 vertebral levels. Muscle contraction values were calculated by subtracting the thickness of the relaxed muscle from that of the contracted muscle. Contraction values were set to missing if the relaxed thickness was greater than the contracted thickness. The combined thickness of the anterolateral abdominal muscles was calculated using the sum of the individual thickness measures of the TrA, IO and EO muscles. MF CSA, muscle thickness and contraction measures are summarized at the four timepoints: preflight, R+1, R+8, R+15 as mean and standard deviation.

Multilevel linear models that incorporated random intercepts for participant, astronaut mission number (two astronauts had flown twice) and side for CSA measures were used to estimate the change in muscle CSA of the lumbar MF muscles at four lumbar vertebral levels (L2, L3, L4, and L5), and thickness and contraction of the anterolateral abdominal muscles (TrA, IO, and EO) and the MF muscles. These measures were analyzed to summarize the change in size over three time periods: (1) time in flight (preflight to R+1); (2) reconditioning time (R+1 to R+15); and total time (preflight to R+15). Restricted maximum likelihood and an autoregressive correlation structure was used, and all analyses were adjusted for the baseline measure at the beginning of the specific time period. Results are presented as estimates of the expected change in the measure across the specified time period (95% confidence intervals), adjusted for the starting measurement of that time period. The estimates were the beta-coefficients for the time in-

Table 1
Summary statistics for measurements of the multifidus and anterolateral abdominal muscles for six astronauts (over eight missions) for four time periods

	Preflight M (SD)	R+1 M (SD)	R+8 M (SD)	R+15 M (SD)
Cross-sectional area (cm^2)				
MFL2 average	3.26 (0.72)	3.47 (0.96)	3.48 (0.79)	3.76 (0.78)
MFL3 average	5.22 (1.02)	4.56 (1.07)	5.06 (0.97)	5.27 (0.92)
MFL4 average	8.00 (1.12)	7.51 (0.87)	7.78 (0.93)	8.21 (0.94)
MFL5 average	10.07 (1.41)	9.03 (1.68)	9.56 (1.50)	10.19 (1.33)
Contraction (*cm*)				
L2 relax	2.81 (0.45)	2.92 (0.40)	3.10 (0.53)	3.05 (0.41)
ΔL2	0.36 (0.23)	0.10 (0.09)	0.27 (0.33)	0.24 (0.21)
L3 relax	3.26 (0.45)	3.20 (0.43)	3.46 (0.50)	3.41 (0.43)
ΔL3	0.4 (0.26)	0.17 (0.19)	0.29 (0.18)	0.23 (0.23)
L4 relax	3.47 (0.35)	3.35 (0.54)	3.73 (0.55)	3.71 (0.35)
ΔL4	0.41 (0.14)	0.46 (0.33)	0.33 (0.18)	0.35 (0.11)
L5 relax	3.53 (0.52)	3.41 (0.62)	3.67 (0.59)	3.74 (0.39)
ΔL5	0.4 (0.2)	0.46 (0.23)	0.25 (0.10)	0.31 (0.18)
TrA relax	0.44 (0.1)	0.29 (0.12)	0.45 (0.14)	0.40 (0.09)
ΔTrA	0.16 (0.11)	0.18 (0.12)	0.17 (0.12)	0.15 (0.09)
IO relax	1.17 (0.18)	0.99 (0.27)	1.13 (0.20)	1.09 (0.20)
ΔIO	0.27 (0.17)	0.25 (0.13)	0.31 (0.19)	0.21 (0.10)
EO relax	0.98 (0.13)	0.89 (0.16)	0.90 (0.12)	0.95 (0.14)
ΔEO	0.07 (0.09)	0.10 (0.07)	0.08 (0.04)	0.06 (0.02)
Abdominal relax	2.59 (0.36)	2.17 (0.36)	2.47 (0.39)	2.45 (0.39)
ΔAbdominal	0.47 (0.20)	0.48 (0.15)	0.50 (0.35)	0.36 (0.13)
TrA Slide	0.76 (0.35)	0.50 (0.34)	0.63 (0.55)	0.76 (0.50)

cm^2, centimeters squared; cm, centimeters; Δ, change in value, calculated by subtracting the relaxed value from the contracted value; MF, multifidus muscle; TrA, transversus abdominis muscle; IO, obliquus internus abdominis muscle; EO, obliquus externus abdominis muscle; R+X, day X after return to Earth. "Abdominal" refers to the thickness of the three abdominal muscles added together. M, mean; SD, standard deviation.

flight and total time models: A linear combination of the daily change for 15 days ($15 \times \beta$) was used to estimate the total change over the reconditioning time.

Stata (Version 14.2 IC, StataCorp LP, College Station, TX, USA) was used for statistical analysis [42].

Results

Table 1 shows the summary statistics for the measures of ultrasound images of the trunk muscles (MF and anterolateral abdominal muscles) at rest and the change associated with muscle contraction, collected from five astronauts over seven missions. Results of the multilevel linear models are shown in Table 2.

