ANESTHESIOLOGY

Back Pain in Outer Space

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ABSTRACT

Space travel has grown during the past 2 decades, and is expected to surge in the future with the establishment of an American Space Force, businesses specializing in commercial space travel, and National Aeronautics and Space Administration's planned sustained presence on the moon. Accompanying this rise, treating physicians are bracing for a concomitant increase in space-related medical problems, including back pain. Back pain is highly prevalent in astronauts and space travelers, with most cases being transient and self-limiting (space adaptation back pain). Pathophysiologic changes that affect the spine occur during space travel and may be attributed to microgravity, rapid acceleration and deceleration, and increased radiation. These include a loss of spinal curvature, spinal muscle atrophy, a higher rate of disc herniation, decreased proteoglycan and collagen content in intervertebral discs, and a reduction in bone density that may predispose people to vertebral endplate fractures. In this article, the authors discuss epidemiology, pathophysiology, prevention, treatment, and future research.

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Space has captivated humanity for millennia. Since the first lunar landing by Apollo XI astronauts, more than 72 countries now have space programs, with more than a dozen having the capability to send objects or people into space. In the future, human space travel is expected to surge with several companies now offering paid space excursions and the establishment of the U.S. Space Force on December 20, 2019, marking the 50th anniversary of the first lunar landing.

Around half a dozen people (but up to 11 for shorter time periods) typically live on the International Space Station which orbits the earth about every 90 min from a mean radius of 254 statute miles, for an average of 4 to 6 months. By 2028, the National Aeronautics and Space Administration (Houston, Texas) plans to have a sustained presence on the moon, which could be used not only for research purposes, but also possibly for intelligence, defense, a bulwark against terrestrial catastrophes, resources, and as a staging point for manned missions to Mars and elsewhere.[1]

In the history of man, fewer than 550 people have traveled to space, with only 24 traveling beyond low earth orbit and only 12 walking on the moon. Therefore, the issue of spinal pain during space travel affects only a tiny fraction of the population, and most physicians will never meet—let alone treat—anyone who has traveled to space. Yet, understanding the epidemiology, causes, and potential treatments for spinal pain in astronauts has the potential to improve care for other populations (*e.g.*, deep sea divers, fighter pilots, people who live at high altitudes, and researchers and explorers in austere settings). In this article, we review the epidemiology, pathophysiology, unique treatment considerations, possible preventative measures, and avenues for future research for low back pain during space travel.

Pathophysiological Effects of Space Environment on Spinal Health

Space travel (defined by crossing the Federation Aeronautique Internationale's [Lausanne, Switzerland] Kármán line of 62 miles or 100 km above Earth's mean sea level) and exposure to microgravity have been linked to lasting transient anatomical and physiologic changes of the spinal column and surrounding musculature (fig. 1), which play a role in spinal pain. Data from the earliest explorations in microgravity demonstrated that astronauts gain up to 3.1 inches of height in the first 9 days in space.[2,3] In parallel, magnetic resonance imaging of the spine pre- and postflight after 6 months in astronauts aboard the International Space Station demonstrated a statistically significant decrease in lumbar lordosis.[4] This was associated with decreased active flexion and extension of the lumbar spine by as much as 30%, as well as a 20% decrease in the functional cross-sectional area of the multifidus muscle, which plays a key role in maintaining lumbar spine stability.[4] These changes occurred despite astronauts following International Space Station exercise protocols in space.[4] Data from rats[5] and rabbits[6] flown to space revealed a reduction in proteoglycan and collagen content in intervertebral discs. A decrease in proteoglycans has been linked to dehydration, aging, and decreased ability of the intervertebral discs to sustain mechanical stress in humans.[7] There is some evidence that

