Supplementary Information

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

Supplementary Note 1, Protocol deviations register Supplementary Note 2, The eligibility criteria as applied against the protocol: six points of difference Supplementary Note 3, Records affected by each eligibility rule tightened during screening Supplementary Note 4, Search strategies as run, reported under PRISMA-S Supplementary Table 1, Instruments by construct: acquisition, what each resolves, and what it does not

Dates are given as day month year. Screening IDs are the record numbers of the review's screening record, which is deposited with the charted data.

Supplementary Note 1. Protocol deviations register

The protocol fixed the questions, eligibility criteria, search design, screening procedure, charting fields, appraisal and synthesis plan before screening began. Every departure from it is listed below with the date on which it took effect, what the protocol specified, what was done instead, the rationale, and where the manuscript reports it. Entries are numbered in the order in which they were identified. Two entries, S1-1 and S1-12, are the most consequential. The first removes the measure of inter-rater agreement the protocol promised, and the second records that the criteria applied at screening differ from the protocol on six points.

No.	Deviation	Protocol specified	What was done	Effective date	Rationale and consequence	Reported in
S1-1	Screening was not independent and duplicate	Blinded independent duplicate screening at both stages, preceded by a calibration exercise on the first 30 records Cohen's kappa reported for the calibration set and the full set	All 679 unique records were screened in a single pass applying the written criteriaevery uncertain record, every rule change and every borderline decision was adjudicated individually. No calibration exercise was run. At full text, the 105 records excluded under rule (iii) were re-examined, 66 at a first re-examination and 36 in an independent second pass between 5 and 18 October 2026, and six were included (S1-12). An	8–10 August 2026	No measure of inter-rater agreement can be calculated for title-and-abstract screeningat full text 36 of the 105 rule (iii) exclusions were read in an independent second pass and no disagreement rate was recordedwrongful exclusion at screening is not detectable in the finished report. Mitigated by a retain-unless-confidently-excludable rule at title and abstract, individual adjudication of every uncertain record, and the independent cross-check of the	Author contributions

No.	Deviation	Protocol specified	What was done	Effective date	Rationale and consequence	Reported in
			independently assembled candidate-study list was cross-checked against the retrieved set on 13 August 2026 and contained no record the search had missed		candidate-study list	
S1-2	A publication window of 2016–2026 was applied	No date limit	The window was adopted on 2 August 2026, before screening, applied to the main search on all three platforms (PubMed `2016:2026[dp]` Embase `[2016-2026]/py` EBSCOhost limiter `DT1:2016-01-01/2026-12-31`), and written into the criteria as applied as an eligibility criterion (Supplementary Note 2, point 5). The collision search carried no date limit	2 August 2026	The review asks what the knowledge-gap agenda published in June 2016 has produced since it was set. The quantified cost is that retrieval falls by 66% in PubMed (1,143 to 390), 66% in Embase (1,599 to 538) and 53% in CINAHL Ultimate (144 to 67) three known reports fall outside the window, Payne et al. 2007 and Evetts et al. 2014, retained as background, and Loehr et al. 2015, excluded by publication year alone	Methods (Eligibility criteria, Search strategy and information sources, Departures from the protocol). Discussion
S1-3	The search is incomplete	Eight bibliographic databases four trial registries four grey-literature sources (NASA Technical Reports Server, NASA Life Sciences Data Archive, ESA Erasmus Experiment Archive, DLR electronic library) Russian-language sources reference-list screening of all included sources forward citation tracking	Three platforms were searched, PubMed, Embase.com (Embase, MEDLINE, Preprints, Clinical Trials) and the EBSCO Discovery Service, which searches the institution's EBSCO databases together, CINAHL Ultimate among them. SPORTDiscus is not held by the institution and access could not be obtained. PEDro, Scopus, Web of Science and Cochrane CENTRAL were not searchedno trial registry was searchedno grey-literature source was searchedno reference list was screenedno citation was tracked forwardthe collision	28 July – 3 August 2026 (searches executed) the remainder not executed as at 15 September 2026	Every statement that a parameter, a field or a horizon is empty is an absence across the three platforms searched and the records they returned, and the literature beyond them is untested. The grey sources not searched are where agency reconditioning is chiefly documented. The count of thirteen included reports is a floor	Supplementary Note 4. Discussion

No.	Deviation	Protocol specified	What was done	Effective date	Rationale and consequence	Reported in
		the search to be re-run before submission	search was completed in PubMed onlythe search has not been re-run			
S1-4	Four eligibility rules were tightened after screening had begun	The eligibility criteria as written in the protocol and in the criteria as applied from 4 August 2026	(i) Horizontal bed rest excluded, restricting bed-rest evidence to head-down tilt. (ii) A ground-based study eligible only where its authors themselves framed the exposure as simulating microgravity or spaceflight. (iii) Delivery of a recovery-phase intervention made a necessary condition, so that recovery-phase observation without an intervention was reclassified as background material. (iv) The exclusion of conference abstracts without retrievable full text extended to trial-registry entries	10 August 2026 (all four)	Each rule narrowed the review, so each is recorded as a deviation. Rule (iii) is the largest determinant of the included set. Records affected by each rule are listed in Supplementary Note 3	Methods (Eligibility criteria, Departures from the protocol). Supplementary Note 3
S1-5	The known-item reference set no longer maps onto the included set	The reference set validates the search strategy its members are eligible studies	Of the reference-set studies retrieved and passed at title and abstract, three are in the final included set (Hides et al. 2021 Petersen et al. 2017 Shur et al. 2024). Rosenberg et al. 2022 was excluded on 11 August 2026 because its authors state twice that the landing-day field tests were not designed as rehabilitation and the comparison is retrospective Grassi et al. 2024 was reclassified as background under rule (iii) as recovery-phase observation	10–11 August 2026	The reference set validates retrieval sensitivity only inclusion is determined separately by the criteria. Both claims are kept apart in the Methods	Methods (Search strategy and information sources)

No.	Deviation	Protocol specified	What was done	Effective date	Rationale and consequence	Reported in
			without an intervention			
S1-6	Charting was not piloted, and independent verification was completed later than the protocol specifies	The charting form piloted independently in duplicate on the first five included sources every charted cell independently verified the exercise-prescription fields charted independently and in duplicate	Data were charted in a single pass (11–13 August 2026). Every charted cell of the seven first-pass reports was subsequently re-checked against the full texts and corrected where the two differed (1 September 2026). That re-check was itself independently audited, and four of its judgements were overturned. A further sweep of the phase-attribution fields (supervision, adherence) was made on 2 September 2026. Every charted cell of all thirteen reports was then independently verified against the full texts, and the six reports added at full-text re-examination were charted (5 to 18 October 2026) no disagreement rate was recorded. The charting pilot on the first five sources was not performed	11 August – 2 September 2026 5–18 October 2026	No disagreement rate is available for the verification. Every count in the Results is a verified extraction without a measured error rate. The re-check moved several published figures, including the prescription-field total (88 of 143)	Methods (Data charting, Departures from the protocol). Discussion
S1-7	The three-level classification was performed later than planned and the one disagreement was resolved by discussion after the manuscript had been drafted	Each ESA Table 5.1 knowledge gap classified as addressed, partially addressed or unaddressed, independently in duplicate, against definitions fixed in advance disagreements resolved by discussion, the more conservative classification	The eleven parameters were classified independently in duplicate, in writing, on 10 and 15 September 2026. The two classifications agree on six of the eight in-scope parameters and differ on two (major muscle groups postural muscles), where one applied the definitions as fixed and the other weighed whether the row's knowledge-gap questions had been	10–15 September 2026, resolved 24 October 2026	The classification was made after charting, once the counts per parameter had been established. The two-parameter disagreement turned on what "addressed" measures, whether the parameter was measured with a baseline and reported, or whether the row's questions were answered, and the definitions fixed in advance take the former, which was	Methods (Appraisal and classification). Results. Table 2

