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Post-flight musculoskeletal reconditioning after spaceflight and microgravity analogues: a scoping review

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Table 5.1 is not available with this version

Post-flight musculoskeletal reconditioning after spaceflight and microgravity analogues: a scoping review

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Abstract

Musculoskeletal loss during spaceflight is well measured, while reconditioning after landing has rarely been studied. In 2016 the European Space Agency listed the unknowns of recovery from six-month missions, still unmet in 2023. This scoping review maps exercise-based reconditioning evidence from the recovery phase after spaceflight or a ground-based analogue against that agenda. Thirteen reports met the criteria, four of spaceflight and nine of bed rest. Their 32 results fall on four of eight in-scope parameters, and spine, cartilage and injury carry none. They completed 88 of 143 prescription fields, none stated a stopping criterion, and nine stopped measuring by the programme's last day. Most recovery-phase data were collected by studies designed for other questions, and neither instruments nor thresholds have been standardised. Geriatric sarcopenia started from the same point and moved from a first consensus to outcome-tested cut-points within ten years, a path space medicine could follow.

Introduction

Musculoskeletal loss during spaceflight is well characterised, and in-flight exercise countermeasures have been synthesised repeatedly, as a systematic review with meta-analysis[1], as a systematic scoping review spanning human and animal studies[2] and as a review of mechanisms and gaps[3]. The first two take the exposure period as their subject. Comfort et al.[1] reported large decreases in lower-limb force production and muscle size despite current in-flight exercise, so crews land with deficits still to be recovered.

How those deficits recover is a different problem from how they arose in flight. In flight, gravity is absent and bone and muscle are unloaded. On landing, gravity and body weight return and both are reloaded. Recovery under that load is neither uniform nor assured. Twelve months after International Space Station (ISS) missions, tibial cortical porosity and trabecular bone had not recovered at weight-bearing sites and had deteriorated further at non-weight-bearing sites[4], and the window for refilling resorption sites appears limited[5]. At the same time the sensorimotor system is readapting to gravity, and balance is at its worst. Postural control comes to rely more on somatosensory input than pre-flight (short-duration missions)[6], and on landing day astronauts' walk-and-turn and tandem-walk performance was comparable to that of individuals with bilateral

vestibulopathy[7]. Load therefore returns to a system of reduced capacity at the moment postural control is least reliable. None of this occurs in flight, so the period needs evidence of its own. The 2016 knowledge-gap table of the European Space Agency (ESA), its Table 5.1, lists injury among its eleven parameters.

Recovery after landing is organised, but thinly documented. ESA delivers a daily two-hour supervised programme, beginning within a day of landing and running for about 21 days, extendable to 45, staffed by a physiotherapist and exercise specialists[8,9]. A 45-day programme at two hours per working day has been described for NASA's ISS returnees, though that account predates the advanced resistive exercise device. For the agencies whose programmes are published, every returning crew member goes through reconditioning as part of standard medical care. Crews receive the programme, but the programme itself has not been the object of research. ESA's own 2016 agenda records that the effectiveness of its programme had yet to be investigated, and the recovery period has left far less literature than in-flight exercise.

Three earlier syntheses come close to this question, but none addresses it directly. The review by Payne, Williams and Trudel[10] is the only overview of spaceflight rehabilitation as such that our collision search retrieved, a narrative account published nine years before the 2016 agenda, spanning orthostatic, bone, muscular and neurovestibular impairments together. Ekman et al.[8], of the ESA Space Medicine Team, systematically reviewed recovery after head-down-tilt bed rest, but extracted only from passive control groups and admitted no spaceflight study, so they traced the natural-history curve and left the reconditioned curve unmapped. Padilha et al.[11] did meta-analyse exercise delivered after disuse, but fitted no post-spaceflight model, because their post-disuse evidence is four post-hospitalisation rehabilitation trials and one in-bed-rest countermeasure trial, with muscle-only outcomes. We identified no review using systematic or scoping methods that has examined recovery-phase reconditioning interventions themselves. The nearest registered work is lumbar-spine only and effectiveness-oriented (PROSPERO CRD420261452151).

That agenda dates from June 2016, when the ESA Post-mission Exercise (Reconditioning) Topical Team reported what was not known[12]. Its Table 5.1 sets out the gaps across eleven parameters for crew returning from six-month ISS missions. Eight fall within this review's scope, major muscle groups, postural muscles, cartilage, bone mineral density, spine, injury, functional performance and psychological status, with the last retained because its gap question asks about motivation and adherence to self-guided reconditioning once supervision ends. Orthostatic intolerance, sensorimotor function and aerobic capacity concern other physiological systems and are outside it. The report noted that studies of reconditioning after bed rest were lacking, and recommended standardised outcome measures with agreed time points and an evaluation of current post-ISS programmes. In the accompanying themed issue of Musculoskeletal Science and Practice, Beard and Cook[13] argued that systematic reviews would be an essential component of this research.

Seven years later, in 2023, Liphardt and colleagues[14], writing with a co-chair of the 2016 Topical Team, restated the unmet needs under the heading "Post-flight – the forgotten period", noting that for skeletal muscle function virtually no post-flight data exist beyond the first few months after landing. In 2025 a review of countermeasures still recorded the near absence of protocols addressing readaptation and post-flight injury prevention[3]. Exploration missions will lengthen

the unloading that precedes reconditioning. This review therefore asks what was named as missing in 2016, what was still missing in 2023, and what the literature had delivered by 2026.

Within that frame we asked three questions. What evidence exists on musculoskeletal reconditioning delivered during the recovery phase after spaceflight or a ground-based microgravity analogue, and how does it map onto ESA Table 5.1? How completely is the exercise prescription reported? And which outcome instruments and time points are in use, with what measurement-property evidence behind them? The review maps the extent, range and nature of the evidence against that agenda. It pools no effect estimates and cannot determine what reconditioning achieves.

Results

Study selection

Searches of PubMed, the EBSCO Discovery Service and Embase retrieved 1,454 records, of which 1,390 were obtained and entered deduplication and screening. The remaining 64 could not be exported from the search platforms at the time of the search, so they did not enter screening and their eligibility is unknown (Methods, Figure 1). Removal of 711 duplicates left 679 unique records, of which 562 were excluded and 117 carried forward. Seven reports met the eligibility criteria at the first full-text pass. The 105 records excluded under rule (iii) at title and abstract were then re-examined at full text, and Figure 1 counts them among the 117 records carried forward. Two were conference abstracts, one preprint had been withdrawn by its repository, and six of the 102 read met the criteria, thirteen reports in all. A further 109 excluded records were retained as background material. Figure 1 shows the flow. All nine analogue reports are bed-rest studies, because the six records of the other two admitted analogues that passed title-and-abstract screening, five of dry immersion and one of parabolic flight, had all measured recovery-phase outcomes without a recovery-phase intervention being delivered and were retained as background material under rule (iii) (Methods).

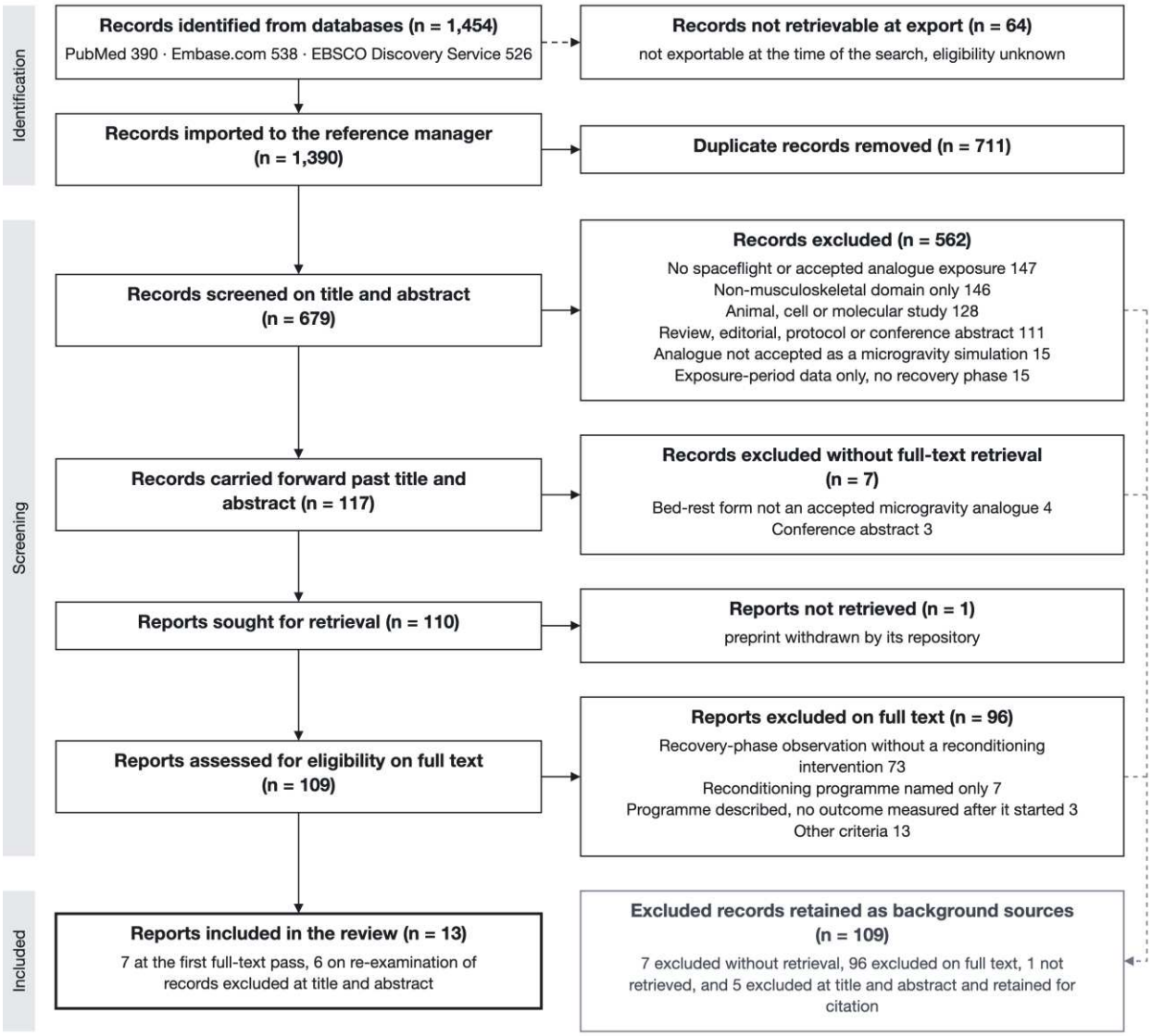


Figure 1. Flow of records through the review. Of 1,454 records retrieved, 1,390 were obtained and entered deduplication and screening. The 64 records that could not be exported from the search platforms are shown in their own box. The 105 records excluded at title and abstract for want of a recovery-phase reconditioning intervention were re-examined at full text and six met the criteria, giving thirteen included reports. The 109 excluded records retained as background sources are cited in the Introduction and Discussion.

