

Exploring short-term microgravity as a therapeutic intervention for spinal degeneration and disc space narrowing

A narrative review

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Abstract

Degenerative disc disease (DDD) and chronic low back pain are prevalent in the general population and athletic populations exposed to high spinal loading. Environments with simulated microgravity, such as dry immersion, water immersion, and parabolic flight, may mimic the spinal unloading experienced in space and have shown potential in enhancing disc hydration, reducing axial stress, and promoting recovery. In this narrative review, we evaluate the therapeutic potential of short-term simulated microgravity exposure for spinal rehabilitation and athletic recovery, highlighting mechanisms and clinical applications. A comprehensive literature search was conducted in PubMed, EMBASE, Web of Science, and EBSCO, following the PICOS framework. Studies involving simulated or real microgravity and reporting outcomes related to disc hydration, extracellular matrix remodeling, biomechanical properties, or molecular signaling were included. A total of 9 original research articles met the inclusion criteria. Short-term microgravity exposure increases intervertebral disc hydration and disc height while stimulating the synthesis of proteoglycans in the matrix. Mechanistically, these effects are mediated by a reduction in axial loading, osmotic water influx, and the activation of pathways such as the transforming growth factor- β (TGF- β)/Smad3 pathway. Clinically, simulated microgravity may serve as a noninvasive modality for recovery in athletes with spinal overload, offering alternatives to conventional therapies via parabolic flight, aquatic therapy, or dry immersion. Simulated microgravity represents a novel, noninvasive modality that may aid in spinal rehabilitation by enhancing disc hydration and reducing mechanical stress. While early evidence is promising, further clinical trials are needed to validate the safety, efficacy, and integration of simulated microgravity into multidisciplinary sports medicine protocols.

Abbreviations: DDD = degenerative disc disease, ECM = extracellular matrix, GAG = glycosaminoglycan, LBP = low back pain, ODI = Oswestry Disability Index, PICOS = Population, Intervention, Comparison, Outcome and Study Design, RWV = rotating wall vessel.

Keywords: biomechanics, microgravity, spinal, therapeutic intervention

1. Introduction

Commercial space travel is becoming a reality with the rapid development of space exploration and the growing success of private space exploration companies such as SpaceX. These advancements have not only attracted

public interest but also significantly increased awareness of aerospace medicine and its clinical implications. Historically, research in this area has focused largely on the adverse effects of microgravity, such as muscle atrophy, bone density loss, and spinal discomfort.^[1-5] Astronauts returning from space missions frequently report low back pain (LBP) and other musculoskeletal issues, largely attributed to physical changes in the spine during prolonged exposure to microgravity environment.^[6-9]

However, emerging evidence suggests that microgravity is not universally harmful; instead, it may represent a unique physiological condition with potential therapeutic benefits, particularly when exposure is brief and occurs in a controlled environment. Recent findings suggest that short-term microgravity exposure may mitigate certain chronic spinal conditions. Specifically, spinal pathologies such as degenerative disc disease (DDD) and disc space narrowing are traditionally viewed as progressive and difficult to reverse. These conditions might be positively influenced by the effects of short-term exposure to microgravity. The unloading of the spine in a weightless environment has been shown to increase intervertebral disc

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hydration, reduce spinal compression, and even lead to temporary spinal elongation.^[10,11]

Disc space narrowing and chronic LBP are among the most prevalent spinal conditions worldwide. Imaging studies have revealed that more than 90% of individuals show signs of disc degeneration at age 50, even asymptomatic DDD^[12] and symptomatic DDD affects approximately 40% of adults over 40 years of age.^[13] LBP alone affects more than 550 million people worldwide and is the leading cause of disability across all age groups.^[14] In the United States, spinal disorders are the costliest medical condition, with more than \$134 billion spent on treatment annually, and cause substantial productivity losses.^[15] In elite athletic populations, this burden is increased by early exposure to spinal loading and repetitive axial stress. Notably, disc degeneration is significantly more common in elite athletes than in nonathletes (75% vs. 31%). In comparison, several studies have shown that one-third of asymptomatic people (nonathletes) in their 20s have degenerated lumbar discs.^[16]