No.	Deviation	Protocol specified	What was done	Effective date	Rationale and consequence	Reported in
		adopted where agreement is not reached the number of disagreements reported the classification repeated for spaceflight evidence alone	answered. The difference was resolved by discussion on 24 October 2026 in favour of the definitions fixed in advance, and both parameters are classified as addressed. The initial difference is reported in the note to Table 2. Repeated on spaceflight evidence alone, the classification is unchanged		accepted on discussion	
S1-8	The Bed Rest Assessment Tool was not applied	The Aerospace Medicine Systematic Review Group Bed Rest Assessment Tool applied to analogue studies, as used by Ekman et al. 2022	Not applied. Study design, comparator and baseline availability were recorded for every included source	Not applied as at 15 September 2026	The four analogue studies are not appraised for fidelity of the bed-rest conditions to spaceflight the review records the exposure form, duration and tilt angle as reported	Methods (Departures from the protocol)
S1-9	Retrieved records not obtained at export	All retrieved records exported and imported	Of 1,454 records retrieved by the main search, 1,390 were obtained and imported 64 could not be obtained, their eligibility is unknown, and none entered screening	3–8 August 2026	The records could not be exported at the time of the search and are drawn in Figure 1 as retrieved but not obtained. Their content overlaps substantially with the other platforms searched, but the proportion recovered elsewhere has not been calculated and is not claimed	Methods (Search strategy and information sources). Figure 1
S1-10	The criteria as applied differ from the protocol on six points	The eligibility criteria as written in the protocol	Screening was performed against the criteria fixed on 4 August 2026, structured as a Population–Concept–Context table, which differs from the protocol on the six points set out in Supplementary Note 2	4 August 2026	The Methods describe the criteria as applied and declare the divergence from the protocol wording. One point (a musculoskeletal outcome required studies solely psychological excluded) closes the psychological component of the Psychological Status	Methods (Eligibility criteria, Departures from the protocol). Supplementary Note 2

No.	Deviation	Protocol specified	What was done	Effective date	Rationale and consequence	Reported in
					parameter by rule, and the Results say so	
S1-11	Rule (ii) for one included study rested on a single protocol-adherence statement and was adjudicated late	Rule (ii) requires the authors' own framing of the exposure as simulating microgravity or spaceflight	For Shur et al. 2024 the only spaceflight connection in the full text is the authors' statement that the study was conducted in accordance with the European Space Agency Standardization of Bed Rest Study Conditions guidelines the terms microgravity, spaceflight, astronaut and weightless do not occur. The study was assessed against the rule independently on 10 September 2026 and judged to meet it the study is retained	10 September 2026	Recorded so that the basis of the decision is visible. The framing is supplied by reference to an agency bed-rest standard. Had the study been excluded the included set would be six	Methods (Departures from the protocol)
S1-12	Rule (iii) exclusions were re-examined at full text.	Title-and-abstract screening followed by full-text assessment of records carried forward for eligibility.	The 105 records initially excluded under rule (iii) at title-and-abstract screening were followed by full text. Sixty-six were read at the first re-examination of the remaining 39, two proved to be conference abstracts, one preprint had been withdrawn and could not be retrieved, and 36 were obtained and independently assessed between 5 and 18 October 2026. Six records met the criteria on full text and were included. The re-examination was intended to check whether the original rule (iii) classification remained justified when the full text was available.	5 October 2026	Re-examining the records at full text allowed the recovery-phase intervention criterion to be checked against the full report and helped identify records whose classification required reconsideration.	Methods (Selection of sources of evidence). Results. Supplementary Note 3, rule (iii) table.

A limitation recorded here that is not a protocol deviation. One record bearing on the evidence map is absent from all 679 screened records. It is Ward et al. 2025, a systematic review of peri-flight neuromusculoskeletal injury (29 studies, 2,388 documented injuries), which the Discussion cites for the epidemiology of injury around flight. An injury-epidemiology synthesis carries

neither an intervention term nor a recovery-phase term in its title and abstract, so the three-block main search excludes it by construction. The known-item reference set contains no injury-epidemiology synthesis, so the validation could not have detected the omission. The empty Injury row of Table 2 therefore records the absence of recovery-phase intervention research on injury, while evidence about injury during the recovery period exists. Reported in the Methods and Discussion.

Supplementary Note 2. The eligibility criteria as applied against the protocol: six points of difference

The eligibility criteria were fixed on 4 August 2026, before screening, as a Population–Concept–Context table, and all 679 unique records were screened against them. They differ from the protocol on the six points below, four of which are also reflected in the exclusion reasons recorded in the screening record.

Point	Protocol	Criteria as applied	Corroboration in the screening record
1	Unilateral lower-limb suspension **included** as an analogue exposure	**Excluded** named as an analogue model "not widely accepted as a microgravity simulation"	Recorded at exclusion as analogue model not accepted
2	Parabolic flight not mentioned	**Included** as an analogue exposure	One parabolic-flight exposure appears in the screened set and passed title-and-abstract screening it was reclassified as background under rule (iii)
3	Adults aged 18 years or over	Spaceflight participants **of any age or sex**	No record was excluded on age
4	Spaceflight of **any duration** any country, agency or commercial programme any rehabilitation setting	Context restricted to the post-flight or post-analogue-exposure period in **long-duration ISS spaceflight**	Applied to the spaceflight side of the Context only the Methods state that a single Context was applied in screening, the recovery period after long-duration ISS spaceflight or after an admitted ground-based analogue of it
5	**No date limit**	**2016–2026 written as an eligibility criterion** in its own row of the table, with its own inclusion and exclusion cells	The date limit was applied at the search stage on all three platforms (Supplementary Note 1, S1-2) no record reached screening from outside the window
6	Musculoskeletal outcomes listed among the outcomes of interest	A musculoskeletal outcome is **required** studies focused solely on cardiovascular, vestibular, sensorimotor or psychological domains with no musculoskeletal outcome are **excluded outright**	Recorded at exclusion as non-musculoskeletal domain only (146 records at title and abstract). As a consequence the psychological component of the Psychological Status parameter of ESA Table 5.1 could not have been populated by any included study, and its empty cell follows from the criteria

Two further properties of the criteria bear on how they were applied. They are silent on source types. Editorials, protocols and conference abstracts were excluded, and reviews and agency technical reports were retained as documentation of practice, under the protocol's source-type rules and rule (iv) of Supplementary Note 3. They state the Concept in three parts, musculoskeletal reconditioning, rehabilitation or recovery protocols, interventions applied after spaceflight, and musculoskeletal outcomes measured during the recovery period. The third part,

read alone, admits recovery-phase observation without an intervention, and rule (iii), added on 10 August 2026, closed that reading by making delivery of a recovery-phase intervention a necessary condition.

The criteria are reproduced below as applied.

> *Population.* Included: human astronauts; cosmonauts; spaceflight participants of any age or sex; human participants in head-down-tilt bed rest, dry immersion or parabolic-flight analogue studies. Excluded: non-human and animal studies; cell-based and molecular studies; analogue models not widely accepted as microgravity simulations (for example isolated unilateral limb suspension). Concept. Included: studies with a musculoskeletal reconditioning, rehabilitation or recovery protocol; studies reporting musculoskeletal outcomes (bone density, muscle mass, strength, functional recovery) during the recovery period; interventions applied after spaceflight. Excluded: studies with only in-flight analogues; studies focused solely on non-musculoskeletal domains (cardiovascular, vestibular, sensorimotor, psychological) with no musculoskeletal outcome. Context. Included: the post-flight or post-analogue-exposure period; long-duration ISS spaceflight. Excluded: data collected exclusively during the in-flight exposure period. Date limit. Included: 2016–2026. Excluded: outside 2016–2026.

