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CASE REPORT

Changes in multifidus and abdominal muscle size in response to microgravity: possible implications for low back pain research

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Abstract
Purpose In microgravity, muscle atrophy occurs in the intrinsic muscles of the spine, with changes also observed in the abdominal muscles. Exercises are undertaken on the International Space Station and on Earth following space flight to remediate these effects. Similar effects have been seen on Earth in prolonged bed rest studies and in people with low back pain (LBP). The aim of this case report was to examine the effects of microgravity, exercise in microgravity and post-flight rehabilitation on the size of the multifidus and antero-lateral abdominal muscles.
Methods Ultrasound imaging was used to assess size of the multifidus, transversus abdominis and internal oblique muscles at four time points: pre-flight and after daily rehabilitation on day one (R + 1), day 8 (R + 8) and day 14 (R + 14) after return to Earth (following 6 months in microgravity).
Results Exercises in microgravity maintained multifidus size at L2–L4, however, after spaceflight, size of the multifidus muscle at L5 was reduced, size of the internal oblique muscle was increased and size of transversus abdominis was reduced. Rehabilitation post-space flight resulted in hypertrophy of the multifidus muscle to pre-mission size at the L5 vertebral level and restoration of antero-lateral abdominal muscle size.
Conclusions Exercise in space can prevent loss of spinal intrinsic muscle size. For the multifidus muscles, effectiveness varied at different levels of the spine. Post-mission rehabilitation targeting specific motor control restored muscle balance between the antero-lateral abdominal and multifidus muscles, similar to results from intervention trials for people with LBP. A limitation of the current investigation is that only one astronaut was studied, however, the microgravity model could be valuable as predictable effects on trunk muscles can be induced and interventions evaluated.
Level of Evidence Case series.

Keywords Ultrasound imaging · Rehabilitation · Lumbar spine · Paraspinal muscles · Exercise therapy · Trunk muscles

Background

While many lumbo-pelvic muscles contribute to the control and support of the lumbar region, key muscles which have been identified in several studies include the lumbar multifidus and the antero-lateral abdominal muscles. The lumbar multifidus muscle contributes to localized control of segments of the lumbar spine and thereby controls the lumbar lordosis [1]. By controlling the amount of vertebral rotation, the segmental multifidus can control load transmission to various anatomical structures and affect the capacity of the spine to bear axial load [1]. In addition, the multifidus muscle plays a key role in neuromuscular

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control of the trunk. This role, which is heavily reliant on feedback from proprioceptors in the muscle itself, has been ascribed predominantly to the multifidus muscle, due to the fact that it is dense in muscle spindles [2]. In addition, transversely orientated muscles of the lumbo-pelvic region, such as the transversus abdominis (TrA), internal oblique (IO), piriformis and coccygeus muscles act to stiffen the lumbo-pelvic joints for weight-bearing [3, 4]. In particular, the TrA muscle stiffens the sacroiliac joint and increases intra-abdominal pressure, thereby contributing to intervertebral stability [3, 5–7].

Changes in the function of the multifidus and abdominal muscles have been demonstrated in people with low back pain (LBP). Acute first episode LBP has been shown to be associated with vertebral and side-specific changes in the size of the multifidus muscle [8, 9]. This was most commonly seen at the lumbo-sacral junction. Even though the symptoms associated with the LBP resolved, and subjects resumed normal work, sport and leisure, persistence of decreased size of the multifidus muscle was associated with increased recurrence of episodes of LBP [10]. Atrophy of the multifidus muscles has also been demonstrated in people with chronic LBP [11, 12]. Changes in timing of recruitment of the TrA muscle have been documented in people with LBP [13] and increased recruitment of the superficial abdominal muscles has also been demonstrated [14–21]. Such changes occurring between the trunk flexor and extensor muscles can be considered as a muscle imbalance.

People exposed to microgravity conditions or prolonged bed rest have been shown to exhibit similar patterns of muscle imbalance of trunk muscles to people with LBP [8, 9, 11, 22]. Atrophy of the lumbar multifidus is greatest at the lower levels of the lumbar spine in response to prolonged bed rest, with atrophy of 4, 7, 13.5 and 12.2 % reported for L2, L3, L4 and L5 vertebral levels, respectively [23]. The abdominal flexor muscle group has been shown to collectively increase in size during bed rest [24, 25]. The increase in size could relate to the trunk being maintained in a flexed position and may reflect muscle shortening [25]. Of interest is that the changes can be long standing in nature. After return to normal activity post-bed rest, a lack of recovery in the multifidus muscle was still evident 3 months later [26], and whilst abdominal size did decrease to baseline levels in the recovery period, an EMG study showed that increased activation of these muscles could persist for as long as 1 year following bed rest [24].