Muscle size measures

Multifidus muscle CSA

The changes in CSA of the MF muscle over time for vertebral lumbar levels L2-L5 are shown in Fig. 5. Results for the MF CSA measures indicated that the CSA of the MF muscle decreased significantly at all lumbar vertebral levels in response to exposure to microgravity (p<.001) except at L2. The CSAs of the MF muscles (L3-L5 vertebral levels) increased in the reconditioning period (p<.001). The CSA of the MF muscle for each vertebral level (averaged across left and right sides) decreased 10.3% (1.04 cm^2) for L5; 6.1% (0.49 cm^2) for L4; and 12.6% (0.66 cm^2) for L3, with the greatest absolute decrease in CSA occurring at the L5 vertebral level (1.04 cm^2). At the L2 vertebral level, while not statistically significant, there was an *increase* of 6.4% (0.21 cm^2).

Multifidus muscle thickness

The pattern of results for the thickness of the MF muscle at rest was similar to that of results for the CSA, as was to be expected, as the thickness and CSA measures reflect measurements of the same muscle in different planes. The thickness measure at rest was collected primarily to allow calculation of the size of voluntary contraction of the MF muscle, which is best seen in a longitudinal view. In line with the results for MF CSA the thickness measures for this muscle also increased at the L3-L5 vertebral levels over the reconditioning period (L3 p<.001, L4 p=.005, L5 p=.024). The changes in thickness of the MF muscle over time for vertebral lumbar levels L2-L5 are shown in Fig. 6.

Thickness of the anterolateral abdominal muscles

The thickness of the muscles of the abdominal wall (sum of individual muscles: TrA, IO, and EO) decreased in between preflight assessment and R+1 (p<.001). The thickness of the TrA muscle decreased during this time (p=.017), as did the thickness of the IO (p=.04) but not the EO muscle (p=.1). The amount of "slide" of the TrA muscle (reflecting concentric shortening the TrA muscle) also decreased significantly in response to exposure to microgravity (p=.031).

Table 2
Expected changes in measures of the CSA of the multifidus muscle, thickness and slide of the anterolateral abdominal muscles, and change in muscle thickness associated with muscle contraction for the multifidus muscles (L2 to L5 vertebral levels) and anterolateral abdominal wall muscles over three time periods

Muscle CSA (cm^2)	Time in flight (preflight to R+1 day)		Reconditioning time (R+1 day to R+15 days)		Total time (preflight to R+15 days)	
	Expected change during flight period β (95% CI)	p	Expected change during reconditioning 15 × β (95% CI)	p	Expected total change β (95% CI)	p
L2	0.21 (-0.02, 0.44)	.07	0.31 (0.08, 0.54)	.008	0.50 (0.31, 0.69)	<.001
L3	-0.67 (-0.98, -0.35)	<.001	0.76 (0.45, 1.07)	<.001	0.05 (-0.13, 0.23)	.61
L4	-0.49 (-0.73, -0.24)	<.001	0.75 (0.51, 0.98)	<.001	0.21 (-0.14, 0.56)	.24
L5	-1.04 (-1.22, -0.85)	<.001	1.23 (0.99, 1.48)	<.001	0.11 (-0.04, 0.26)	.14
Muscle thickness (cm)						
L2 relax	0.11 (-0.08, 0.30)	.27	0.14 (-0.08, 0.35)	.21	0.24 (-0.02, 0.49)	.07
L3 relax	-0.06 (-0.28, 0.16)	.59	0.22 (0.11, 0.34)	<.001	0.15 (-0.09, 0.38)	.22
L4 relax	-0.11 (-0.33, 0.11)	.31	0.38 (0.12, 0.65)	.005	0.24 (0.11, 0.38)	<.001
L5 relax	-0.12 (-0.42, 0.18)	.44	0.35 (0.05, 0.66)	.024	0.21 (-0.02, 0.44)	.07
TrA relax	-0.14 (-0.26, -0.03)	.017	0.10 (0.03, 0.18)	.008	-0.05 (-0.13, 0.04)	.26
IO relax	-0.18 (-0.35, -0.01)	.040	0.09 (-0.02, 0.20)	.13	-0.10 (-0.24, 0.04)	.18
EO relax	-0.10 (-0.21, 0.02)	.10	0.06 (-0.06, 0.17)	.36	-0.04 (-0.19, 0.10)	.55
Abdominal relax	-0.42 (-0.62, -0.21)	<.001	0.24 (0.02, 0.47)	.035	-0.19 (-0.48, 0.11)	.21
TrA Slide	-0.26 (-0.49, -0.02)	.031	0.19 (-0.06, 0.44)	.14	-0.06 (-0.34, 0.22)	.68
Contraction (cm)						
ΔL2	-0.25 (-0.42, -0.07)	.007	0.14 (0.00, 0.27)	.046	-0.11 (-0.43, 0.20)	.46
ΔL3	-0.25 (-0.47, -0.02)	.032	0.10 (-0.05, 0.26)	.19	-0.17 (-0.44, 0.10)	.22
ΔL4	0.05 (-0.14, 0.25)	.60	-0.17 (-0.36, 0.01)	.06	-0.09 (-0.21, 0.02)	.12
ΔL5	0.05 (-0.17, 0.27)	.67	-0.12 (-0.31, 0.07)	.21	-0.08 (-0.27, 0.10)	.37
ΔTrA	0.02 (-0.10, 0.15)	.73	0.00 (-0.08, 0.07)	.93	0.00 (-0.13, 0.12)	.97
ΔIO	-0.01 (-0.15, 0.12)	.84	-0.01 (-0.13, 0.11)	.93	-0.02 (-0.17, 0.12)	.76
ΔEO	0.00 (-0.08, 0.07)	.98	-0.06 (-0.14, 0.03)	.19	0.02 (-0.01, 0.05)	.17
ΔAbdominal	0.01 (-0.11, 0.14)	.85	-0.03 (-0.16, 0.11)	.70	-0.01 (-0.10, 0.08)	.77