Supplementary Note 3. Records affected by each eligibility rule tightened during screening

Four rules were tightened on 10 August 2026, after title-and-abstract screening had begun. The records each rule affected are listed with their screening IDs, year, source and title. The totals match Figure 1. Of 679 unique records, 562 were excluded on title and abstract and 117 carried forward. Seven were excluded without full-text retrieval (4 on bed-rest form and 3 conference abstracts), 110 were sought and 1 could not be retrieved, 109 were assessed on full text, 96 were excluded on full text and 13 were included, 7 at the first full-text pass and 6 on re-examination. The 109 excluded records retained as background material are the 7, the 96, the 1 and 5 records excluded at title and abstract and retained for citation.

Rule (i), horizontal bed rest excluded

Title-and-abstract stage (6 records, 10 August 2026).

Screening ID	Year	Source	Title	Note
39	2018	Experimental Gerontology	Aging-related effects of bed rest followed by eccentric exercise rehabilitation on skeletal muscle macrophages and in…	Bed-rest form not stated as head-down tilt excluded as an analogue model not accepted
111	2016	clinicaltrials.gov	CB147 - Physical Activity and Nutrition for Quality Ageing	ClinicalTrials.gov record of a bed-rest and rehabilitation study excluded on source type and on bed-rest form

Screening ID	Year	Source	Title	Note
116	2025	SSRN	Changes in gait and postural control after 10-day bed rest and 30-day recovery: A Comparison of young vs. older adults	Preprint version of screening ID 117 recorded as a duplicate
117	2026	Gait and Posture	Changes in gait and postural control after 10-day bed rest and 30-day recovery: A comparison of young vs. older adults	Horizontal bed rest, 30-day recovery programme excluded as an analogue model not accepted
157	2020	Journal of applied physiology (Bethesda,	Countering disuse atrophy in older adults with low-volume leucine supplementation	Bed-rest form not stated as head-down tilt excluded as an analogue model not accepted
183	2023	Aging Cell	Disuse-induced muscle fibrosis, cellular senescence, and senescence-associated secretory phenotype in older adults ar…	Bed-rest form not stated as head-down tilt excluded as an analogue model not accepted

Full-text stage (4 records, all from the Izola 14-day bed-rest campaign, whose full text states that the bed rest was horizontal).

Screening ID	Year	Source	Title	Note
209	2018	PLoS ONE	Effects of 14 days of bed rest and following physical training on metabolic cost, mechanical work, and efficiency dur…	Same campaign as 398 excluded on bed-rest form
285	2016	Journal of applied physiology (Bethesda,	Greater loss in muscle mass and function but smaller metabolic alterations in older compared with younger men followi…	Same campaign as 398 excluded on bed-rest form
363	2018	The Journal of physiology	Loss of maximal explosive power of lower limbs after 2 weeks of disuse and incomplete recovery after retraining in ol…	Same campaign as 398 excluded on bed-rest form
398	2019	Frontiers in Physiology	Mitochondrial adaptations in elderly and young men skeletal muscle following 2 weeks of bed rest and rehabilitation	Full text states that participants remained in the horizontal position excluded as an analogue model not accepted

Three further records whose full text states horizontal bed rest were excluded under rule (iii) and are recorded under that rule in the screening record. They are listed here because the exposure form would also have excluded them, and because one of them (screening ID 41) is discussed in the manuscript as the single background source that both prescribed a recovery programme in full and measured 30 days after unloading.

Screening ID	Year	Source	Title	Note
41	2026	Medicine and science in sports and exerc	Alterations in Muscle Contractile Properties, Structure, and Function during 10-d Bed Rest, Postrecovery, and after C…	10-day horizontal bed rest with a fully prescribed recovery programme and measurement at R+30 recorded as recovery-phase observation without an intervention (see Table 5, Panel B note)

Screening ID	Year	Source	Title	Note
609	2018	Frontiers in Physiology	The effect of bed rest and hypoxic environment on postural balance and trunk automatic (re)actions in young healthy m…	21-day horizontal bed rest (PlanHab) recorded as recovery-phase observation without an intervention
634	2020	Physiological Reports	The influence of a sustained 10-day hypoxic bed rest on cartilage biomarkers and subchondral bone in females: The Fem…	10-day horizontal bed rest (FemHab) recorded as recovery-phase observation without an intervention

Rule (iii), delivery of a recovery-phase intervention as a necessary condition

105 records reclassified from the title-and-abstract pass to background material (recovery-phase observation without a delivered reconditioning intervention). The initial decisions were made on the information available at title and abstract screening on 10 August 2026. Subsequently, the 105 records were reviewed against the full-text eligibility criteria. On full text, 73 were recovery-phase observation without an intervention, 7 named a programme only, 3 described a programme without an outcome after it started, 13 were excluded on other grounds, 2 were conference abstracts, 1 was a preprint withdrawn by its repository and 6 were included.

Screening ID	Year	Source	Title
30	2025	Archives of Physical Medicine and Rehabi	Achilles' Tendon Experiences Reduced Depth and Volume After 3 Months of Recovery From 60 Days Bedrest
36	2025	Medicine and science in sports and exerc	Aerobic Exercise and Subsequent Venoconstrictive Thigh Cuffs Preserve Cardiorespiratory Fitness but Not Muscle Functi…
41	2026	Medicine and science in sports and exerc	Alterations in Muscle Contractile Properties, Structure, and Function during 10-d Bed Rest, Postrecovery, and after C…
51	2021	Journal of Nutrition	Antioxidant Supplementation Does Not Affect Bone Turnover Markers during 60 Days of 6° Head-Down Tilt Bed Rest: Resul…
54	2023	NeuroImage	Artificial gravity during a spaceflight analog alters brain sensory connectivity
55	2026	Journal of Physiology	Artificial gravity during prolonged bed rest preserves resting metabolic rate but not muscle function: Evidence from …
77	2022	Spine Journal	Biomechanical changes in the lumbar spine following spaceflight and factors associated with postspaceflight disc hern…
82	2025	Journal of the American Academy of Ortho	Bone Health in Space Flight: Incomplete Bone Mineral Density Convalescence at 1 Year Postmission Without Increased Fr…
87	2021	Investigative Radiology	Bone Marrow Reconversion With Reambulation: A Prospective Clinical Trial
88	2022	NPJ microgravity	Bone metabolism during strict head-down tilt bed rest and exposure to elevated levels of ambient CO2.
89	2026	Osteologie	Bone resorption during bedrest occurs predominantly in anatomical regions previously optimized to mechanical loading …
91	2022	Cerebral Cortex	Brain and Behavioral Evidence for Reweighting of Vestibular Inputs with Long-Duration Spaceflight
92	2026	Proceedings of the National Academy of S	Brain displacement and nonlinear deformation following human spaceflight
93	2017	PLoS ONE	Brain plasticity and sensorimotor deterioration as a function of 70 days head down tilt bed rest

