Journal of Pain Research

Dovepress
Taylor & Francis Group

Open Access Full Text Article

ORIGINAL RESEARCH

Detrimental Effects of Space Flight on the Lumbar Spine May Be Correlated to Baseline Degeneration: Insights From an Advanced MR Imaging Study

Rakan Bokhari[1], Daniel G Bisson[2], Maryse Fortin[3], Marie Vigouroux[4], Juan Pablo Cata[5,6], Ken-Pin Hwang[7], Melissa M Chen[8], Guillermo Ceniza-Bordallo[9], Jean A Ouellet[2,10], Pablo M Ingelmo[3,10,11]

[1]Division of Neurosurgery, Department of Surgery, College of Medicine, King Abdulaziz University, Jeddah, Saudi Arabia; [2]Department of Pediatric Orthopedics, McGill University, Montreal, QC, Canada; [3]Department of Health, Kinesiology & Applied Physiology, Concordia University, Montreal, QC, Canada; [4]Edwards Family Interdisciplinary Center for Complex Pain, Montreal Children's Hospital, Montreal, QC, Canada; [5]Department of Anesthesia and Perioperative Medicine, The University of Texas – MD Anderson Cancer Center, Houston, TX, USA; [6]Anesthesiology and Surgical Oncology Research Group, Houston, TX, USA; [7]Department of Imaging Physics, The University of Texas – MD Anderson Cancer Center, Houston, TX, USA; [8]Department of Neuroradiology, The University of Texas – MD Anderson Cancer Center, Houston, TX, USA; [9]Department of Radiology, Rehabilitation and Physiotherapy, Faculty of Nursing, Physiotherapy, and Podiatry, University Complutense of Madrid, Madrid, Spain; [10]Alan Edwards Centre for Research on Pain, McGill University, Montreal, QC, Canada; [11]Research Institute, McGill University Health Center, Montreal, QC, Canada

Correspondence: Guillermo Ceniza-Bordallo, Email gcenizaprof@gmail.com

Introduction: Pain in lower back is a common condition reported by astronauts, both during and after space missions. Investigating the alterations in the spine and the mechanisms driving these changes is essential for a deeper understanding of how microgravity impacts the human spine. This knowledge could also open pathways for therapeutic or preventive interventions. Nevertheless, there is a limited evidence regarding changes in intervertebral discs (IVDs) due to space travel.

Materials and Methods: In this study, 2 astronauts were enrolled in a space travel. Before the space flight, a lower back magnetic resonance imaging (MRI) scan was performed. We repeated an MRI instantly after 17-days space travel, and again 3 months after landing. The water content and glycosaminoglycan (GAGs) levels in the lumbar IVDs were evaluated using DIXON water-only phase imaging and T1rho MRI sequences. Additionally, alterations in the size and quality of the paraspinal muscles (PSMs), including fatty infiltration, were examined.

Results: Varied alterations were observed in the IVDs and PSMs of both astronauts. One astronaut experienced a reduction in water and GAGs content, while the other showed an increase. These changes in the IVDs following spaceflight appeared to be linked to the degree of baseline degeneration. Regarding the PSMs, differences in size and fatty infiltration also varied between the two astronauts. Notably, these changes had not stabilized by the final follow-up at 3 months.

Conclusion: Our findings offer initial evidence indicating that even brief exposures to microgravity might be linked to biochemical alterations in IVDs and changes in the quality of PSMs, which could continue evolving for more than 3 months after returning from space.

Keywords: MRI, neuroimaging, spaceflight, spine, low back pain

Introduction

Low back pain (LBP) is a widespread issue in the general population, with its occurrence rising as individuals age.[1] It is also among the most commonly reported problems by astronauts, both during space missions and following their return to Earth.[2,3] Nearly 70% of astronauts experience lower back pain within the immediate period after space flight, and 40% had chronic LBP for up to one year after flights.[2–6] Pain during spaceflight hinders the performance of tasks and scheduled activities in space missions. It increases the risk of accidents or mission failure.[7]

Exposure to microgravity eliminates the natural diurnal loading patterns typically experienced by the spine, disrupting lumbar stabilization; this results in muscle atrophy and bone loss, increasing the risk of LBP and disc injuries in astronauts.[3,8–11] Previous evidence also suggests that disc herniations are noted at an increased frequency in astronauts during this time period.[12] A growing

Received: 17 November 2024
Accepted: 12 March 2025
Published: 19 March 2025

body of literature links microgravity to unfavorable changes in the intervertebral discs (IVDs), vertebrae, and paraspinal musculature, which may partly explain these observations.[8,13–15] In a preliminary study[16] involving 2 astronauts after an Axiom Space's AX-1 commercial spaceflight with 240 orbits and 17 days of duration in the International Space Station (ISS), where we investigated the pain experience and sensory alterations associated with this spaceflight. Musculoskeletal pain was experienced by both astronauts during and after the spaceflight, which resolved within three months. However, limited information exists regarding the biochemical alterations in IVDs caused by space travel, and the impact of microgravity on spinal structures remains poorly understood. Understanding these changes and their underlying mechanisms is essential for comprehending how microgravity affects the spine and for developing effective therapeutic or preventive strategies.

Building upon our previous study, which investigated LBP in astronauts during and after spaceflight,[16] this study aimed to evaluate changes in spinal structures within the same sample. Specifically, we hypothesized that spaceflight would induce alterations in IVDs water content, affect lower back health, and lead to muscular atrophy—data that have not been previously analyzed or published.

Materials and Methods

Study Design

We conducted a longitudinal observational case series following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for observational studies.[17] We include the 2 astronauts after an Axiom Space's AX-1 commercial spaceflight with 240 orbits and 17 days of duration in the ISS, but analyzing different data that previously published.[16] The data presented here have not been published before.

Ethics and Informed Consent

This research received approval from the Institutional Review Boards of the National Aeronautics and Space Administration (NASA) (#STUDY00000403), McGill University Health Centre for Applied Ethics (#2022-7768) and the University of Texas - M.D. Anderson (#2021-1179). All study procedures were conducted in accordance with the principles outlined in the Declaration of Helsinki. Consent was obtained by the principal investigator and a research coordinator from each participant prior to their involvement in the study. Following an informed consent session in October 2021, two crew members agreed to join the study and signed the initial consent forms in December 2021, prior to the baseline assessments. In March 2022, after a modification to the protocol, both participants signed updated consent forms. Additionally, both individuals provided consent for the publication of the study results.