cm^2, centimeters squared; cm, centimeters; Δ, change in value, calculated by subtracting the relaxed value from the contracted value; TrA, transversus abdominis muscle; IO, internal oblique muscle; EO, external oblique muscle. “Abdominal” refers to the thickness of the three abdominal muscles added together. R+X, day X after return to Earth. Negative β values indicate decreases in muscle size/contraction and positive values indicate increases. Analyses were adjusted for time-period specific baseline measures.

The thickness of the TrA muscle (p=.008) and the combined anterolateral muscles (p=.035) recovered in response to reconditioning. Following reconditioning, there were no significant differences between thickness values measured at this time and the preflight assessment, indicating that reconditioning mediated the changes associated with exposure to microgravity in size of these muscles. The changes in thickness of the anterolateral abdominal wall muscles over time are shown in Fig. 7.

Muscle contraction measures

Voluntary isometric contraction of the multifidus muscle

As can be seen from Table 2, results showed that overall, the amount of contraction of the MF muscle decreased significantly from preflight to R+1, at the L2 (p=.007) and L3 (p=.032) vertebral levels. The amount of contraction at the L2 vertebral level increased by the end of the reconditioning period (L2 p=.046). There were no significant differences between the amount of voluntary contraction of the MF muscle assessed at the end of the reconditioning period compared with the preflight measurements for any of the vertebral levels assessed. The changes in contraction of the MF muscle over time are shown in Fig. 8.

Voluntary isometric contraction of the anterolateral abdominal muscles

There were very few changes observed in the ability of the participants to voluntarily contract the muscles of the abdominal wall, with no significant differences following exposure to microgravity. There were no significant differences between the amount of voluntary contraction of the anterolateral abdominal muscles at the end of the reconditioning period compared with the preflight measurement. The changes in contraction of the muscles of the anterolateral abdominal wall over time are shown in Fig. 9.

Discussion

The results of the current investigation showed that there were changes in the size and function of the MF and anterolateral abdominal muscles over the three time periods studied, in association with prolonged (6 months) exposure to