Screening ID	Year	Source	Title
101	2020	Scientific reports	Cardio-postural interactions and muscle-pump baroreflex are severely impacted by 60-day bedrest immobilization
113	2022	Annals of Biomedical Engineering	Change in Lumbar Muscle Size and Composition on MRI with Long-Duration Spaceflight
115	2018	Journal of Neurophysiology	Change of cortical foot activation following 70 days of head-down bed rest
121	2024	NPJ microgravity	Changes in real-world walking speed following 60-day bed-rest
125	2023	JBMR Plus	Changes in Vertebral Bone Density and Paraspinal Muscle Morphology Following Spaceflight and 1 Year Readaptation on E…
133	2023	Frontiers in Neurology	Cognitive and balance functions of astronauts after spaceflight are comparable to those of individuals with bilateral…
140	2026	NPJ microgravity	Comparison of musculoskeletal responses and its variability after long-term spaceflight and prolonged bed rest condit…
147	2023	Nature Communications	Comprehensive assessment of physiological responses in women during the ESA dry immersion VIVALDI microgravity simula…
154	2017	Journal of Bone and Mineral Research	Cortical and Trabecular Bone Microstructure Did Not Recover at Weight-Bearing Skeletal Sites and Progressively Deteri…
155	2022	Brain Structure and Function	Cortical thickness of primary motor and vestibular brain regions predicts recovery from fall and balance directly aft…
161	2018	Frontiers in Physiology	Critical Role of Somatosensation in Postural Control Following Spaceflight: Vestibularly Deficient Astronauts Are Not…
164	2021	European journal of applied physiology	Daily 30-min exposure to artificial gravity during 60 days of bed rest does not maintain aerobic exercise capacity bu…
165	2023		Daily Artificial Gravity Partially Mitigates Vestibular Processing Changes Associated with Head-down Tilt Bedrest.
197	2026	NPJ microgravity	Early skeletal deteriorations following short-duration spaceflight.
199	2021	Scientific reports	Effect of 5-day dry immersion on the human foot morphology evaluated by computer plantography and soft tissues stiffn…
201	2025	Experimental Physiology	Effect of artificial gravity on calcaneal bone marrow adipose tissue and mineral content in female and male participa…
210	2026	Experimental Physiology	Effects of 14 days of head-down bed rest with or without exercise, and subsequent recovery on bone turnover, density …
212	2020	European journal of applied physiology	Effects of 21 days of bed rest and whey protein supplementation on plantar flexor muscle fatigue resistance during re…
214	2023	Nutrition bulletin	Effects of antioxidant supplementation on bone mineral density, bone mineral content and bone structure in healthy me…
215	2026	SSRN	Effects of bed rest and an exercise countermeasure on muscle and bone in middle-aged to older adults: A pQCT analysis…
220	2023	NPJ microgravity	Effects of exercise countermeasures on multisystem function in long duration spaceflight astronauts.
224	2024	Frontiers in Physiology	Effects of intermittent seating upright, lower body negative pressure, and exercise on functional tasks performance a…
226	2020	Journal of Bone and Mineral Research	Effects of Long-Duration Spaceflight on Vertebral Strength and Risk of Spine Fracture
231	2025	PloS one	Effects of repeated gravity changes during parabolic flight: Evidence of the need to assist space tourists to outer s…
232	2025	Frontiers in Physiology	Effects of short-duration spaceflight on the execution of critical mission tasks
240	2023	Frontiers in Human Neuroscience	Elevated biomarkers of neural injury in older adults following head-down bed rest: links to cardio-postural deconditi…

Screening ID	Year	Source	Title
241	2025	Aerospace medicine and human performance	Elevated Coronary Artery Calcium Scores in Astronauts
244	2020	Frontiers in Physiology	Evaluation of an Antioxidant and Anti-inflammatory Cocktail Against Human Hypoactivity-Induced Skeletal Muscle Decond…
252	2018	PLoS ONE	Exercise effects on bed rest-induced brain changes
253	2016	Extreme Physiology and Medicine	Exercise in space: The European Space Agency approach to in-flight exercise countermeasures for long-duration mission…
264	2020	Frontiers in Physiology	Fetuin-A as a Potential Biomarker of Metabolic Variability Following 60 Days of Bed Rest
268	2019	Journal of Biomechanical Engineering	Forecasting Postflight Hip Fracture Probability Using Probabilistic Modeling
272	2018	Spine Journal	From the international space station to the clinic: how prolonged unloading may disrupt lumbar spine stability
274	2018	Aerospace medicine and human performance	Functional Task and Balance Performance in Bed Rest Subjects and Astronauts
296	2018	Frontiers in Physiology	High Intensity Jump Exercise Preserves Posture Control, Gait, and Functional Mobility During 60 Days of Bed-Rest: An …
297	2020	NPJ microgravity	High intensity training during spaceflight: results from the NASA Sprint Study.
299	2017	BMJ open sport & exercise medicine	High-intensity flywheel exercise and recovery of atrophy after 90 days bed–rest.
300	2017	PLoS ONE	High-intensity jump training is tolerated during 60 days of bed rest and is very effective in preserving leg power an…
315	2024	Osteoarthritis and Cartilage	Immobilization by 21 days of bed rest results in type II collagen degradation in healthy individuals
316	2025	Osteoarthritis and Cartilage Open	Immobilization by 21-days of bed rest causes changes in biomarkers of cartilage homeostasis in healthy individuals
318	2026	Experimental Physiology	Impact of 14 days of head-down bed rest and an exercise countermeasure on skeletal muscle atrophy, proteome and circu…
329	2022	Scientific reports	Incomplete recovery of bone strength and trabecular microarchitecture at the distal tibia 1 year after return from lo…
330	2022	Journal of Bone and Mineral Research	Incomplete recovery of bone strength, density and trabecular microarchitecture at the distal tibia 12 months after re…
336	2021	Journal of applied physiology (Bethesda,	Intermittent short-arm centrifugation is a partially effective countermeasure against upright balance deterioration f…
338	2016	Frontiers in Physiology	Intervertebral disc swelling demonstrated by 3D and water content magnetic resonance analyses after a 3-day dry immer…
357	2020	Journal of Orthopaedic Research	Locomotion replacement exercise cannot counteract cartilage biomarker response to 5 days of immobilization in healthy…
370	2016	Spine	Lumbar Spine Paraspinal Muscle and Intervertebral Disc Height Changes in Astronauts After Long-Duration Spaceflight o…
397	2022	Frontiers in Physiology	Mission-critical tasks for assessing risks from vestibular and sensorimotor adaptation during space exploration
408	2022	Frontiers in Physiology	Multiple field tests on landing day: Early mobility may improve postural recovery following spaceflight
416	2019	Frontiers in Physiology	Neck Muscle Changes Following Long-Duration Spaceflight
417	2019	Spine	Negative Effects of Long-duration Spaceflight on Paraspinal Muscle Morphology
418	2020	Frontiers in Systems Neuroscience	Neural Correlates of Vestibular Processing During a Spaceflight Analog With Elevated Carbon Dioxide (CO2): A Pilot Study