Participants

The participants were astronauts with no history of chronic pain, spinal surgery, or disorders affecting the peripheral nervous system. They exhibited asymptomatic degenerative changes in the lumbar spine, such as baseline IVDs herniation and facet joint degeneration. A typical day for these astronauts included 16 hours of mission activities, consisting of experiments, planning, meals, and exercise, followed by eight hours of sleep. Each astronaut was required to dedicate two hours per day to physical activity, utilizing equipment like a treadmill or stationary bicycle. Additionally, the crew members were actively involved in conducting their own experiments. During their mission, the private crew successfully completed more than 25 different research experiments on the ISS.

Data Collection Time Points

We data were collected at three time points 1) 2 weeks before the flight (T1: before-flight), 2) 2 weeks after the flight (T2: post-flight), and 3) 3 months after the flight (T3=3-month follow-up).

Variables

Lumbar IVDs Water Content

We assessed the IVDs water content using advanced MRI techniques, specifically the DIXON water-only phase and T1rho MRI sequences.[18] These sequences provide detailed information on the hydration and biochemical properties of the IVDs.[18]

The DIXON water-only phase isolates the water signal, allowing for precise water content measurement. At the same time, T1rho sequences are sensitive to proteoglycan content, which correlates with water retention in the discs.[18]

Additionally, we used T2-weighted axial images to evaluate the paraspinal muscles. These images offer high contrast resolution between different tissue types, making them ideal for assessing muscle morphology and composition, including identifying fatty infiltration and muscle atrophy.[18]

All MRI scans were uniformly acquired using the same device and standardized parameters. This consistency in imaging acquisition ensures that the data are comparable across different time points and participants, eliminating the need for intensity standardization. This methodological rigour enhances the reliability and validity of the quantitative measurements obtained from the MRI scans.[18]

Evaluation of the Composition and Structure of the Discs

We assessed the composition and structure of the IVDs using advanced imaging techniques. Using different MRI sequences, we measured the mean signal intensity, which is indicative of the discs' biochemical and structural properties.

For Dixon sagittal imaging, the mean signal intensity was measured for seven IVDs in the thoracolumbar spine (T11/12 to L5/S1). This measurement was conducted across nine consecutive slices centred around the middle of each disc, using manually generated regions of interest (ROIs). These ROIs allow for precise targeting of the disc area, ensuring that the measurements accurately reflect the disc's condition.[19] The mean signal intensity from the nine slices was averaged to provide a representative value for each disc.[19]

For Dixon axial imaging, the mean signal intensity was measured for the five IVDs in the lumbar spine (L1/L2 to L5/S1). This process involved six consecutive slices centred around the midpoint between the two adjacent vertebrae. ROIs were manually drawn to capture the relevant disc area.[19] The final signal intensity for each disc was averaged from the six measurements. These measurements were repeated at two time points: pre-flight (T1) and post-flight (T2). Unfortunately, the quality of the axial Dixon images at T3 (three months post-flight) was insufficient for quantitative analysis, preventing a third data point.

For T1rho sagittal imaging, the mean signal intensity and standard deviation were derived from manually drawn ROIs of seven IVDs (T11/12 to L5/S1) of the lumbar spine.[19] This involved scanning nine slices centred around the midline of each disc, with the signal from all nine slices averaged to produce a representative value for each disc. Similar to the Dixon axial imaging, the T1rho images were missing for T3 (three months post-flight), so quantification was only possible for the pre-flight (T1) and post-flight (T2) time points.[19]

The Degree of Intervertebral Disc Degeneration

We used the Pfirrmann grading system to evaluate IVDs degeneration.[20] This system is a widely recognized and validated tool for assessing the degree of disc degeneration based on MRI criteria.[20] The Pfirrmann grading system considers several factors,[18] including disc structure, differentiation between the nucleus pulposus and the annulus fibrosus, disc signal on MRI images, and disc height. This system classifies disc degeneration on a five-grade scale, from a normal, healthy disc (Grade I), to a disc with a total loss of signal and nucleus pulposus structure (Grade V) 18. We evaluated the participants' IVDs using this scale at different time points: pre-flight (T1), immediate post-flight (T2), and three months post-flight (T3).

We used the Pfirrmann grading system to assess degenerative changes in IVDs over time.[18]

Muscle Atrophy

We quantitatively evaluated the multifidus, erector spinae, psoas, and quadratus lumborum muscles using the T2-weighted axial MR images. After performing multiplanar reconstruction (3D MPR) with Horos software,[21] we used the ImageJ software to position the image slices perpendicular to the muscle mass accurately. We obtained bilateral paraspinal muscle measurements at the mid-disc level across all lumbar vertebrae (L1-L2 to L5-S1). The key measurements included the cross-sectional area (CSA) and the ratio of functional CSA (FCSA, fat-free mass) to CSA (1 - FCSA/CSA), which serves as an indicator of muscle composition, particularly fatty infiltration.[15,22]

Statistics

We used paired t-tests to evaluate the differences in averaged percentage differences among IVDs signals before and after spaceflight using DIXON and T1-rho modalities. We chose this statistical test due to the paired nature of the data, allowing for the assessment of within-subject changes over the spaceflight period. We presented the data as means ± standard deviations (S.D.) for the percentage differences. The results were considered statistically significant when p-values were less than 0.05. We conducted the statistical analyses using GraphPad Prism version 10.3.0 23.[29]

Results

The participants (astronaut 01 and astronaut 02) were healthy male astronauts of 53 and 64 years of age. They had no history of chronic pain or spinal surgery, nor did they present a history of peripheral nervous system disorder. However, both astronauts showed asymptomatic degenerative changes on the lumbar spine, including baseline IVDs herniation and facet joint degeneration.

IVDs Water Content

The DIXON phase revealed variability in IVDs water content between the three time points for the first astronaut. In aggregate, there was no difference between pre- and post-flight images. However, a trend suggests that lower lumbar discs (L3/L4 to L5/S1) might have lost water content. We identified an opposite trend in the lower thoracic region (T11/T12 to T12/L1). Of note, all discs lost water signal intensity at the 3-month timepoint post-flight compared to post-flight images.

For astronaut 02, the DIXON phase increases between the three time points except in L5/S1, which shows a slight signal loss three months post-flight. Remarkably, the disc showed continued progressive increases in disc hydration at all time points, suggesting that these changes may continue beyond three months.

Composition and Structure of the Discs

Axial DIXON MRI

Astronaut 01: The axial DIXON water-only images from astronaut one show that lumbar IVDs overall gained signal intensity after space travel. The discs gained about 64% signal intensity post-flight (Figure 1).