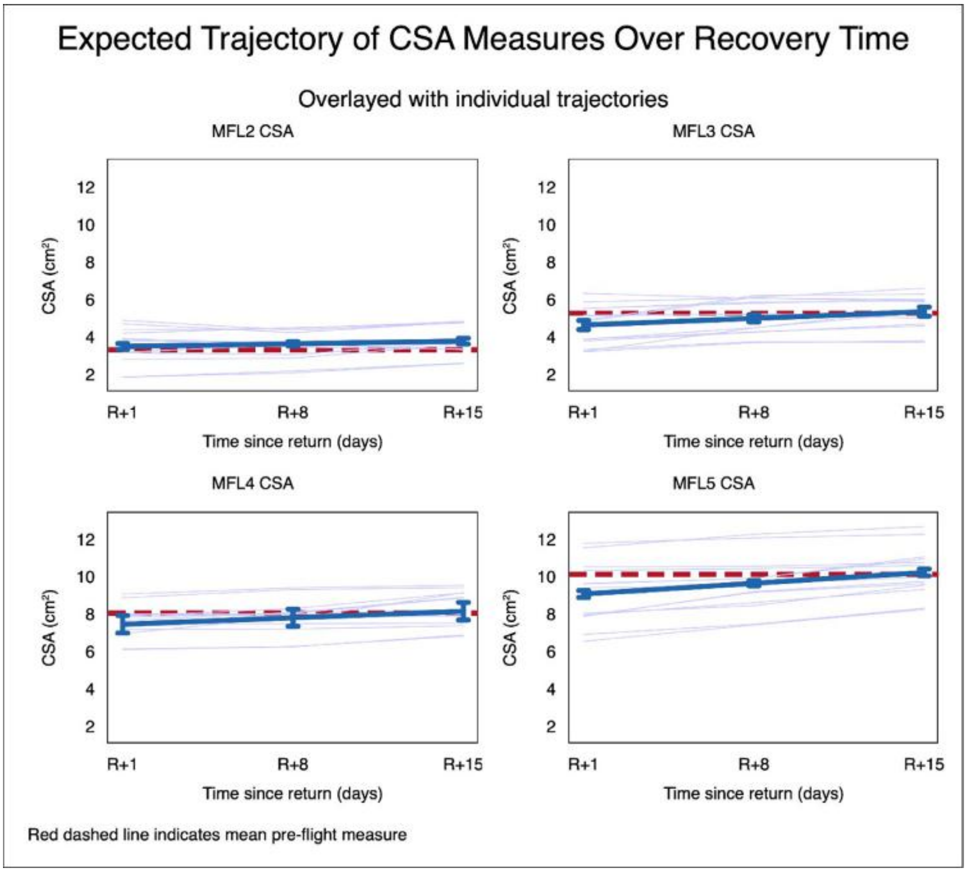

Fig. 5. Trajectory plots of cross-sectional area (CSA) measures of the multifidus muscles at three timepoints postflight (compared with preflight). CSA, cross-sectional area; MF, multifidus muscle; cm^2, centimeters squared; R+X, day X after return to Earth. Red-dashed lines indicate the preflight measure, the dark blue line indicates the mean values for the three timepoints, overlayed with light blue lines indicating results from individual astronauts.

microgravity on the ISS and 15 days of individualized intensive daily reconditioning on Earth.

Multifidus muscle size and contraction

The results of the current investigation confirmed previous reports that the CSA of the MF muscles decreased after exposure to microgravity on the ISS [3,8]. With respect to the amount of atrophy of the MF muscle, results at the L3-4 vertebral level (averaged) were similar to those recently reported for a population of astronauts who were on the ISS [3]. However, because the observed changes in the CSA of the MF muscle varied considerably across vertebral levels in the current investigation, results from one vertebral level should not be generalized to reflect changes at all other levels of the lumbar spine, especially given that the L2 level did not atrophy at all. In the current investigation, the greatest absolute decreases in MF CSA occurred at the L5 vertebral level, supporting results from a recent case history of an astronaut [27], and results from prolonged bed rest studies and studies of people on Earth with LBP (for review see [40]). Reconditioning has previously been shown to successfully restore MF muscle size in people on Earth after prolonged bed rest [33] and also in those with LBP, where increases in muscle size and function were commensurate with decreases in reported pain levels and improved function [43,44]. In the current investigation, results from the reconditioning period also showed that the initially decreased size of the MF muscle could be successfully recovered at L3-L5 vertebral levels.

Of note, the results for the MF muscles at the L2 vertebral level differed from those seen at the other vertebral levels after a period of exposure to microgravity. Unlike the L3 to L5 vertebral levels, the MF muscles at the L2 level did not atrophy, and while not statistically significant, *increased* by 6.4% after spaceflight. However, the astronauts in the current investigation were shown to be *less* able to contract the MF muscles at the upper lumbar vertebral levels (L2 and L3) after their exposure to microgravity, and the CSA of at the L2 level remained increased following reconditioning ($p<.008$) and was significantly different (increased) relative to preflight values ($p<.001$).

The explanation for the lack of atrophy of the MF muscle at the L2 level may be related to the in-flight execution of exercises on the ARED and the effects of microgravity on the lumbar lordosis. Maintaining an optimally aligned spinal position (i.e., a lumbar lordosis and thoracic kyphosis in an “S” curve) in microgravity can be challenging due to