While bed rest studies provide a more feasible experimental model than experiments performed in microgravity (because they can be conducted on Earth and are not reliant on recruiting astronauts as participants), the microgravity model has some additional benefits over the bed rest model. The effects of the microgravity environment on the musculoskeletal system are rapid. LeBlanc et al. [27] showed that the CSA of the intrinsic spinal muscles occurred quickly in a shuttle mission of only 17 days duration. In addition, in microgravity the astronauts can move freely, whereas in bed rest studies, movement is restricted.

For this reason, examination of the effects of exposure to microgravity on trunk muscles presents a valuable model. Studying astronauts pre- and post-spaceflight provides a unique model where predictable and rapid effects, which parallel findings seen on Earth, can be induced and the effects of rehabilitation approaches can be evaluated.

The aims of this case study were to assess:

(a) the size of the lumbar multifidus and antero-lateral abdominal muscles using ultrasound imaging pre- and post-space flight, to determine the effects of microgravity (and exercise in microgravity) on these muscles.
(b) the response of the multifidus and antero-lateral abdominal muscles to post-space flight rehabilitation.

Case description

Assessment protocol

The astronaut who participated in this case study was a 38-year-old male, of height 185 cm and of weight 83 kg. Repeated measures of the multifidus, TrA and IO muscles were conducted using ultrasound imaging at: pre-flight and at Day 1 (R + 1), Day 8 (R + 8) and Day 14 (R + 14), respectively, following return to Earth after a period of six months in microgravity on the International Space Station (ISS). The astronaut provided informed consent regarding the use of his data.

Multifidus and abdominal muscle assessment

Ultrasound imaging was used to assess the cross-sectional area (CSA) of the multifidus muscle at vertebral levels L2–L5 as per the protocols described previously by Hides et al. [28] and Wallwork et al. [29]. For the antero-lateral muscles, the protocol of Hides et al. was used [30]. The assessor performing the ultrasound imaging assessments of muscle size had intensive training in this assessment technique, and prior to this study demonstrated very high intra-rater reliability ($ICC_{1,1}$ range of 0.83–0.99) and inter-rater reliability ($ICC_{2,1}$ range of 0.88–0.99) for measurement of the multifidus, TrA and IO muscles. The mean ICC (95 % confidence interval; standard error of measurement) was 0.95 (0.83–0.93; 0.15) for intra-rater reliability.

The ultrasound imaging apparatus used (GE LOGIQ *e*) was equipped with a 5-MHz convex array transducer. For collection of images of the multifidus muscles, the astronaut was positioned in a prone lying position and the lumbar spinous processes were palpated and marked with a pen to assist with identification of vertebral level. Electro-conductive gel was applied to the transducer which was placed transversely over the relevant spinous process. The astronaut was instructed to relax the para-spinal musculature, the muscles were palpated to ensure that they were relaxed, and bilateral transverse images of the multifidus muscle were obtained where possible except in the case of larger muscles where left and right sides were imaged separately (Fig. 1). Landmarks used for identifying the borders of the multifidus muscle on ultrasound imaging were the skin, subcutaneous tissue and thoraco-lumbar fascia (dorsally), the shadow of the spinous process (medially), the echogenic vertebral lamina (inferiorly) and the fascial border between the multifidus muscles and the lumbar erector spinae muscles (laterally) [31]. This technique for imaging and measuring the size of the multifidus muscles has been validated by comparison with MRI [31].

Ultrasound images of the TrA and IO muscles were captured in a supine lying position (Fig. 2). The transducer was placed on the abdomen perpendicular to the surface plane of the abdominal muscles. The subject was instructed to relax the abdominal wall, and relaxation was verified by palpation of the abdominal wall. The instructions given were “to breathe in and out, and then to pause breathing”. At this point, a transverse image was obtained at rest along a line midway between the inferior angle of the rib cage and the iliac crest for the right side [30–32]. The subject was then instructed to “draw in the abdominal wall”, and ultrasound images were obtained on contraction [32]. In order to standardize the location of the ultrasound transducer for each participant, the anterior fascial insertion of the TrA muscle was positioned approximately 2 cm from the medial edge of the ultrasound image when the subject was relaxed [30, 33, 34].