Astronaut 02: Like the first individual, the signal for the DIXON water-only phase gained intensity for most discs in the axial images at the post-flight time point. Compared with the sagittal analysis, the lowest lumbar disc showed negligible change between the two time points. Overall, signal intensity increased by 20% after spaceflight across all discs measured (Figure 2).

T1-Rho Sagittal Imaging

Astronaut 01: T1rho signal intensity measurements for astronaut 01 revealed slight-to-moderate increases in water content in all discs analyzed. When compounded, we found a significant 15% increase in signal strength across all discs (Figure 3).

Astronaut 02: T1-rho signal intensity measurements for astronaut 02 revealed comparable slight-to-moderate increases in water content in all discs analyzed. When compounded, we found a significant 10% increase in signal strength across all discs (Figure 4).

The Degree of IVDs Degeneration

To analyze whether the disc water content trajectory depends on its initial state pre-flight, we segregated all discs analyzed from both astronauts into degenerated and non-degenerated subgroups using the Pfirrmann grading system.[18] While the changes from pre-flight to 3 months post-flight are not clinically significant, we can appreciate a trend of signal gain in the degenerated IVDs group compared to the non-degenerated.

Muscle Atrophy

Observed changes in paraspinal muscle were not consistent between both astronauts, as astronaut 01 showed a minor decrease in multifidus and erector spinae CSA only caudally (L4-5 and L5-S1) immediately post-flight, which recovered

 https://doi.org/10.2147/JPR.S492600

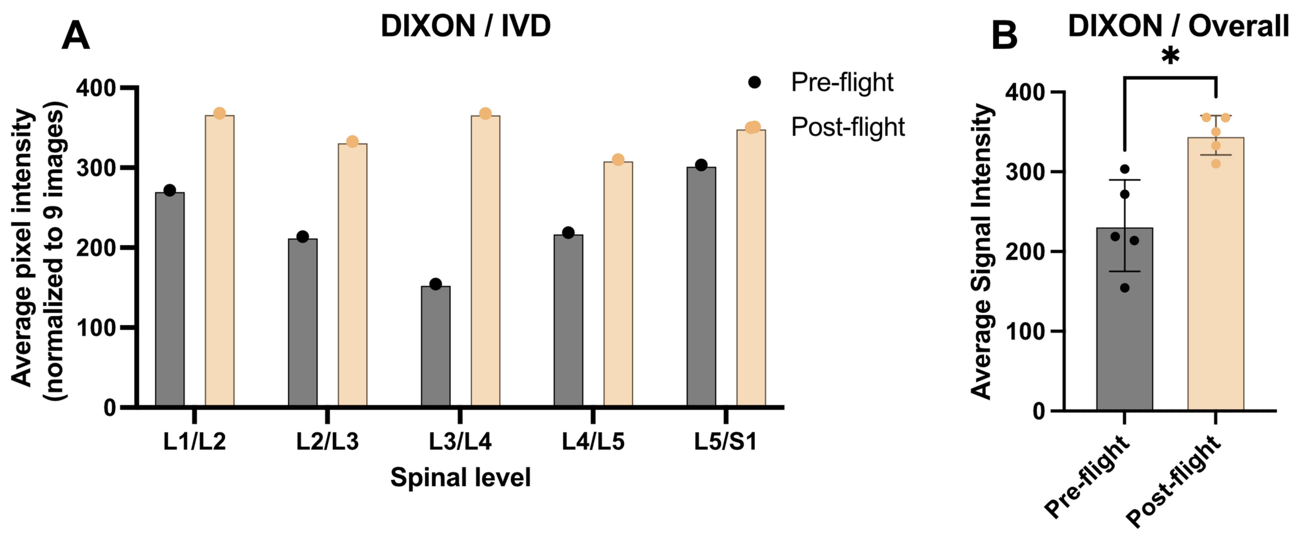

Figure 1 Comparison of Average Signal Intensity in DIXON Images of Intervertebral Discs at Different Spinal Levels Before and After Spaceflight, including the comparison of signal intensity across various spinal levels (L1/L2 to L5/S1) before and after spaceflight, as shown by the gray and beige bars in the graphs (**A** and **B**) in Astronaut 1 Graph (**A**) Shows the average pixel intensity in DIXON images of the intervertebral discs (IVD) at five different spinal levels (L1/L2, L2/L3, L3/L4, L4/L5, L5/S1). It compares the intensity before (pre-flight, gray bars) and after spaceflight (post-flight, beige bars). Graph (**B**) Presents the overall average signal intensity in DIXON images across all spinal levels combined, also comparing before and after spaceflight. An asterisk (*) is shown here, which typically indicates a statistically significant difference between the two.