LBP, spinal degeneration, and intervertebral disc narrowing are prevalent issues in athletic individuals—especially those who frequently engage in high-impact sports.^[17–19] These conditions are linked to cumulative loading, repetitive motion, and axial compression during training and competitions.^[20–22] In addition to spinal structural changes, athletes often experience persistent neuromuscular fatigue, joint irritation, and systemic inflammation, all of which can delay recovery and limit long-term performance.^[23,24] Consequently, recovery modalities that promote tissue regeneration, reduce axial load, and restore spinal alignment are essential in high-performance settings.

Intervertebral disc health depends on the maintenance of a delicate balance among proteoglycans, collagen, and water to maintain structural integrity.^[25–27] The development of disc degeneration is a complicated process influenced by various factors, many of which are not fully understood. It is believed that disc degeneration involves both genetic and environmental components.^[27–29] Several studies on intervertebral disc degeneration have identified 3 potential triggers: biomechanical wear, insufficient nutritional support, and the presence of pathogens.^[27,30–32] Degenerative changes typically originate in the nucleus pulposus, where cell loss and proteoglycan degradation compromise the ability of the disc to retain water and cause structural collapse.^[25,33–36] These changes compromise disc height and elasticity, leading to biomechanical instability and chronic pain. DDD is a progressive condition that can lead to several debilitating complications if left untreated.^[37] Height and hydration loss occur as intervertebral discs degenerate, which can result in severe nerve root compression (radiculopathy) and spinal cord compression (myelopathy).^[38] These conditions often cause chronic pain, muscle weakness, and sensory loss and, in severe cases, may lead to significant motor deficits or loss of bladder and bowel control.^[29,37,39] In advanced stages, DDD may lead to spinal

stenosis or spondylolisthesis.^[40,41] Both conditions can compress nerves and cause functional disability, often requiring surgical intervention to stabilize the spine or decompress the nerves. Osteophyte (bone spur) formation and facet joint arthritis can further narrow nerve exit pathways, exacerbating pain and limiting movement.^[42] Given these significant sequelae, there is an urgent need for innovative, noninvasive strategies that not only alleviate symptoms but also target the underlying degenerative processes.

Current treatment approaches for these spinal issues—including chiropractic care, physical therapy, surgical interventions, and various pharmaceutical treatments^[43–45]—focus mainly on symptom management rather than structural reversal.^[43,46–50] Conditions such as DDD and disc space narrowing involve progressive changes in the spine. These conditions cause disc height loss and intervertebral disc dehydration, eventually leading to chronic pain, stiffness, and limited mobility.^[22,51–54] Although therapeutic strategies such as spinal traction, cryotherapy, and active rehabilitation can support short-term functional gains, they are often insufficient for restoring intervertebral disc integrity or mitigating chronic spinal loading over time.

Simulated microgravity, delivered through ground-based analogs such as dry immersion or head-down tilt bed rest, has demonstrated spinal unloading effects similar to those that occur in space. These technologies may offer a controlled environment to facilitate spinal decompression and tissue rehydration while reducing musculoskeletal stress. In athletic recovery, this could translate into faster restoration of spinal function, improved disc health, and a reduced risk of reinjury—particularly in individuals who participate in sports that impose high spinal demand, such as gymnastics, wrestling, football, and weightlifting.

In this narrative review, we critically evaluate the therapeutic potential of simulated microgravity as a regenerative and neuromechanical intervention for spinal rehabilitation and athletic recovery. We examine the mechanistic underpinnings, clinical evidence, and translational opportunities while identifying current limitations and outlining directions for future research aimed at integrating these approaches into comprehensive sports medicine protocols.

2. Search strategy and results

We conducted a comprehensive literature search in PubMed, EMBASE, Web of Science, and EBSCO. We limited our searches to articles published in English, with no restriction on the publication date. Our search strategy was developed using the Population, Intervention, Comparison, Outcome and Study Design (PICOS) framework.