The exposures and cohorts that generated the evidence

Four sources report spaceflight and nine a ground analogue, and the unloading stimulus differs across the set by roughly two orders of magnitude, from 3 days of −6° head-down tilt to approximately 180 days of orbital flight (Table 1). Seven of the thirteen sit inside randomised designs. In six the randomised contrast was the countermeasure given during unloading, as in Schoenrock et al.[15], and one of the six is a substudy drawn from the control arm of another trial. Only De Martino et al.[16] randomised how reconditioning was delivered, between two programmes (Table 1), so the set has no between-participant un-reconditioned comparator. The one un-reconditioned contrast is within-limb, Shur et al.[17]'s ambulation-only contralateral leg,

inside the shortest exposure here. The four spaceflight sources are two single-case reports, one NASA series of ten astronauts and one ESA series of five astronauts across seven long-duration ISS missions. Taken at face value that is seventeen crew members, but the four sources are not certainly four independent participant sets. The two case reports described a 38-year-old man of the same stature and body mass returning from a mission of the same length under the same agency programme, and neither stated an Increment or Expedition number, so they may describe one astronaut. Whether that astronaut is also among the series' five cannot be settled either way, because that source reported no ages and no crew identifiers. The same source stated its own denominator inconsistently, five astronauts across seven missions in its abstract, methods and results and six across eight in the caption of its Table 1. The first is charted and the second recorded. The spaceflight evidence therefore rests on fifteen to seventeen crew members, and the published texts cannot close either bound. The nine analogue reports draw on six bed-rest cohorts and 100 distinct participants, nine of them women. Schoenrock et al.[15] and Kramer et al.[18] report the same RSL cohort, the 60-day reactive-jump bed-rest study at the German Aerospace Center (DLR) in Cologne, and De Martino et al.[16], Grassi et al.[19] and Wesselink et al.[20] the same AGBRESA cohort, the Artificial Gravity Bed Rest Study with the European Space Agency. For these reasons the unit of analysis throughout is the report.

Table 1

Exposure, cohort and recovery-phase programme, by axis

Source	Design	Exposure	Contributing recovery data	Sex and mean age (y)	Conditions during exposure	Programme window	Sessions	Prescription fields reported (of 11)
Spaceflight, days after landing								
Hides 2016[21]	Case report	ISS ~180 d	1 astronaut	1 M 38	ARED plus treadmill or cycle ergometer squats, heel raises, deadlifts	Start NR first phase 3 weeks, second phase open-ended, total NR	Daily, 120 min	7
Petersen 2017[22]	Case report	ISS ~180 d	1 astronaut	1 M 38	Daily 2 h in-flight countermeasure exercise	R+1 to R+21	Daily 90 min in the programme template, 120 min in this crew member's own schedule	10
Hides 2021[23]	Prospective longitudinal series	ISS ~180 d, 7 missions	5 astronauts	4 M, 1 F NR	ISS countermeasures including ARED, monitored from Earth by the ESA physiotherapist and sports scientist via video downlink	R+1 15 d measured, ESA first phase 21 d	Daily, 120 min	8
Sibonga 2020[24]	Prospective observational surveillance study (pilot QCT study)	ISS missions ≥ 45 d (study mean 157 ± 21 d)	10 astronauts	48 ± 5 sex distribution for the 10-person QCT sample NR	Participants were drawn from prior flight studies: ARED with or without alendronate, or Sprint aerobic/resistive exercise versus standard ARED	Routine NASA post-flight reconditioning, 45 d exact start day and individual schedule NR	Typically 2 h 7 d/week for at least the first 2 weeks, then 5 d/week to day 45	6
Analogue, days after the end of unloading								
Schoenrock 2018[15]	Randomised bed-rest trial the same recovery protocol given to both arms	HDT bed rest, 60 d, −6°	23 of 24 randomised	23 M CTR 28.30 ± 5.76 / JUMP 29.90 ± 6.57	Reactive sledge jumps, 48 sessions (JUMP) none (CTR)	R+0 to R+14 (15 d reconditioning) sessions R+2 to R+14	6 sessions, 30 min	6
Scott 2020[25]	Prespecified substudy of a randomised trial (control arm)	HDT bed rest, 70 d, −6°	9	8 M, 1 F 36 ± 6	Twice-daily stretching, alternate-day massage no exercise countermeasure	R+0, 11 d (BR+1 to BR+11 in the source)	11 consecutive days, no rest day (day 6 reduced-load)	8

Source	Design	Exposure	Contributing recovery data	Sex and mean age (y)	Conditions during exposure	Programme window	Sessions	Prescription fields reported (of 11)
							total session duration NR	
De Martino 2022[16]	Randomised comparison of two reconditioning programmes	HDT bed rest, 60 d, angle not stated	24 (12 per arm)	16 M, 8 F 35 ± 10 / 32 ± 9	Short-radius centrifugation one randomised arm received none	Standard R+4 to R+11 FRED R+1 to R+13	Standard 7 × 60 min FRED 13 daily, 6 → 25 min	9
Shur 2024[17]	Within-participant contralateral-limb comparison	HDT bed rest, 3 d, −6°	10	10 M 24 ± 1	None	R+0, 3 d	Daily, 5 × 30 reps session duration NR	7
Martin-Rodriguez 2026[26]	Randomised, three-group bed-rest study	HDT bed rest, 60 d, −6°	24	24 M (control 29 ± 7 EX 30 ± 5 EX-AG 30 ± 6)	Artificial-gravity intervention arms during bed rest	R+0 to R+13 (14 d)	Daily supervised rehabilitation, ~45 min	8
Grassi 2024[19]	AGBRESA secondary analysis of real-world walking speed	HDT bed rest, 60 d, −6°	22 of 24	8 F, 16 M of the 24 randomised (control 2F/6M cAG 3F/5M iAG 3F/5M)	AGBRESA artificial-gravity allocation standard reconditioning in recovery, with FRED in 12/24	Daily recovery walking-speed measurements R+0 to R+13 additional follow-ups R+21 to R+28 and R+83 to R+90	30 min daily FRED in 12/24	4
Kramer 2017[18]	RSL study report, companion to Schoenrock et al.[15]	HDT bed rest, 60 d, −6°	23	23 M JUMP 30 ± 7 CTR 28 ± 6	JUMP: high-intensity jump training during HDT, 5–6 sessions/week. CTR: no jump-training countermeasure	R+2 to R+14	Six 30-min multifocal reconditioning sessions	8
Šimunič 2019[27]	Bed-rest recovery study	HDT bed rest, 35 d, −6°	10	10 M 24.3 ± 2.6	35-day, −6° HDT bed rest no exercise countermeasure during bed rest passive physiotherapy three times weekly.	30 d supervised recovery	12 sessions, 3/week, ~60 min	5
Wesselink 2025[20]	Secondary analysis using computer-vision muscle segmentation	HDT bed rest, 60 d AGBRESA cohort	24	16 M, 8 F NR	AGBRESA, 60-day, −6° HDT bed rest. Same exposure-period groups as the companion De Martino report	Recovery endpoint R+13	Standard reconditioning FRED allocation as reported in the AGBRESA protocol	2

Note. Design, comparator and baseline availability are recorded as reported. The final column counts the prescription fields reported by each source, of the eleven defined in the Methods. Where a source gives two values for one field (Petersen et al.[22], session duration) both are shown. Charting decisions for individual entries are given in the notes to Supplementary Table 1. Abbreviations. NR, not reported. HDT, head-down tilt, with HDT+n day n of bed rest. FRED, Functional Re-adaptive Exercise Device. ARED, Advanced Resistive Exercise Device. QCT, quantitative computed tomography. RSL, 60-day reactive-jump bed-rest study, DLR Cologne, 2015–2016. AGBRESA, Artificial Gravity Bed Rest Study with the European Space Agency, DLR Cologne, 2019–2020. ISS, International Space Station.

Sex was reported by twelve of the thirteen sources, all except Sibonga et al.[24], and a mean age by eleven. Analogue cohort means run 24 ± 1 y to 36 ± 6 y. The flown ages are 38 y in both case reports[21,22] and 48 ± 5 y in the NASA series, and even the younger of these lies fourteen years above the youngest analogue cohort mean and two above the oldest. Hides et al.[23] and Wesselink et al.[20] reported no age.

Mapping onto ESA Table 5.1

The thirteen reports yielded 32 charted results, which Table 2 maps onto the eleven parameters of ESA Table 5.1. Eight parameters are within this review's scope, and orthostatic intolerance, sensorimotor function and aerobic capacity were not charted, so the review does not record whether the included studies measured them. The 32 results, twelve from spaceflight and twenty from analogue exposure, fall on four of the eight rows, postural muscles (16 results from 7 studies), major muscle groups (12 from 8), functional performance (3 from 3) and bone mineral density (2 from 1). The other four rows, cartilage, spine, injury and psychological status, carry no result. Thirty-one of the 32 results have a pre-exposure baseline. The exception is the myotonometry result, whose baseline is HDT+1, the first day of bed rest, so it carries no recovery-to-baseline verdict (Table 3). That result spans postural and major muscle groups and is charted under both, so the rows of Table 2 total 33 assignments for 32 results. Against the definitions fixed in advance (Methods), the four occupied rows are addressed and the four empty rows unaddressed.