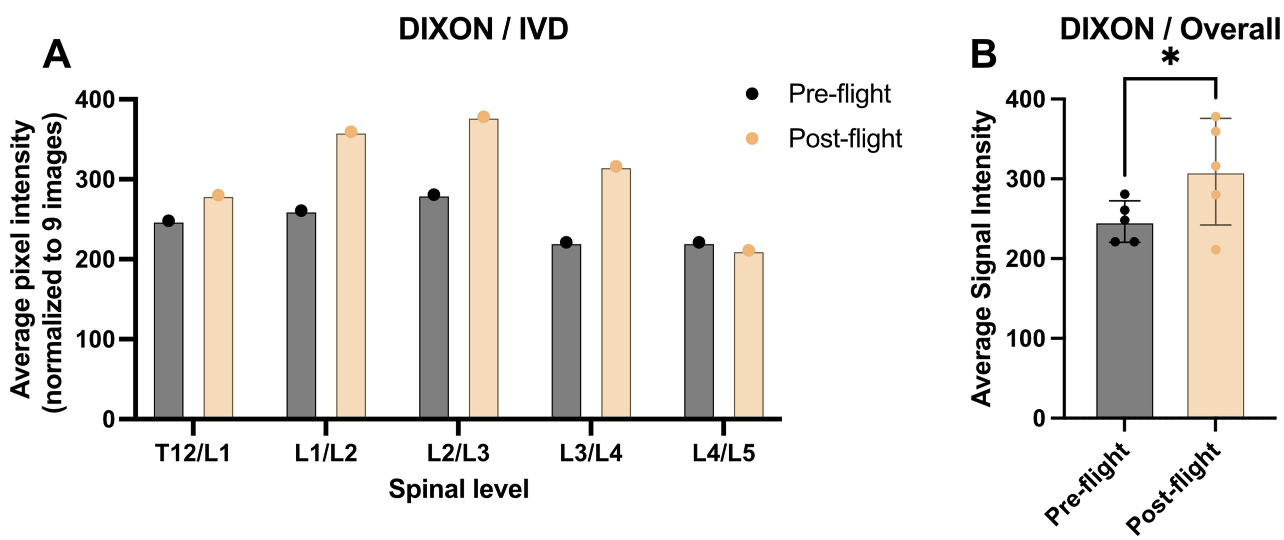

Figure 2 Comparison of Average Signal Intensity in DIXON Images of Intervertebral Discs at Different Spinal Levels Before and After Spaceflight, including the comparison of signal intensity across various spinal levels (L1/L2 to L5/S1) before and after spaceflight, as shown by the gray and beige bars in the graphs (**A** and **B**) in Astronaut 2 Graph (**A**) Shows the average pixel intensity in DIXON images of the intervertebral discs (IVD) at five different spinal levels (L1/L2, L2/L3, L3/L4, L4/L5, L5/S1). It compares the intensity before (pre-flight, gray bars) and after spaceflight (post-flight, beige bars). Graph (**B**) Presents the overall average signal intensity in DIXON images across all spinal levels combined, also comparing before and after spaceflight. An asterisk (*) is shown here, which typically indicates a statistically significant difference between the two.

to baseline at the three-month time point. However, when looking at paraspinal fatty infiltration, we found a consistent increase in almost all the levels (Figure 5).

Astronaut 02 showed a more noticeable reduction in multifidus and erector spinae CSA. An increase in fatty infiltration was only observed for the multifidus in astronaut 02, with no appreciable effect on the erector spinae (Figure 6).

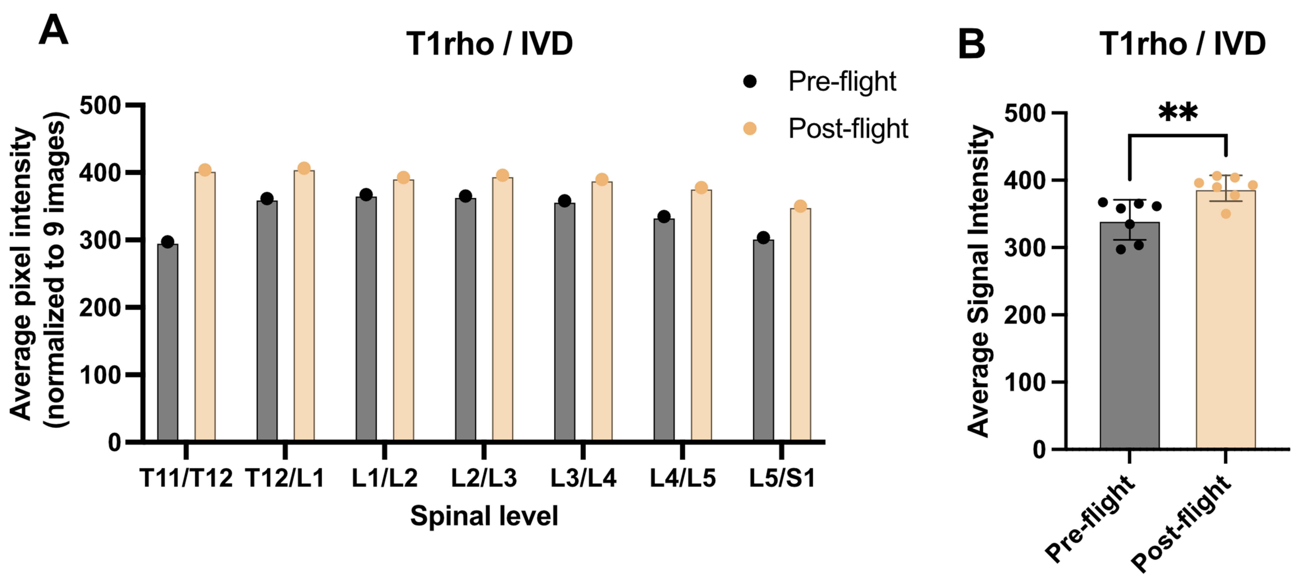

Figure 3 Comparison of Average Signal Intensity in T1 rho Images of Intervertebral Discs at Different Spinal Levels Before and After Spaceflight, including the comparison of signal intensity across various spinal levels (L1/L2 to L5/S1) before and after spaceflight, as shown by the gray and beige bars in the graphs (**A** and **B**) in Astronaut 1. Asterisks (**) is shown here, which typically indicates a statistically significant difference between the two.

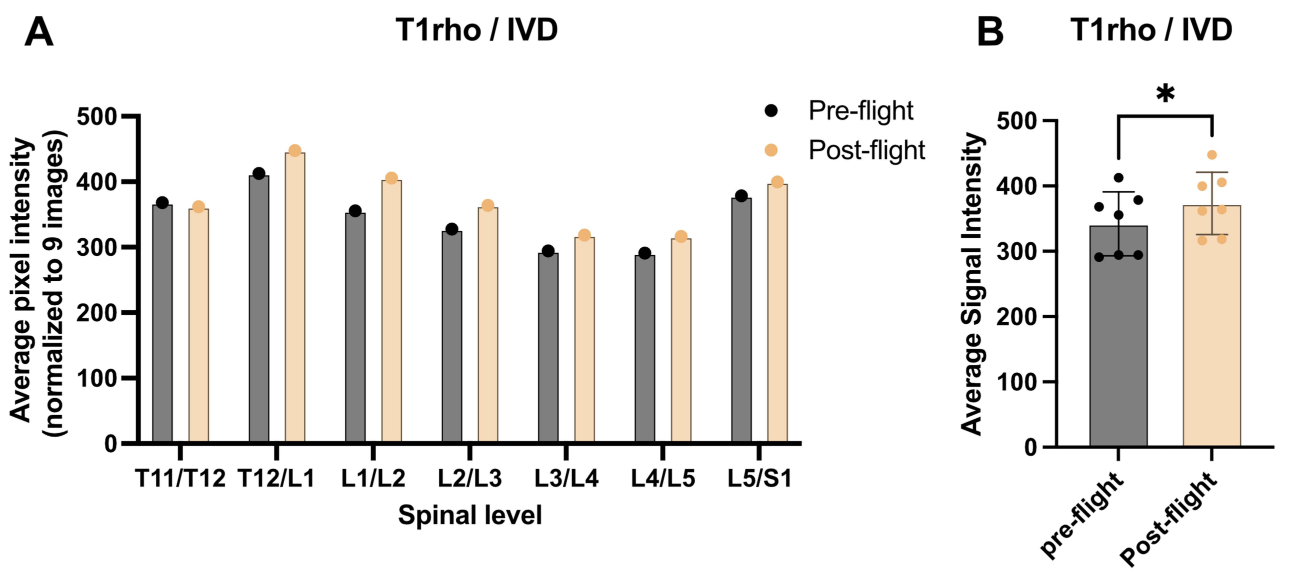

Figure 4 Comparison of Average Signal Intensity in T1 rho Images of Intervertebral Discs at Different Spinal Levels Before and After Spaceflight, including the comparison of signal intensity across various spinal levels (L1/L2 to L5/S1) before and after spaceflight, as shown by the gray and beige bars in the graphs (**A** and **B**) in Astronaut 2. An asterisk (*) is shown here, which typically indicates a statistically significant difference between the two.