The following search terms were used: (intervertebral disc OR spinal disc OR nucleus pulposus OR annulus fibrosus) and (simulated microgravity OR spaceflight OR dry immersion OR hindlimb unloading OR rotating wall vessel) and (hydration OR disc height OR proteoglycan

OR glycosaminoglycan OR extracellular matrix OR biomechanics OR MMP OR TGF-beta OR stiffness OR viscoelasticity).

We retrieved a total of 123 publications from our search. After 17 duplicate records were removed, 85 studies were excluded on the basis of a title and abstract review due to irrelevance, nonoriginal data, or a lack of full text. Twenty-one full-text articles were assessed for eligibility, of which 9 peer-reviewed original research studies met the inclusion criteria and were included in this review.

The eligibility criteria were as follows:

1. Investigated human, animal or in vitro models involving the intervertebral discs or related spinal fibrocartilage tissues (e.g., nucleus pulposus, annulus fibrosus, and endplates).
2. Examined the effects of real or simulated microgravity, including dry immersion, real spaceflight, rotating wall vessel, and hindlimb unloading.
3. Reported outcomes related to at least one of the following:
 - a. Disc hydration or height
 - b. Proteoglycan or glycosaminoglycan (GAG) expression
 - c. Extracellular matrix (ECM) remodeling (e.g., MMPs, collagen)
 - d. Biomechanical properties (e.g., stiffness and viscoelasticity)
 - e. Molecular signaling pathways (TGF- β /Smad)
 - f. Publication as an original research article in a peer-reviewed journal
 - g. Full-text availability and written in English

The detailed findings and experimental conditions of the included studies are summarized in Table 1.

3. Mechanisms of microgravity-induced spinal healing

3.1. Disc hydration and height restoration

Short-term exposure to microgravity alleviates disc degeneration through 2 primary mechanisms: increased disc hydration and increased disc height. Although research on disc changes under microgravity conditions is limited, several studies have been conducted, with notable key findings. A summary of these findings is provided in Table 1. Under microgravity conditions, the absence of gravitational forces significantly reduces both compressive and shear loads on the spine, allowing water to flow into the intervertebral discs.^[6,62,63] This osmotic-driven hydration is facilitated by a decrease in hydrostatic pressure and a reduction in external mechanical forces.^[6,62] As a result, the discs absorb more fluid, increasing their water content and restoring lost height.^[56,63] The reduction in axial loading also allows the intervertebral discs to recover from constant compressive forces experienced on Earth. Research has demonstrated that this unloading not only facilitates fluid transfer into the discs but also supports disc regeneration.^[56] Research has indicated that

microgravity-induced rehydration increases disc height by 2–3 cm and may lead to recovery of conditions such as disc space narrowing and degeneration.^[57,64–66]

Intervertebral disc degeneration is characterized by dehydration and structural disorganization of the annulus fibrosus, as well as reduced proteoglycan content in the nucleus pulposus.^[56] Proteoglycans are critical for maintaining the water retention and biomechanical integrity of the disc. By attracting and retaining water molecules, these macromolecules ensure that the nucleus pulposus remains hydrated and functional under axial loading conditions. The enhanced hydration in microgravity may counteract these degenerative changes by stimulating proteoglycan synthesis and improving the composition of the ECM.^[26,67,68] Increased hydration and proteoglycan levels could promote the repopulation of damaged discs with cells or enhance the function of existing cells, potentially reversing degenerative processes.

These physiological changes offer significant therapeutic potential. Increased disc height alleviates nerve compression, reduces symptoms such as radiculopathy and numbness, and restores spinal alignment. Improved disc alignment also helps redistribute spinal loads more evenly, enhancing the shock absorption capacity of the spine and reducing the risk of adjacent segment degeneration. This redistribution of mechanical stress is particularly relevant in populations with chronic spinal overload, such as athletes and manual laborers. These findings suggest that spinal structures may demonstrate short-term plasticity under unloading conditions. However, whether this leads to sustained structural recovery or true regeneration remains to be validated in clinical trials.