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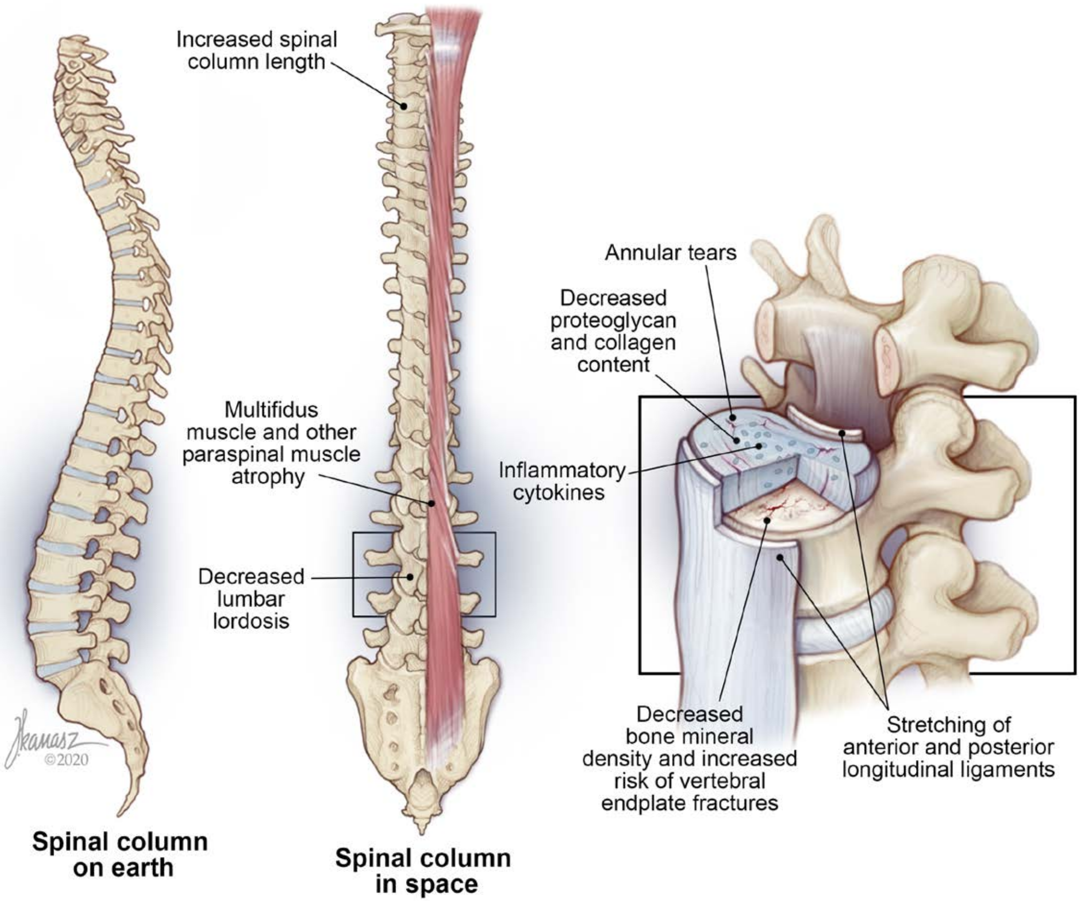

Fig. 1. Pathophysiologic effects of space travel on spinal health.

microgravity may predispose space travelers to vertebral endplate fractures, which can either directly cause pain or result in the introduction of inflammatory cytokines into discs, which may result in pain when these cytokines come into contact with nerve endings.[8] Anecdotally, comparison of clinically indicated pre- and postflight lumbar spine magnetic resonance imaging studies has revealed new and worsening posterolateral annular fissures, sometimes lasting months until treatment (*i.e.,* with epidural steroid injections) after return from space (personal communication from R.A.S.). In addition, the bone mineral density of the spinal column decreases by about 1% per month during space travel[9] in the absence of preventive measures.[10]

Apart from microgravity, astronauts are exposed to excess radiation from cosmic and solar sources in space.[11] Mice exposed to a radiation dose similar to that of galactic cosmic rays demonstrated compromised trabecular and cortical bone.[12] Irradiation of skeletal muscle decreases adaptation to and inhibits recovery from overload (fig. 1).[12]

Given the pathophysiologic musculoskeletal changes of the spinal column during space travel, it is not surprising that the incidence of herniated intervertebral discs in astronauts was 4.3 times higher than matched controls in a study that followed 983 astronauts during 50 yr.[13] This risk was not attributable to previous exposure to high acceleration or vibratory forces (*i.e.,* astronauts with jet pilot or rotary wing experience had a similar incidence of disc herniation compared to nonpilot control patients).[13] Furthermore, the risk of disc herniation was dramatically higher during the first 12 months upon return to a terrestrial environment, thus identifying the period of transition between microgravity and the terrestrial environment as the most vulnerable period for injury.[13]

Space Adaptation Back Pain

Despite the negative impact of space travel on spinal health, most astronauts experience only transient, self-limited low back pain upon initial exposure to microgravity, referred to as "space adaptation back pain." In a large retrospective study of 722 astronaut flights, up to 52% of astronauts endorsed back pain; however, it was mild in more than

80% of the cases, with maximal onset during sleep periods between days 2 to 5 and resolution by day 12 of exposure to microgravity.[14] More than 90% of those afflicted reported significant improvement in symptoms by spinal flexion and loading of the spine by bending the knees to the chest.[14] Other effective treatments included nonsteroidal anti-inflammatory drugs, muscle relaxants, and exercise, which provided relief in approximately 85% of the cases.