Screening ID	Year	Source	Title
426	2016	Aerospace medicine and human performance	Neuromuscular Adaptations Following 90 Days Bed Rest With or Without Resistance Exercise
433	2025	Journal of applied physiology (Bethesda,	New insights into the impact of bed rest on lumbopelvic muscles: a computer-vision model approach to measure fat frac…
445	2017	Aerospace medicine and human performance	One-Year Mission on ISS Is a Step Towards Interplanetary Missions
472	2018	Medicine and science in sports and exerc	Physiological and Functional Alterations after Spaceflight and Bed Rest
475	2018	Frontiers in Physiology	Plyometrics can preserve peak power during 2 months of physical inactivity: An RCT including a one-year follow-up
487	2020	Journal of Bone and Mineral Research	Preflight Biomarkers of Bone Remodelling Predict Bone Loss on Long-Duration Spaceflight
497	2021	Aerospace medicine and human performance	Protein Intake and Physical Performance Following Long-Term Stay on the International Space Station
504	2020	Frontiers in Physiology	Reactive Jumps Preserve Skeletal Muscle Structure, Phenotype, and Myofiber Oxidative Capacity in Bed Rest
505	2018	Journal of ultrasound in medicine : offi	Real-time Ultrasound Assessment of Astronaut Spinal Anatomy and Disorders on the International Space Station
510	2025	NPJ microgravity	Recovery of bone microarchitecture and density four years after spaceflight: two case studies.
522	2026	Aerospace medicine and human performance	Reorganization of Human Gait and Foot Pressure Patterns After 1-Week Dry Immersion
523	2016	Bone Reports	Replacement of daily load attenuates but does not prevent changes to the musculoskeletal system during bed rest
527	2019	Bone	Resistive exercise in astronauts on prolonged spaceflights provides partial protection against spaceflight-induced bo…
528	2020	Translational Sports Medicine	Response of thigh muscle cross-sectional area to 21-days of bed rest with exercise and nutrition countermeasures
540	2018	NPJ microgravity	Sarcolab pilot study into skeletal muscle's adaptation to long-term spaceflight.
546	2025	NPJ microgravity	Sensory network segregation as a predictor of post spaceflight balance impairments and sensory re-weighting.
549	2016	Journal of Bone and Mineral Metabolism	Serum sclerostin and DKK1 in relation to exercise against bone loss in experimental bed rest
554	2026	Journal of shoulder and elbow surgery	Shoulder Injury and Surgery Patterns Among Astronauts Across Spaceflight Phases and Mission Operations: An Analysis o…
555	2022	PNAS nexus	Signatures of muscle disuse in spaceflight and bed rest revealed by single muscle fiber proteomics.
567	2025	JSES International	Space flight missions over 6 months significantly increase the risk of shoulder pathology and rotator cuff tears
568	2023	International Journal of Molecular Scien	Space Omics and Tissue Response in Astronaut Skeletal Muscle after Short and Long Duration Missions
575	2019	JAMA Neurology	Spaceflight-Associated Brain White Matter Microstructural Changes and Intracranial Fluid Redistribution
581	2022	American Journal of Physiology - Regulat	Spinal changes after 5-day dry immersion as shown by magnetic resonance imaging (DI-5-CUFFS)
599	2019	Journal of applied physiology (Bethesda,	Tensiomyography detects early hallmarks of bed-rest-induced atrophy before changes in muscle architecture
609	2018	Frontiers in Physiology	The effect of bed rest and hypoxic environment on postural balance and trunk automatic (re)actions in young healthy m…

Screening ID	Year	Source	Title
618	2022	Frontiers in Neural Circuits	The Effects of 30 Minutes of Artificial Gravity on Cognitive and Sensorimotor Performance in a Spaceflight Analog Env…
621	2021	Frontiers in Neural Circuits	The Effects of Long Duration Spaceflight on Sensorimotor Control and Cognition
625	2026	Archives of Osteoporosis	The effects of spaceflight countermeasures on trabecular bone score (TBS) of the lumbar spine
627	2026	NPJ microgravity	The impact of 14-day head-down bed rest with or without an exercise countermeasure on standing balance control: a ran…
634	2020	Physiological Reports	The influence of a sustained 10-day hypoxic bed rest on cartilage biomarkers and subchondral bone in females: The Fem…
643	2023	Extreme Medicine	THE ROLE OF FAST RUNNING IN PREVENTION OF NEGATIVE EFFECTS OF PROLONGED EXPOSURE TO WEIGHTLESSNESS
645	2017	Musculoskeletal Science and Practice	The role of physiotherapy in the European Space Agency strategy for preparation and reconditioning of astronauts befo…
650	2025	Life Sciences in Space Research	Thoracolumbar spine muscle size and composition changes in long-duration space missions
656	2024	Science advances	Tracking of spaceflight-induced bone remodeling reveals a limited time frame for recovery of resorption sites in humans
660	2016	NPJ microgravity	Treadmill exercise within lower-body negative pressure attenuates simulated spaceflight-induced reductions of balance…
672	2026	Osteoporosis International	Use of DXA-based software to identify astronauts at risk for persisting spaceflight-induced bone loss
673	2020	Journal of Clinical Densitometry	Use of Quantitative Computed Tomography to Assess for Clinically-relevant Skeletal Effects of Prolonged Spaceflight o…
688	2020	Journal of applied physiology (Bethesda,	Whey protein supplementation with vibration exercise ameliorates lumbar paraspinal muscle atrophy in prolonged bed rest
691	2016	Journal of applied physiology (Bethesda,	WISE 2005: Aerobic and resistive countermeasures prevent paraspinal muscle deconditioning during 60-day bed rest in w…

Rule (iv), registry entries excluded on the same basis as conference abstracts without retrievable full text

13 trial-registry records excluded on source type. Registry records that were also excluded for another reason (no spaceflight or analogue exposure, no musculoskeletal outcome, or exposure-period data only) are not attributed to this rule.

Screening ID	Year	Source	Title
16	2018	clinicaltrials.gov	A Low Glycemic Index Diet for Prevention of Glucose Intolerance During Bed Rest
21	2024	clinicaltrials.gov	A Randomized Controlled Study on 24 Healthy Male Volunteers Evaluating the Effects of Centrifugation and Exercise to …
67	2022	clinicaltrials.gov	B-Complex: A Nutraceutical SANS Countermeasure
111	2016	clinicaltrials.gov	CB147 - Physical Activity and Nutrition for Quality Ageing
174	2018	clinicaltrials.gov	Determination of the Time-course of Development of Insulin Resistance, and Associated Molecular and Muscular Adaptati…
213	2024	clinicaltrials.gov	Effects of 60-day-6° Head-down Bed Rest on Cartilage and Function of the Knee Joint
239	2024	clinicaltrials.gov	ElectroMyoStimulation (EMS Body Suit) Protocol to Improve Exercise Outcome in Space Missions (EasyMotion-2)

Screening ID	Year	Source	Title
254	2019	clinicaltrials.gov	Exercise Training as an Intervention to Improve Muscle Function and Recovery Following Bed Rest in Older Adults With …
375	2019	clinicaltrials.gov	MARS-PRE: MARcatori Biologici e Funzionali Per la Biomedicina aStronautica di PREcisione
385	2017	clinicaltrials.gov	Metformin to Prevent Inactivity-induced Loss of Muscle Health During Aging
392	2021	clinicaltrials.gov	Microgravity Research Analogue (MRA): Understanding the Health Impact of Inactivity for the Benefit of Older Adults a…
538	2021	clinicaltrials.gov	Safe and Effective Countermeasures to Reduce Intracranial Pressure and Ameliorate Visual Impairment in Astronauts (ST…
585	2022	clinicaltrials.gov	Standardization of the Dry Immersion Model Used as a Ground-based Model to Mimic Weightlessness. Phase 2: a 5-day Dry…

Rule (ii), a ground-based study eligible only where its authors themselves framed the exposure as simulating microgravity or spaceflight

No record was excluded under this rule. At title and abstract, 23 of the records carried forward had no explicit spaceflight vocabulary in the abstract (ten with none and thirteen with head-down tilt or artificial gravity only). Of the eleven whose full text could be read at that stage, all eleven carried an explicit framing in the Introduction or Methods, and the remaining twelve are records of agency bed-rest campaigns that were later reclassified as background under rule (iii). One included study, Shur et al. 2024 (screening ID 71), rests on a single protocol-adherence statement and was independently adjudicated on 10 September 2026 as meeting the rule (Supplementary Note 1, S1-11). The records excluded on bed-rest form under rule (i) were also the records with the weakest framing.