3.2. Proteoglycan synthesis

Although direct research on the effects of short-term microgravity exposure on proteoglycan production is limited, preliminary findings suggest that gravitational unloading may stimulate ECM synthesis in intervertebral discs. At the cellular level, the absence of gravity may stimulate the production of proteoglycans, a critical component for disc hydration and elasticity, by nucleus pulposus cells. Multiple studies conducted under simulated microgravity conditions (including dry immersion models) have revealed that, after dry immersion, the protein content (proteoglycans) inside intervertebral discs is increased.^[57] Research conducted on 12.5-day spaceflight revealed an increase in the orientation of hyaluronidase-sensitive GAGs in the internal zones of annulus fibrosus and nucleus pulposus.^[61] These changes are believed to support disc hydration and preserve the shock-absorbing properties of the spine under reduced gravitational stress.

Importantly, these effects may be mediated by alterations in the cellular mechanotransduction pathway under microgravity, potentially leading to the upregulation of ECM-related genes and the suppression of catabolic activity. However, the precise molecular mechanisms underlying this response remain to be fully elucidated. Future research should assess the expression

Table 1
Summary of original studies investigating the effects of real or simulated microgravity on intervertebral disc physiology.

Study	Subjects	Intervention	Time	Key findings
Yue et al. ^[55]	L929 fibroblasts (in vitro)	SMG via RCCS	1, 3, and 5 days	<ul style="list-style-type: none"> * Short-term SMG (1 day) did not affect the cell cycle. * Longer exposure (3–5 days) induced G1 arrest, apoptosis, and the suppression of ECM production (collagen I/III).
Jin et al. ^[25]	Rat lumbar discs	SMG via RWV bioreactor	2–4 weeks	<ul style="list-style-type: none"> * SMG also activated the TGF-β1/Smad3 pathway * Rotating conditions (SMG) decreased glycosaminoglycan (GAG) content within 2 weeks. * By 30 days, MMP expression (MMP-3, MMP-13) increased in both the annulus fibrosus and nucleus pulposus
Wu et al. ^[6]	Human lumbar spine finite element model (L2–L5)	SMG via computational modeling	N/A	<ul style="list-style-type: none"> * Under neutral 0 G, lumbar disc compressive forces decreased by 62%–70%, muscle force decreased by 56%–93%, disc height decreased by 2%–3%, and volume decreased by 6%–9%.
Treffel et al. ^[56]	Healthy male volunteers ($n = 11$)	SMG via DI	3 days	<ul style="list-style-type: none"> * Fetal tuck posture partly reversed changes * SMG induced significant increases in the spine height (1.5 ± 0.4 cm) * SMG induced an increase in the IVD volume of $+8 \pm 9\%$ at T12–L1 and $+11 \pm 9\%$ at L5–S1 * SMG induced an increase in intervertebral disc water content $17 \pm 27\%$
Treffel et al. ^[57]	Healthy male volunteers ($n = 12$)	SMG via DI	5 days	<ul style="list-style-type: none"> * SMG increased lumbar disc water content and apparent diffusion coefficient (ADC) * Proteoglycan levels also increased in nucleus pulposus after stimulation
Fitzgerald et al. ^[58]	Male C57BL/6N mice, age 19–20 weeks ($n = 6$)	RM via BION-M1 biosatellite	30 days	<ul style="list-style-type: none"> * Microgravity caused moderate cartilage surface damage and the loss of proteoglycan in weight-bearing articular cartilage * Nonweight-bearing sternal cartilage is unaffected by microgravity.
Bailey et al. ^[59]	Mice (C57BL/6J), both male and female	RM via ISS	30 days	<ul style="list-style-type: none"> * No irreversible cartilage degradation was observed after 30 days * After 15 days, no change was observed in lumbar disc height or nuclear swelling pressure; Endplate permeability and annular viscoelasticity were unaffected. * After 30 days, lumbar IVDs exhibited reduced compressive stiffness and altered matrix composition, while caudal IVDs were unaffected
Bailey et al. ^[60]	Human astronauts ($n = 6$)	RM via ISS	6 months	<ul style="list-style-type: none"> * No herniation reported, no change in disc water content pre- to postflight
Foldes et al. ^[61]	Wistar rats	RM via Cosmos 1887 biosatellite	12.5 days	<ul style="list-style-type: none"> * Notochordal cells in the nucleus pulposus expanded and migrated laterally. * Cartilage endplates showed swelling, hypertrophic cells, and mild mineralization. * Collagen fiber orientation slightly decreased in the outer AF and endplate. * Hyaluronidase-sensitive GAGs showed increased alignment in inner AF and NP.