Space adaptation back pain may be an important herald of the pathophysiologic changes occurring in the spinal column during exposure to microgravity, but other processes may contribute to the phenomenon as well. This notion is substantiated by data from military helicopter pilots and crewmembers who experience low back pain at similar rates (46%) to astronauts[15] and are 2.6-fold more likely to develop lumbar disc herniation compared to matched controls.[15] In fighter pilots, one study found the annual (32% *vs.* 19%) and lifetime (58% *vs.* 48%) prevalence rates for back pain to be significantly higher than for age- and sex-matched controls.[16] Similar to rotary wing pilots, astronauts experience intense vibrational forces during ascent—and to a lesser extent reentry—and are subject to comparable acceleration and deceleration forces as fighter pilots. There are also striking parallels between the physical and psychologic training regimens between military aircraft and spacecraft crewmembers. In one longitudinal study evaluating six astronauts who spent 6 months on the International Space Station, the two astronauts with preexisting spinal pathology were the only ones who reported chronic low back pain at 1-yr postflight follow-up, supporting the concept of space flight worsening antecedent pathobiology.[4]

There is a lack of consensus regarding the mechanisms of space adaptation back pain. One theory identifies intervertebral discs as the primary pain generator secondary to reduced amplitude and frequency of spinal motion in microgravity.[17] According to this hypothesis, reduced axial loading of the spine results in decreased hydrostatic pressure of the intervertebral discs, leading to increased fluid imbibition.[17] This would result in intervertebral disc swelling, stimulating nociceptive fibers embedded in the discs as well as type 4 mechanoreceptors.[17] Spinal flexion or the fetal tuck position may relieve pain by promoting fluid diffusion away from intervertebral discs, thus relieving the stress from fluid imbibition.[17] Although intervertebral disc swelling has been demonstrated in microgravity models, including during bed rest,[18] magnetic resonance imaging upon return to Earth has consistently failed to demonstrate intervertebral disc swelling,[4] though small increases in disc height in some subjects were demonstrated during in-flight ultrasound imaging on the International Space Station.[19]

Muscles have been implicated as possible pain generators secondary to strains, which may arise from reduced lumbar lordosis and spinal elongation.[20] Increased tension on spinal ligaments and nerve roots secondary to spinal cord elongation may also result in pain.[21] The fetal tuck position may relieve tension generated by reduced lordosis. In addition, lift-off is associated with significant whole-body vibration in astronauts,[20] which has been linked to musculoskeletal injury through muscular fatigue, tissue microtrauma, and chronic degenerative changes in military helicopter pilots.[22]

Knowledge Gained from Microgravity Terrestrial Models

Despite the inherent difficulties of studying spinal health in space due to practical challenges including limited equipment and research capabilities, there have been several microgravity ground-based analogues designed to simulate the effect of axial unloading on the spine (tables 1 and 2).[23]

Most ground-based microgravity model studies consistently demonstrate elongation of the spinal column associated with the development of acute low back pain that is similar in incidence, onset, and duration to that experienced in astronauts in space. Nevertheless, the elongation demonstrated by ground-based axial unloading is close to three-fold less than that experienced by astronauts in space.[2,3] A key discrepancy between data from space and that from ground-based models is the lack of consistent intervertebral disc expansion in space.[19] This discrepancy may be secondary to limited truncal mobility in subjects undergoing ground-based microgravity simulation compared to astronauts who float freely in space and engage in substantial physical activity. Such activities may generate higher intervertebral disc pressures, accounting for the relative lack of intervertebral disc expansion in space. Thus, ground-based microgravity models that simulate the degree of truncal physical activity of astronauts in space may better reflect the intervertebral disc changes that take place during space travel.

Alternatively, ultrasound imaging, the only modality to investigate intervertebral disc volume changes in space, may be less sensitive than magnetic resonance imaging in detecting such changes. This, however, seems less likely since magnetic resonance imaging of astronauts after 6 months on the International Space Station also failed to detect any changes in intervertebral discs.[29] This is in contrast to ground-based

Table 1. Microgravity Ground-based Models

Microgravity Model	Design
Horizontal bed rest	Recumbent positioning that results in 0 gravitational force on the cephalad-caudate spinal axis
Head-down tilt bed rest	4- to 15-degree Trendelenburg tilt employed to simulate the cephalad fluid redistribution that occurs in space
Head-out water immersion	Subjects sit or lie in a 34–35°C water bath with their head remaining out; this minimizes gravitational force on the torso by submersion in water
Head-out dry immersion	Similar to head-out water immersion with subjects kept dry by the use of waterproof, elastic clothing

