Preflight, In-Flight, and Postflight Imaging of the Cervical and Lumbar Spine in Astronauts

Michael F. Harrison; Kathleen M. Garcia; Ashot E. Sargsyan; Douglas Ebert; Roy F. Riascos-Castaneda; Scott A. Dulchavsky

BACKGROUND: Back pain is a common complaint during spaceflight that is commonly attributed to intervertebral disc swelling in microgravity. Ultrasound (US) represents the only imaging modality on the International Space Station (ISS) to assess its etiology. The present study investigated: 1) The agreement and correlation of spinal US assessments as compared to results of pre- and postflight MRI studies; and 2) the trend in intervertebral disc characteristics over the course of spaceflight to ISS.

METHODS: Seven ISS astronauts underwent pre- and postflight US examinations that included anterior disc height and anterior intervertebral angles with comparison to pre- and postflight MRI results. In-flight US images were analyzed for changes in disc height and angle. Statistical analysis included repeated measures ANOVA with Bonferroni post hoc analysis, Bland-Altman plots, and Pearson correlation.

RESULTS: Bland-Altman plots revealed significant disagreement between disc heights and angles for MRI and US measurements while significant Pearson correlations were found in MRI and US measurements for lumbar disc height ($r^2 = 0.83$) and angle ($r^2 = 0.89$), but not for cervical disc height ($r^2 = 0.26$) or angle ($r^2 = 0.02$). Changes in anterior intervertebral disc angle—initially increases followed by decreases—were observed in the lumbar and cervical spine over the course of the long-duration mission. The cervical spine demonstrated a loss of total disc height during in-flight assessments ($\sim$0.5 cm).

DISCUSSION: Significant disagreement but significant correlation was noted between US and MRI measurements of disc height and angle. Consistency in imaging modality is important for trending measurements and more research related to US technique is required.

KEYWORDS: spaceflight, back pain, spine, International Space Station, microgravity.

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Exposure to microgravity has been associated with multiple spinal conditions and findings, including increased total height,[27,37] back pain,[19,29,31] and increased risk of intervertebral disc herniation.[17] Benign back pain, described as "space adaptation back pain," is a frequent complaint and one that is generally more pronounced in the beginning of a mission.[19,29] Increases in height up to 6 cm have been documented with on-orbit measurements;[27,38] however, due to the lack of on-orbit imaging capability, the exact mechanism(s) remain unclear and head-down bed rest[17] or cadaver[18] studies serve as terrestrial surrogates. Hypothesized causes may include postural changes, including the loss of lordosis and other biomechanical alterations with $+G_z$ unloading associated with microgravity exposure,[17,18,35] elongation of the spinal column,[17,18] decreased muscle tone and volume due to microgravity exposure,[7,30,35] modified exercise prescriptions,[30] forced positioning within a spacecraft designed to minimize spacecraft volume,[19] and predisposition to spinal complaints based on prior chronic occupational exposures to high-performance jet[14,33] and rotary[13,25] aircraft flight. Overall, the pain is hypothesized to be discogenic and possibly the result of swelling of the intervertebral disc

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(IVD) structures as noted during periods of unloading in head-down bed rest studies.[3,17,30] However, on-orbit imaging studies of the spinal structures are lacking with respect to confirmatory or contradictory evidence.

Magnetic resonance imaging (MRI) provides a noninvasive methodology to assess the spine in returning crewmembers or in subjects of other experimental models and represents the gold standard of imaging modalities.[16,28,36] Unfortunately, space and power constraints do not currently allow advanced radiological capabilities such as MRI or computed tomography (CT) to be incorporated into the International Space Station (ISS). As a result, National Aeronautics and Space Administration (NASA) science and medical teams have used near real-time ultrasonography (US) to answer a number of clinical questions during long duration spaceflight. Recent publications provide evidence in support of the utility of US in assessing the structures of the lumbar and cervical spine during preflight, in-flight, and postflight periods without the performance of quantitative analysis and trending of results from repeated examinations.[11,24]

The primary objective was to trend the quantitative change in these variables (i.e., lumbar and cervical anterior disc height and anterior disc angle) with US imaging over the course of a long duration spaceflight mission to the ISS. Based on previous reports of increased total height in microgravity,[27,38] we hypothesized that increased anterior disc height would be observed that may be associated with increased (i.e., straightening) anterior disc angle. These anticipated structural findings would potentially shed light on the etiology of space adaptation back pain or risk for injury upon return to gravitational loading after long duration spaceflight by confirming what is widely hypothesized with respect to spinal elongation.[17,19,29]

The secondary objective of the present study was to assess the level of agreement between US and MRI measurements of anterior disc height and anterior disc angle during pre- and postflight assessments when both modalities were available. Based on available references,[2,8] we hypothesized no statistically significant disagreement would be observed between the two imaging modalities. The agreement and correlation between results and findings from spinal MRI examinations and ultrasound examinations remains unclear. Our previous publication provided evidence that novel sonographers with minimal training who are receiving online near real-time guidance during image acquisition are able to obtain diagnostic quality images with no statistically significant differences between rates of observed pathology.[11]

METHODS

Subjects

The research protocol was approved by the Human Investigation Committee and the NASA Lyndon B. Johnson Space Center (JSC) Institutional Review Board. Nine crewmembers ($N = 9$) provided informed consent and were trained as operators to perform the spinal US procedure while on-orbit. Two crewmembers were trained only as crew operators to collect data from one of the total compliment of seven subjects ($N = 7$), but did not reciprocally serve as research subjects. A detailed description of the research protocol is available in our previous publications[11,24] and a brief description is provided here.