Supplementary Note 4. Search strategies as run, reported under PRISMA-S

4.1 Overview

Two searches were designed for every database, differing by one Boolean block. The main search (exposure AND intervention AND recovery phase, animal-only records excluded where the platform allowed, 2016–2026) fed screening and the flow diagram. The collision search (exposure AND intervention, no date limit, no publication-type filter) was run in PubMed only and inspected for prior reviews, overviews and position papers. It contributed no records to screening.

Platform and interface	Sources covered	Date run	Limits and settings	Records retrieved (main search)	Records obtained
PubMed (NCBI web interface records retrieved by E-utilities	MEDLINE, PubMed Central citations, in-process records	28 July 2026 (development no date limit) and 2 August	`NOT (animals[mh] NOT humans[mh]) AND 2016:2026[dp]`	390 (1,143 without	390

Platform and interface	Sources covered	Date run	Limits and settings	Records retrieved (main search)	Records obtained
`esearch`/`efetch`, MEDLINE format)		2026 (as run date limit)	no language or publication-type limit	the date limit)	
Embase.com (Elsevier), via the Kaohsiung Chang Gung Memorial Hospital library proxy	Embase, MEDLINE, Preprints, Clinical Trials	2 August 2026	All Emtree mapping options disabled (map to preferred term search also as free text in all fields explode narrower terms search as broadly as possible major focus) `AND [2016-2026]/py` no language or publication-type limit	538 (1,599 without the date limit)	532
EBSCO Discovery Service (EBSCOhost), Kaohsiung Chang Gung Memorial Hospital	The institution's EBSCO databases searched together, CINAHL Ultimate among them (the institution holds nine: AgeLine, CINAHL Ultimate, eBook Collection, Health Source: Nursing/Academic Edition, MEDLINE Ultimate, Psychology and Behavioral Sciences Collection, Rehabilitation & Sports Medicine Source, eBook Nursing Collection, eBook Medical Collection)	3 August 2026	Boolean/Phrase mode (`searchMode=bool`) expanders off (`expanders=`) autocorrect off (`autocorrect=n`) limiter `DT1:2016-01-01/2026-12-31` no language or publication-type limit animal-only records not excludable at the search stage	526	468
CINAHL Ultimate searched alone (EBSCOhost), same institution	CINAHL Ultimate only the other eight databases deselected	2 August 2026	As above	67 (144 without the date limit)	Recorded as a count only CINAHL content entered the review through the Discovery Service search
Total, main search				**1,454**	**1,390**

Sixty-four records retrieved by the main search could not be obtained at export. None entered screening. Records were deduplicated in Zotero on 8 August 2026 (711 duplicates removed, 679 unique records), after which duplicate groups were verified by title similarity, and three records that had been merged as one duplicate group were found to be three distinct reports and restored (10 August 2026). A peer review of the search strategy (PRESS) was not performed. The search has not been re-run since 3 August 2026.

4.2 PubMed

Main search, as run on 2 August 2026 (390 records). The same string without the final line returned 1,143 records on 28 July 2026 and again on 2 August 2026.

```
("Space Flight"[Mesh] OR "Weightlessness"[Mesh] OR "Weightlessness
Simulation"[Mesh] OR "Astronauts"[Mesh] OR "Bed Rest"[Mesh] OR "Head-Down
Tilt"[Mesh] OR spaceflight[tiab] OR "space flight"[tiab] OR
microgravity[tiab] OR weightlessness[tiab] OR astronaut*[tiab] OR
cosmonaut*[tiab] OR "bed rest"[tiab] OR bedrest[tiab] OR "head-down
tilt"[tiab] OR "head down tilt"[tiab] OR "dry immersion"[tiab] OR "limb
suspension"[tiab])
AND
("Exercise Therapy"[Mesh] OR "Physical Therapy Modalities"[Mesh] OR
"Weightlessness Countermeasures"[Mesh] OR "Recovery of Function"[Mesh] OR
reconditioning[tiab] OR rehabilitat*[tiab] OR physiotherap*[tiab] OR
"physical therapy"[tiab] OR remobili*[tiab] OR reambulat*[tiab] OR "re-
ambulation"[tiab] OR readaptation[tiab] OR "re-adaptation"[tiab] OR
recovery[tiab] OR "exercise training"[tiab] OR countermeasure*[tiab] OR
exercise[tiab] OR training[tiab])
AND
(postflight[tiab] OR "post-flight"[tiab] OR "post flight"[tiab] OR "after
landing"[tiab] OR "following landing"[tiab] OR "return to earth"[tiab] OR
"return to 1g"[tiab] OR "return to gravity"[tiab] OR "return to duty"[tiab]
OR readaptation[tiab] OR "re-adaptation"[tiab] OR reconditioning[tiab] OR
reambulat*[tiab] OR "re-ambulation"[tiab] OR remobili*[tiab] OR "after bed
rest"[tiab] OR "following bed rest"[tiab] OR "post-bed rest"[tiab] OR "post
bed rest"[tiab] OR "post-HDBR"[tiab] OR "post HDBR"[tiab] OR "post-HDT"[tiab]
OR "post-immersion"[tiab] OR "recovery period"[tiab] OR "recovery
phase"[tiab] OR "recovery time"[tiab] OR "recovery of"[tiab] OR
reloading[tiab] OR "re-loading"[tiab] OR reconvalescen*[tiab] OR
convalescen*[tiab] OR "upright posture"[tiab] OR "return to
ambulation"[tiab])
NOT (animals[mh] NOT humans[mh])
AND 2016:2026[dp]
```

Three properties of the string are recorded. Animal-only records are excluded with NOT (animals[mh] NOT humans[mh]) rather than by requiring humans[mh], so that records reporting both animal and human data, and newly indexed records without a human tag, are retained. Ground analogues are retained in the exposure block. Restricting to spaceflight was tested (2,781 records without the date limit) and loses eligible analogue recovery studies, De Martino et al. 2022 and Shur et al. 2024 among them. Review publication types are not filtered at the search stage (see 4.6). On re-running the strategy, PubMed reported five quoted phrases as not found in its phrase index, "after bed rest", "following bed rest", "return to 1g", "return to gravity" and "following landing". Each retrieves zero records alone, and removing all five leaves the main search at 1,143 records without the date limit. They are retained because phrase handling differs between platforms, and their contribution in PubMed is nil.

Collision search, as run (4,715 records on 28 July 2026 and 4,717 on 2 August 2026, the difference reflecting database growth, with 4,716 recorded in the registration for the same day). No date limit, no publication-type filter, no animal exclusion.

```
("Space Flight"[Mesh] OR "Weightlessness"[Mesh] OR "Weightlessness
Simulation"[Mesh] OR "Astronauts"[Mesh] OR "Bed Rest"[Mesh] OR "Head-Down
Tilt"[Mesh] OR spaceflight[tiab] OR "space flight"[tiab] OR
microgravity[tiab] OR weightlessness[tiab] OR astronaut*[tiab] OR
cosmonaut*[tiab] OR "bed rest"[tiab] OR bedrest[tiab] OR "head-down
tilt"[tiab] OR "head down tilt"[tiab] OR "dry immersion"[tiab] OR "limb
suspension"[tiab])
AND
("Exercise Therapy"[Mesh] OR "Physical Therapy Modalities"[Mesh] OR
"Weightlessness Countermeasures"[Mesh] OR "Recovery of Function"[Mesh] OR
reconditioning[tiab] OR rehabilitat*[tiab] OR physiotherap*[tiab] OR
"physical therapy"[tiab] OR remobili*[tiab] OR reambulat*[tiab] OR "re-
ambulation"[tiab] OR readaptation[tiab] OR "re-adaptation"[tiab] OR
recovery[tiab] OR postflight[tiab] OR "post-flight"[tiab] OR "return to
earth"[tiab] OR "return to duty"[tiab] OR "exercise training"[tiab] OR
(countermeasure*[tiab] AND (postflight[tiab] OR "post-flight"[tiab] OR
recovery[tiab] OR recover*[tiab] OR readaptation[tiab] OR "after bed
rest"[tiab] OR "following bed rest"[tiab] OR reambulat*[tiab] OR
remobili*[tiab])))
```