Table 2. Key Data Obtained from Ground-based Microgravity Studies

First Author, Year	Microgravity Model	Study Population/ Methods	Major Findings
LeBlanc *et al.*, 1994[18]	Bed rest	5 females and 2 males (26 ± 6 yr) undergoing 5 weeks of ambulatory control, 5 (n = 3) or 17 (n = 4) weeks of bed rest and 6–7 weeks of recovery	10–40% (mean, 22%) expansion of intervertebral disc (T12–L5) volume as measured by magnetic resonance imaging within 4 days bed rest Residual intervertebral disc volume expansion lasting at least 6 weeks after reambulation in the 17-week group
Hutchinson *et al.*, 1995[24]	6-degree head-down tilt	8 males (36 ± 6 yr) undergoing 4 days ambulatory control, 16 days head-down tilt, and 1 day upright recovery	Increase in height by 2.1 ± 5 cm with 63% incidence of dull, burning, low back pain Maximal intensity of back pain on days 1–3 with only 25% incidence on day 9 and resolution by day 11 Lifting knees to chest relieved the pain
Hides *et al.*, 2007[25]	Bed rest	10 males (33.4 ± 6.6 yr) undergoing 6 weeks of bed rest	Isolated atrophy of the multifidus, an increase in the size of the rectus abdominis and psoas muscles, and no change in the erector spinae and quadratus lumborum musculature, measured by magnetic resonance imaging
Belavý *et al.*, 2011[26]	6-degree head-down tilt	9 males (33.1 ± 7.8 yr) undergoing 60 days of 6-degree head-down tilt	Increased length of the lumbar spine by 2.8% with decreased lower lumbar lordosis and increased upper lumbar lordosis Increased volume of lumbar intervertebral disc by 6.5% after 60 days of bed rest Atrophy of the quadratus lumborum, multifidus, and erector spinae musculature, with the greatest atrophy of the multifidus occurring at L4–L5 50% incidence of low back pain with resolution of symptoms by day 5 Low back pain was associated with greater atrophy of the multifidus at the L4–L5 level
Treffel *et al.*, 2016[27]	Head-out dry immersion	12 males (31.8 ± 4.1 yr) with no preexisting spinal pathology undergoing 3 days of head-out dry immersion and 2 days of recovery	Increase in spine column height by 1.5 ± 0.4 cm Decrease in lumbar lordosis by –4 ± 2.5 degrees, with decreased spinal flexion range 92% incidence of lumbar back pain Increase in intervertebral disc volume by 8 ± 9% at T12–L1 and 11 ± 9% at L5–S1 intervertebral disc associated with a 17 ± 27% increase in water content as measured by magnetic resonance imaging spectroscopy Resolution of back pain with return to the recumbent position
Treffel *et al.*, 2020[28]	Head-out dry immersion	18 males (34 ± 5.4 yr) undergoing 4 days ambulatory control, 5 days head-out dry immersion, and 2 days of ambulatory recovery	Increase in height by 1.25 cm Decrease in lumbar lordosis by 6 ± 0.72 degrees Intervertebral disc water content increased by 7.34 ± 2.23% and increased proteoglycan content by 10.09 ± 1.39%, as measured on magnetic resonance imaging Maximal low back pain onset by day 2

models that describe persistent intervertebral disc volume increases for up to 6 weeks after return to ambulation.[18] Future studies are needed to refine ground-based models and determine the causes of discrepancies.

Preventative Measures

Strategies focused on prevention of space adaptation back pain are of paramount importance due to limited treatment capabilities. Multiple hypothesized etiologies for space adaptation back pain are discussed in the preceding sections, and can be distilled down to three main factors: (1) the direct effect of microgravity environment on the body; (2) stress and trauma from traveling in space vehicles; and (3) space-associated nutritional deficits/imbalances causing tissue dysfunction and impaired healing.

Microgravity etiologies for space adaptation back pain include lengthening of the spine (causing tension on spinal ligaments and muscles), stiffness and/or flattening of the lumbar spine, hyperhydration of intervertebral discs, and in more delayed cases, possible atrophy of the multifidus and other paraspinal muscles.[4] Mechanical and vibratory stresses and trauma can occur through the take-off and landing phases of space flight, and may be associated with extreme force vectors.[30] Astronauts may also be predisposed to having nutritional and caloric deficits, as studies of energy requirements in space suggest that resting energy expenditure in space is elevated compared to the earth environment. This increased resting energy expenditure places astronauts in a double bind because their tissues are already being depleted at an increased rate due to metabolic demands, and any physical activity aimed at mitigating muscle atrophy results in even greater catabolism, which worsens the atrophy.[31] In addressing and preventing space adaptation back pain, corrective measures must be aimed at mitigating these three primary factors so that astronauts can be returned to the conditions that resemble the terrestrial environment as closely as possible.

Addressing Microgravity Factors

To address the problem of microgravity, one possible solution is to create an artificial gravity system. Science fiction media has popularized the use of centrifugal force mechanisms;

however, this solution is complex and costly, and potentially introduces unintended consequences such as spatial disorientation and extreme additive force vectors, which could cause navigational risks and physical trauma.[32,33] In light of this, a much "simpler" alternative to replicate gravity has been utilized for several decades: dynamic and static axial loading. Through these mechanisms, the bones and muscles that are normally responsible for postural resistance to gravity are placed under physical tension to emulate the effect of gravity.

Dynamic axial loading includes the use of exercises aimed at body regions involved in resisting gravity, including the trunk (back, pelvis, and abdomen) and lower extremities.[34] Since exercises are effective in maintaining muscle mass and decreasing back pain in a terrestrial environment,[35] it is hypothesized that beneficial effects would be observed in space. A retrospective study of 722 astronaut flights demonstrated that two modalities of dynamic loading implemented in space (treadmill with harness and cycle ergometry) were 85% effective in relieving symptoms of space adaptation back pain.[14] Experimental results have been mixed, however, with resistance exercise showing only partial protection against bone loss and muscle atrophy.[36,37] The process is also time-consuming, with astronauts spending 2 to 3 h per day for as many as 6 days per week on these efforts.[37] Lastly, these exercise devices may not be compatible with long distance space travel wherein vehicles are restricted on allocations for volume and mass.[35]