Table 2

Charted intervention-phase results and background sources against the eleven parameters of ESA Table 5.1

#	ESA Table 5.1 parameter	Position in the report's table	In scope	Classification	Intervention results ■ spaceflight □ analogue	Spaceflight (results / studies)	Analogue (results / studies)	Total (results / studies)	Background sources
1	Major Muscle Groups	under *Musculoskeletal System*	yes	Addressed[a]	■■■□□□□□□□□□	3 / 2	9 / 6	12 / 8	11
2	Postural muscles	under *Musculoskeletal System*	yes	Addressed[a]	■■■■■□□□□□□□□□	6 / 3	10 / 4	16 / 7	7
3	Cartilage	under *Musculoskeletal System*	yes	Unaddressed	*none*	0 / 0	0 / 0	0 / 0	6
4	Bone Mineral Density	under *Musculoskeletal System*	yes	Addressed	■■	2 / 1	0 / 0	2 / 1	28
5	Spine	under *Musculoskeletal System*	yes	Unaddressed	*none*	0 / 0	0 / 0	0 / 0	8
6	Injury	under *Musculoskeletal System*	yes	Unaddressed	*none*	0 / 0	0 / 0	0 / 0	2
7	Orthostatic Intolerance	table margin	no, outside this review's scope	not classified	not charted	not charted	not charted	not charted	no corresponding group
8	Sensorimotor Function	table margin	no, outside this review's scope	not classified	not charted	not charted	not charted	not charted	13
9	Functional Performance	table margin	yes	Addressed	■□□	1 / 1	2 / 2	3 / 3	19
10	Aerobic Capacity	table margin	no, outside this review's scope	not classified	not charted	not charted	not charted	not charted	no corresponding group
11	Psychological Status	table margin	yes	Unaddressed[b]	*none*	0 / 0	0 / 0	0 / 0	0
	Total, the eight parameters within scope			4 addressed / 4 unaddressed		12 / 4	20 / 9	32 / 13	81

Note. Rows follow Table 5.1 of the ESA Post-mission Exercise (Reconditioning) Topical Team final report of 30 June 2016, in its labels and order, with six rows under its Musculoskeletal System header and five at the table margin. Rows 7, 8 and 10 lie outside this review's scope. The intervention columns count charted results and contributing studies from the outcome-level charting form, spaceflight and analogue separately. Filled squares are spaceflight results and open squares analogue results. Rows count assignments. One result, myotonometry spanning postural and major muscle groups, is charted under both, so 32 results give 33 assignments. The classification column applies the three-level definitions fixed in the Methods. The background column counts the 109 excluded records retained as background, grouped by the parameter most prominent in each record's title and abstract. Of the 109, 81 fall under a parameter within scope, 13 under sensorimotor function and 15 under no parameter of the ESA table, namely two multi-system reports, two agency programme descriptions, four horizontal bed-rest records and seven records retained as designated background citations.

[a] Classified as addressed under the pre-specified definitions after discussion of two independent classifications that had at first differed. The row's knowledge-gap questions themselves remain open.

[b] Unaddressed by definition and closed by an eligibility rule, since studies reporting only psychological outcomes were excluded.

The four empty rows are empty for different reasons. Cartilage is empty by coding, since two Schoenrock et al.[15] results bear on connective tissue, Achilles tendon and plantar fascia mechanics and intramuscular collagen-1, but the tendon and fascia points sit inside the myotonometry result charted under the two muscle parameters, and the collagen-1 result is charted under postural muscles because that source named soleus its postural reference muscle. Psychological status is empty partly by eligibility rule, since studies reporting only psychological outcomes were excluded at screening (Methods), and partly because none of the thirteen reports measured a psychological outcome alongside a musculoskeletal one. Spine is empty because the four reports that measured the lumbar region measured its musculature, lumbar multifidus, erector spinae, quadratus lumborum, psoas major, the anterolateral abdominal muscles and paraspinal fat, all charted under postural muscles, and none measured spinal shape, spinal bone mineral density or the intervertebral discs. Injury carries no charted result from the included studies.

Outcomes by tissue and construct

The 32 results fall into five constructs, muscle size, muscle composition, passive mechanical properties, protein turnover, and function and capacity, and within each the instruments do not convert into one another (Table 3, Supplementary Table 1). Muscle size was measured as seven quantities on three modalities, whole-leg volume by magnetic resonance imaging (MRI)[17], mean axial cross-sectional area traced across eight muscles[25], segmental volume by intervertebral level[16], level-specific cross-sectional area and anterolateral abdominal thickness by ultrasound[21,23], muscle thickness and pennation angle by ultrasound[27], and lean mass or fat-free mass index by dual-energy X-ray absorptiometry (DXA)[18,24,26], and no arithmetic converts one into another. Ultrasound resolves an abdominal-wall layer no MRI protocol here imaged, while MRI integrates whole muscles that ultrasound cannot follow end to end. The region of interest also matters, since in Scott et al.[25] the grouped quadriceps was below baseline at BR+10 while vastus lateralis, traced from the same images, was not, and rectus femoris, also inside that region, never declined. The same source counted the muscles that recovered in two ways, four in its results and three in its discussion, and both statements are recorded.

Table 3

Charted results, by tissue and construct: baseline, direction and status at the last measurement

Construct	Source	Axis	Time points	Baseline	Direction and size, as reported	Status at last measurement
Whole-leg muscle volume	Shur 2024	Analogue	Pre-BR end of BR R+4	Y	−2.5 to −2.6% after 3 d bed rest at R+4, exercised leg −0.7%, ambulation-only leg −2.3% vs pre-BR	Exercised leg returned ambulation-only leg not returned
Myofibrillar protein FSR	Shur 2024	Analogue	Bed rest d 0–1, 1–3 across remobilisation	Y	−43% during bed rest across remobilisation, exercised leg at pre-BR rate, non-exercised leg 35% lower	Exercised leg returned non-exercised leg not returned
Mean axial CSA, quadriceps, hamstrings, adductors, RF, VL	Scott 2020	Analogue	BR−6 nine points during BR+3, +6, +10	Y	At BR+10: quadriceps −3.74 cm² (95% CI −7.36 to −0.12), hamstrings −2.30 (−4.07 to −0.54) RF (no decline at any point), VL and adductors not different from baseline	Not returned (quadriceps, hamstrings)
Mean axial CSA, soleus, medial and lateral gastrocnemius	Scott 2020	Analogue	as above	Y	At BR+10: soleus −1.85 cm² (−2.90 to −0.81), medial gastrocnemius −0.62 (−1.10 to −0.14) lateral gastrocnemius not different. Highest atrophy rate during bed rest in soleus (−0.33%/d)	Not returned (soleus, medial gastrocnemius)
Lumbar multifidus volume by level	De Martino 2022	Analogue	BDC HDT+59 R+13	Y	At R+13 vs BDC, multifidus at L4/L5 and L5/S1 differed	Not returned
Lumbar erector spinae, quadratus lumborum and psoas major volume	De Martino 2022	Analogue	BDC HDT+59 R+13	Y	At R+13 vs BDC, lumbar erector spinae at L1/L2 and quadratus lumborum at L3/L4 differed psoas major at L1/L2 larger than baseline	Not returned
Paraspinal fat content	De Martino 2022	Analogue	BDC HDT+59 R+13	Y	Centro-medial multifidus at L4/L5 and L5/S1 higher at R+13 than BDC	Not returned
Passive tone, stiffness, elasticity, relaxation	Schoenrock 2018	Analogue	HDT+1, +10, +20, +29, +39, +49, +59 R+10, no pre-bed-rest value enters the analysis	Not pre-exposure analysis baseline HDT+1, already in −6° head-down tilt	Greatest changes in thigh and calf muscle and tendon, little change in shoulder muscles at R+10 trapezius in the JUMP arm still showed altered tone and relaxation	Partly reversed at R+10 relative to HDT+59, tone closer to the HDT+1 value in the JUMP group than in CTR, trapezius tone and relaxation still altered in JUMP no return to a pre-exposure value can be stated for this row
Intramuscular collagen-1	Schoenrock 2018	Analogue	BDC−5 HDT+59 R+10	Y, genuine pre-	Increased anti-collagen-1 immunoreactivity in CTR soleus at HDT+59, absent in JUMP	Not returned, CTR immunoreactivity at R+10 remained above its BDC−5

Construct	Source	Axis	Time points	Baseline	Direction and size, as reported	Status at last measurement
				exposure baseline, unlike the myotono metry row above	CTR–JUMP difference P < 0.001 at HDT+59 and R+10	value (≈62 vs ≈50 a.u., read from the source's bar chart)
Multifidus CSA L2–L5	Hides 2016	Spaceflight	Pre-flight R+1 R+8 R+14	Y	Size maintained at L2–L4 in flight L5 reduced after flight, at pre-mission size by R+14	Returned (L5)
TrA and IO thickness	Hides 2016	Spaceflight	as above	Y	TrA reduced and IO increased after flight at R+14 TrA increased and IO decreased, restoring the balance with multifidus	Returned
Multifidus CSA L2–L5	Hides 2021	Spaceflight	Pre-flight R+1 R+8 R+15	Y	In flight L3 −12.6%, L4 −6.1%, L5 −10.3% (L2 unchanged) increased again during reconditioning (P < 0.001)	L3–L5 returned by R+15 L2 15.3% larger than pre-flight
TrA, IO, EO thickness	Hides 2021	Spaceflight	as above	Y	In flight TrA −34.1%, IO −15.4%, combined −16.2% increased again during reconditioning (TrA P < 0.008 combined P = 0.035)	Returned
Multifidus voluntary contraction	Hides 2021	Spaceflight	as above	Y	In flight L2 12.8% → 3.4%, L3 12.2% → 5% L2 increased again after reconditioning (P = 0.046)	Partial L3 not stated
1RM squat and bench press	Petersen 2017	Spaceflight	L−52 d R+6 R+21	Y	Squat 148 → 134 → 147 kg, bench 108 → 99 → 105 kg: ≈ −8 to −9% at R+6 −1% and −3% at R+21, both inside the 5–10% day-to-day band the source itself cited for this instrument	Near-complete
Jump height and force (CMJ, SJ, DJ)	Petersen 2017	Spaceflight	as above	Y	All three reduced at R+6, largest in drop jump (height −31%, force −34%). Residuals at R+21 from the source's own table: height −15%, −9%, −14% peak force −12%, −21%, −7%. CMJ peak force did not move in one direction, 2,070 N at L−52, 2,141 N at R+6 (+3%), 1,827 N at R+21 (−12%)	Not returned, no jump parameter had returned by R+21
Hip flexibility	Petersen 2017	Spaceflight	as above	Y	Sit and Reach 37 → 31 → 36 cm (−16% at R+6, −3% at R+21) Thomas Test right 32 → 33 → 27° (+3%, −16%) and left 30 → 30 → 23° (0%, −23%)	Instrument-dependent and contradictory Sit and Reach near-complete, Thomas Test further from pre-flight at R+21 than at R+6. Fits none