AF = annulus fibrosus, DI = dry immersion, ISS = international space station, NP = nucleus pulposus, RCCS = rotary cell culture system, RM = real microgravity, RWV = rotating wall vessel, SMG = simulated microgravity, TS = tail suspension.

profiles of key matrix-associated genes, such as aggrecan, decorin, and biglycan, and examine whether microgravity exposure influences regulatory pathways, such as SOX9 and HIF-1 α , which are implicated in disc matrix homeostasis.

3.3. TGF- β /Smad3 pathway activation

Wound healing is regulated by complicated signaling pathways, with the transforming growth factor β 1/Smad3 signaling pathway has been confirmed to play a fundamental role in regulating this process.^[55,69] An

experiment in which L929 fibroblasts were utilized under simulated microgravity conditions revealed that microgravity may upregulate the TGF- β signaling pathway, which plays a crucial role in tissue repair and matrix synthesis, further supporting the regeneration of intervertebral discs.^[55] The TGF- β /Smad3 axis has been shown to influence cellular proliferation, ECM remodeling, and the suppression of catabolic cytokines, making it a promising target for disc regeneration. In the context of spinal repair, upregulation of this pathway could modulate the inflammatory microenvironment and promote reparative matrix deposition.

4. Clinical applications

4.1. Simulated microgravity modalities

4.1.1. Parabolic flight. One such method is parabolic flight, which can provide short bursts of microgravity. During parabolic flight, an aircraft follows a parabolic trajectory, inducing microgravity for brief periods of approximately 20–30 seconds at a time.^[10,70,71] Although the exposure to microgravity in these flights is temporary, repeated parabolic flights could serve as a therapeutic tool. The reduced axial loading during these periods mimics the effects of space travel, allowing the spine to decompress and the intervertebral discs to rehydrate.^[10] Research on parabolic flight has shown that the spine responds to these short periods of microgravity similarly to how it responds in space, with temporary disc swelling and increased height.^[27] While parabolic flight only offers short-term microgravity exposure, a series of parabolic flights could be incorporated into a therapeutic regimen for patients with conditions such as disc degeneration or herniation.

Parabolic flight may also provide an opportunity for researchers and clinicians to study the immediate spinal biomechanical response. Wearable sensors or MRI-compatible devices could be used pre- and post-flight to study unloading in real time. Although currently impractical for routine clinical use owing to cost and infrastructure limitations, parabolic flight serves as an important analog to validate physiological mechanisms relevant to regenerative spinal care. Future commercial parabolic flight platforms could provide experimental windows for personalized unloading therapy, especially for severe or refractory spinal degeneration.

4.1.2. Water immersion therapy. Another method to simulate microgravity on Earth is water immersion therapy, which creates a near-gravity-free environment by reducing the effects of body weight on the spine. Water immersion therapy, especially using deep water tanks, allows for a significant reduction in gravitational forces on the spine, mimicking some of the benefits of microgravity.^[72,73] In an aquatic environment, buoyancy counteracts body weight, decreasing spinal compression and allowing the intervertebral disc to rehydrate.^[63] Research has shown that water immersion can relieve pressure on the spine, promote disc hydration, and reduce back pain, suggesting that water immersion is a promising option for patients who cannot access a true microgravity environment.^[73,74] The versatility and low barrier to access make water immersion therapy one of the most practical microgravity analogs for rehabilitation. Aquatic therapy pools are already widely used in physical therapy for musculoskeletal unloading, and their role can be extended to spine-specific recovery protocols. Clinicians may prescribe water-based recovery sessions during postcompetition rehabilitation or early-stage conservative management of discogenic pain. Water immersion may also facilitate active

recovery protocols, allowing integration of mobility, proprioceptive training, and neuromuscular reactivation in a reduced-load setting.