Static axial loading was pioneered in the 1970s by the Russian Space Program through the use of the Pingvin Suit, which utilizes a belt placed on the waist with elastic bands extending to the shoulders and legs, thereby replicating the effect of gravity on the spine and lower extremities. Although this system was shown to reduce muscle atrophy and bone mineral density loss, it had design limitations that made its use impractical.[38,39] This suit concept was recently updated and redesigned *via* the Gravity Loading Countermeasure Skinsuit, which utilizes a breathable bidirectional elastic microweave to progressively increase tension on the limbs and the spine. Whereas the Gravity Loading Countermeasure Skinsuit has improved upon many measures, remaining challenges for extended missions include higher minute ventilation during exercise testing, variance in fit, and impaired joint motion.[39–41]

Stress and Trauma Secondary to Space Vehicular Travel

Whole body vibration, high gravitational force equivalents, and vectored forces creating abnormal postural stresses (*e.g.*, abnormally directed forces on spine curvature) are a potential source of space adaptation back pain. These risks have been studied for years in rotary wing aviation and high-performance jets, and numerous countermeasures have been developed to mitigate their effects on aircrew including exercise, stretching, reconditioning, traction, and behavioral interventions.[30] Unsurprisingly, subjects who have undergone physical conditioning and incorporate consistent strength training regimens experience a lower incidence of pain symptoms.[42]

Effective engineering countermeasures for vibration- and acceleration-related injuries are needed for effective prevention efforts. To accomplish this, space vehicles must be engineered to optimize impact protection, with flight controls, propulsion systems, and crew seating designed to best align forces/acceleration with human anatomy.[30]

As previously discussed, cosmic radiation exposure is a potential etiology of space adaptation back pain. Mitigation strategies against this threat include mission planning to minimize solar radiation exposure, radiation shielding, genetic testing for crew selection, and biologic countermeasures. Currently, crew selection for radiation sensitivity may have the highest payoff in reducing risk.[43]

Nutritional Implications of Space Travel

The space environment may contribute to increased metabolism, thereby accelerating muscle atrophy. Voluntary dietary intake is reduced during space flight by about 20%,[44] while serum levels of micronutrients (*e.g.*, vitamins B, D, E, and K) are adversely impacted.[45] Since vitamin D deficiency has been correlated with skeletal pain,[46,47] nutritional plans to prevent and correct deficiencies are important. Examples of preventive strategies that may be considered include bisphosphonate supplementation combined with resistive exercises,[36] and supplementation with irisin, a myokine released after physical exercise, which has been shown to prevent and restore bone loss and muscle atrophy in animals.[48]

Additional Prevention Strategies

Neuromuscular electrical stimulation, which creates passive contraction of skeletal muscle and increases muscle blood flow, oxidative capabilities, and maximal force generation capacity,[35] is an effective treatment for muscle weakness in adults with advanced disease illness.[49] Although promising, it may be most appropriate as an adjunct, as its use appears to be less effective than stabilizing exercises focusing on individual muscle groups.[50]

Lower body negative pressure devices apply ambient pressure lower than atmospheric pressure to the lower body to induce footward fluid shifts. Combined with treadmill running, lower body negative pressure can generate a force similar to body weight as measured on earth. This technology has been used on the Mir space station, Skylab, and shuttle programs.[37] Research shows this modality is associated with normalized lumbar lordosis, spine length, and intervertebral disc height compared to control subjects.[51]

Manual therapies may play a role in the prevention of space adaptation back pain. Massage has been shown to alleviate fatigue and provides limited effects on blood flow in the lumbar muscles after exercise.[52] Gua sha, a specialized manual therapy in which the skin over affected muscles is scraped with a blunt tool, has been correlated with significantly increased weightlifting ability, decreased perceived exertion, and decreased creatine kinase, immunoglobulin A, and blood urea nitrogen levels.[53] Manual modalities may therefore prove useful in preventing space adaptation back pain through addressing fluid dynamic problems,[54] back stiffness, and inflammatory factors associated with spinal pain.

Psychologic Considerations of Space Adaptation Back Pain

Psychologic distress is integrally related to back pain with high co-prevalence rates.[55] The presence of psychologic comorbidities has been linked to the chronification of acute low back pain,[56]and though the literature is less robust, characteristics such as anxiety and depression have also been linked to acute back pain episodes.[57,58]

Clinical studies have demonstrated high anxiety levels in a variety of contexts relevant to space travel. In a retrospective study evaluating 86 nonastronaut volunteers exposed to centrifuge-simulated suborbital space flight, 18 (21%) individuals self-reported anxiety, including 12 in whom anxiety interfered with their ability to complete training.[59]Although the incidences of anxiety and depression in astronauts have not been extensively evaluated in peer-reviewed publications, there is evidence from postmission reports and debriefings that astronauts, particularly those involved in long-duration space missions, exhibit anxiety related to the mission itself and peer-to-peer interactions, as well as depression and loneliness, along with other psychologic morbidities.[60,61]

The treatment of psychologically reinforced or precipitated low back pain is challenging in space. Antidepressants such as duloxetine have been shown to alleviate anxiety and depression as well as radicular and mechanical low back pain in terrestrial environments, but may have cognitive and psychomotor effects and therefore are not routinely prescribed in astronauts.[62,63] However, pre- and postadministration testing, which can be done before a mission, may help identify individuals at risk for adverse effects. Combining pharmacotherapy with cognitive behavioral therapy may provide added benefit to psychologically reinforced low back pain.