Construct	Source	Axis	Time points	Baseline	Direction and size, as reported	Status at last measurement
						of the categories used in this column
Core endurance	Petersen 2017	Spaceflight	as above	Y	Ventral hold 260 → 262 → 251 s no deficit from pre-flight recorded at either measurement	No deficit recorded
Lower-body fat-free mass index (FFMI)	Martin-Rodriguez 2026	Analogue	BDC−2 HDT+16, HDT+32, HDT+44, HDT+56 R+3 (R+11 acquired, not reported)	Y	At R+3, lower-body FFMI remained below baseline in all groups: control −0.40, exercise −0.28, exercise + artificial gravity −0.17 $kg \cdot m^{-2}$ exercise attenuated loss versus control.	Not returned at R+3
Maximal voluntary isometric contraction torque	Martin-Rodriguez 2026	Analogue	BDC−4 R+2	Y	Knee and ankle torque declined in all groups no group-by-time interaction for ankle extension or flexion.	Not returned at R+2
Countermovement jump performance	Martin-Rodriguez 2026	Analogue	BDC−3 R+0	Y	Explosive performance declined after bed rest no group differences were reported.	Not returned at R+0
Real-world walking speed	Grassi 2024	Analogue	Pre-bed-rest daily R+0 to R+13 R+21 to R+28 R+83 to R+90	Y	Mean walking speed fell 13% during the 13-day post-bed-rest period (0.96 to 0.84 m/s), then increased by approximately 0.009 m/s per day no difference between FRED and no-FRED participants.	Returned by R+21 to R+28 and R+83 to R+90
Total-body lean mass	Kramer 2017	Analogue	BDC−3 HDT+60 R+7 (R+14)	Y	Lean mass was preserved in JUMP (56.4 kg at BDC−3 and R+7) CTR declined from 56.9 kg to 55.4 kg at R+7 after reaching 53.0 kg at HDT+60.	Mixed by group: JUMP preserved CTR remained below baseline at R+7
Muscle thickness and pennation angle	Šimunič 2019	Analogue	BDC BR1–BR10, BR16, BR28, BR35 R+1, R+3, R+30	Y	Muscle thickness declined by 4.5–15.2% during bed rest and returned by R+30 pennation angle fell 13–17% and returned by R+30 in the reported muscles.	Returned by R+30 for thickness and reported pennation-angle measures
Twitch contractile properties (Dm and Tc)	Šimunič 2019	Analogue	BDC BR1–BR10, BR16, BR28, BR35 R+1, R+3, R+30	Y	Dm rose 42–84% by BR35 and returned by R+3 biceps femoris contraction time remained prolonged at R+30 (+32.1% at BR35).	Mixed: Dm returned by R+3 biceps femoris Tc not returned at R+30
Lumbopelvic muscle fat fraction (spatial distribution)	Wesselink 2025	Analogue	BDC HDT+59 R+13	Y	LM elevated at L5/S1 deep centrolateral tile (T7 13.2 ± 15.5%, $P < 0.001$), LES elevated at upper L4 deep medial tile (T5 3.6 ± 5.9%, $P = 0.023$), QL elevated (T8 1.8 ± 3.2% $P = 0.033$)	Not returned in the identified deep regions at R+13

Construct	Source	Axis	Time points	Baseline	Direction and size, as reported	Status at last measurement
Psoas major fat fraction	Wesselink 2025	Analogue	BDC (2 d pre-HDT) HDT+59 R+13	Y	No significant differences in fat fraction at any tile or vertebral level during HDT+59 or R+13.	No significant change reported
Gluteus maximus fat fraction, upper and lower regions	Wesselink 2025	Analogue	BDC (2 d pre-HDT) HDT+59 R+13	Y	Fat fraction increased at HDT+59 in both regions: upper +1.0 ± 1.0% and lower +1.6 ± 1.7% (both $P < 0.05$).	Returned by R+13 no longer different from BDC ($P > 0.05$) in either region
Gluteus medius/minimus fat fraction, anterior and posterior regions	Wesselink 2025	Analogue	BDC (2 d pre-HDT) HDT+59 R+13	Y	No significant effect of bed rest or reconditioning in either muscle, either region, or either post-exposure time point.	No significant change reported
Trabecular volumetric BMD, total hip (QCT)	Sibonga 2020	Spaceflight	Pre-flight 30–45 d before launch first post-flight scan R+5–22 d (mean 11 ± 3 d) R+1 y conditional R+2 y if QCT vBMD had not recovered at R+1 y	Y	QCT showed incomplete trabecular vBMD recovery in 5/10 astronauts at R+1 y (deficit exceeded the 2.3% QCT least significant change) of those five, 4/5 remained unrecovered at R+2 y. The R+2 y scan was conditional	Not returned in 5/10 at R+1 y 4/5 of those at conditional R+2 y
Areal BMD, total hip (DXA)	Sibonga 2020	Spaceflight	Pre-flight 30–45 d before launch first post-flight scan R+5–22 d R+1 y	Y	DXA showed recovery or near-recovery of total-hip aBMD in 9/10 astronauts at R+1 y, judged against the 2.1% DXA least significant change.	Returned or within measurement error in 9/10 at R+1 y
Leg lean mass (DXA)	Sibonga 2020	Spaceflight	Pre-flight 30–45 d before launch first post-flight scan R+5–22 d (mean 11 ± 3 d) R+1 y	Y	From the first post-flight scan to R+1 y, leg lean mass changed by 0.1 to 3.4% in each of the ten astronauts, all within the 95% least significant change for serial measurements that the source cites	Within measurement error at R+1 y relative to the first post-flight scan, change from pre-flight not reported

Note. Direction and status are as the sources reported them. “Not returned” means the source reported a difference from the pre-exposure value at the last measurement. Thresholds were cited for three results only, a 5–10% day-to-day band for the 1RM row and modality-specific least significant changes for the two hip bone-density rows. Time points are as the sources give them. R+n is n days after landing or the end of unloading, BR+n n days after bed rest, BR−n and BDC−n n days before bed rest, HDT+n day n of head-down-tilt bed rest, BRn day n of bed rest in Šimunič et al.[27] and L−n n days before launch. Abbreviations. BR, bed rest. BDC, baseline data collection. HDT, head-down tilt. CMJ, countermovement jump. FRED, Functional Re-adaptive Exercise Device. QCT, quantitative computed tomography. DXA, dual-energy X-ray absorptiometry. 1RM, one-repetition maximum. CSA, cross-sectional area. TrA, transversus abdominis. IO, internal oblique. EO, external oblique. RF, rectus femoris. VL, vastus lateralis. FSR, fractional synthetic rate. LM, lumbar multifidus. LES, lumbar erector spinae. QL, quadratus lumborum. T5, T7, T8, tiles of the segmentation grid. Dm, maximal radial displacement. Tc, contraction time. SJ, squat jump. DJ, drop jump. vBMD, volumetric bone mineral density. aBMD, areal bone mineral density. CI, confidence interval. a.u., arbitrary units. JUMP, reactive-jump arm. CTR, control arm.

Muscle composition, passive mechanical properties and protein turnover were each measured in one to three studies, with instruments that have no counterpart elsewhere in the set. Composition was measured as paraspinal fat content by Dixon MRI[16], as lumbopelvic muscle fat fraction by computer-vision segmentation of Dixon MRI in the same cohort[20] and as intramuscular collagen-1 immunoreactivity on soleus biopsy cryosections[15], voxel-level fat measures in vivo and a stain intensity on a section that cannot be converted into one another. The collagen-1 result was reported only graphically, as a control–exercise difference with $P < 0.001$ at HDT+59 and at R+10 and no numeric value in the text. Passive mechanical properties were measured by Schoenrock et al.[15] with a hand-held myotonometer at 22 skin-marked points. The instrument records tone, dynamic stiffness, elasticity and stress-relaxation time of a superficial tissue column and yields no force, torque, area or volume, so it cannot share an axis with the size measures even for soleus and gastrocnemius, which were measured both ways in different studies. Protein turnover was measured by Shur et al.[17], who gave oral deuterium oxide with serial vastus lateralis microbiopsies to compute cumulative myofibrillar protein fractional synthetic rate across bed rest and across remobilisation. However, a fractional synthetic rate is integrated over an interval and cannot be aligned with a scan, which samples an instant, and it describes the protein synthesis behind a change in muscle size, which is a different quantity from the size.

Function and capacity were measured in four reports, two of them in spaceflight. Petersen et al.[22] applied the ESA Astronaut Fitness Assessment, a ten-test battery of flexibility, one-repetition maximum (1RM), jump and core-endurance measures (Supplementary Table 1), at L−52 d, R+6 and R+21. Hides et al.[23] measured multifidus voluntary contraction as contracted minus relaxed thickness on the same ultrasound images used for size. Martin-Rodriguez et al.[26] reported maximal voluntary isometric knee and ankle torque at R+2, and Grassi et al.[19] recorded real-world walking speed daily through R+13 and in two later weeks. A fifth report measured torque without reporting it. Scott et al.[25] assessed knee extension and flexion strength on an isokinetic dynamometer at BR−5, BR+2 and BR+10 but published only its correlation with muscle size, so the only dynamometric strength series spanning a recovery phase in this set is unpublished, charted as measured but not reported and outside the 32 results.