The term `countermeasure*` is gated on a recovery term. Unrestricted, it added 1,450 records dominated by in-flight countermeasure work (eleven of twelve sampled records unrelated), and removed entirely it lost borderline studies in which a countermeasure was applied during bed rest and an outcome measured afterwards. The broad heading `"Rehabilitation"[Mesh]` was removed (1,305 records alone) with no loss against the reference set. The records the collision search added over the main search were inspected for reviews, overviews and position papers. The inspection found no completed synthesis of post-flight musculoskeletal reconditioning. The nearest registered work, PROSPERO CRD420261452151 (Kalia et al.), was identified in the PROSPERO register on 28 July 2026, before the protocol was written. On 31 August 2026 PROSPERO (24 free-text terms, 205 unique records), OSF Registries (18 terms, 126 registrations), INPLASY (7 terms, 3 records) and the Research Registry (all 1,998 systematic-review records screened) were searched, and no registration with the same scope was found. No record of the inspection of the collision-search records was retained beyond its outcome.

4.3 Embase.com

Ten lines were run on 2 August 2026, each twice by different access routes, with identical counts. Line #8 is the main search. Lines #9 and #10 were run and are reported to show that adding outcome and comparator terms was tested.

Line	Concept	Records
#1	Exposure	44,923
#2	Intervention	3,195,534
#3	Comparator	15,424,431
#4	Outcome	4,425,518

Line	Concept	Records
#5	Recovery phase	91,343
#6	#1 AND #2	8,623
#7	#1 AND #2 AND #5	1,599
#8	**#1 AND #2 AND #5 AND [2016-2026]/py, main search**	**538**
#9	#1 AND #2 AND #4 AND [2016-2026]/py	1,741
#10	#1 AND #2 AND #3 AND #4 AND [2016-2026]/py	961

```
#1  'space flight'/exp OR 'weightlessness'/exp OR 'bed rest'/exp OR
astronaut*:ti,ab,kw OR cosmonaut*:ti,ab,kw OR spaceflight:ti,ab,kw OR 'space
flight':ti,ab,kw OR microgravity:ti,ab,kw OR weightlessness:ti,ab,kw OR 'bed
rest':ti,ab,kw OR bedrest:ti,ab,kw OR 'head-down tilt':ti,ab,kw OR 'head down
tilt':ti,ab,kw OR 'dry immersion':ti,ab,kw OR 'limb suspension':ti,ab,kw
#2  'rehabilitation'/exp OR 'physiotherapy'/exp OR 'kinesiotherapy'/exp OR
'convalescence'/exp OR reconditioning:ti,ab,kw OR rehabilitat*:ti,ab,kw OR
physiotherap*:ti,ab,kw OR 'physical therapy':ti,ab,kw OR remobili*:ti,ab,kw
OR reambulat*:ti,ab,kw OR 're-ambulation':ti,ab,kw OR readaptation:ti,ab,kw
OR 're-adaptation':ti,ab,kw OR recovery:ti,ab,kw OR 'exercise
training':ti,ab,kw OR countermeasure*:ti,ab,kw OR exercise:ti,ab,kw OR
training:ti,ab,kw
#3  control*:ti,ab,kw OR placebo:ti,ab,kw OR 'usual care':ti,ab,kw OR 'no
intervention':ti,ab,kw OR compar*:ti,ab,kw
#4  'muscle atrophy'/exp OR 'bone density'/exp OR 'muscle strength'/exp OR
'body equilibrium'/exp OR musculoskeletal:ti,ab,kw OR muscle*:ti,ab,kw OR
muscular:ti,ab,kw OR bone:ti,ab,kw OR 'bone density':ti,ab,kw OR
atrophy:ti,ab,kw OR strength:ti,ab,kw OR spine:ti,ab,kw OR spinal:ti,ab,kw OR
lumbar:ti,ab,kw OR multifidus:ti,ab,kw OR cartilage:ti,ab,kw OR 'functional
performance':ti,ab,kw OR balance:ti,ab,kw OR gait:ti,ab,kw
#5  postflight:ti,ab,kw OR 'post-flight':ti,ab,kw OR 'after landing':ti,ab,kw
OR 'following landing':ti,ab,kw OR 'return to earth':ti,ab,kw OR 'return to
1g':ti,ab,kw OR 'return to gravity':ti,ab,kw OR 'return to duty':ti,ab,kw OR
readaptation:ti,ab,kw OR 're-adaptation':ti,ab,kw OR reconditioning:ti,ab,kw
OR reambulat*:ti,ab,kw OR 're-ambulation':ti,ab,kw OR remobili*:ti,ab,kw OR
'after bed rest':ti,ab,kw OR 'following bed rest':ti,ab,kw OR 'post-bed
rest':ti,ab,kw OR 'post-HDBR':ti,ab,kw OR 'post-HDT':ti,ab,kw OR 'post-
immersion':ti,ab,kw OR 'recovery period':ti,ab,kw OR 'recovery
phase':ti,ab,kw OR 'recovery time':ti,ab,kw OR reloading:ti,ab,kw OR 're-
loading':ti,ab,kw OR convalescen*:ti,ab,kw OR 'upright posture':ti,ab,kw OR
'return to ambulation':ti,ab,kw
```

Embase.com searched four sources (Embase, MEDLINE, Preprints, Clinical Trials), so the counts overlap substantially with the PubMed search. The overlap was removed at deduplication and is reported in Figure 1. Of 538 records retrieved, 532 were obtained.

4.4 CINAHL Ultimate, searched alone

Run on 2 August 2026 in Boolean/Phrase mode with expanders and autocorrect disabled. S8 is the main search. The concept strings are the Embase strings term for term in EBSCOhost syntax. Subject-heading lines carry the heading names as entered.