Discussion

This study presents the imaging findings of two astronauts who participated in a 17-day space mission.[16] Imaging and associated clinical findings up to three months postflight are presented, including advanced MRI sequences for the first time. We provide a descriptive account of our observations and place it within the greater context of the known literature.[3,15] This work presents preliminary evidence suggesting that short-term space travel may result in changes in the vertebral column and paraspinal musculature extending to at least the third month post-spaceflight period, similar changes have been shown in previous studies with limited samples.[3]

The IVDs are composed of a central, gel-like nucleus pulposus (NP) encased by a robust, fibrous outer ring known as the annulus fibrosus. Between the adjacent bony vertebral endplates and these structures lie the cartilaginous endplates

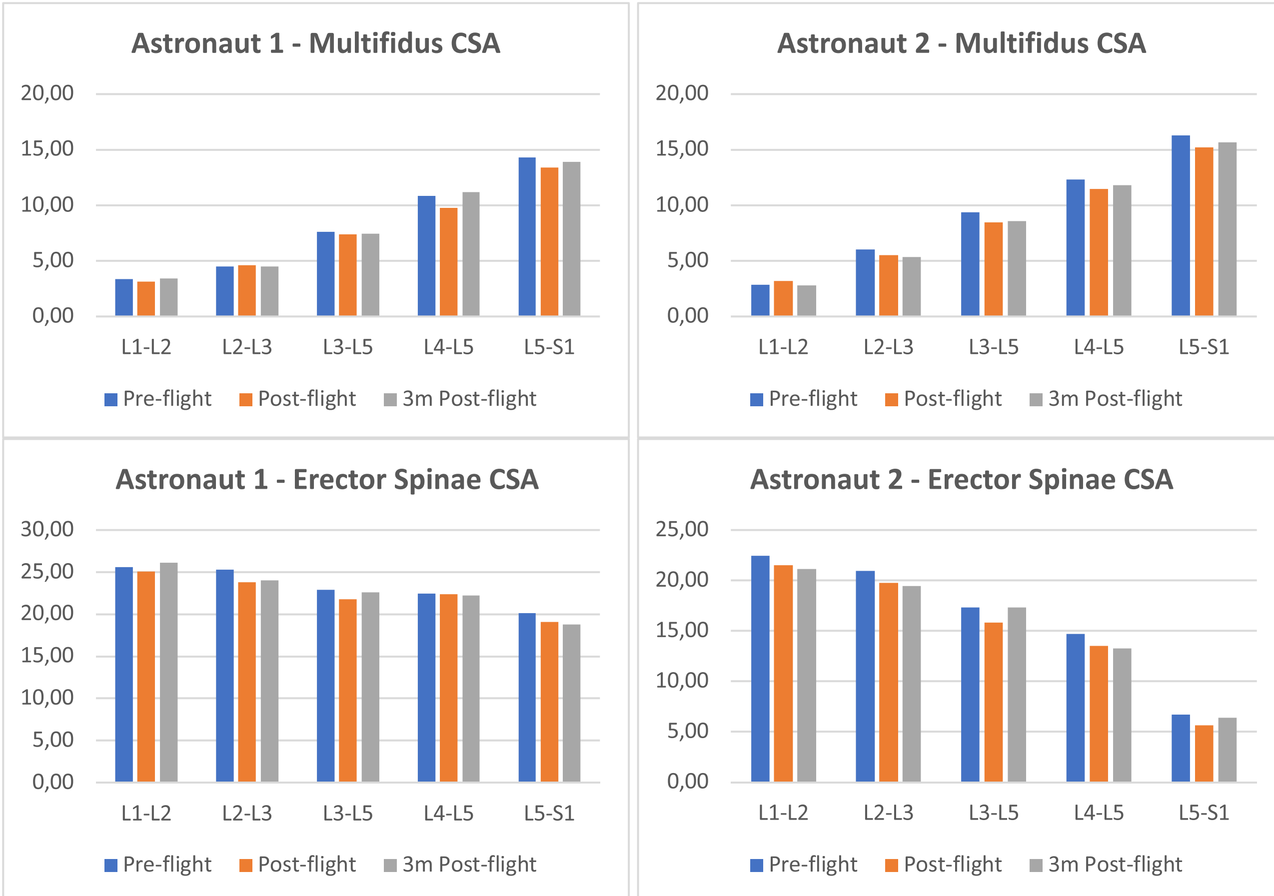

Figure 5 Multifidus and erector spinae muscles cross-sectional area (CSA) measurements at each time point and spinal level (eg, average of right and left sides).

controlling the diffusion of water, nutrients, and metabolites between the systemic circulation and the disc.[8] The hydrophilic glycosaminoglycans in the NP draw water in and maintain its turgor.[8] This osmotic force is balanced by the hydrostatic pressure exerted by the body weight and the resistance of the annulus to further swelling.[8] Microgravity negates this hydrostatic pressure and allows the ingress of more water than average into the disc.[5,8,11–14] This increases NP volume and exerts further tension on the annulus. Disc distension is believed to underlie the pain experienced by astronauts and explain the increased incidence of disc herniation following spaceflight.[5,8,11–14] However, supraphysiologic NP hydration caused by microgravity, similar to bed rest, is believed to be rapidly reversed upon axial loading under gravity.[15] This helps explain the inconsistent findings between studies assessing IVDs water content in astronauts returning from space missions, as results are influenced by the interval between their return and subsequent imaging.[15]

In our study, we evaluate with advanced MRI sequences both water changes (DIXON) and GAG content (T1rho) in the lumbar IVDs of two individuals after spaceflight. We observed that most lumbar discs modestly gained signal intensity immediately postflight. However, a significant difference between the two astronauts lies in the three-month postflight follow-up. While astronaut 01's discs saw an overall decreased signal intensity during follow-up, the opposite was observed for astronaut 02 despite identical exposure to microgravity and similar imaging protocols and timings. However, pre-existing baseline differences in IVDs state pre-flight were observed between the two participants.