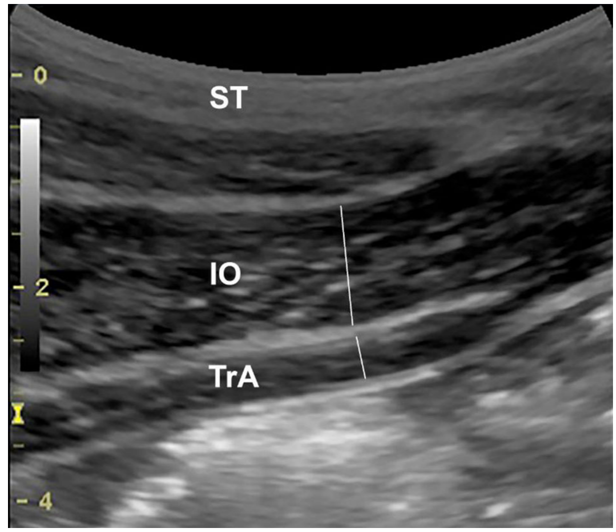

Fig. 2 Ultrasound image of the right antero-lateral abdominal musculature. Parasagittal ultrasound image of the antero-lateral abdominal muscles with linear thickness measurements of the transversus abdominis (*TrA*) and internal oblique (*IO*) muscles taken at rest. *ST* subcutaneous tissue

Ultrasound images were stored on the GE LOGIQe apparatus and subsequently measured on the ultrasound equipment after data collection was completed. For measurements of multifidus CSA, the border of the muscle was traced on both sides. The thickness of the IO and TrA muscles was measured. The external oblique (EO) muscle was not assessed in this study as previous ultrasound measurements of the thickness of the EO muscle have been found to correlate poorly with other measures of muscle activity [35]. Image measurement was conducted by an investigator who was blinded to date of image collection.

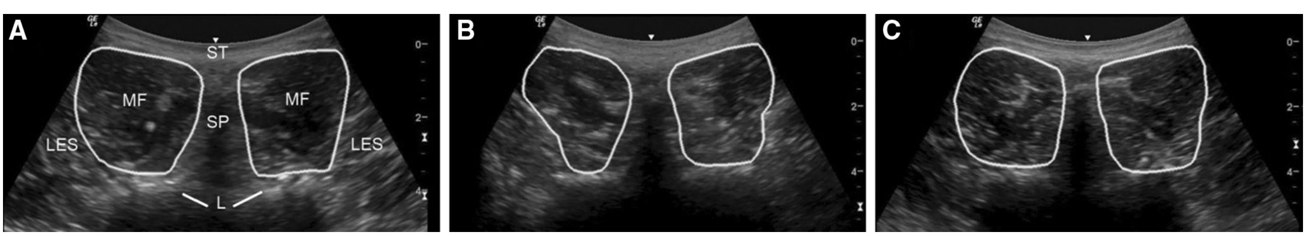

Fig. 1 Ultrasound image of the L5 multifidus muscles. **a** Pre-spaceflight, **b** Day 1 (R + 1) post-spaceflight, **c** Day 14 (R + 14) post-spaceflight. *MF* multifidus, *SP* spinous process, *ST* subcutaneous tissue, *L* lamina, *LES* lumbar erector spinae. Cross-sectional areas of the right and left multifidus muscles have been traced around in *white* in images **a**–**c**. Note in image **b**, the increased amounts of non-contractile tissue (white tissue) at the deep ventro-medial corner of the multifidus muscles

Exercise on the ISS

In microgravity, there is marked deconditioning of the body which requires an extensive in-flight countermeasure program to counteract adaptation of the body in response to exposure to this changed environmental condition. The aim of the in-flight exercise program was to prevent significant loss of terrestrial physical capability and health [36]. The exercise program focused on cardiovascular exercise and resistance exercise concentrating on leg and overall trunk strength retention [37]. The countermeasure training performed during this mission comprised intensive strength and cardiovascular exercises performed on the advanced resistive exercise device (ARED) and either the treadmill (T2 or BD–2) or cycle ergometer (CEVIS or VELO) installed on the space station. Exercises included squats, heel raises and deadlifts aimed at generating axial loading for maintenance of muscle and bone strength and performance for ambulation in gravity. The daily resistive exercise training sessions were of approximately one-hour duration and were accompanied by high crew compliance and motivation. Resistive exercise training was combined with cardiovascular exercise performed on the treadmill and cycle ergometer with the program individually tailored to meet the particular goals set for this crew member. The training protocol was prepared and monitored by exercise specialists on ground. In order to prevent injury and increase efficiency of training at high intensities, real-time support sessions were provided, requiring direct communication between the astronaut and ground support during an exercise session.