Equipment

US was collected using a portable ultrasound device with a similar configuration to the ultrasound machine on the ISS (GE, Vivid q, Milwaukee, WI) and a variety of probe selections: 12 HHz linear array, 8 MHz tightly curved array (8C-RS), 4 MHz curved array (4C-RS), and rarely a 4 MHz matrix array. For the majority of the data collection, the 4C-RS and 8C-RS broadband curved array probes were selected for the lumbar and cervical regions, respectively. MRI assessments were obtained using a 3-Tesla magnet, Verio 3T with a 32-channel head coil (Siemens, Erlangen, Germany).

Procedure

Pre- and postflight MRI, pre- and postflight US, and in-flight US images were obtained as early in the morning as possible and prior to any exercise, hyperbaric chamber sessions, neutral buoyancy training, or other axial loading to reduce exercise/load induced spinal alterations. Subjects were asked to avoid eating any heavy meals 6 h prior to US to reduce abdominal gas. MRI and US images included multiplanar, sagittal, axial, and coronal views of the lumbar spine [between the 12th thoracic (T12) vertebra and the level of the sacral spine (S1)] and the cervical spine [first cervical (C1) vertebra and the second thoracic (T2) vertebra]. All seven astronauts had MRI data collected 4 to 6 mo preflight and repeated at 7 to 8 d post-spaceflight. Every effort was made to collect the pre- and post-spaceflight US on the same day as the MRI studies or, if this was not possible due to scheduling conflicts, within a 10-d window.

L-spine US images were collected in both short- and long-axis using a novel transabdominal approach while the astronaut was supine on the Crew Medical Restraint System (CMRS). The large abdominal vessels, the aorta, and inferior vena cava, were identified as reproducible landmarks and created acoustic windows that facilitated US image acquisition of the IVD and the surface of the spine (**Fig. 1**). US beams had a direct path through the disk, resolving the structure of the disk itself, including its annulus fibrosus and the relatively hypo-echoic nucleus pulposus, the posterior longitudinal ligament (PLL), and the cross-section of the thecal sac with its contents. C-Spine cine-loop data were collected in a similar fashion using the esophagus to optimize the acoustic window.

The crewmembers were partnered in pairs and began their US training approximately 6 mo prior to their mission with didactic sessions of spinal anatomy, procedure demonstration, equipment set-up, and review of Spinal Ultrasound Experiment Software, a flash-based experiment specific software with embedded video that provided a linked review of the ultrasound probe and placement with the corresponding US image. Training also included 1-h, hands-on US sessions that covered

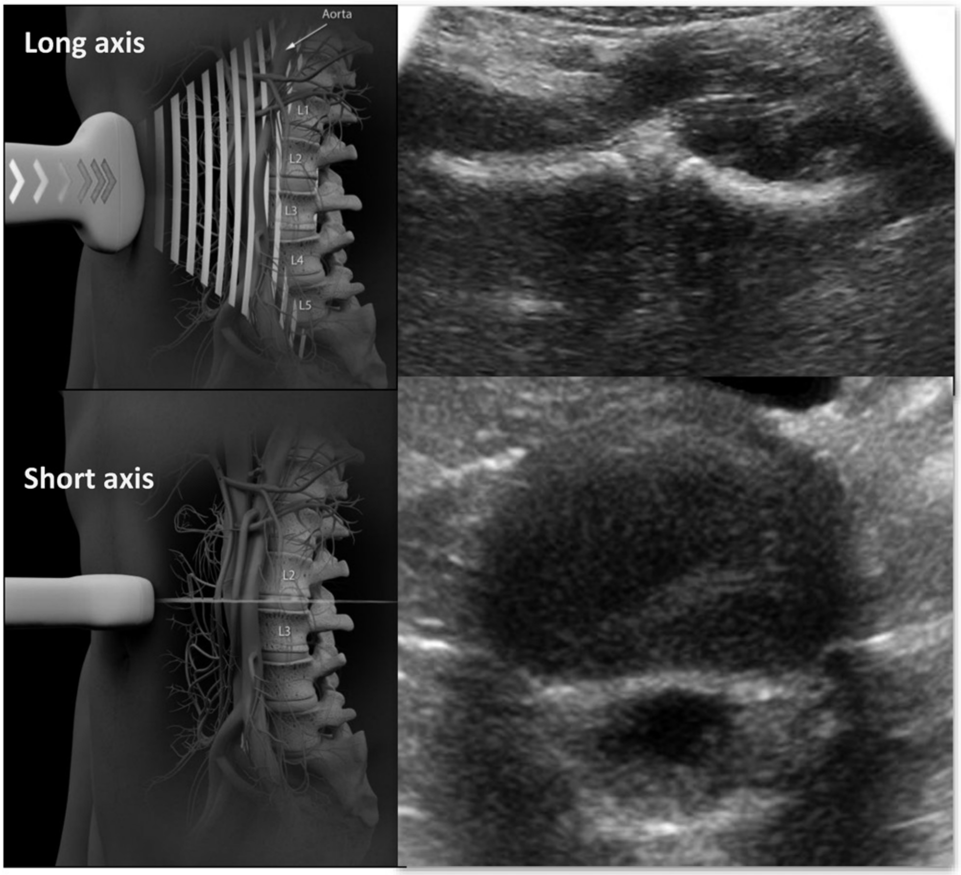

Fig. 1. Computer based software provided just in time education to simplify spinal ultrasound for the crewmembers. This demonstrates probe positioning for visualizing an intervertebral disc space with two orthogonal imaging planes from the transabdominal approach with the aorta or inferior vena cava providing acoustic windows to enhance image quality when possible. In this example, representative images of the probe application Lumbar 2-Lumbar 3 intervertebral disc space in the long and short axes are provided.

real-time collection of US data on their respective crew partner to develop a better understanding of the US approaches to the spine.