4.1.3. Dry immersion therapy. Dry immersion therapy is the most feasible approach among all these methods. Dry immersion is a ground-based model normally used in research settings for simulating microgravity conditions.^[56,73,75] However, this approach could be used in clinical settings to provide microgravity conditions for therapeutic purposes.

Dry immersion may offer a controlled environment for facilitating spinal decompression and tissue rehydration while reducing musculoskeletal stress. In athletic recovery, this could translate into faster restoration of spinal function, improved disc health, and a reduced risk of reinjury—particularly for individuals who participate in sports that impose high spinal demands, such as gymnastics, wrestling, football, and weightlifting.

Unlike water immersion, dry immersion prevents direct water contact by enclosing the patient in waterproof fabric, maintaining thermal and hygiene control while preserving microgravity analog properties. The passive nature of this approach allows for prolonged spinal unloading without patient effort, making it highly suitable for acute injury recovery, postsurgical care, or early-stage disc rehydration. Although the use of water immersion is currently limited to specialized facilities, portable or modular versions could be developed for rehabilitation clinics or high-performance training centers. Further validation of dosage, safety, and outcome metrics is needed before wide-scale adoption.

4.2. Integration with sports rehabilitation

In 2016, approximately 10% (31.6 million people) of the U.S. population reported having chronic LBP.^[76] Epidemiological studies estimate that 18% to 65% of athletes experience LBP during their careers.^[77] In addition, the total cost of LBP in the United States exceeds \$100 billion per year.^[78]

Simulated microgravity approaches offer a promising adjunct to conventional sports rehabilitation, particularly for athletes who endure repetitive spinal loading, high-impact collisions, and axial stress. The mechanical demands from sports activities could cause not only early-onset DDD but also chronic LBP, intervertebral disc stenosis, facet joint irritation, and neuromuscular dysfunction.

Conventional rehabilitation strategies for these conditions—such as core stabilization, manual therapy, nonsteroidal antiinflammatory drugs, and physical therapy—primarily focus on pain mitigation and symptom management. However, they often fall short in reversing structural deterioration or restoring disc integrity. Furthermore, limited spinal decompression, incomplete neuromuscular recovery, and persistent inflammation remain key barriers to full functional return in athletic populations.

Simulated microgravity offers a novel opportunity to integrate spinal unloading into sports rehabilitation in a way that addresses both mechanical dysfunction and structural compromise. By temporarily offloading the spine, microgravity analogs such as dry immersion and aquatic therapy can reduce vertebral compression, alleviate nerve impingement in stenotic regions, and provide a recovery environment conducive to tissue restoration. These interventions may support early-stage recovery from discogenic pain, spinal overload, or facet joint inflammation—conditions commonly seen in individuals who participate in sports such as wrestling, gymnastics, and weightlifting.

Importantly, simulated microgravity can serve as a pre-rehabilitation platform to reset mechanical alignment and reduce axial stress before reintroducing neuromuscular reeducation and load-bearing exercises. When combined with active therapies such as proprioceptive training, dynamic core stabilization, and manual spinal manipulation, microgravity analogs may enhance sensorimotor control and reduce the risk of recurrent dysfunction. They may also assist with deloading phases of periodized training or postcompetition recovery, facilitating earlier return-to-play by accelerating spinal recovery trajectories.