The spaceflight functional-performance result contradicts itself between two instruments. Petersen et al.[22] measured hip flexibility two ways on the same days. Sit and Reach, a composite forward-reach distance, ran 37 → 31 → 36 cm, 16% below pre-flight at R+6 and 3% below at R+21. The Thomas Test, a hip-angle measurement, ran 32 → 33 → 27° on the right and 30 → 30 → 23° on the left, at or above pre-flight at R+6 and 16% and 23% away from it at R+21. One instrument returned towards the pre-flight value while the other moved away from it, in the same participant, on the same two days, for the same construct. A reach distance integrates hip, lumbar spine, hamstring and thoracic contributions at once while a hip angle isolates one joint, and no arithmetic converts either into the other, so the result is recorded as instrument-dependent and contradictory, the one result of the 32 that fits none of the recovery categories in Table 3. The source stated no direction of benefit for the Thomas Test angle, so the residual is read as distance from pre-flight.

No combination of outcome metric and instrument recurs in three or more included studies. Two recur in two, multifidus cross-sectional area and anterolateral abdominal thickness, both by ultrasound, both in Hides et al.[21] and Hides et al.[23], which report the same ESA programme from the same group and may share a participant. The two recurrences therefore come from a single

measurement tradition. MRI appears in four reports from three datasets, on three sequences, and no metric recurs across datasets.

Completeness of the exercise prescription

Across eleven prescription fields the thirteen sources reported 88 of 143 entries (Table 1, final column, and Table 4). Exercise type was reported by all thirteen, session frequency and total programme duration by twelve, session duration by ten, individualisation and start point by nine, supervision by eight, a progression rule by seven, intensity by six and adherence by two. No included study stated a threshold at which reconditioning ends or a crew member is discharged, and the closest approach is a 45-minute walk on programme day 11, the final day, in Scott et al.[25]. The fields that thin out are the mechanical ones. No included source reported an external load in kilograms or as a percentage of 1RM for any resistance exercise delivered during the recovery phase. Three absolute mechanical variables appear in the set, Shur et al.[17]'s 90°/s at five sets of 30 maximal voluntary repetitions, De Martino et al.[16]'s Functional Re-adaptive Exercise Device (FRED) target of 0.42 rev/s with nothing added beyond bodyweight, and Scott et al.[25]'s sets and repetitions, typically 2 × 10 rising to 4 × 10. Petersen et al.[22] graded intensity only as low, low–medium and medium. Progression, where reported, is by repetitions, fixed schedule or phase description, and in no included study by a rule tied to a measured response.

Table 4

Prescription-field reporting, and what is missing mechanically

Field	Reported (of 13)	Note
Frequency	12	Schoenrock et al.[15]'s weekly rate is derived from "6 sessions, R+2 to R+14", not stated. Not reported by Wesselink et al.[20]
Type (modality, named exercises)	13	From one movement to a five-domain battery
Individualisation	9	Five individualised[15,18,21,22,23] one a standard protocol identical for every participant[17]two both, De Martino et al.[16] randomised to one of two fixed programmes and tailored individual exercises where a specific deficit was seen, and Martin-Rodriguez et al.[26] applied one framework to all with progression and intensity individually adjusted. Scott et al.[25] is internally inconsistent and is charted both ways: eTable 1 sets one day-by-day schedule with a column per day and none per participant, while the same supplement states that participants were provided individualised reconditioning exercises and gates plyometrics on tolerance. Neither reading is preferred, and the field is reported on either. Not reported by Grassi et al.[19], Šimunič et al.[27], Sibonga et al.[24] or Wesselink et al.[20]
Start point	9	Not reported by Hides et al.[21], Šimunič et al.[27] or Wesselink et al.[20]Grassi et al.[19] identified the recovery phase but did not state a specific R+ start day.
Total programme duration	12	Not reported by Hides et al.[21], which gave a three-week first phase and then a second, open-ended phase 3 to 45 d among the twelve that stated one. Schoenrock et al.[15] distinguished a 15-day reconditioning period (R+0 to R+14) from the 13-day window holding its six sessions
Intensity	6	Not stated by Schoenrock et al.[15]. No external load in kg or %1RM anywhere, and three absolute mechanical variables in the whole set. Two sources reported intensity only as reaching a level similar to pre-flight training by the end of the programme, which gives a benchmark without a quantity
Session duration	10	Not stated by Shur et al.[17], Wesselink et al.[20] or Scott et al.[25], the last having given the aerobic component only. Petersen et al.[22] gave two figures, a 90-minute programme template and a 120-minute schedule for this crew member, and the field is counted as reported

Field	Reported (of 13)	Note
Supervision	8	Reported by eight of the thirteen reports. Not stated for Schoenrock et al.[15]'s recovery programme, and not stated anywhere in Hides et al.[23], in which "supervis-" does not occur. Shur et al.[17] and Scott et al.[25] both stated supervision, the first in its supporting information, the second in its online supplement, and neither in the article itself Shur et al.[17] still did not name the profession
Progression rule	7	By repetitions, fixed schedule or phase description never tied to a measured response
Adherence	2	Petersen et al.[22] qualitative only, "excellent compliance to postflight reconditioning", with no figure and no stated method. Its three other compliance statements describe the in-flight period and are excluded from the cell *Kramer et al.[18] reported that one of the scheduled sessions was not performed, 99% delivered*
Stopping / discharge criteria	0	No threshold or consequence stated by any included source, searched in all thirteen full texts

Note. Fields sum to 88 of 143, and the per-study counts are in the final column of Table 1. Abbreviations. 1RM, one-repetition maximum.

Measurement-property evidence and interpretability

Measurement-property evidence was graded, as defined in the Methods, by what each source cited rather than by whether what it cited is fit for the outcome. Three sources cited it in full, Hides et al.[21] giving intra-rater intraclass correlation coefficients (ICCs) of 0.83–0.99 and inter-rater ICCs of 0.88–0.99 for their ultrasound measures, Hides et al.[23] intra-rater ICCs of 0.83–0.99 and a mean inter-rater ICC of 0.95 for the same measures, and Scott et al.[25] inter-experimenter coefficient of variation (CV) 2.8–3.8% and ICC 0.946–0.986 for MRI cross-sectional area tracing. Four cited it partially and one not at all (Supplementary Table 1, final column). No source cited a minimal clinically important difference for any charted outcome. Sibonga et al.[24] cited least significant changes of 2.3% for QCT and 2.1% for DXA, the measurement-error limits used to judge bone recovery, and Petersen et al.[22] quoted a day-to-day range of 5–10% for 1RM scores[28], within which its own R+21 residuals of −1% for squat and −3% for bench press lie. No other result has a source-specific threshold against which a residual difference can be judged.

Measurement time points

Nine of the thirteen reports made their last measurement on or before the final day of the programme they delivered, three measured after it ended, and Šimunič et al.[27] cannot be placed because its start day is not reported (Table 5, Panel A). Three reports also measured beyond R+21, Grassi et al.[19] monitoring real-world walking speed during recovery through R+83 to R+90, Šimunič et al.[27] measuring at R+1, R+3 and R+30 after reambulation, and Sibonga et al.[24] measuring hip bone mineral density by quantitative computed tomography (QCT) and DXA, and leg lean mass by DXA, at R+5–22 d and R+1 y, with QCT at R+2 y conditional on incomplete recovery at R+1 y. That conditional measurement is the latest in the included set, made long after the 45-day NASA programme had ended, and it is observational.

The 109 background sources, recovery-phase observation without a delivered intervention, programme descriptions without recovery-phase outcomes, and records failing the bed-rest-form or source-type criteria, record the recovery horizon without the intervention attached (Table 5,

Panel B). Of them, 34 measured a musculoskeletal or functional outcome later than the third week, 22 after spaceflight and 12 after analogue unloading, 21 reaching twelve months or more and one four years[29]. Among those 34 the programme delivered was fully prescribed in one, a 30-day follow-up after horizontal bed rest, excluded here on exposure form, partly described in two, named without content in two, and absent in 29. The pool was assembled as background reading, so it characterises the literature this review read and carries no absence claim of its own.

Table 5

Measurement horizons: the included studies against their own programmes (Panel A), and the background sources against the reconditioning described (Panel B)

Panel A. Measurement time points on their own axes, against the programme window, the thirteen included studies.