Post-mission rehabilitation

Due to the greater demands on the human postural system on Earth, re-adaptation to gravity on Earth is more difficult than adapting to microgravity conditions. Physical adaptations to microgravity include marked changes to the motor control system which affect postural equilibrium, locomotion and balance, changes to muscle morphology and function. These changes place the astronaut's musculoskeletal system at increased risk of injury and pain on return to Earth. Post-mission rehabilitation is therefore essential and has an initial focus on the stimulation of the motor control system, the recovery of the gravity axis and a gradual progression of load-bearing exercises to retrain the stabilizing and protective function of the muscles on return to full function under Earth's gravity.

The first phase of rehabilitation comprised three weeks of daily two-hour exercise sessions. A detailed patient history and physical examination preceded the first rehabilitation session. The first phase of rehabilitation focused on implementation of the individual physiotherapy treatment for the crew member. This 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 (proposed to fall anterior to its normal position after time spent in microgravity). These exercises were performed both in the pool and on land and were progressively incorporated into gym training and targeted an exercise training protocol of similar intensity to pre-flight by the end of the rehabilitation phase. After completion of the first phase of rehabilitation (three weeks), the frequency of monitored exercise sessions were reduced, however, an individually tailored training program was provided and partly performed with supervision by a coach. In this phase, the astronaut returned to an exercise workout regimen similar to that used prior to the mission, as all medically assessed parameters had returned to pre-flight values [38].

Outcomes

The response of the multifidus muscle to microgravity varied for different vertebral levels, and can be seen in Figs. 3, 4, 5, 6. For vertebral levels L2 and L3, CSA was retained between pre-flight and R + 1 time points and for both levels there was a 7 % increase in size (averaged across vertebral side). For the L4 vertebral level, there was little change in CSA in response to microgravity (1 %). For the L5 vertebral level a large decrease in the CSA of the multifidus muscle was seen, from 9.86 cm^2 pre-flight to 6.99 cm^2 post-flight (averaged across sides), representing a 29 % decrease in CSA at the lumbo-sacral junction. The response of the TrA muscle to microgravity was a decrease in thickness. In contrast, the thickness of the IO muscle increased in response to exposure to microgravity (Fig. 7).

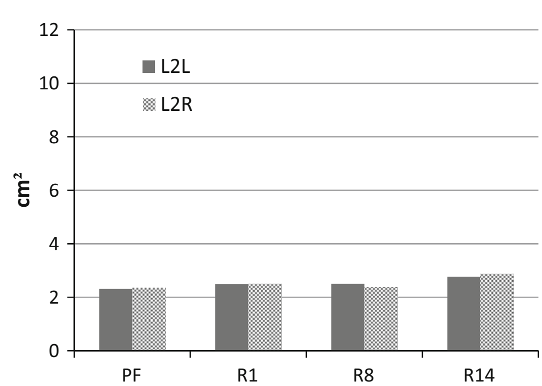

Fig. 3 Change in cross-sectional area (CSA) of lumbar multifidus muscle at L2 over time. *PF* pre-flight, *R1* Day 1 post-return to Earth, *R8* Day 8 post-return to Earth, *R14* Day 14 post-return to Earth

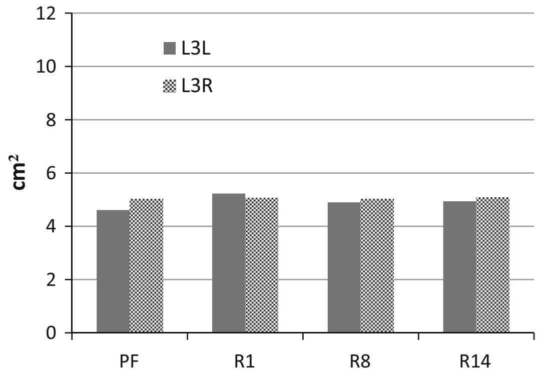

Fig. 4 Change in cross-sectional area (CSA) of lumbar multifidus muscle at L3 over time. *PF* pre-flight, *R1* Day 1 post-return to Earth, *R8* Day 8 post-return to Earth, *R14* Day 14 post-return to Earth