The in-flight procedures were designed to obtain ultrasound images that corresponded to pre- and postflight data from the MRI and US studies. Pre- and postflight spinal US were collected by experienced sonographer scientists. In-flight L- and C-spine data were scheduled for collection in a single session. Three data collection sessions were scheduled for each subject on flight day 30 (FD 30), flight day 90 (FD90), and flight day 150 (FD150) to evaluate time-dependent effects of microgravity exposure on the spine. Data collection occurred on the appropriate day with a range of ± 15 d based on on-orbit crew schedules. The astronaut operator was assisted thru the data collection with near real-time remote guidance from the subject matter expert from the Tele-Science Center at the Johnson Space Center. The remote expert guider used two-way voice communications, and monitored the set-up and subject/crew positioning with cabin video and US image acquisition from the video stream connected to the video-out of the onboard ultrasound. Images were saved and analyzed as cine-loop video files.

Statistical Analysis

The data were compiled in spreadsheet format (Microsoft Excel 2008, Redmond, WA) and analyzed with SPSS v. 22.0 (IBM, Armonk, NY). Student's *t*-test was performed to identify any differences in pre- and postflight characteristics, including height (m), weight (kg), and body mass index (BMI; $kg \cdot m^{-2}$) with significance determined as $P < 0.05$. A generalized linear model repeated measures analysis of variance (ANOVA) with Bonferroni post hoc analysis was performed to identify differences in US measurement of disc height and anterior disc angle from preflight to in-flight to postflight with significance determined as $P < 0.05$. A Bland-Altman analysis with the appropriate Student's *t*-test ($P < 0.05$) was performed to compare the intrasubject agreement of the pre- and postflight ultrasound measurements with the gold standard pre- and postflight MRI measurements.[4,5,12] A Pearson-r correlation analysis was performed to assess the correlation between pre- and postflight US measurements with the corresponding MRI measurements for disc height and anterior disc angle with significance determined by $P < 0.01$ due to repeated measurements.

RESULTS

The seven experienced astronauts who provided informed consent to participate as imaged research subjects were predominantly male ($N = 6$; 86%) with a mean age of 46.1 ± 6.4 yr. Basic preflight anthropometric data included height 1.79 ± 0.07 m, weight 79.9 ± 11.4 kg, and BMI 24.7 ± 2.7 $kg \cdot m^{-2}$. Postflight anthropometric data were collected within 1 d of landing and showed a height of 1.78 ± 0.06 m, weight 80.1 ± 11.5 kg, and BMI 25.0 ± 2.9 $kg \cdot m^{-2}$. Overall, the average decrease in height was statistically significant [−0.09 ± 0.01 m; $t(6) = -3.14$, $P = 0.02$]. A significant number of the astronaut subjects reported back and neck pain during early spaceflight ($N = 6$; 86%) and shortly after returning to Earth ($N = 4$; 57%). Three (43%) astronauts subsequently underwent clinical MRI evaluations for spine associated conditions outside of this protocol.

Comprehensive lumbar and cervical spine US examinations were completed in approximately 60 min by the nonexpert astronaut operators. As presented in our previous publication, the success rate of the image acquisition was extremely high in all investigated regions;[11] the average image acquisition success rate in the lumbar region was 95% and 90% in the cervical region over the course of the data collection sessions (**Table I**). The lost data occurred in the extremes of both the lumbar (L1–L2 segment) and cervical (C7–T1 segment) regions and the nadir for both assessments occurred on FD90. There was no appreciable difference in image quality between expert operators and astronaut crewmembers with respect to ground measurements (preflight and postflight).

With respect to our primary object, changes in the height of the IVD and intervertebral angle were noted in the in-flight ultrasound data. The lumbar IVD disk height demonstrated a trend toward increased height during the mission with a peak at FD90; these results were not statistically significant [$F(31) = 1.53$, $P = 0.22$]. An opposite effect was seen in the cervical spine region; the combined cervical IVD height had a decreased trend by FD30 and the statistically significant nadir occurred at FD90 [$F(31) = 4.98$, $P = 0.04$]. The cervical IVD height remained decreased through the postflight exam, though this lacked statistical significance (**Fig. 2**). The angle analysis is an indication of movement or change in the disc-to-disc relationship. The changes noted in the vertebral body angles over the course of this in-flight study suggested an overall straightening of the spine and loss of lordosis in multiple segments of the lumbar spine (**Fig. 3A**). Cervical angle data were less consistent with respect to overall trend though significant changes—initially an increase in the angle during the early phases of spaceflight followed by a decrease toward preflight measurements as the mission progressed—were noted in the C4–C5 region during multiple phases of the spaceflight (**Fig. 3B**).

Bland-Altman analysis to address our secondary objective demonstrated significant disagreement between MRI and US measurements for lumbar [$t(69) = -4.60$, $P = 0.004$; **Fig. 4A**] and cervical [$t(69) = -3.08$, $P = 0.009$; **Fig. 4B**] IVD height and lumbar [$t(69) = -3.78$, $P = 0.004$; **Fig. 4C**] and cervical [$t(69) = -4.24$, $P = 0.001$; **Fig. 4D**] anterior disc angle. The overall trend was for a larger measurement to be obtained with US as compared to the measurements obtained with MRI.