Treatments that conform to accession and continuation standards for astronauts should be prioritized. Self-administered treatments such as meditation, guided imagery, acceptance and commitment therapy, and even cognitive-behavioral therapy and biofeedback can be preemptively taught. Modules such as those designed to promote pain coping skills can be accessed in remote, austere environments. Larger missions may also include astronauts trained to administer not only first aid, but also acute mental health care.

Astronauts, and to a lesser extent civilian space travelers, are subject to intense screening that includes a comprehensive psychologic evaluation. Given the rigorous requirements, some space travelers who might benefit from psychologic treatment may not seek care or seek care from providers outside of accepted personnel. Instead of a rigid, punitive system, a more flexible system that allows for a personalized approach to mental health care might be most beneficial for selecting space travelers.

Diagnosis and Treatment Considerations of Space Adaptation Back Pain

Background

Acute back pain in space is generally attributed to elongation of the spine and can be broadly grouped as exacerbation of preexisting pain, space adaptation back pain, or in-flight injury–related back pain. Preexisting asymptomatic spine pathology (*e.g.,* facet arthropathy, disc degeneration) is present in the low back, mid-back, and cervical spine in more than half of all individuals by the 4th decade of life and may become symptomatic as the spine elongates, making it difficult to distinguish between pure space adaptation back pain and other etiologies in previously asymptomatic individuals.[64–66] Hence, correlating the clinical picture with the typical presentation of space adaptation back pain is important. Space adaptation back pain typically occurs without a precipitating event within the first 5 days of space flight, with a peak prevalence on day 2.[14,67] In contrast, around half of the cases of specific spinal pain can be attributed to an inciting event, though the pathophysiological relationship between the event and etiology may be nebulous.[68–70] The reported incidence of space adaptation back pain in astronauts is 52% to 68%, with up to 4% experiencing severe symptoms.[14,67] The duration of space adaptation back pain generally does not exceed 12 days and has been effectively treated with oral medications, position changes (knees-to-chest), and exercise.[14] Although seemingly benign, the in-flight operational impact of recalcitrant space adaptation back pain or spine pain from an in-flight injury has the potential to negatively impact the success of a mission. Yet to date, no mission-critical task has been compromised secondary to back pain.

There are numerous postulated mechanisms for spine pain in space including preexisting degenerative disc disease (*e.g.,* disc swelling, chemical sensitization from nerve ingrowth), thoracolumbar alignment changes (*i.e.,* loss of lordosis), facet pathologies (*e.g.,* stretching of the capsule), stretching of spinal ligaments or joint capsules, and atrophy of spinal stabilizer muscles (including the abdomen) leading to deconditioning and cramps. Between 2005 and 2018, the National Aeronautics and Space Administration dedicated four specialty meetings to the study of spine pain in space. The most recent meeting reinforced possible etiologies for space adaptation back pain and the use of protective exercises.[67]

In space, the spine elongates up to 4 to 7 cm.[71] Whereas intervertebral disc swelling was previously thought to be a significant contributor, studies by Bailey *et al.* refuted this theory and suggested that microgravity resulted in multifidus atrophy and fatty infiltration, which was more strongly associated with loss of lumbar lordosis and increased lumbar stiffness.[4] This suggests that core destabilization and altered skeletal alignment may be a more proximate contributor to spine elongation and space adaptation back pain.[4,71,72] Decreased cross-sectional area (*i.e.*, atrophy) of the paraspinal muscles (specifically the multifidus) is predictive of low back pain and disability in terrestrial models.[73,74] Consequently, Hides *et al.* performed a longitudinal study comparing ultrasound imaging of trunk musculature in astronauts before and after a mission to the International Space Station and found that the cross-sectional areas of the multifidus and transversus abdominus muscles decreased significantly at all lumbar vertebral levels upon return from space.[71] This study also found multifidus impairment as measured by muscle thickness during contraction.[71]The National Aeronautics and Space Administration 2018 Spine Workshop aptly questioned whether multifidus dysfunction could serve as a predictor for back pain in space.[67] This raises questions as to what extent vertebral neurovestibular function and proprioception are impaired with a dysfunctional multifidus. In addition to contributing to space adaptation back pain, the loss of spine stabilizer musculature during a mission poses a theoretical risk of decreased function during emergency procedures such as egress from the space vehicle.