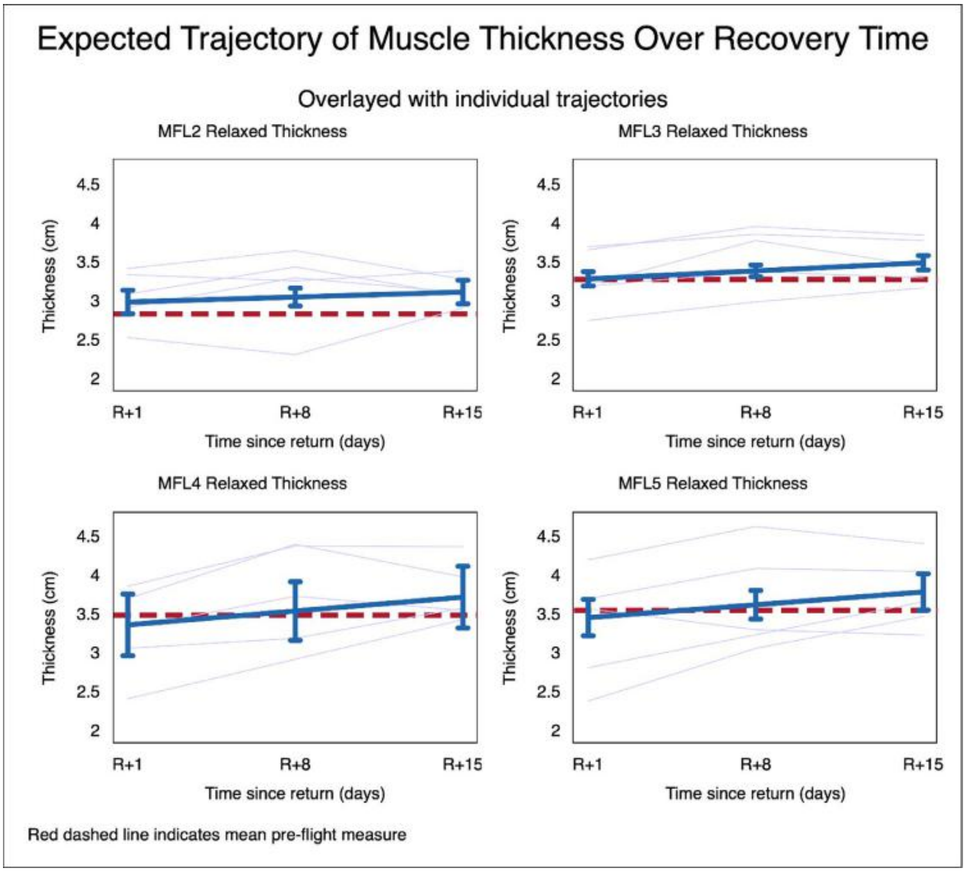

Fig. 6. Trajectory plots of the thickness of the multifidus muscle at rest at three timepoints postflight (compared with preflight). MF, multifidus muscle; cm, centimeters; R+X, day X after return to Earth. Red-dashed lines indicate the preflight measure, the dark blue line indicates the mean values for the three timepoints, overlayed with light blue lines indicating results from individual astronauts.

the reduced awareness secondary to decreased proprioceptive feedback in the absence of gravitational load and muscle activation, despite the best efforts of the astronaut and provision of real time video and audio feedback on exercise performance by the medical team [28]. Additionally, flattening of the lumbar lordosis associated with exposure to microgravity [3] and possible extension of the upper lumbar spine (thoracolumbar junction) as seen in association with prolonged bed rest [16] may help to explain this finding. The importance of a lumbar lordosis (and thoracic kyphosis) for a human's ability to support loads has been previously highlighted [45-48]. It has been proposed that rather than generating moments, the musculature closely surrounding the spine is required to constrain the load to follow the "S" curvature of the spine, provide compressive force to maintain stability, and control the spinal position. More recent modeling studies have demonstrated that curvature of the lumbar spine is one of the biggest factors associated with changes in spinal loading [49-51]. It is possible that in microgravity, the astronauts performed their loaded exercises on the ARED (such as squats, deadlifts, and bent-over rows) in a position of relative extension of the thoracolumbar junction (or a long "C" curve), which may have preferentially recruited the MF muscle at the L2, most likely in conjunction with recruitment of the thoracic erector spinae muscles, such as the longissimus thoracis, which is the longest spinal extensor muscle.

A further understanding of the close and important relationship between spinal posture and muscle recruitment can be gained from studies which have been performed on Earth. For example, people with LBP who sat in a position of thoracolumbar extension (or long "C" curve) showed increased recruitment of the longissimus thoracis muscle in this region [52]. In contrast, when people without LBP sat in a lumbar lordosis/thoracic kyphosis posture (or "S" curve), they recruited the MF muscles at the lower lumbar spine [53]. The deeper fascicles of the MF muscle at the lower lumbar spine are thought to "fine-tune" intersegmental motion of the lumbar spine [54]. Additionally, a potential benefit which was observed when the spine was positioned in a lumbar lordosis/thoracic kyphosis posture, was concomitant recruitment of the IO and TrA muscles. This did not occur in the thoracolumbar extended position. Assuming a position of thoracolumbar extension during exercise may therefore be detrimental, as activity of the longissimus thoracis also has potential consequences for generating increased loading of spinal segments [52].