5. Analysis comparing microgravity therapy with conventional treatments

Unlike surgical options such as spinal fusion or disc replacement, microgravity therapy is noninvasive and directly addresses disc hydration. Surgical methods carry risks such as adjacent segment degeneration, whereas microgravity can restore disc height and flexibility without altering spinal mechanics. Additionally, surgeries such as fusion often limit spinal mobility, potentially shifting mechanical stress to adjacent segments and accelerating degeneration in nearby discs.^[79] In contrast, microgravity therapy may preserve segmental motion while enhancing tissue quality.

By using simulated microgravity—such as parabolic flight, water immersion therapy, and dry immersion therapy—patients can intermittently experience spinal decompression and disc rehydration without the need for real space travel. These techniques offer a more accessible and feasible approach for achieving the benefits of microgravity. They can be used periodically, depending on a patient's condition and therapeutic needs, providing relief from the constant compressive forces of gravity that contribute to disc degeneration and other spinal disorders. Compared with mechanical traction devices, which focus primarily on static elongation, microgravity methods create a full-body unloading state that may enhance systemic recovery and allow for passive rehydration throughout the entire spine.

This intermittent treatment strategy leverages the benefits of microgravity, whether real or simulated, and could offer a novel approach for managing spinal degenerative conditions. The incorporation of these treatments

into clinical practice could significantly improve patient outcomes by restoring disc height, relieving nerve compression, and preventing further degeneration—all while avoiding the long-term risks of prolonged microgravity exposure. This is particularly relevant for patients who fall between conservative care and surgical candidacy, where microgravity interventions could serve as bridge therapies to delay or eliminate the need for invasive procedures. Additionally, outcome measures such as the Oswestry Disability Index, VAS pain score and MRI-based disc hydration metrics could be used to monitor treatment response.

Importantly, while microgravity offers the potential for significant therapeutic benefits, these effects are inherently temporary. An integrated treatment approach is essential to address degenerative spinal diseases effectively. However, microgravity therapy alone is not sufficient; it must be combined with other interventions, such as postural muscle stability exercises, nutritional support, proprioception training, and functional rehabilitation. The synergy between mechanical unloading and active stabilization may help not only relieve symptoms but also reprogram dysfunctional motor patterns and reduce reinjury risk. This holistic approach can improve spinal health and support long-term recovery. As with other novel therapies, cost, access, and long-term efficacy should be carefully assessed through clinical trials before widespread implementation.

6. Controversies and limitations

The current body of evidence supporting microgravity-based interventions has important limitations. Among the 9 studies included in this review, 6 relied on *in vitro* or animal models, which may not adequately replicate the complex biomechanical and biochemical environment of the human spine. For example, studies using rat lumbar disc or L929 fibroblast cultures offer mechanistic insights but have limited translational applicability to athletes or patients with chronic spinal pathology.^[25,55] Sample sizes are also notably small across studies. The human investigations included 10 to 12 participants, often healthy male volunteers. These narrow demographics limit generalizability to broader populations, including females, elderly individuals, and individuals with preexisting spinal degeneration.

Study quality and methodological rigor vary, with limited use of control groups, randomization, or blinding procedures in many reports. There is also a lack of standardized protocols regarding exposure duration, frequency, or follow-up periods, making comparisons across studies difficult.

Importantly, some studies have suggested that microgravity may contribute to the degeneration of spinal discs,^[25,80] whereas other studies have shown that microgravity has no significant effect on vertebral discs.^[59,60] However, these conclusions remain subject to debate and are not entirely conclusive. For example, experiments

have reported decreases in GAG content under microgravity conditions; however, no significant changes in hydroxyproline levels—a key component of collagen—were observed. These discrepancies highlight the need to differentiate between the short-term and long-term effects of microgravity.

In the short term, microgravity conditions appear to promote disc swelling and increased hydration due to a reduced gravitational load on the spine. However, prolonged exposure to microgravity may result in a progressive reduction in proteoglycan expression accompanied by an increase in matrix metalloproteinases, enzymes associated with disc degeneration.^[25] Interestingly, one study examining fibrocartilage responses to microgravity revealed no microgravity-induced decrease in proteoglycans,^[58] further indicating discrepancies between short-term and long-term exposure outcomes.