Significant correlations were found between MRI and US measurements for lumbar IVD height [$r^2(68) = 0.83$, $P = 0.0001$; **Fig. 5A**] and anterior disc angle [$r^2(68) = 0.89$, $P = 0.0001$; **Fig. 5B**]. However, no statistically significant findings were noted for cervical IVD height [$r^2(68) = 0.26$, $P = 0.03$; **Fig. 5C**] or anterior disc angle [$r^2(68) = 0.02$, $P = 0.20$; **Fig. 5D**]. The distinct change in IVD anterior disc angle in the region of transition from the lumbar to sacral region of the spine is evident in Fig. 5B.

Table I. Success Rates for Lumbar and Cervical Spine Image Acquisition ($N = 7$) Across the Preflight, In-Flight, and Postflight Data Collection Sessions.

	PREFLIGHT	FD30	FD90	FD 150	POSTFLIGHT
L5–S1	100%	100%	100%	100%	100%
L4–L5	100%	100%	100%	100%	100%
L3–L4	100%	100%	100%	100%	100%
L2–L3	100%	100%	86%	100%	100%
L1–L2	100%	71%	43%	71%	100%
C7–T1	100%	29%	14%	29%	100%
C6–C7	100%	86%	100%	100%	100%
C5–C6	100%	100%	100%	100%	100%
C4–C5	100%	100%	100%	100%	100%
C3–C4	100%	100%	100%	100%	100%

DISCUSSION

The present study follows our previous publications detailing the utility of US in diagnosing and monitoring pathology in the structures of the vertebral column during prolonged microgravity exposure[11,24] and specifically addresses anatomical changes in spinal structures over the course of long duration spaceflight. This study provides strong evidence that a novel user is able to obtain images on orbit that can document anatomical changes over the course of a long-duration ISS spaceflight mission. There is a need for information about the acute and chronic effects of microgravity exposure on the spine as there is longitudinal data that suggests that astronauts are at higher risk for spinal pathology than a normal cohort population.[17,35] A number of historic observations have noted changes in astronaut crew height during shorter duration missions; for example, in a microgravity environment, a "crewman grows taller"[27] in multiple references, with reports of spinal lengthening during microgravity exposure being reported to be between 4 and 7 mm.[27,32,38] This change is hypothetically attributed to increased fluid volume in the unloaded nucleus pulposis and thus a change in IVD height.[1] The inset US images in Fig. 2 demonstrate an atrophied IVD in L4–L5 as compared to the previously postulated swelling and Fig. 3 demonstrates an overall trend toward spinal straightening in the microgravity environment with statistically significant changes observed in both the cervical and lumbar regions. Until now, these images and results were unobtainable, but US provides a tool that, even in the hands of a novel user with remote guidance, is able to consistently measure key anatomical landmarks and anthropometric variables with the acquisition of diagnostic quality imaging. Obviously, future refinements in the technique with an increased sample size would be of significant benefit, but this represents NASA's earliest efforts in this realm.

We anticipated that we would corroborate the earlier findings of increased astronaut height as a result of loss of lordosis and increased IVD volume. While the trend over the course of the ISS mission did not support this hypothesis, the data does not entirely discredit these earlier claims. The initial response to microgravity in the lumbar spine demonstrated a trend toward increased disc height that would support prior sources. The initial response to microgravity in both the cervical and lumbar spine demonstrated loss of curvature and straightening initially (statistically significant peak at approximately FD30 in D1–L5, L2–L3, and C4–C5), followed by decreased spinal angle and increased curvature by FD150 and continued into postflight assessments. These findings are consistent with the degenerative changes supported by our findings of loss of disc volume

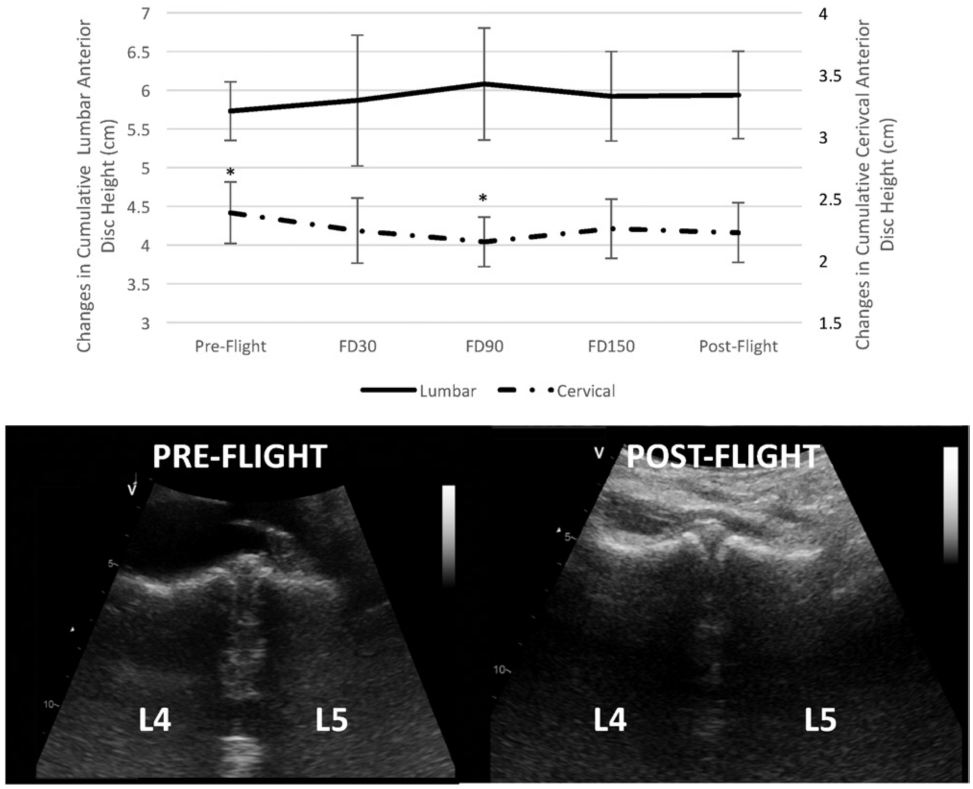

Fig. 2. Cumulative anterior disc height in the lumbar (left y-axis) and cervical (right y-axis) spine over the course of the long-duration spaceflight with US images representative of decreased intervertebral disc height inset. * Denotes significant difference ($F = 4.98$; df = 31; $P = 0.04$) between preflight and FD90 measurements in the cervical vertebrae.