More precisely, the baseline grade of lumbar IVDs degeneration was more advanced in astronaut 02 compared to 01. This suggests that degenerated discs are more susceptible to water ingress in weightlessness. This is biologically plausible, as disc degeneration is characterized by progressive incompetence of the annulus, allowing for more distension of the IVDs at similar pressures.[7,8,11–13,15,23] In addition, degeneration of the cartilaginous endplate may result in either ossification and impaired diffusion or fissuring and increased passage of solutes into the IVDs.[13] If we couple this with

https://doi.org/10.2147/JPR.S492600

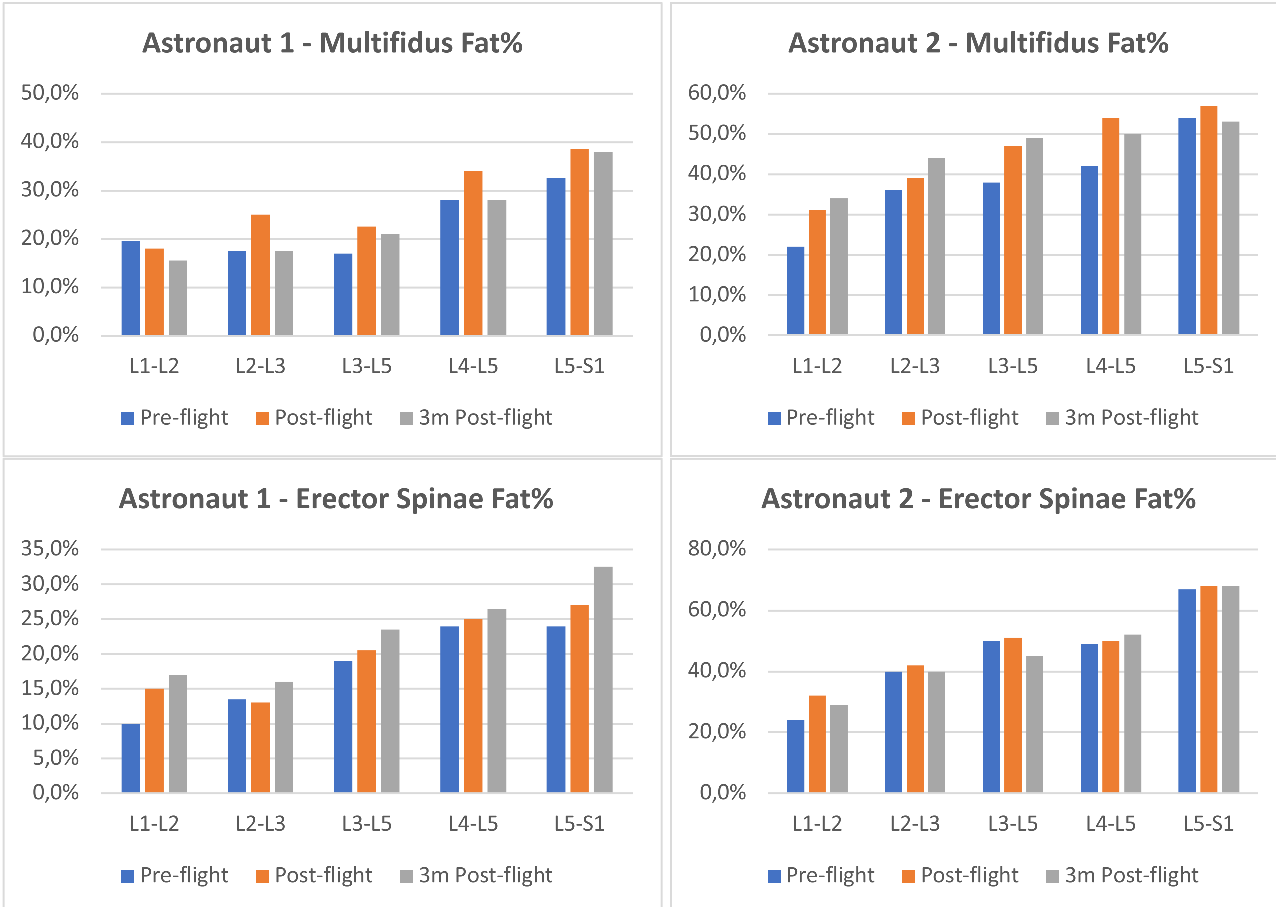

Figure 6 Multifidus and erector spinae muscles fat% measurements at each time points and spinal level (eg, average of right and left sides).

the observed ingrowth of nociceptive nerve fibres into the IVDs with degeneration, we can better explain the variability of clinical and imaging observations between subjects and between discs within the same subjects.[12,13,15,22,24] The heterogeneity in effect based on the degree of degeneration demonstrates the need to segregate analysis results accordingly. It explains variation in results between studies, as some have shown no relation between space flight and IVDs water content.[12] Should this observation be reproduced, we can use it as a risk stratification to offer space tourists better-tailored informed consent. A disc herniation can have catastrophic consequences, and some patients may opt out in the presence of significant asymptomatic disease.

One of the most noteworthy findings of this study is the presence of muscular atrophy three months post-flight, suggesting prolonged alterations in the lumbar musculature beyond the immediate post-flight period, which did not recover at three months postflight. This aligns with previous evidence[3] indicating that spinal unloading during spaceflight leads to significant muscle deconditioning. However, few studies have systematically examined the extent of these changes beyond the acute recovery phase.

Our findings complement the work of Ceniza-Bordallo et al (2024),[3] which explored the relationship between spinal adaptations and low back pain in astronauts, highlighting that musculoskeletal alterations may persist well beyond re-entry. While changes affect the size and the quality of the muscle tissue, the effect appeared to be heterogeneous, with differences between astronauts, muscle groups, and levels. This finding warrants further research into the matter, as others have shown these changes reversed at two months post-space flight.[25–27] Notably, paraspinal muscle degenerative changes may predispose to disc herniations.[8,15].

The observed atrophy at three months post-flight suggests that recovery mechanisms might be slower than previously assumed, emphasizing the need for targeted rehabilitation strategies tailored to prolonged spinal muscle deconditioning.[26]

 https://doi.org/10.2147/JPR.S492600

Moreover, these findings underscore the importance of implementing interventions aimed at preventing muscular atrophy not only post-flight but also before and during space missions. Pre-flight conditioning programs, in-flight resistance training, and optimized post-flight rehabilitation protocols should be prioritized to mitigate these structural changes and preserve musculoskeletal integrity. Future research should investigate whether such atrophy is fully reversible with specific countermeasures and how it relates to functional impairments or pain over extended follow-up periods.