Studying back pain associated with space flight is a pressing concern given government and commercial interests in space travel. On November 15, 2020, after a nearly 10-yr hiatus, the United States launched an international crew of astronauts from the Kennedy Space Center in Florida to the International Space Station on the first National Aeronautics and Space Administration–certified commercial human spacecraft system in history using the SpaceX Falcon 9 rocket and Crew Dragon spacecraft.[75] Space travel will likely only increase in the future, exposing greater numbers of space travelers to space-flight risks. Johnston *et al.* demonstrated that the incidence of herniated nucleus pulposus was 4.3 times higher in the astronaut population than a control population and was highest (35.9×) in the immediate 12-month postflight time period.[13] Whereas Johnston *et al.* postulated in 2010 that intervertebral disc pathology was the main contributor to herniated nucleus pulposus, Bailey *et al.* noted that the increased postflight risk may actually be secondary to atrophy, and therefore dysfunction, of lumbar stabilizer musculature, specifically the multifidus.[4] Since the multifidus also plays an important role in spine proprioception, pre- and postflight neurovestibular and proprioceptive training is an area of future research.[76]

Diagnosis and Treatment

Back pain in space travelers should be evaluated with a thorough history documenting motor and/or sensory deficits, as well as bowel or bladder changes, which may suggest serious pathology. This is important because the classification of spinal pain as neuropathic or nonneuropathic has prognostic and treatment implications at all levels of care. The physical exam should include a neurologic assessment of strength, sensation, and spinal reflex testing, which can be accomplished remotely with the surgeon in Mission Control if necessary. A thorough history can also help differentiate space adaptation back pain from other common causes of low back pain (table 3). After more serious causes of in-flight back pain have been ruled out (*e.g.,* acute radiculopathy from a herniated disc) and a diagnosis of space adaptation back pain is suggested, conservative management is appropriate. Generally, a nonsteroidal anti-inflammatory drug such as naproxen or ibuprofen (shorter acting) taken for 2 to 3 days is sufficient to manage symptoms; however, if severe muscle spasm is present, a muscle relaxant may be added. Given their risk for physical dependence and prominent psychomotor effects, benzodiazepines should not be a first-line treatment for space adaptation back pain.[77] In addition to oral analgesics, spinal loading, position changes such as knees-to-chest hip flexion, and use of a Nada-chair have been shown to treat symptoms.[14,72,78] As space adaptation back pain appears to be most symptomatic while sleeping, sleep position changes can be made by shortening the sleeping bag at the foot end to prevent full extension of the legs, thereby creating a partial knees-to-chest tuck position. The same position can be obtained by sleeping strapped into a space vehicle/capsule seat. Given that it is rare for space adaptation back pain to persist beyond flight day 12, with most cases resolving by day 5, back pain persisting longer than 12 days or described with neuropathic characteristics should raise suspicion for a more serious etiology.[67] Spinal loading *via* exercise can also be used to treat space adaptation back pain; however, care must be taken to avoid exercise-related injury/trauma which could confound the picture. While in space, exercising early is encouraged, beginning with aerobic training and progressing to resistance training, with gradual increases in percentage body weight load as tolerated.

Current data on the treatment of space adaptation back pain do not support in-flight countermeasures targeting intervertebral disc expansion such as prolonged passive axial loading (*e.g.* the Russian Penguin suit) to reduce the incidence of space adaptation back pain or herniated nucleus pulposus. On the other hand, measures targeting the core stabilizer musculature responsible for establishing physiologic lumbar lordosis and spine proprioception show promise. The quadratus lumborum, pelvic floor, diaphragm, and transversus abdominus work in concert to stabilize the spine and should be considered targets, along with the multifidus and erector spinae, for preventive exercises.[67] There remain compelling questions regarding the use of ultrasound for diagnosing in-flight back pain and monitoring in-flight treatment progress as it relates to the size (atrophy) and function (contraction strength) of stabilizer muscles. Under this premise, the routine diagnosis

Table 3. Types of Low Back Pain and Common Features to Help Guide Diagnosis in Space