between pre- and postflight measurements. Overall, statistically significant crew height decreases over the course of the mission as assessed with basic anthropometry.

The most likely reason for the difference in trends between the present study and prior reports is the change in mission lengths. A publication related to the validation of the current countermeasure device, the advanced resistive exercise device (ARED), identifies a threshold of ">4 months" as the period in which catabolism occurs.[22] The prior findings were measured during short duration Apollo or Shuttle missions[21,27,38] and it is possible that our current methodology involving direct evaluation of the IVD with the first in-flight measurement taken on approximately FD-30 did not reflect these earlier adaptive changes. Future studies should make an effort to collect data during the early phase of long duration spaceflight to investigate if this is in fact the reason.

The analysis of the images and other data highlights a number of challenges and opportunities pertaining to spinal health in spaceflight. Despite the increased risk of cervical IVD herniation in astronauts as compared to the general population,[17] little is known about the risk of IVD herniation and other pathology in the cervical structures of astronauts.[3] Belavy et al. recently stated "For the cervical IVDs, the knowledge base is too limited to postulate a likely mechanism or recommend approaches for prevention. Basic research on the impact of unloading on the cervical IVD and translational research is needed."[3] Our present study represents an initial effort to address this need. Imaging the cervical spine with ultrasound is challenging, but our data indicate differences in response to microgravity between different segments, specifically the lumbar and cervical spine.

The cervical spine trend inflight was toward a loss of total IVD height with statistically significant losses occurring on FD90 as compared to preflight measurements. This may be an indication the astronauts in the present study are demonstrating under-appreciated evidence of microgravity-associated degeneration in the cervical region. As the evidence that some degenerative changes that occur in the spine as result of microgravity exposure are irreversible,[1] preventive strategies for the cervical spine should become a priority in preparation for longer duration missions to deeper space as injuries to the cervical spine, the most delicate and mobile of the spinal structures, has potential for catastrophic consequences,[34] though this vertebral region does not appear to be a priority at present.[23] Cervical injuries and degenerative conditions are of concern to other aviation communities and opportunities exist for overlap in the development of countermeasures and therapeutic strategies.[13]

The unexpected changes observed in the cervical spinal measurements may be attributed to the exercise countermeasure device and associated exercise protocol. The ARED replaced the previous countermeasure device, the interim resistive exercise device (iRED), and was installed on the ISS in 2008[22] in response to statements such as "no amount of exercise has yet been able to counteract the progressive deconditioning of the human body in zero-gravity."[6] The ARED provides significant axial loading for crew exercise routines and might contribute to a reduction in crew height changes during long duration missions due to a reduction in bone mineral density loss and muscle atrophy. The presence of the ARED may also explain the difference in trends between the cervical and lumbar regions of the spinal column; the ARED provides means by which to provide axial load and stress to the structures of the lumbar spine and thus mitigate microgravity-associated degenerative changes. However, the structures of the cervical spine are not afforded the same opportunity for axial loading and over the course of the 180-d ISS mission. Publications from the ARED's initial testing in terrestrial settings supports its benefit in minimizing musculoskeletal catabolism in numerous regions, including the lumbar spine; however, no mention of