Source	Time points, as the source gives them	Programme window	Last measurement vs programme end
Spaceflight, days after landing (R+n)			
Hides 2016	Pre-flight R+1 R+8 R+14	Start NR first phase 3 weeks second phase open-ended, total NR	7 d before the first phase ended
Petersen 2017	L−52 d R+6 R+21	R+1 to R+21	On the final day
Hides 2021	Pre-flight R+1 R+8 R+15	R+1, ESA first phase 21 d	6 d before the phase ended
Sibonga 2020	Pre-flight R+5–22 d R+1 y conditional R+2 y	7 d/week for at least the first 2 weeks, then 5 d/week to day 45	R+1 y 320 d after R+45 conditional R+2 y is about 685 d after R+45
Analogue, days after the end of unloading (R+n)			
Schoenrock 2018	Myotonometry HDT+1, +10, +20, +29, +39, +49, +59 R+10. Biopsy BDC−5 HDT+59 R+10	R+0 to R+14 (15 d reconditioning) sessions R+2 to R+14	4 d before the programme ended
Scott 2020	BR−6 nine points during bed rest BR+3, +6, +10	R+0, 11 d (BR+1 to BR+11)	1 d before the programme ended
De Martino 2022	BDC HDT+59 R+13	Standard R+4 to R+11 FRED R+1 to R+13	On the final day
Shur 2024	Pre-bed-rest end of bed rest R+3 (biopsy) and R+4 (MRI)	R+0, 3 d	About 1 d after the programme ended
Martin-Rodriguez 2026	BDC−4 (MVC) BDC−3 (CMJ) BDC−2 HDT+16, +32, +44, +56	R+0 to R+13 (14 d structured rehabilitation)	10 d before the programme ended

Source	Time points, as the source gives them	Programme window	Last measurement vs programme end
	R+0 (CMJ, timing stated inconsistently by the source) R+2 (MVC) R+3 (DXA R+11 acquired but not reported)		
Grassi 2024	Pre-bed-rest daily R+0 to R+13 R+21 to R+28 and R+83 to R+90 (home weekly averages)	Recovery phase R+0 to R+13 standard reconditioning start day not stated in this report (R+4 to R+11 in the companion report, De Martino et al.[16]) FRED R+1 to R+13	77 d after the end of the longer programme window (R+90 vs R+13)
Kramer 2017	BDC−13, BDC−3 HDT+13, +30, +45, +60 R+7, R+14	Recovery R+0 to R+14 six sessions R+2 to R+14	On the final day of the session window (R+14)
Šimunič 2019	BDC BR1–BR10, BR16, BR28, BR35 R+1, R+3, R+30	30 d of recovery	Programme start day is not reported last measurement R+30
Wesselink 2025	BDC HDT+59 R+13	Standard reconditioning R+4 to R+11 SR+FRED R+1 to R+13 (AGBRESA companion programme)	On the final day of the longer programme window (R+13)

Panel B. Follow-up horizon against completeness of the reconditioning description, the 34 background sources that measured beyond the third week.

Follow-up beyond the third week	Nothing	Named only	Partly described	Fully prescribed	Total
Spaceflight, days after landing					
> 3 weeks to < 3 months	6	0	0	0	6
3 to < 12 months	1	0	0	0	1
≥ 12 months	13	2	0	0	15
Subtotal	20	2	0	0	22
Analogue, days after the end of unloading					
> 3 weeks to < 3 months	2	0	0	1	3
3 to < 12 months	1	0	2	0	3
≥ 12 months	6	0	0	0	6
Subtotal	9	0	2	1	12
All 34 sources	29	2	2	1	34
Read in full text, spaceflight	9	2	0	0	11
Read in full text, analogue	3	0	2	1	6
Full-text subset	12	2	2	1	17

Note. Panel A sets each included report's programme duration against its own last measurement. Panel B sets the follow-up horizon of the 34 background sources that measured beyond the third week against how completely each described the reconditioning its participants received, with the subset read in full text repeated at the foot. The two panels are separate datasets. Sampling density varies by an order of magnitude, from 13 MRI scans in Scott et al.[25] and eight myotonometry sessions in Schoenrock et al.[15] to three or four

sessions in the other analogue studies. Analogue and spaceflight blocks differ in loading, age and unloading stimulus and are read on their own axes. “Named only” means the programme is identified by a service name without content, and “partly described” that a supervised in-facility week is characterised without the later interval. Twenty-one sources reached twelve months or more, seventeen on the most conservative count, which merges two records of one astronaut cohort, treats two injury registries as surveillance and sets aside one self-reported outcome. Charting decisions for individual entries are given in the notes to Supplementary Table 1. Time points are as the sources give them, with R+n, BR+n, BDC−n, HDT+n and L−n as in Table 3. Abbreviations. NR, not reported. BR, bed rest. BDC, baseline data collection. HDT, head-down tilt. MVC, maximal voluntary contraction. CMJ, countermovement jump. FRED, Functional Re-adaptive Exercise Device. DXA, dual-energy X-ray absorptiometry. AGBRESA, Artificial Gravity Bed Rest Study with the European Space Agency, DLR Cologne, 2019–2020. SR, standard reconditioning.

Discussion

Set against the unknowns that ESA listed parameter by parameter in 2016, the intervention literature ten years later amounts to thirteen reports, which support three arguments. First, the recovery period has been measured at length, but the reconditioning delivered during it has almost never been recorded. Second, four of the eight in-scope parameters of ESA Table 5.1 carry no intervention-phase result at all (Table 2), an absence that holds within the reach of this search and remains to be tested beyond it. Third, the programmes that have been studied cannot be reproduced, because the fields that define a prescription were not reported, and no evidence exists even for the release decision that the ESA report itself singles out. The three arguments share a cause, in that most recovery-phase evidence was collected incidentally by studies designed for other questions and neither the instruments nor the thresholds have ever been standardised, two problems that another field on Earth has already worked through.

The time course of recovery is well recorded, since among the background sources 34 followed recovery beyond the third week, 21 to a year or more and one to four years (Table 5), and three of the thirteen included reports measured beyond the end of their programme, Sibonga et al.[24] following hip bone density to two years. The programmes delivered during those follow-ups are far thinner on record, since of the 34 only one described in full the programme its participants received and 29 said nothing. English et al.[30] measured strength, one-repetition maximum and agility at R+30 without the words reconditioning or physiotherapy appearing in the paper. Gabel et al.[31] stated that a 45-day NASA reconditioning period is standard care and noted that post-flight training is not logged as in-flight training is. Nine of the thirteen included reports stopped measuring on or before the last day of the programme they delivered, and the three long follow-ups are observational, with no record of what, if anything, was delivered after the programme ended (Table 5). The programmes themselves exist, ESA's running to R+21 and extendable to 45 days[8,9,22], NASA's 45-day programme citable only from a 2003 conference abstract, and other agencies' programmes appearing only in web pages and news reports, drawn in Figure 2 as compiled from public web sources. Measurement and reconditioning are therefore recorded apart, in that the studies that measure recovery do not describe the programme and the documents that describe the programme do not measure recovery. This is also why Ekman et al.[8] could trace only the natural-history curve from passive control groups, since the reconditioned curve has never been recorded.

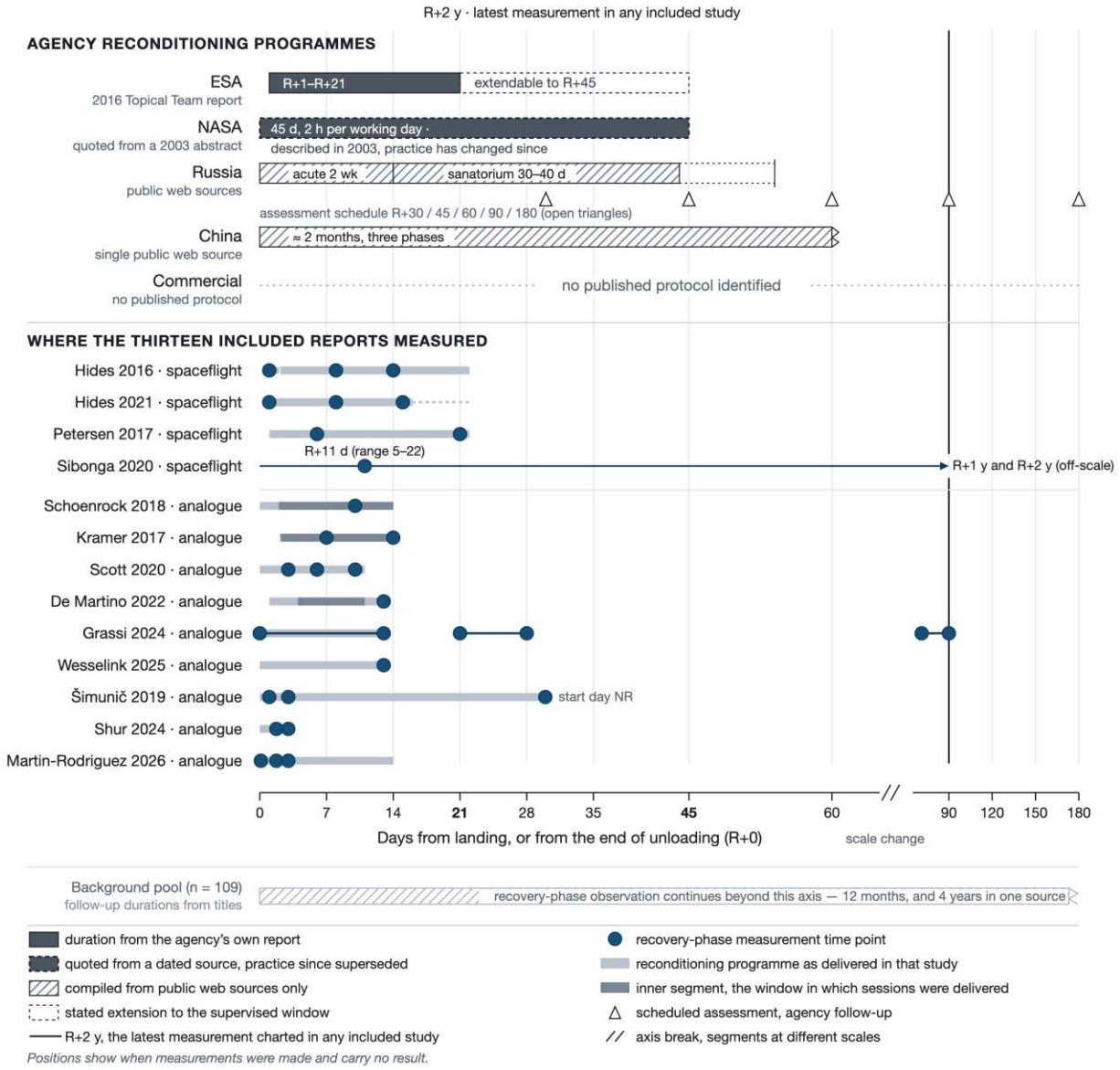


Figure 2. Agency reconditioning programmes and the measurement time points of the thirteen included reports on one time axis, from landing or, for analogue studies, from the end of unloading (R+0). Upper band, agency programmes. The ESA window of R+1 to R+21 with its extension to 45 days and the 45-day NASA programme are taken from the 2016 ESA Post-mission Exercise (Reconditioning) Topical Team report, which attributes the NASA figure to a 2003 conference abstract (dashed bar). The Russian and Chinese programmes are compiled from public web sources (hatched bars). Lower band, included reports. Bars show each programme as delivered, from its charted start to its charted end, with an inner segment where sessions were delivered within a longer reported period. A dashed bar end marks a start day the source did not state (Hides et al.[21]) and a dashed continuation the remainder of a phase beyond the last measured day (Hides et al.[23]). Circles are recovery-phase measurement time points from the full texts, and the vertical rule marks R+2 y, the latest time point in any included report. Lower rule, background sources. Of 109 records retained as background, 34 measured a musculoskeletal or functional outcome beyond the third week and 21 reached twelve months or more.