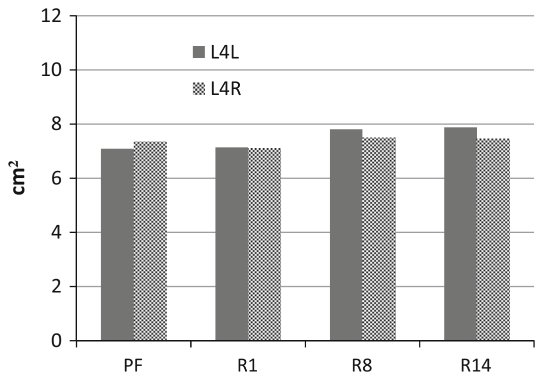

Fig. 5 Change in cross-sectional area (CSA) of lumbar multifidus muscle at L4 over time. *PF* pre-flight, *R1* Day 1 post-return to Earth, *R8* Day 8 post-return to Earth, *R14* Day 14 post-return to Earth

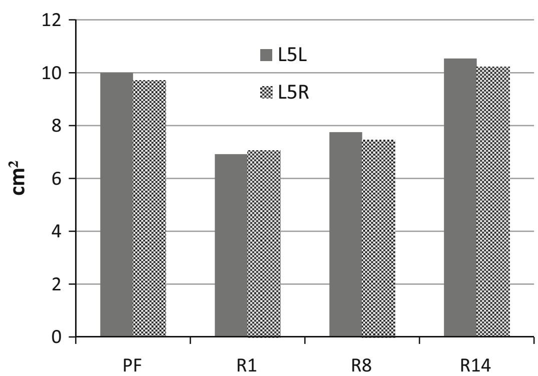

Fig. 6 Change in cross-sectional area (CSA) of lumbar multifidus muscle at L5 over time. *PF* pre-flight, *R1* Day 1 post-return to Earth, *R8* Day 8 post-return to Earth, *R14* Day 14 post-return to Earth

Post-flight rehabilitation was effective in restoring the CSA of the lumbar multifidus muscles. For the L4 and L5 vertebral levels, the post-rehabilitation values (R + 14 days) exceeded the pre-flight muscle CSA values,

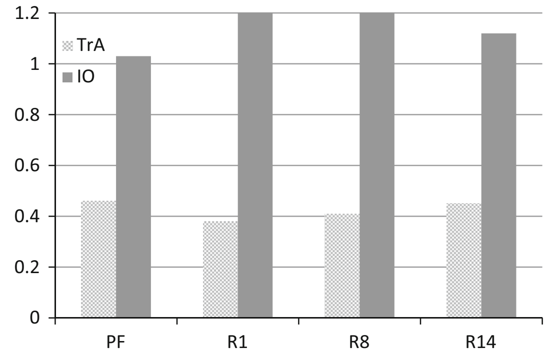

Fig. 7 Change in thickness of the right transversus abdominis muscle (TrA) and internal oblique muscle (IO) over time. *PF* pre-flight, *R1* Day 1 post-return to Earth, *R8* Day 8 post-return to Earth, *R14* Day 14 post-return to Earth

indicating that muscle size was restored. Post-flight rehabilitation also restored the thickness of the abdominal muscles. The thickness of the TrA muscle increased in response to rehabilitation, and the thickness of the IO muscle decreased in response to rehabilitation by R + 14 days.

Discussion

Exposure to microgravity resulted in a muscle imbalance between the trunk flexor and extensor muscles measured in the astronaut studied. Whilst the lumbar intrinsic muscles have been examined as a group during spaceflight [27, 39], this case study provides a novel insight into the effect of spaceflight-induced microgravity on the individual size of muscles. The main finding for the multifidus muscle was that the L5 vertebral level underwent significant reductions in muscle size with exposure to microgravity. This was accompanied by a lack of marked changes at the other vertebral levels for multifidus muscle. With respect to the antero-lateral abdominal muscles, the thickness of the TrA muscle decreased in size, whilst the thickness of the IO muscle increased in size.