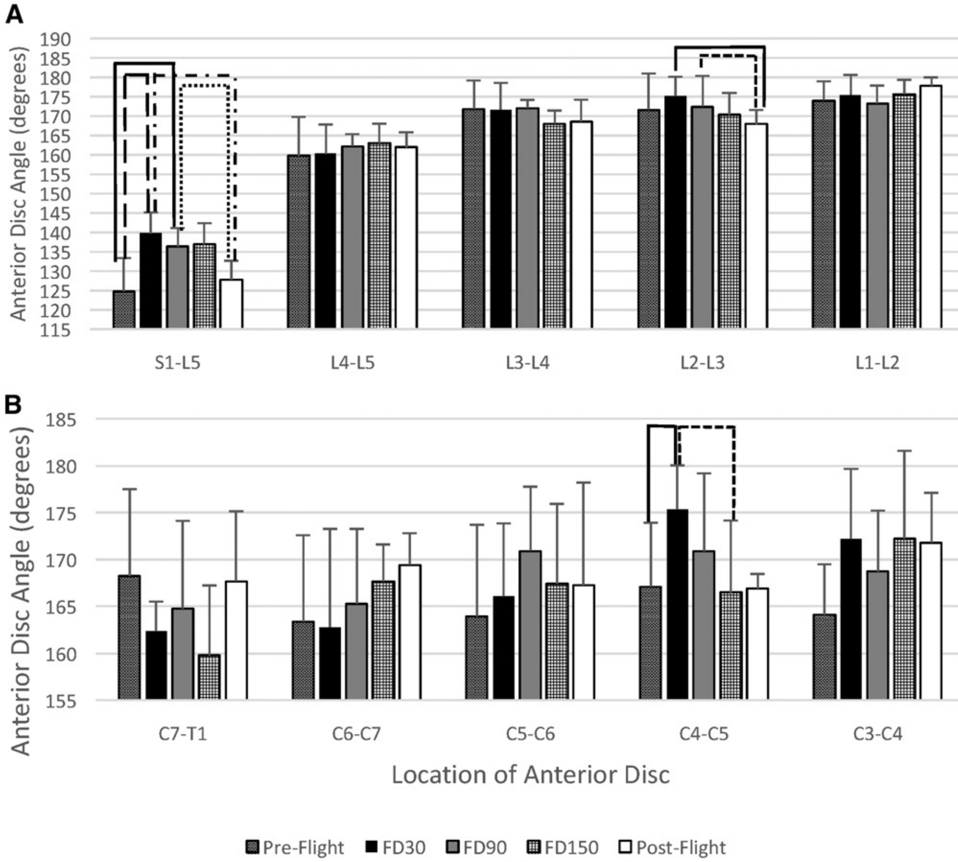

Fig. 3. A) Lumbar and B) cervical anterior disc angles over the course of the long duration spaceflight; significant differences were identified at the S1–L5 disc ($F = 7.46$; df = 32; $P < 0.01$), L2–L3 disc ($F = 3.46$; df = 31; $P = 0.02$), and C4–C5 disc ($F = 2.74$; df = 31; $P = 0.05$).

any benefit or intended benefit specific to the cervical spine is discussed.[9,22]

Our data suggest the pattern of spinal changes during long duration spaceflight may occur in multiple distinct phases. The first phase appears to be the lengthening of the spine as previously reported and hypothesized to be caused in part by the swelling of the IVDs in response to gravitational unloading.[3,17,30] The increase in spinal length reported by these earlier shorter duration missions is consistent with the proposed pathophysiological mechanisms for "spaceflight associated back pain."[19] This syndrome is attributed to stretching of the connective tissues, specifically the posterior ligaments of the spine, due to either an increase in the volume of the nucleus pulposis or to the unloading of the spinal column in microgravity.[17,19,37] It has been hypothesized that exposure to reduced gravity causes an imbalance in the fluid dynamics of the IVD that expands the nucleus and the annulus fibrosis, deforming the collagen in the disc and increasing disc volume.[29,30] The second phase of spaceflight associated spinal change appears to be degenerative in nature and results in shrinkage of the IVD. Clinically, MRI and ultrasound analysis revealed asymptomatic but radiologically notable deviations in the spine structure or geometry in six subjects preflight and in all seven subjects postflight. The majority of the spinal changes observed in our astronauts were degenerative in nature (disc desiccation, endplate sclerosis, etc.),[11] further supporting the hypothesis that degenerative processes are persistently present in the spinal structures during long-duration spaceflight. Degenerated IVD alter the dispersion of load and biomechanical behavior and changes the dynamics of the loaded spine and can be a source for back pain.[26] While these changes may be acute, our current findings may be an indication of the changes to be expected as a result of long-duration space missions. Within our seven subjects, three crewmembers had significant pain postflight; one had a micro-discectomy and two others requested copies of their MRI for specialist follow-up. Early studies documenting spinal lengthening and IVD swelling were performed on Shuttle astronauts,[21,32,38] who experienced much shorter duration exposure to microgravity (approximately 2 wk). These prior data primarily reflect the early swelling phase of adaptation to microgravity; however, based on the fact that even Shuttle crew were nearly four times more likely to experience disc herniation and other spinal related injuries in the immediate postflight period,[17,30] it is clear that degenerative processes, or at least damaging adaptations, are likely occurring early in spaceflight.

With respect to our secondary objective, our Bland Altman analysis indicates statistically significant changes that may be a result of the inherent differences in image quality and fidelity between US and MRI assessments of the spinal column. Pearson correlation analysis demonstrates excellent correlation between MRI and US measurements in the lumbar spine and room for improvement in the cervical spine. This improvement in the cervical spine assessments can likely be achieved with further refinement of technique and analytic techniques that would address the challenges in image acquisition in this region (i.e., air-filled structures such as the esophagus and trachea overlying the anterior approach to cervical structures as compared to the fluid-filled structures such as the aorta and inferior vena cava overlying the anterior approach to the lumbar region).

To the best of our knowledge, precision analysis of spinal structures to test concordance between MRI and US data at the disc and IVD level has not been previously reported. Previous work has highlighted the utility of US in assessing spinal pathology in neonates[2,8,10] and the agreement of US with MRI in assessing changes in muscle cross-sectional area.[15] The present study highlights the challenges associated with comparing US