Low Back Pain Type	Etiology	Presentation	Onset	Characteristics
Space adaptation back pain[4,14]	Controversial diagnosis; likely associated with spinal column elongation, loss of lumbar lordosis, and myofascial stretch, resulting in relative loss of lumbar stability and increased stiffness; not precipitated by injury	Axial pain without radiation	Acute (days 1–5 of space travel)	Dull ache Worse after prolonged recumbent position (*i.e.*, sleeping), improved with knees-to-chest position Self-limited and transient (resolves within 5 days)
Facetogenic[79,80]	Osteoarthritis of the facet joints or tears in the capsule; some may experience entrapment of the medial branch under the mamilloaccessory ligament secondary to swelling in microgravity	Paraspinal axial back pain with or without nondermatomal radiation extending into the hip, flank, and posterolateral aspects of the thigh	Generally insidious	Deep, dull ache Worse with activity, sometimes relieved with sitting or recumbency Increasing prevalence with age
Discogenic[81,82]	Intervertebral disc degeneration without herniation resulting from annular tears and increased cytokine levels; microgravity may enhance intervertebral disc degeneration; peak prevalence in 40s	Midline axial pain with variable, nondermatomal radiation into the upper legs	Insidious	Deep, dull ache Improves with lying flat; exacerbated by activity, forward flexion, and prolonged sitting
Deconditioning[79,80]	Muscle atrophy and decreased neuromuscular coordination from diminished activity	Diffuse, typically bilateral pain precipitated by movement; axial pain without radiation, though patients may have deconditioning of nonspinal muscles	Subacute (generally weeks to months)	Similar to pain experienced after exercise Worse with activities that stress the deconditioned muscles Reduced range of motion of the affected muscles
Myofascial pain[79,80]	Acute stretch injuries, spasm, muscle tears	Severe pain with movements, loss of lordosis or functional scoliosis with spasm, low back “fullness” with muscle tears or spasms; often unilateral	Acute	Sharp pain May be precipitating by abrupt movements, coughing, or sneezing Trigger points may be present.
Herniated nucleus pulposus[79,80,82]	Annular tear of the intervertebral disc resulting in nucleus pulposus herniation and mechanical compression or chemical irritation of adjacent nerve roots; peak prevalence in 30s and 40s	Radicular pain (extending below the knee) in a dermatomal distribution; focal neurologic signs often present	Acute (minutes to days after inciting event)	Often described as sharp, lancinating, burning pain Worse with forward bending, coughing, prolonged sitting Sometimes accompanied by sensory findings and neurologic weakness

of back pain in space may evolve to include qualitative and quantitative assessment of spine stabilizer muscles *via* ultrasound measurement in pre- and postflight settings. If in-flight or postflight abnormalities are found, targeted exercises may be initiated and progress monitored by serial ultrasonography. Furthermore, biofeedback utilizing live ultrasonography could be used to more effectively activate the multifidus muscle, which could be trended for future study.

As the number of space travelers increases to include nonprofessionals, fitness standards will likely also vary widely, presenting the aerospace medicine community with a generous opportunity to compile data on the roles of genetics, lifestyle factors, psychologic factors, and preexisting spine pathology on spinal pain during and after space travel. Considering that some systematic reviews report more than a 50% prevalence rate of lumbar facet joint pain within the chronic low back pain population,[83] one example of useful data relevant to pain medicine specialists might involve testing the role of facet joint capsule stretch as a pain generator for space adaptation back pain in early space flight by comparing the incidence of pain in travelers who have undergone radiofrequency ablation of the medial branches *versus* those who have not.[83] Similarly, associating multifidus atrophy—which occurs after radiofrequency ablation of the lumbar facet joints—with back pain may provide important clues on its contribution to space adaptation back pain.[84] Stretch of the facet joint capsule as the spine elongates may cause medial branch neuropraxia, in essence unifying the potential roles of facet joint capsule stretch and multifidus dysfunction. Although no single structure is responsible for space adaptation back pain, investigating connections such as these may enhance risk mitigation as more travelers with preexisting spine pathology are permitted in space.

Future Research Considerations

Research is critical in preventing and treating spinal pain in space travelers, but is fraught with challenges. These include the development of validated animal models, challenges in translating preclinical studies to very small populations, travel restrictions on equipment, and lack of financial incentives for industry to invest in space-related health research.

Although some preclinical research has been conducted on the effects of microgravity in animals, these have focused on pathology after relatively short exposures rather than the treatment of antinociceptive behaviors.[85,86] The limitations of animal models on disc degeneration include translating animal behaviors to the complex human experience of pain and differences in longevity and biomechanics.[87] Future studies should ideally involve longer exposure periods and focus on the prevention and treatment of space adaptation back pain.

Personalized medicine, which entails precise approaches based on individual characteristics, has been absent in space research due to the homogeneous population. Identifying genotypic and phenotypic variables that can predict disease development and treatment response ideally involves large-scale clinical trials, or in their absence, big data analysis (*e.g.*, registries).[88] Considering the small number of space travelers and logistical challenges in collecting real-time data, there has been little research in this area. Yet, with the anticipated growth of the space tourist industry and the expected diversity of this new population, using precision medicine to prevent spine pain and improve treatment will assume increasing importance.

The development of low back pain can interfere with mission requirements, so prevention plays a key role in readiness. Trials devoted to identifying effective preventive strategies typically require very large populations since not everyone exposed to the intervention will develop the index condition. This is challenging for space medicine because there are so few astronauts. Future preclinical studies and large-scale cohort studies involving airline personnel may seek to evaluate preventive strategies focusing on exercise, psychologic therapies, nutrition, design and engineering, and possibly pharmaceutical- and interventional-based approaches in preventing spinal pain in space travelers.[89]

Finally, preventive measures such as equipment for exercising and certain treatment modalities may be inaccessible due to logistical constraints during travel. The development of lightweight exercise equipment that can be adapted for different usages and telemedicine capabilities that could allow astronauts to perform simple procedures or receive psychologic treatment (*e.g.*, cognitive behavioral therapy) are areas ripe for investigation.

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