Limitations & Recommendations for Future Research

This study provides preliminary evidence of structural changes in the vertebral column and paraspinal musculature following short-term spaceflight, with findings extending up to three months post-flight. However, given the small sample size and the heterogeneity observed between participants, further research is needed to validate and expand upon these observations. Expanding the sample size and incorporating long-term follow-ups beyond three months post-flight will be essential to determine the persistence and reversibility of both IVD changes and muscular atrophy.

Given that some studies have reported reversal of spinal adaptations within two months, additional timepoints will help establish a clearer timeline of recovery. Our findings suggest that pre-existing disc degeneration may influence the response to microgravity, particularly in terms of water ingress and post-flight recovery. Future research should investigate how different degrees of baseline degeneration affect IVD adaptations in space, as this could help refine risk stratification for astronauts and space tourists, potentially guiding individualized countermeasures.

Additionally, due to the participants' tight scheduling, we could not control the time of day at which the MRI acquisitions were made. Literature shows that the height and hydration of IVDs on Earth change throughout the day. Therefore, the timing of image acquisition should be standardized across participants and time points to ensure consistent results.

Unlike similar studies, we relied on MRI alone and did not perform dynamic fluoroscopy or CT imaging. As such, we cannot comment on changes in bone quality or segmental mobility, which may also be relevant. We also only completed follow-ups three months after the flight, at which point these changes continued progressing and had yet to stabilize.

One important limitation of this study is the use of the Pfirrmann classification to assess intervertebral disc degeneration. While this system is widely used and facilitates comparisons with previous studies, it has been criticized for its limited precision and high intra- and inter-observer variability. More detailed and discriminative systems, such as the recently proposed classification by Soydan et al (2024),[28] may provide greater accuracy in evaluating disc degeneration.

We recommend future studies consider adopting this innovative classification to enhance the granularity and reliability of imaging analyses. This approach could help uncover subtle structural and biochemical changes in intervertebral discs and their relationship with clinical outcomes, thereby advancing our understanding of spinal adaptations in various contexts, including spaceflight.

While our study provides structural imaging findings, further research should integrate clinical assessments of pain and disability. The observed heterogeneity in post-flight muscle atrophy and IVD hydration suggests that individual differences may contribute to variations in symptoms. Future studies should explore whether these structural changes translate into functional impairments and pain, as previously suggested by Ceniza-Bordallo et al (2024).[3]

The persistence of paraspinal muscle atrophy at three months post-flight highlights the need for more effective in-flight and post-flight rehabilitation strategies. Future research should explore novel exercise interventions, nutritional strategies, and potential pharmacological approaches to prevent or mitigate spinal muscle atrophy during extended missions. Understanding the specific mechanisms driving atrophy and delayed recovery will be critical for designing targeted interventions.

As commercial space travel expands, risk assessment for non-professional astronauts becomes increasingly relevant. If IVD hydration changes and muscular atrophy are more pronounced in individuals with pre-existing degeneration, screening protocols and personalized conditioning programs may be necessary to ensure safe spaceflight experiences.

By addressing these research gaps, future studies can provide a more comprehensive understanding of the long-term effects of spaceflight on spinal health and contribute to the development of targeted strategies to protect astronauts and space travelers from potential musculoskeletal complications.

Conclusion

This work adds to the growing body of evidence showing a deleterious effect of even short periods of space travel on myogenic and disc changes in the lumbar spine. Notably, we provide preliminary evidence to suggest that microgravity may exacerbate degenerative processes in IVDs by altering their biochemical composition and structure. The observed heterogeneity in the response of the spine to microgravity, particularly in terms of water ingress and signal intensity changes in degenerated discs, underscores the potential vulnerability of pre-existing degenerative IVDs to the unique environment of space. Degenerated discs, characterized by compromised annulus fibrosus integrity and altered endplate permeability, may be more prone to further distension and biochemical imbalance under microgravity, as our findings suggest. Additionally, the degeneration of PSMs observed in this study, which includes atrophy and likely fatty infiltration, may contribute to the destabilization of the lumbar spine, further predisposing astronauts to mechanical dysfunction and disc herniation. These changes, extending at least three months post-flight, highlight the need for a deeper understanding of how degeneration interacts with microgravity-induced biomechanical stresses.

Our findings also suggest that such changes may continue to progress beyond the acute recovery phase and may vary significantly among individuals. Future research should aim to identify factors such as age, baseline degeneration, and individual biomechanics that may increase the spine's susceptibility to microgravity, with the goal of developing tailored interventions to mitigate the risk of lumbar spine degeneration in astronauts.

Abbreviations

LBP, Low back pain; MRI, Magnetic Resonance Imaging; CSA, Cross-sectional area; FCSA, Functional cross-sectional area; ISS, International Space Station; IVDs, Intervertebral discs; GAG, Glycosaminoglycan; PSM, Paraspinal muscle size; STROBE, STrengthening the Reporting of OBservational studies in Epidemiology guidelines to observational studies; ROIs, Regions of interest; NP, Nucleus pulposus.

Acknowledgments

The academic and research activities of Dr Ingelmo are supported by the Louise and Alan Edwards Family Foundation and the Montreal Children's Hospital Foundation. The Montreal Children's Hospital Foundation founded the project Pain in Space with a special donation.

Guillermo Ceniza-Bordallo was funded with a postdoctoral fellowship by the doctoral program in health care of the Faculty of Nursing, Physiotherapy and Podiatry of the Complutense University of Madrid and Banco Santander (CT58/21-CT59/21).

We thank Maggie Fung and Michael Carl at GE Healthcare for providing the T1 Rho sequence. We also appreciate the additional technical assistance provided by Ari Borthakur at the University of Pennsylvania.

Funding

This work was supported by the Montreal Children's Hospital Foundation. Guillermo Ceniza-Bordallo was funded with a postdoctoral fellowship by the doctoral program in health care of the Faculty of Nursing, Physiotherapy and Podiatry of the Complutense University of Madrid and Banco Santander (CT58/21-CT59/21).

Disclosure

Dr Ken-Pin Hwang reports non-financial support from GE Healthcare, during the conduct of the study; grants from GE Healthcare, grants from Siemens Healthineers, outside the submitted work. Dr Jean Ouellet reports Fellowship funding from AO foundation, outside the submitted work. The authors report no conflicts of interest related to this work.