Each of the four empty rows is empty for its own reason. The psychological status row is partly a consequence of our own eligibility rule, so the rows that deserve attention are injury, spine and cartilage, and bone for the opposite reason. Injury is the clearest case, since of the 2,388 peri-flight neuromusculoskeletal injuries compiled by Ward et al.[32], 16.5% occurred after flight, about

one in six. That is a distribution across mission phases, the source reports no crew denominator and it cannot be converted into an incidence, but it shows that injuries do occur in the period when crew are loaded back into gravity, and no included study recorded an injury outcome while a programme ran. For spine, the ESA row asks about spinal shape, spinal bone density and the intervertebral discs, and the four reports that measured the lumbar region measured only musculature. For cartilage, Liphardt et al.[14] noted that recovery of cartilage, tendon and ligament remains unknown. The included evidence touches the tendon end, the Achilles tendon and plantar fascia mechanics of Schoenrock et al.[15], but because the ESA row is cartilage those results were not filed there. Bone shows the opposite imbalance, with twenty-eight background records under bone mineral density against one included report, Sibonga et al.[24], whose results were measured during and after a 45-day programme described only in general terms (Table 2). Bone is the parameter most observed and least studied by intervention, injury the parameter with epidemiology but no intervention research, and spine and cartilage the parameters that measurement has passed by.

Across 143 prescription fields the thirteen reports completed 88, and the mechanical fields were the thinnest. No report gave an external load, six gave intensity, seven a progression rule and none a stopping or discharge criterion (Table 4). The 2016 report called the R+1–21 window a compromise with the competing demands on an astronaut's time and asked what evidence exists to say that an astronaut is good enough, for example, to take a transatlantic flight. That question concerns a release decision, one step short of a discharge threshold, and the report found no evidence even for it. Ten years on, no included study reported a stopping or discharge criterion, the nearest being a 45-minute walk on a final programme day to confirm tolerance of sustained locomotion. Two reported adherence, Petersen et al.[22] qualitatively and Kramer et al.[18] as 99% of scheduled sessions delivered. Return-to-duty standards sit in medical-standards documents that this search did not cover. Other prescription details exist but are dispersed, one analogue study's dose and exercise list sitting in a supplement its open-access record does not carry, another citing its protocol elsewhere and a third its programme description elsewhere again. The report's own objection is that inter-individual differences and diverse mission profiles do not permit a standard programme. That objection leaves the point standing, since a programme tailored daily can still state its progression rule, its stopping criterion and where to find them.

The common cause is the purpose for which the thirteen reports were written. Only five were designed to study recovery-phase reconditioning, the case report of Petersen et al.[22], the prospective series of Hides et al.[23], the comparison of two programmes by De Martino et al.[16], the two-leg remobilisation contrast of Shur et al.[17] and the rehabilitation substudy that Scott et al.[25] attached to the control arm of a randomised trial. Only De Martino et al.[16] randomised the reconditioning itself. The recovery-phase data of the other eight were collected incidentally by studies designed for other questions. The RSL and BRACE (Bed Rest with Artificial gravity and Cycling Exercise) campaigns randomised jump training and artificial gravity during bed rest, and the two AGBRESA companion reports re-analysed one dataset. Šimunič et al.[27] set out to detect atrophy early during bed rest, Hides et al.[21] to describe the changes of microgravity itself and Sibonga et al.[24] to follow the long-term effects on bone (Table 1). The length of the recovery period was therefore set by the campaign schedule, 13 to 15 days in the ESA bed-rest campaigns, and by no reconditioning hypothesis. The sources are also concentrated in a few institutions. The four spaceflight reports come from ESA's physiotherapy team and one NASA bone study, and six of the nine analogue reports from ESA bed-rest campaigns at DLR and the Institute for Space

Medicine and Physiology (MEDES), the other three from a NASA bed-rest study and two small cohorts. This follows from the structure of space medicine, in which a handful of crew return from long-duration missions each year and a few institutions can run bed-rest campaigns, so a concentration of evidence in one team and one series of campaigns is to be expected. It does mean that the evidence on post-flight reconditioning currently amounts largely to how ESA's practice looks in ESA's own participants. Sex is the other face of the same structure. Nine of the 100 analogue participants and one of the five astronauts in the ESA series are women, twelve of the thirteen reports stated sex and none analysed by it (Table 1), so whether recovery under a programme differs between women and men has no evidence either way.

Even if every report had been designed for reconditioning, the present results could not be turned into decisions, for three reasons. First, there are no thresholds. Apart from the least significant change for bone density in Sibonga et al.[24] and the day-to-day 1RM band cited by Petersen et al.[22], no result has a source-specific change threshold, so every "not returned" entry in Table 3 is a comparison with a pre-exposure value whose size relative to measurement error is unknown. Second, there are no stopping rules. None of the thirteen reports states when a programme counts as complete or a crew member as fit for release, so "recovered" can only be read as the value at the last session. Third, measurement stops with the programme. Nine of the thirteen made their last measurement on or before the programme's final day (Table 5), and whether the state measured there holds, continues to improve or regresses afterwards is unrecorded. The only measurements beyond a year are the observational bone density and leg lean mass of a 45-day programme described only in outline. The ESA report anticipated the first point, recommending that clinically meaningful change values be established in terrestrial cohorts because the astronaut population is too small to derive them[12]. Ten years later those values still do not exist.

The reason thresholds cannot be established lies one step earlier, in the instruments, which have not converged. Among the 32 results, muscle size was measured as four geometric quantities that do not convert into one another, no combination of metric and instrument recurs in three or more studies, and the same participant measured on the same days with two instruments for hip flexibility moved in opposite directions (Table 3, Supplementary Table 1). Chapter 8.5 of the 2016 report asked for standardised outcome measures and agreed time points, and ten years later the progress is nil. One field on Earth started from the same point and completed the journey. The loss at issue is the same, loss of muscle mass and strength, and before 2010 studies of sarcopenia in older adults each measured it in their own way. The European Working Group published the first operational consensus definition in 2010, naming the instruments and giving cut-points[33]. The Asian Working Group adjusted the cut-points to Asian reference values in 2014[34]. Both groups revised their definitions in 2019 on the accumulated evidence, placing strength first and adding chair-stand and Short Physical Performance Battery (SPPB) cut-points[35,36]. In 2020 pooled cohort data were used to test which cut-points actually predicted mobility disability[37]. Super-aged societies have written the standards into long-term care, Japan's long-term care insurance with a preventive tier from 2005[38] and Taiwan's Long-Term Care 2.0 with community reablement from 2017[39], both with standardised functional assessment at entry and exit. From the first consensus to outcome-tested cut-points took ten years and four steps, a working group, named instruments and cut-points, regional reference values, and revision on pooled data. Post-flight reconditioning stands before the first step, yet the reference data are already being generated. ESA's Astronaut Fitness Assessment has ten tests, NASA has the Functional Task Test, and the ESA bed-rest campaigns run cohorts of 24 (Table 1). What is

missing is a multi-agency working group that writes down the instruments, the time points and interim thresholds, tests them first in bed-rest analogues and then writes them into agency programmes. The minimal clinically important changes of geriatric rehabilitation, for example 0.10 m/s in gait speed and one point on the SPPB[40], could serve as interim thresholds until astronaut-specific values exist. What transfers is the framework, because astronauts are 38 to 48 years old, highly trained and acutely deconditioned, and the thresholds will in the end have to be recalibrated in astronauts and bed-rest participants.

What this review implies for the next studies follows from where the evidence came from. The cheapest designed evidence lies in the 60-day bed-rest campaigns, which already pay for the unloading, already keep a cohort of 24 for about two weeks after it ends and already deliver a reconditioning programme in that time (Table 1). Three additions would turn their incidental data into designed data. A recovery-phase arm would be registered before the campaign, with the reconditioning itself randomised, as De Martino et al.[16] randomised it. Measurement would continue past the programme's last day, where nine of the thirteen reports stopped (Table 5). The prescription would be reported against the Consensus on Exercise Reporting Template[41,42], so that load, progression rule and stopping criterion are stated where the results are. In spaceflight the obstacles are structural and will not be designed away. A handful of crew return from long-duration missions each year, their first three weeks are scheduled around medical and operational demands that the 2016 report itself called a compromise, and a randomised contrast against no reconditioning is neither feasible nor defensible. A registry is feasible, the same instruments at the same time points across agencies, with post-flight training logged as in-flight training already is[31], and it would accumulate the reference values that single studies cannot. Two constraints, identifiability and sex balance, need settling first. Identifiability limits what can be published, since one included series withheld ages and crew identifiers and two case reports cannot be told apart, so a registry needs an agreed convention for reporting small numbers. Sex balance is a design choice in bed rest and a crew-selection fact in spaceflight, and only the first can be fixed by investigators. Commercial returnees will add numbers, mostly from short flights, and they sit outside the context of this review. The empty rows of Table 2 and the unreported fields of Table 4 list what such a registry would have to record.