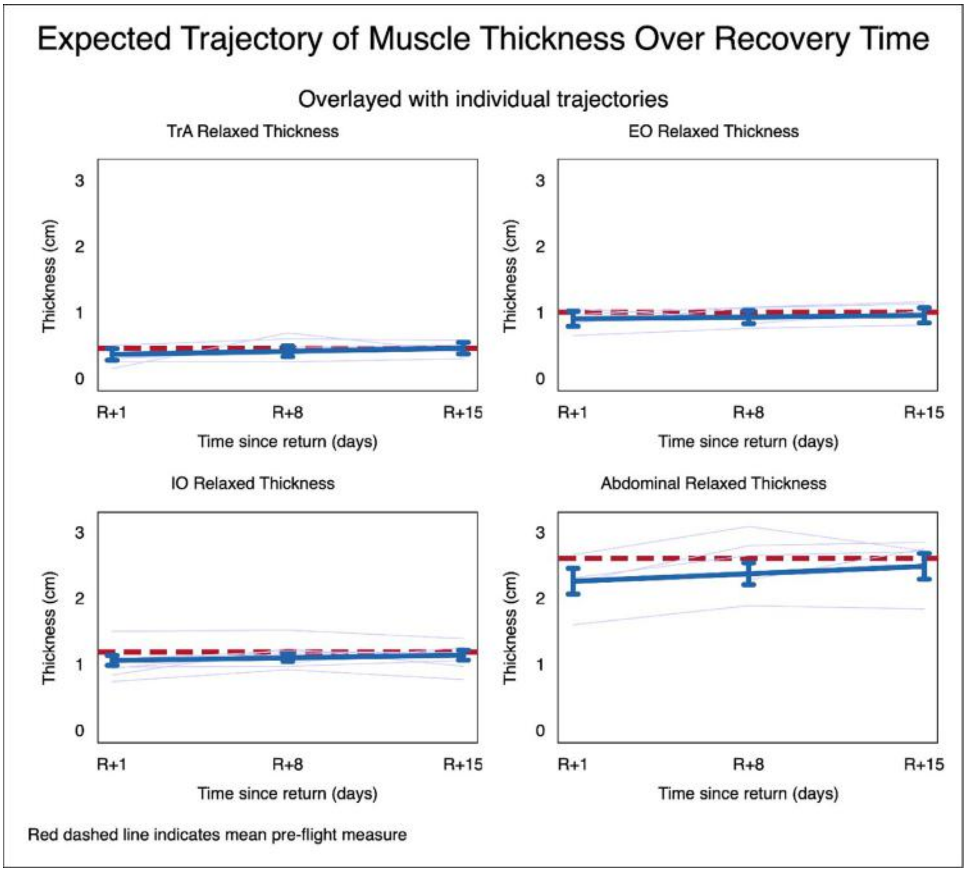

Fig. 7. Trajectory plots of thickness of the anterolateral abdominal muscles at rest at three timepoints postflight (compared with preflight). TrA, transversus abdominis muscle; IO, obliquus internus abdominis; EO, obliquus externus abdominis muscle. “Abdominal” refers to the thickness of the three abdominal muscles added, cm, centimeters; R+X, day X after return to Earth. Red-dashed lines indicate the preflight measure, the dark blue line indicates the mean values for the three timepoints, overlayed with light blue lines indicating results from individual astronauts.

In contrast to in-flight countermeasures, postflight reconditioning of astronauts is performed on Earth, including all benefits of a comprehensive gym and exercise environment, the presence of a supporting team of experts and the presence of gravity. This enables a comprehensive and more functional assessment and development of a targeted exercise program for muscle groups affected by exposure to microgravity. With current technical means, and the existing operational and logistic space constraints, this environment cannot yet be reproduced on the ISS. For example, although high intensity exercise may be required, there are in-flight limitations for increasing loads beyond those currently possible relating to both the capability of the technical hardware available and discomfort associated with using the equipment (e.g., vertical loading imposed by the harness on the treadmill, see Fig. 3) [29]. Postflight reconditioning therefore encompasses complementary exercise strategies and related benefits that are currently only feasible on Earth. Exercise devices that replace the pull of gravity in comparable dosage as those present on Earth are still to be developed and evaluated in microgravity. Although efforts are ongoing to close this gap, in-flight exercise devices explicitly targeting muscles such as the MF and other postural muscles reliant on constant axial loading associated with gravity do not currently exist [27,28,55]. Consequently, the ESA program provides an individual, targeted and gradual program for each crew member returning from space. This includes physiotherapy treatments in the initial phase, and progressively integrating physical exercises in the gym and outside facilities, with a focus on providing a large range of exercises to trigger re-adaptation processes in gravity, functional re-loading of body segments and rebuilding of strength and fitness, while ensuring precise control of movement and loading [28,29,40]. Premission preparation and training and postflight reconditioning of astronauts on Earth currently aims at compensating for the inability to train these muscles in microgravity.

In sum, these results suggest that careful positioning of the spine in the reconditioning phase on Earth is likely to be very important for astronauts and, similar to exercise prescription on Earth, the addition of load should not be progressed before optimal spinal posture and muscle control can be achieved [41]. The continued increase in the size of MF muscle at the L2 vertebral level in the reconditioning period in the current investigation may also help to explain the results of Bailey et al. [3], who showed that astronauts