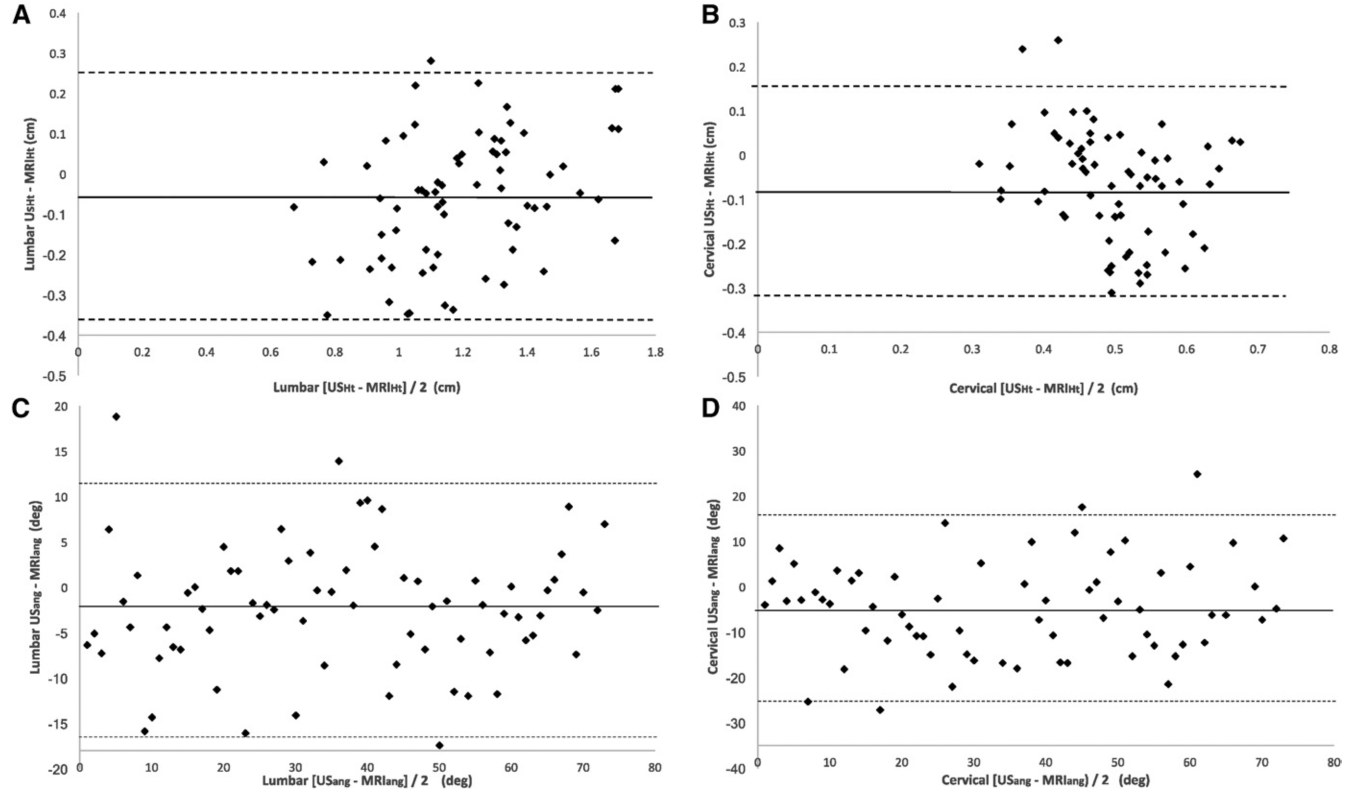

Fig. 4. Bland-Altman analysis of pre- and postflight A) lumbar and B) cervical anterior disc height, and C) lumbar and D) cervical anterior disc angles collected by ultrasound and MRI.

and MRI measurements of intervertebral disc measurements (anterior disc height and angles) and pathological findings while highlighting some strengths and opportunities. Despite the small sample size that is often inherent in human research performed with orbiting astronauts, the present study lends support to continued efforts to refine and perfect the technique associated with US assessment of the human spinal column. Even with the present small sample size, the statistical analysis demonstrates exciting potential when the results are compared to the current gold-standard, MRI.

Bland-Altman analysis compares the agreement in the measurement obtained between an experimental technique (i.e., US) as compared to the measurement of the same structure or object obtained with a gold-standard technique (i.e., MRI).[12] The agreement between the two imaging modalities, US and MRI, during pre- and postflight testing demonstrates statistically significant differences in the anterior disc height and intervertebral angles in both the cervical and lumbar regions. In the present case, the results of the Bland Altman and correlation analysis indicate that a measurement discrepancy is present between MRI and US. Larger measurement values were obtained with US and this is likely a result of the differences in image fidelity that exists between MRI and US.

Further evidence that the disagreement between MRI and US measurements may be a function of image fidelity is provided by the presence of statistically significant correlations between the US and MRI results of lumbar anterior disc height and intervertebral angles. Given the concentration of the vast majority of the IVD pathology in the lumbar region, this strong correlation bodes well for future research and diagnostic efforts using US. The capability of measuring changes in the lumbar region was a primary focus of this project given the vast majority of herniated discs are reported in the lumbar spine of the astronaut population.[3,17] Further refinement of the technique should only enhance accuracy and thus agreement; the correlation analysis suggests the potential is there. It should also be noted that a Bland Altman analysis does not suggest superiority of one method (MRI) in comparison to another method (US), but rather suggests, for the sake of consistency, that repeated measurements should only be required with the same modality.[12] This would allow a clinician to document and monitor spinal changes over time with US. Given the lack of MRI capability on the ISS, this finding as it relates to repeated US examinations is promising. The previous publications from the pediatric literature suggest that an ultrasonographic examination only needs a follow-up imaging with MRI if a positive finding is obtained.[2,10] Literature in the general adult or other aviation communities suggests that MRI is not warranted for the vast majority of cases and may lead to false positive results or results with questionable clinical significance,[20,33,36] though it has been used to document lean muscle mass loss as a result of long-duration spaceflight.[7]

Exposure to a microgravity environment produces changes in an astronaut's relaxed posture. Measurements recorded in orbit by NASA astronauts have demonstrated that the human body assumes a trunk-to-thigh angle of 128° in its most unstressed