Several decisions that narrow the review are ours. Mapping eight of the eleven parameters of ESA Table 5.1 set aside any sensorimotor, orthostatic or aerobic result without charting it. Recovery was counted from landing, whereas the report's window is R+1. Horizontal bed rest was excluded, which removed the one identified study that both prescribed a recovery programme and measured thirty days out. Ground studies without an explicit spaceflight framing were excluded, a rule whose application to one included study rests on that study's protocol-adherence statement alone (Methods). The 2016–2026 publication window was applied as an eligibility criterion, which places roughly two thirds of the retrievable recovery-phase literature outside the review and excludes three reports the criteria would otherwise admit (Methods). The concept was held to exercise-based reconditioning, so nutritional, pharmacological or orthotic recovery-phase interventions are outside the review, which bounds the bone mineral density row in particular, the parameter for which a non-exercise intervention is most plausible. The context was restricted to long-duration ISS missions, so returnees from commercial spaceflight are outside it. The independent charting pilot specified in the protocol was not performed and no disagreement rate was recorded at either verification pass (Methods), so every count above is a verified extraction without a measured error rate. Every proportion also depends on conventions

that are ours, what counts as one result and which parameter it is coded to, so whether the cartilage row is empty depends on where the tendon and fascia results were filed. The sarcopenia comparison is a proposal, since the geriatric rehabilitation literature was not searched, the sources cited are consensus documents, and whether the framework transfers remains to be tested.

Reconditioning after spaceflight is delivered daily and studied rarely. The recovery period has been measured at length and almost never with a record of what was being done to the person during it, the programmes that have been studied state no stopping criterion and no threshold, and four parameters carry no intervention-phase evidence. The programmes exist, and the evidence describing them stops when they do. Making the evidence outlast the programme does not require more astronauts. A multi-agency working group that writes down the instruments, the time points and interim thresholds would let bed-rest campaigns and the fitness assessments already in use begin to accumulate reference values.

Methods

Design and reporting

We conducted a scoping review following the Joanna Briggs Institute (JBI) methodology for scoping reviews[43] and reported it according to PRISMA-ScR[44] and, for the search, PRISMA-S[45]. A protocol fixing the questions, eligibility criteria, search design, screening procedure, charting fields and synthesis plan was written before screening began. The points on which the completed review departs from it are gathered at the end of this section and dated in Supplementary Note 1.

Eligibility criteria

Eligibility was defined by population, concept and context, fixed before screening and reproduced in Supplementary Note 2. The population comprised astronauts, cosmonauts and spaceflight participants of any age or sex, and human participants in head-down-tilt bed rest, dry immersion or parabolic flight studies, a ground-based study qualifying where its authors themselves framed the exposure as simulating microgravity or spaceflight. The concept was an exercise-based reconditioning, rehabilitation or recovery programme delivered during the recovery period and reporting at least one musculoskeletal outcome. The context was the recovery period after long-duration ISS spaceflight or after a ground-based analogue of it, counted from landing (R+0) or from the end of unloading, and for an intervention spanning both periods only the recovery-phase component was charted. Eligible reports were published between 2016 and 2026, the window over which the review asks what the 2016 agenda has produced, in any language. Reviews and agency technical reports were retained as documentation of practice, and reports describing the recovery phase without a programme as background material. Editorials, protocols, conference abstracts and registry entries were excluded, as were animal, cell and molecular studies and analogue models not widely accepted as microgravity simulations.

Search strategy and information sources

The main search combined exposure, intervention and recovery-phase terms, with an exercise-based intervention block, and was the only search that fed screening. It was run in MEDLINE via

PubMed, in Embase.com and in the EBSCO Discovery Service, which covers the institution's EBSCO databases including CINAHL Ultimate, with a 2016 to 2026 publication-date limit and no publication-type limit. The PubMed strategy was validated by known-item testing against a fifteen-item reference set, and without the date limit the main search retrieved twelve of the fifteen. The three not retrieved are reviews of in-flight countermeasures (Moosavi et al.[2], Comfort et al.[1] and Liphardt et al.[14]) that the recovery-phase block is designed to exclude, and an independently assembled list of thirteen candidate studies was present in full in the retrieved set. One record that bears on the evidence map, the systematic review of peri-flight neuromusculoskeletal injury by Ward et al.[32], is absent from the screened records because it carries no intervention or recovery-phase term. A collision search of exposure and intervention terms only, run in PubMed to locate existing syntheses, found no completed synthesis of recovery-phase reconditioning. The nearest registered work, a systematic review of lumbar-spine countermeasures that includes post-flight rehabilitation (PROSPERO CRD420261452151)[46], was identified in the PROSPERO register on 28 July 2026, before the protocol was written, and a sweep of four registries on 31 August 2026 found no registration with the same scope. The main search retrieved 390, 538 and 526 records, 1,454 in total, of which 1,390 were obtained and imported. The 64 that could not be exported at the time appear in Figure 1 as retrieved but not obtained. Full strategies, limits and dates are reported in Supplementary Note 4 under PRISMA-S.

Selection of sources of evidence

Deduplication in Zotero, with duplicate groups verified by title similarity before merging, removed 711 of the 1,390 obtained records and left 679. Screening ran in two stages, title and abstract then full text, retaining a record at the first stage unless it could confidently be excluded and recording one reason per exclusion. Both stages were screened against the written criteria, with uncertain and borderline records decided individually. The 105 records excluded at title and abstract because they described the recovery phase without an intervention were re-examined at full text. Sixty-six were read at a first re-examination and 36 in an independent second pass, after two conference abstracts and one withdrawn preprint were set aside, and six met the criteria and were included. One record flagged as borderline was included after discussion. Each decision on an obtained report was documented with its supporting evidence.

Data charting

Data were charted on two linked forms, one at study level and one at outcome level. The outcome-level form recorded for each result the ESA Table 5.1 parameter, the instrument as named by the source, the time points, whether a pre-exposure baseline existed and whether recovery to baseline was reached, with time points standardised to days from landing or from the end of unloading. The prescription was charted across eleven fields of the review's own. Every charted cell of all thirteen reports was then verified against the full texts, and differences were resolved on the forms.

Data items and counting rules

The unit of analysis is the report and the unit of counting is the charted result, one outcome construct in one source whatever the number of muscles, levels, limbs or instruments behind it. Each result was assigned to every Table 5.1 parameter it bears on, so the parameter counts in the

Results and in Table 2 are assignments and can exceed the number of results. Assignment followed the report's own row wording, and the decision that governs the cartilage row is reported with that row (Results). A source's own online supplement was treated as part of the source, and a field described only in a separate methods paper or companion report was charted as not reported, because completeness of intervention reporting is one of the review's questions. An outcome measured but not reported was recorded as a reporting finding and kept out of the results count. Measurement-property evidence was graded from what a source cites, in full, partially or not at all, without assessing the adequacy of what was cited. Supervision and adherence fields were read against the phase the supporting sentence describes rather than its position in the report.

Appraisal and classification

Consistent with JBI guidance, inclusion was decided on the eligibility criteria alone, and design, comparator and baseline availability were recorded for each report. Evidence was mapped onto ESA Table 5.1 with spaceflight and analogue evidence kept distinguishable throughout. Against criteria fixed in advance, each gap was classified as addressed where an included study measured the parameter during the recovery phase with a baseline and reported it, partially addressed where the evidence was indirect, or unaddressed. Each in-scope parameter was classified independently in duplicate, and the two classifications agreed on six of the eight. For major muscle groups and postural muscles one classification at first read the row's knowledge-gap questions as only partly answered, and after discussion both parameters were classified as addressed because the definition turns on measurement during the recovery phase with a baseline (Table 2, Supplementary Note 1).

Synthesis

The synthesis was narrative. Charted results were tabulated, mapped onto ESA Table 5.1 and reported by tissue and construct, with spaceflight and analogue evidence kept separate. No effect estimates were pooled, a decision fixed before synthesis and following from the structure of the evidence. The only randomised comparison is between two reconditioning variants, three of the thirteen included studies enrolled five or fewer participants, and no combination of outcome metric and instrument recurs in three or more of them.

Departures from the protocol

The completed review departs from the protocol in the following respects, each dated and explained in Supplementary Note 1. A 2016–2026 publication window was applied as an eligibility criterion and as a search limit where the protocol set no date limit. Its cost is quantified in Supplementary Note 2, and three reports the criteria would otherwise admit fall outside it[10,47,48]. Four eligibility rules were tightened after screening had begun, and the records affected by each are listed in Supplementary Note 3. (i) Horizontal bed rest was excluded, restricting bed-rest evidence to head-down tilt. (ii) A ground-based study qualified only on its authors' own framing of the exposure as simulating microgravity or spaceflight, which for one included study rests on a single protocol-adherence statement that was independently assessed and judged sufficient. (iii) Delivery of a recovery-phase intervention became a necessary condition, the rule that most determines the included set. (iv) The exclusion of conference abstracts without retrievable full text was extended to registry entries. The remaining differences between the

criteria as applied and the protocol are set out in Supplementary Note 2. The Consensus on Exercise Reporting Template[41,42] was scored for eleven of the thirteen sources in a single pass where the protocol specifies two independent scorers, so the scores are not reported. The charting pilot was not performed, no disagreement rate was recorded, and the Bed Rest Assessment Tool[49] was not applied to the analogue studies. The protocol's composite label "adherence and psychological status" is not used here, and adherence is treated as a reporting observation.

Ethics

This review analysed published reports only. No ethical approval or participant consent was required.

Additional declarations

During the preparation of this work the authors used a large language model (Claude, Anthropic) mainly to translate draft text between Chinese and English and to edit language. The authors reviewed and edited all output and take full responsibility for the content of the manuscript.

Data availability

The charted data, the screening record and the search strategies as run are available from the corresponding author on reasonable request and will be deposited in the Open Science Framework before publication.

Code availability

Not applicable.

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Author contributions

Both authors contributed to the conception and design of the review and approve the final manuscript. JCK drafted the protocol, designed and ran the searches, performed the known-item validation, screened at both stages, charted and re-checked seven reports, scored eleven sources against the Consensus on Exercise Reporting Template, drafted the manuscript, and is the guarantor and corresponding author. EE assembled an independent candidate-study list to cross-check the search, designed the exercise-prescription reporting fields and drafted the first Results on them, independently assessed the tightened eligibility rules and classified the ESA Table 5.1 parameters, re-examined at full text the records excluded under rule (iii), charted six reports and verified every charted cell of all thirteen against the full texts, and critically reviewed the manuscript.

Competing interests

Both authors declare no financial or non-financial competing interests.

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