References

1. Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: a systematic analysis for the global burden of disease study 2019. *Lancet*. 2020;396(10258):1204–1222. doi:10.1016/s0140-6736(20)30925-9
2. Wing PC, Tsang IK, Susak L, Gagnon F, Gagnon R, Potts JE. Back pain and spinal changes in microgravity. *Orthop Clin North Am*. 1991;22(2):255–262. doi:10.1016/S0030-5898(20)31651-5

3. Ceniza-Bordallo G, Zimmermann E, Vigouroux M, et al. Low back pain during and after spaceflight: a systematic review with meta-analysis. *J Pain Res*. 2024;17:4103–4139. doi:10.2147/JPR.S491060
4. Sayson JV, Hargens AR. Pathophysiology of low back pain during exposure to microgravity. *Aviat Space Environ Med Apr*. 2008;79(4):365–373. doi:10.3357/asem.1994.2008
5. Kerstman EL, Scheuring RA, Barnes MG, DeKorse TB, Saile LG. Space adaptation back pain: a retrospective study. *Aviat Space Environ Med*. 2012;83(1):2–7. doi:10.3357/asem.2876.2012
6. Styf JR, Hutchinson K, Carlsson SG, Hargens AR. Depression, mood state, and back pain during microgravity simulated by bed rest. *Psychosom Med*. 2001;63(6):862–864. doi:10.1097/00006842-200111000-00002
7. Pool-Goudzwaard AL, Belavý DL, Hides JA, Richardson CA, Snijders CJ. Low back pain in microgravity and bed rest studies. *Aerosp Med Hum Perform*. 2015;86(6):541–547. doi:10.3357/amhp.4169.2015
8. Chang DG, Healey RM, Snyder AJ, et al. Lumbar spine paraspinal muscle and intervertebral disc height changes in astronauts after long-duration spaceflight on the international space station. *Spine*. 2016;41(24):1917–1924. doi:10.1097/brs.0000000000001873
9. Shackelford L. *Principles of Clinical Medicine for Space Flight*. Springer New York; 2019.
10. Fritsch-Yelle JM, Charles JB, Jones MM, Wood ML. Microgravity decreases heart rate and arterial pressure in humans. *J Appl Physiol*. 1996;80(3):910–914. doi:10.1152/jappl.1996.80.3.910
11. Paul AM, Mhatre SD, Cekanaviciute E, et al. Neutrophil-to-lymphocyte ratio: a biomarker to monitor the immune status of astronauts. *Front Immunol*. 2020;11:564950. doi:10.3389/fimmu.2020.564950
12. Johnston SL, Campbell MR, Scheuring R, Feiveson AH. Risk of herniated nucleus pulposus among U.S. astronauts. *Aviat Space Environ Med*. 2010;81(6):566–574. doi:10.3357/asem.2427.2010
13. Bailey JF, Hargens AR, Cheng KK, Lotz JC. Effect of microgravity on the biomechanical properties of lumbar and caudal intervertebral discs in mice. *J Biomech*. 2014;47(12):2983–2988. doi:10.1016/j.jbiomech.2014.07.005
14. Bailey JF, Miller SL, Khieu K, et al. From the international space station to the clinic: how prolonged unloading may disrupt lumbar spine stability. *Spine J*. 2018;18(1):7–14. doi:10.1016/j.spinee.2017.08.261
15. Bailey JF, Nyayapati P, Johnson GTA, et al. Biomechanical changes in the lumbar spine following spaceflight and factors associated with postspaceflight disc herniation. *Spine J*. 2022;22(2):197–206. doi:10.1016/j.spinee.2021.07.021
16. Sauer AK, Vigouroux M, Dougherty PM, Cata JP, Ingelmo PM. Pain experience and sensory changes in astronauts during and after short-lasting commercial spaceflight: a proof-of-concept study. *J Pain Res*. 2023;16:4253–4266. doi:10.2147/JPR.S440630
17. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The strengthening the reporting of observational studies in epidemiology (STROBE) statement: guidelines for reporting observational studies. *PLoS Med*. 2007;4(10):e296. doi:10.1371/journal.pmed.0040296
18. Pfirrmann CW, Metzdorf A, Zanetti M, Hodler J, Boos N. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine*. 2001;26(17):1873–1878. doi:10.1097/00007632-200109010-00011
19. Sollmann N, Mönch S, Riederer I, Zimmer C, Baum T, Kirschke JS. Imaging of the degenerative spine using a sagittal T2-weighted DIXON turbo spin-echo sequence. *Eur J Radiol*. 2020;131:109204. doi:10.1016/j.ejrad.2020.109204
20. Grant MP, Epure LM, Bokhari R, Roughley P, Antoniou J, Mwale F. Human cartilaginous endplate degeneration is induced by calcium and the extracellular calcium-sensing receptor in the intervertebral disc. *Eur Cell Mater*. 2016;32:137–151. doi:10.22203/ecm.v032a09
21. Horos. Horos project 2024. Available from: https://horosproject.org/. Accessed March 12, 2025.
22. LeBlanc A, Schneider V, Shackelford L, et al. Bone mineral and lean tissue loss after long duration space flight. *J Musculoskelet Neuronal Interact*. 2000;1(2):157–160.
23. Lee SU, Hargens AR, Fredericson M, Lang PK. Lumbar spine disc heights and curvature: upright posture vs. supine compression harness. *Aviat Space Environ Med*. 2003;74(5):512–516.
24. Mulligan KR, Ferland CE, Gawri R, Borthakur A, Haglund L, Ouellet JA. Axial T1ρ MRI as a diagnostic imaging modality to quantify proteoglycan concentration in degenerative disc disease. *Eur Spine J*. 2015;24(11):2395–2401. doi:10.1007/s00586-014-3582-6
25. Hides JA, Lambrecht G, Stanton WR, Damann V. Changes in multifidus and abdominal muscle size in response to microgravity: possible implications for low back pain research. *Eur Spine J*. 2016;25(Suppl 1):175–182. doi:10.1007/s00586-015-4311-5
26. Hides JA, Lambrecht G, Sexton CT, et al. The effects of exposure to microgravity and reconditioning of the lumbar multifidus and anterolateral abdominal muscles: implications for people with LBP. *Spine J*. 2021;21(3):477–491. doi:10.1016/j.spinee.2020.09.006
27. Lee PHU, Chung M, Ren Z, Mair DB, Kim DH. Factors mediating spaceflight-induced skeletal muscle atrophy. *Am J Physiol Cell Physiol*. 2022;322(3):C567–c580. doi:10.1152/ajpcell.00203.2021
28. Soydan Z, Bayramoglu E, Urut DU, Iplikcioglu AC, Sen C. Tracing the disc: the novel qualitative morphometric MRI based disc degeneration classification system. *JOR Spine*. 2024;7(1):e1321. doi:10.1002/jsp2.1321
29. 2024GraphPad Software. 2024.