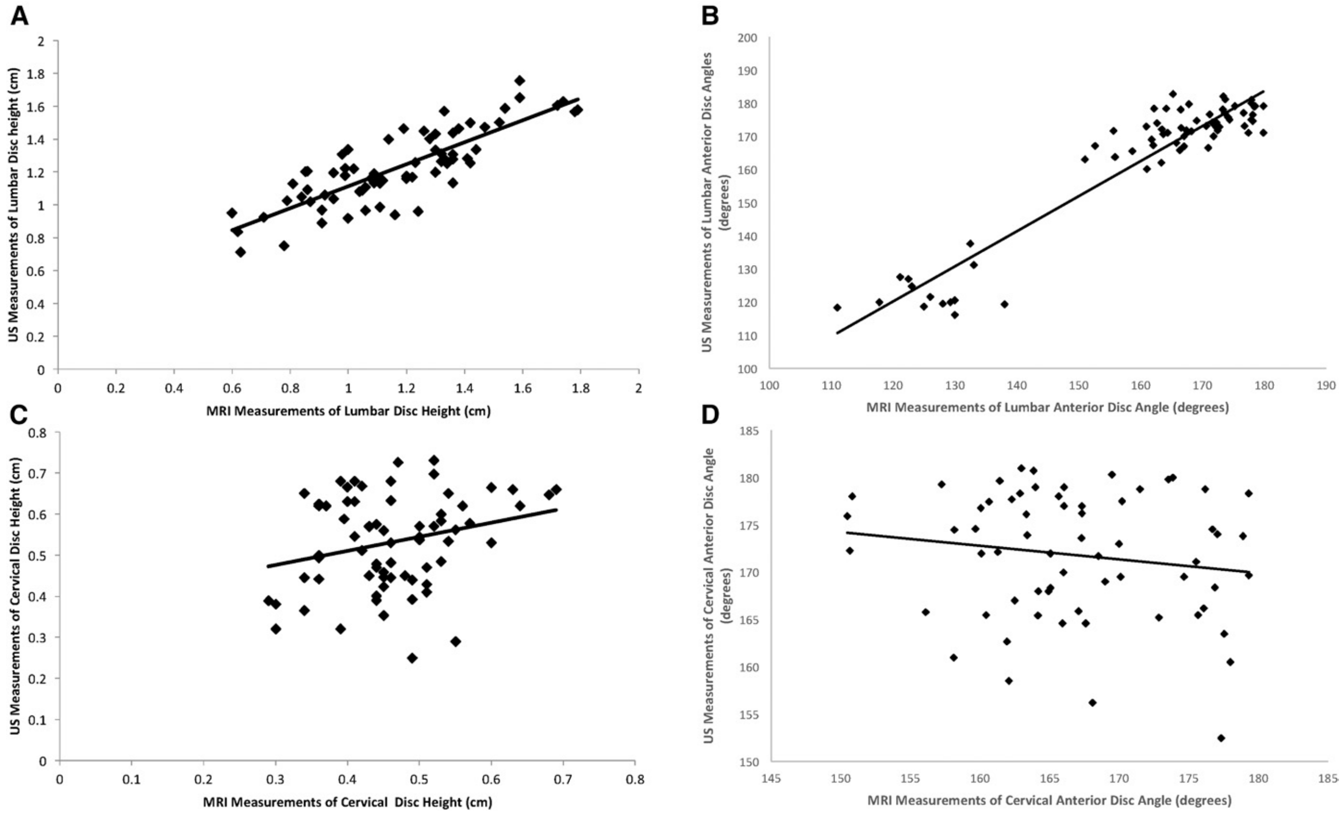

Fig. 5. Correlation between A) lumbar and C) cervical anterior disc height, and B) lumbar and D) cervical anterior disc angles collected by ultrasound (x-axis) and MRI (y-axis). Preflight and postflight data points are included in this analysis.

and relaxed state. We evaluated changes in crewmember spinal positioning by calculating a disc-to-disc angle in the cervical and lumbar spine regions. Previous studies on the effect of bed rest or microgravity on the spine have generally relied on either direct anthropometric observations on the entire spine or ultrasound directed measurements of changes in the distance between spinal processes. These measurements do not include the centers of axis of motion of the spine. The "centrode of motion" of the spine is complex and consists of a series of instantaneous axes of rotation that can contribute to an overall effect on spinal height measurements, necessitating including posture in distance calculations.

Overall, these results demonstrate the importance of refining the US imaging technique of the vertebral anatomy and function in microgravity. Our results strongly suggest that previously reported findings of increased spinal height due to IVD swelling and spinal straightening was likely the cause of increased spinal height during short duration spaceflight, but degenerative changes occur over the course of long duration spaceflight that ultimately result in increased spinal curvature as assessed by anterior disc angle and decreased anterior disc height as assessed with US. Our data related to the changes observed in the cervical segment of the spinal column also suggest a concentrated effort to include cervical structures in future exercise countermeasure prescription should be a focus. Strong correlation between MRI and US measurements were noted in the lumbar spine when US images were obtained by novice users. This suggests that US assessment of spinal structures in astronauts, despite being a novel imaging modality, demonstrates promise that warrants further investigation and technique refinement. This is particularly true in the cervical region. These results also suggest that consistency in the choice of imaging modality is important for trending and comparing measurements and a change of modality should only be considered when clinically indicated (i.e., an acute event such as pain, injury, or focal neurological deficit). As long-duration spaceflight missions progress further and deeper into space (i.e., Mission to Mars), a refinement and perfection of this imaging modality and its associated technique to monitor in-flight spinal health in astronauts will become even more crucial. The current data demonstrate positive potential with respect to the ability of a novice user with expert guidance to use the only imaging modality that is currently feasible on an orbiting or exploration class spacecraft. As future spaceflights increase in duration and travel further beyond the Earth's atmosphere, the present results should reassure astronauts and flight surgeons alike that spinal health can be monitored dynamically over the course of the microgravity exposure.

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