Effects of decreased loading on the lumbar multifidus and antero-lateral abdominal muscles

It is of interest to compare the results of the current astronaut case history with the results from prolonged bed rest studies, as both conditions induce changes in the multifidus and abdominal muscles. After 60 days of prolonged bed rest, the CSA of the multifidus muscle at the L5 vertebral level decreased by 12.2 %, while changes at the L2, L3 and L4 vertebral levels were 4, 7 and 13 %, respectively [23]. The pattern of change of muscle size in bed rest was that the lowest lumbar vertebral levels were most affected. In the astronaut studied in this case report, the greatest loss of multifidus muscle size occurred at the lumbo-sacral junction (29 %), and the amount of atrophy exceeded that seen at L5 in response to prolonged bed rest (12.2 %). Furthermore, it would appear that exercise on the ISS maintained the CSA of the multifidus muscles at the L2, L3 and L4 vertebral levels. For the antero-lateral muscles, it is difficult to directly compare the results from bed rest with the results from microgravity, as in the bed rest studies, the antero-lateral muscles were measured together. However, as the hypertrophy of the IO muscle exceeded the atrophy of the TrA in the astronaut studied, the overall result would be similar to the results obtained from bed rest studies, in that taken together, there would be an overall increase in size of the antero-lateral abdominal muscles in response to microgravity.

The clinical relevance of these findings is that changes documented in the multifidus and antero-lateral abdominal muscles exposed to microgravity represent an induced muscle imbalance, which parallels findings seen in people on Earth. In people with LBP, the pattern of greatest loss of multifidus size occurs at the L5 vertebral level [9] and increased recruitment of the superficial abdominal muscles has also been reported [14–21]. In addition, similar patterns are associated with playing certain sports. In Australian Football League, which is a flexor dominant sport, atrophy of the multifidus muscles occurred over the season, and there was an 11.8 % increase in thickness of the IO muscle and corresponding atrophy of the TrA muscle [40], paralleling the results seen for the astronaut studied. The hypertrophy of the IO muscle was in line with its role in production of trunk flexion torque [41]. In space, video footage of astronauts moving through the ISS shows a movement similar to swimming and movement patterns on the ISS appear to preferentially recruit trunk flexor muscles. Similar to explanations used in bed rest studies, increased size of the IO muscle in astronauts may relate to the trunk being maintained in a flexed position, and may reflect muscle shortening [25]. In contrast, one of the roles of the TrA muscle is to stiffen the lumbo-pelvic joints for weight-bearing [3, 4], a role which is not required in microgravity.

Effects of post-flight rehabilitation on the lumbar multifidus and antero-lateral abdominal muscles

Similar to the results published in a prolonged bed rest study [42], rehabilitation of the astronaut in this case study was effective at restoring multifidus muscle loss at the L5 vertebral level and size of the antero-lateral abdominal muscles. Rehabilitation restored the size of the TrA muscle, and almost returned the size of the IO muscle back to pre-flight size. This is comparable to results obtained in athletes with LBP [43, 44]. The length of rehabilitation required appears to be different following spaceflight and bed rest when compared with rehabilitation periods for people with LBP. Recovery occurred within a two-week period in both the post-spaceflight and post-bed rest conditions [42]. This period of rehabilitation is shorter in duration than the eight-week period reported for football players with decreased size of the multifidus muscles [45], or the ten-week rehabilitation period reported for people with chronic LBP [46]. This may reflect that the response of muscles to changes in environment such as exposure to microgravity and prolonged bed rest are less difficult to rehabilitate than changes in muscle which are secondary to pathology, such as spinal degeneration and intervertebral disc derangements.

Future directions

An observation which was not quantified in this case history was that time spent in the microgravity condition appeared to result in changes in consistency of the muscle, in the deep ventro-medial corner of the muscle. This is similar to the location where these changes have been documented in people with chronic LBP. Studying changes in muscle consistency which occur in astronauts over a short period of time could provide further insights into this phenomenon, which would be very difficult to achieve on Earth. Also, the effects of rehabilitation on muscle consistency could be assessed, as it has been shown that in older adults, paravertebral muscle fatty infiltration can be improved with strength training [47].

In summary, the results of this case study suggest that the microgravity model could be used to provide insight into conditions seen on Earth, ranging from LBP, prolonged bed rest associated with many conditions (e.g., hospitalized patients with long-term conditions) and muscle imbalance in sporting populations. The advantage of the microgravity model is that study participants can be assessed before exposure, after exposure and during and after rehabilitation.

The main limitation of this study is that these data have been collected from only one astronaut. Whilst the microgravity model provides valuable insight into conditions experienced on Earth, there are considerable expenses and logistic considerations associated with studying astronauts. Collection of data from a number of astronauts could provide useful information for the optimization of rehabilitation post-space missions.

Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict of interest.

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