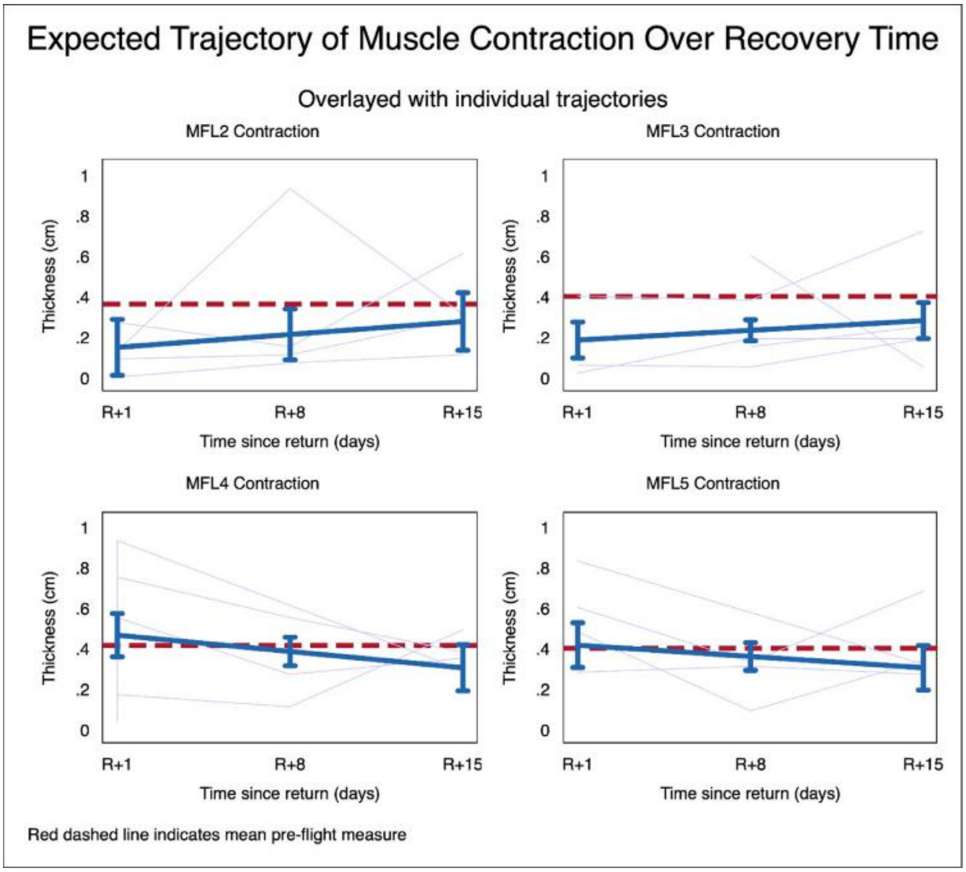

Fig. 8. Trajectory plots of ability to contract the multifidus muscles at three timepoints postflight (compared with preflight). MF, multifidus muscle; cm, centimeters; R+X, day X after return to Earth. Red-dashed lines indicate the preflight measure, the dark blue line indicates the mean values for the three timepoints, overlayed with light blue lines indicating results from individual astronauts.

after their return to Earth demonstrated decreased intersegmental flexion-extension range of motion of the mid lumbar spine segments in a standing position (but not when lying down). The muscle fibers of the L2 MF muscle originate from the spinous process (SP) and lamina of the L2 vertebra and insert caudally on the laminae and facet joints of the L4, L5, and S1 vertebral levels [56]. The MF muscle controls the intersegmental "rocking" action of one vertebra on the one below during flexion of the lumbar spine. A possible consequence of preferential and increased recruitment of this muscle at the L2 vertebral level would most likely result in increased intersegmental stiffness of the L2, L3, and L4 vertebral levels during flexion of the lumbar spine in standing. The reason that the increased stiffness would not have been present in the lying position in this investigation [3], would most likely be that the MF muscle has been shown to be inactive when lying down [57].

With respect to changes in morphology of the abdominal muscles, results of the current investigation showed that the thickness of the TrA and IO muscles and the combined anterolateral abdominal wall decreased in response to prolonged exposure to microgravity. Weightbearing on Earth has been shown to activate the TrA and IO muscles [21], therefore, it is perhaps not surprising that these muscles atrophied in microgravity in the current investigation. The result regarding atrophy of the TrA muscle supports the results of a previous case report of an astronaut for this muscle [27] but the results for the IO muscle differed from this previous report and from results of studies of people with LBP on Earth [22-24]. In the current investigation, the combined thickness of the anterolateral abdominal wall decreased in response to exposure to microgravity, which differs from the results observed in prolonged bed rest, where the combined thickness of the muscles increased [25]. A possible explanation for the difference between results observed in microgravity and bed rest may be that in bed rest studies, gravity is not eliminated, rather the axis is shifted 90°. Bed rest participants positioned in supine lying may recruit their trunk flexors against gravity to allow them to lift their head to eat, perform daily hygiene activities and access computer screens. The atrophy of the TrA muscle is in contrast with the results observed in an animal study where the TrA muscle did not atrophy, but the torque producing EO muscle did [26]. In the current investigation, the reverse was observed whereby the EO muscle was the only muscle of the anterolateral abdominal wall which did not atrophy significantly. This difference could be related to the differences between muscle function in quadrupeds compared with bipeds. The