Additionally, studies on needle puncture-induced disc degeneration and intradiscal saline injections have shown a significant increase in the expression of neutrophils and neuropeptides associated with pain.^[10,70,71,81,82] These findings raise important questions about how externally applied physical loads—such as microgravity conditions—can positively affect pain expression in damaged discs. To better understand this, it is crucial to distinguish between inflammation induced by experimental interventions such as needle puncture and that which arises naturally from disc degeneration. In experimental models, inflammation is caused by the physical trauma of the procedure itself, whereas in naturally occurring disc degeneration, it is driven primarily by dehydration and disc space narrowing.

7. Future research directions

Several areas of investigation warrant further attention to advance the clinical translation of microgravity-based therapies for spinal rehabilitation and athletic recovery. First, *in vitro* studies are needed to examine the cellular and molecular responses of intervertebral disc cells subjected to short-term simulated microgravity. These studies could clarify how microgravity influences proteoglycan synthesis, ECM remodeling, and overall disc cell behavior in controlled environments.

Second, animal model research should be expanded to evaluate structural and biomechanical changes in intervertebral discs exposed to microgravity. Such studies would offer critical insights into the tissue adaptation process, including disc height restoration, hydration dynamics, and the progression or reversal of degeneration over time.

Third, well-designed clinical trials are essential to validate the safety, feasibility, and efficacy of simulated microgravity therapies in human subjects. These trials should aim to determine the optimal exposure duration, therapeutic frequency, and selection criteria for patients with disc degeneration or chronic spinal conditions. Key outcomes should include disc height improvement, pain reduction, functional recovery, and reinjury prevention.

Finally, future research should explore how microgravity therapy can be integrated with other established rehabilitation modalities. The combination of short-term microgravity exposure with chiropractic care, core stabilization exercises, proprioceptive training, and nutritional support may have synergistic effects that enhance recovery outcomes. Investigating the effects of these integrated treatment strategies will be essential for developing comprehensive, multidisciplinary rehabilitation protocols that maximize patient benefit.

8. Conclusion

Short-term microgravity may play a potential therapeutic role in managing spinal degenerative conditions, with a particular focus on disc hydration, spinal decompression, and nerve relief. While microgravity has traditionally been associated with adverse effects on musculoskeletal health, emerging evidence suggests that brief, controlled exposure may temporarily reverse some pathological changes associated with disc degeneration. Mechanistically, microgravity promotes disc hydration, increases proteoglycan synthesis, and may activate reparative signaling pathways such as the TGF- β /Smad3 pathway. These effects may alleviate pain, restore disc height, and reduce spinal loading, which are particularly relevant for athletes exposed to high-impact or repeated axial stress.

Clinical applications of simulated microgravity, including parabolic flight, water immersion, and dry immersion protocols, offer promising adjuncts to conventional rehabilitation. These modalities may facilitate early recovery, support intervertebral disc health, and reduce downtime for athletes. When integrated into multimodal rehabilitation strategies that include chiropractic care, strength training, and proprioceptive conditioning, simulated microgravity may contribute meaningfully to long-term spinal function and injury prevention.

Despite these promising insights, several controversies and limitations remain. Importantly, the current evidence base is preliminary, and many of the proposed benefits remain hypothetical until they are validated in larger clinical and translational studies. The long-term safety, cost-effectiveness, and accessibility of simulated microgravity interventions must be addressed. Furthermore, more robust clinical and translational research is needed to establish standardized protocols and evaluate long-term outcomes. Nevertheless, simulated microgravity presents a novel and underexplored approach to spine care and athletic recovery, with the potential to transform the management of disc health and athletic recovery in both clinical and high-performance settings.

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Ethical statement

This review article does not involve any studies with human participants or animals conducted by the authors. All information presented was derived from previously published research and publicly available sources. Ethical approval and informed consent were therefore not required.

Conflicts of interest

The authors have no conflicts of interest to disclose.

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All data that support the findings of this study are included in this manuscript and its supplementary information files.

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