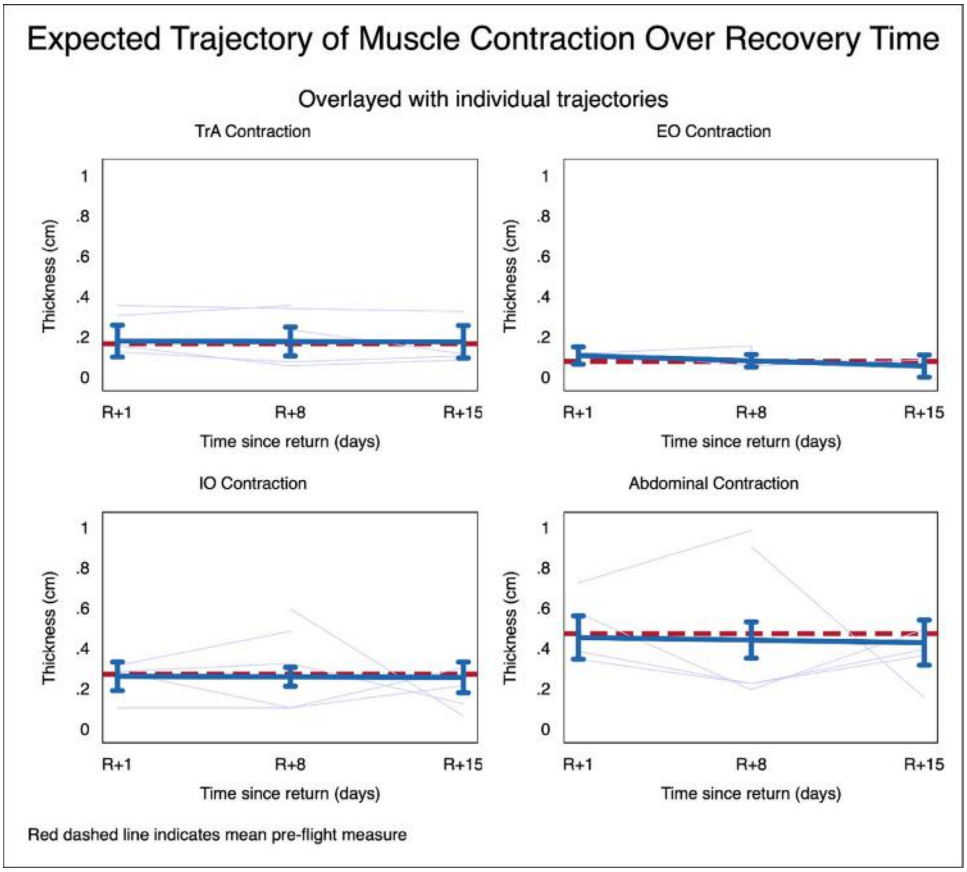

Fig. 9. Trajectory plots of the ability to contract the anterolateral abdominal muscles at three timepoints postflight (compared with preflight). TrA, transversus abdominis muscle; IO, obliquus internus abdominis; EO, obliquus externus abdominis. “Abdominal” refers to the thickness of the three abdominal muscles added, cm, centimeters; R+X, day X after return to Earth. Red-dashed lines indicate the preflight measure, the dark blue line indicates the mean values for the three timepoints, overlayed with light blue lines indicating results from individual astronauts.

TrA muscle and the combined thickness of the abdominal muscles did significantly increase in size in the reconditioning period in the current investigation, and there were no significant differences observed in abdominal muscle size and function when compared with preflight values, suggesting that reconditioning was effective.

Conclusions

Drawing parallels between changes which occur to the neuromuscular system in microgravity and which exercises best recover muscle size and function could help health professionals tailor improved interventions for terrestrial populations with chronic LBP. The effects of microgravity on muscle size and function are specific, which is very similar to clinical presentation of patients with chronic LBP, where changes are also very specific. The implication of the results of the current investigation, which applies equally to astronauts and people on Earth with chronic LBP, is that the exercise programs should be based on identifying, quantifying, and addressing specific impairments, be tailored to the individual, and progressed with careful attention to optimal spinal posture and muscle recruitment. Another key implication of the current investigation for people on Earth with chronic LBP is that exercises should be targeted at functional improvement and involve a focus on self-management. From our perspective, exercise and reconditioning principles for astronauts are in alignment with current guidelines for the management of people with chronic LBP [58].

Limitations

Due to the unique microgravity environment on ISS, this work is subject to limitations in sample size. In addition, assessment of morphology of muscles included measures of muscles size, but not measures of increased intramuscular fatty infiltration, which have also been observed in measurements of astronauts after spaceflight [31]. Also, we do not have in-flight ultrasound data of the trunk muscles evaluated in this investigation, which would help to clarify the effects of the in-flight countermeasure program on the ISS on the trunk muscles.

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