Line	Concept	Records
S1	Exposure	4,249
S2	Intervention	720,263
S3	Comparator	1,849,413
S4	Outcome	607,313
S5	Recovery phase	10,457
S6	S1 AND S2	1,081
S7	S1 AND S2 AND S5	144
S8	**S7 with limiter DT1:2016-01-01/2026-12-31, main search**	**67**
S9	S1 AND S2 AND S4 with the limiter	194
S10	S1 AND S2 AND S3 AND S4 with the limiter	87

```
S1  (MH "Space Flight+") OR (MH "Weightlessness+") OR (MH "Bed Rest+") OR TI
( astronaut* OR cosmonaut* OR spaceflight OR "space flight" OR microgravity
OR weightlessness OR "bed rest" OR bedrest OR "head-down tilt" OR "head down
tilt" OR "dry immersion" OR "limb suspension" ) OR AB ( astronaut* OR
cosmonaut* OR spaceflight OR "space flight" OR microgravity OR weightlessness
OR "bed rest" OR bedrest OR "head-down tilt" OR "head down tilt" OR "dry
immersion" OR "limb suspension" )
S2  (MH "Physical Therapy+") OR (MH "Therapeutic Exercise+") OR (MH
"Convalescence+") OR TI ( reconditioning OR rehabilitat* OR physiotherap* OR
"physical therapy" OR remobili* OR reambulat* OR "re-ambulation" OR
readaptation OR "re-adaptation" OR recovery OR "exercise training" OR
countermeasure* OR exercise OR training ) OR AB ( reconditioning OR
rehabilitat* OR physiotherap* OR "physical therapy" OR remobili* OR
reambulat* OR "re-ambulation" OR readaptation OR "re-adaptation" OR recovery
OR "exercise training" OR countermeasure* OR exercise OR training )
S3  TI ( control* OR placebo OR "usual care" OR "no intervention" OR
compar* ) OR AB ( control* OR placebo OR "usual care" OR "no intervention" OR
compar* )
S4  (MH "Muscular Atrophy+") OR (MH "Bone Density+") OR (MH "Muscle
Strength+") OR (MH "Postural Balance+") OR TI ( musculoskeletal OR muscle* OR
muscular OR bone OR "bone density" OR atrophy OR strength OR spine OR spinal
OR lumbar OR multifidus OR cartilage OR "functional performance" OR balance
OR gait ) OR AB ( musculoskeletal OR muscle* OR muscular OR bone OR "bone
density" OR atrophy OR strength OR spine OR spinal OR lumbar OR multifidus OR
cartilage OR "functional performance" OR balance OR gait )
S5  TI ( postflight OR "post-flight" OR "post flight" OR "after landing" OR
"following landing" OR "return to earth" OR "return to 1g" OR "return to
gravity" OR "return to duty" OR readaptation OR "re-adaptation" OR
reconditioning OR reambulat* OR "re-ambulation" OR remobili* OR "after bed
rest" OR "following bed rest" OR "post-bed rest" OR "post-HDBR" OR "post-HDT"
OR "post-immersion" OR "recovery period" OR "recovery phase" OR "recovery
time" OR reloading OR "re-loading" OR convalescen* OR "upright posture" OR
"return to ambulation" ) OR AB ( postflight OR "post-flight" OR "post flight"
OR "after landing" OR "following landing" OR "return to earth" OR "return to
1g" OR "return to gravity" OR "return to duty" OR readaptation OR "re-
adaptation" OR reconditioning OR reambulat* OR "re-ambulation" OR remobili*
OR "after bed rest" OR "following bed rest" OR "post-bed rest" OR "post-HDBR"
OR "post-HDT" OR "post-immersion" OR "recovery period" OR "recovery phase" OR
```

```
"recovery time" OR reloading OR "re-loading" OR convalescen* OR "upright
posture" OR "return to ambulation" )
```

Two counts exist for CINAHL Ultimate and both are reported, 67 when searched alone and 62 as the records attributed to CINAHL Ultimate by a combined EBSCOhost search of the institution's six subject databases run with the same query (498 records in total), in which the platform removes records held in more than one database and assigns each surviving record to a single content provider. Neither the 67 nor the 498 is the set that entered screening.

4.5 EBSCO Discovery Service

Run on 3 August 2026 with the query of line S8 above (S1 AND S2 AND S5 with the date limiter), Boolean/Phrase mode, expanders and autocorrect disabled, and retrieved 526 records. The Discovery Service search has not been broken down by the content provider. Records were exported in CSV in batches of 50 and converted to RIS for import. In all, 475 rows were downloaded across ten files, of which 468 were unique by accession number, and the remaining 58 could not be exported after repeated attempts. The shortfall is reported in Figure 1 as records retrieved but not obtained.

4.6 Known-item validation and the variants tested

Reference sets. A thirteen-item set assembled during the preliminary search was used to test the two-block variants, PMIDs 32966906, 35774286, 28173929, 25022167, 36187781, 38343303, 38216584, 17167347, 35874509, 39705358, 33992043, 34115344 and 36707515. One record initially listed, Lindsay et al. 2020 (PMID 32861357), was found on full-text checking to be a terrestrial chronic low-back-pain study with no spaceflight or analogue exposure and was removed. Its non-retrieval is correct. For the three-block main search the set was extended to fifteen and separated into twelve primary-study candidates and three background reviews (Moosavi et al. 2021, Comfort et al. 2021 and Liphardt et al. 2023). The unrestricted main search retrieved twelve of the fifteen, every primary-study candidate and none of the three background reviews, which concern in-flight countermeasures and are excluded by the recovery-phase block by design. The collision search retrieved all fifteen. The identifiers of the two primary-study candidates added to the thirteen were not preserved in the search record and are not reproduced here. Known-item validation was performed in PubMed only. No sensitivity claim is made for Embase.com or the EBSCO Discovery Service.

Two-block variants (no date limit, thirteen-item set).

Variant	Records	Reference items retrieved
Exposure block including *unloading*, full intervention block	7,926	13 of 13
unloading removed	6,495	13 of 13
recovery also removed	5,254	12 of 13
Musculoskeletal outcome block added	2,939	11 of 13
Review and meta-analysis publication types excluded	5,369	8 of 13
*countermeasure** and broad Rehabilitation heading removed	4,704	13 of 13
Adopted for the collision search, *countermeasure with a recovery gate**	**4,715**	**13 of 13**

Three-block variants (fifteen-item set).

Variant	Records	Primary-study candidates	Background reviews
Two blocks (collision search)	4,715	12 of 12	3 of 3
Two blocks with animal-only excluded	3,879	12 of 12	3 of 3
Spaceflight only, analogues excluded	2,781	not retained	not retained
Three blocks	1,459	12 of 12	0 of 3
Adopted for the main search, three blocks with animal-only excluded	**1,143**	**12 of 12**	**0 of 3**
The above with 2016–2026 applied	**390**		

Unloading was redundant (18% of records saved, no loss). Adding an outcome block and removing *recovery* both lose eligible records and were rejected on retrieval grounds. Excluding review publication types at the search stage was the most damaging variant, losing five reference items, Payne 2007, Ekman 2022, Moosavi 2021, Comfort 2021 and Liphardt 2023, and severing the reference lists of prior syntheses.

Comparison with a four-block strategy. A four-block strategy (population, intervention, outcome and post-flight) written independently of the main strategy, run in PubMed with the 2016–2026 limit, retrieved 132 records and 3 of the 13 reference items. The three-block main search retrieved 390 and 8 of 13. Five of the thirteen cannot be retrieved by either strategy once the year limit applies (two predate 2016 and three are reviews), so on the achievable maximum of eight the strategies reach 3 of 8 and 8 of 8. The five records the four-block strategy misses, De Martino 2022 (PMID 35774286), Rosenberg 2022 (36187781), Shur 2024 (38343303), Grassi 2024 (38216584) and Walle 2024 (39705358), all fall inside the year window. The four-block population block carries no ground-analogue term, and its seven-term intervention block lacks *readaptation*, *reloading*, *recovery*, *remobili**, *reambulat**, *exercise* and *training*.

Limitations of the validation. The reference set was assembled from a preliminary PubMed search and is not independent of PubMed strategies. It contains no injury-epidemiology synthesis, so the retrieval of that class of evidence was never tested (Supplementary Note 1, final note). The date-limited sensitivity is not stated as a single figure, because the two known-eligible reports outside the window (Payne 2007 and Evetts 2014) are documented against the thirteen-item set, whose denominator is not interchangeable with the fifteen-item set.

4.7 Sources not searched

PEDro, Scopus, Web of Science and Cochrane CENTRAL were not searched. SPORTDiscus is not held by the institution, and access was sought and unavailable. The NASA Technical Reports Server, the NASA Life Sciences Data Archive, the ESA Erasmus Experiment Archive, the DLR electronic library, Russian-language sources and the trial registries (ClinicalTrials.gov, ISRCTN, EU CTR, WHO ICTRP) were not searched, reference lists of included sources were not screened, and no citation was tracked forward. Scopus and Web of Science do not index animal and human records in a way that permits exclusion at the search stage, so had they been searched the animal exclusion would have been applied at screening instead. The difference is recorded so that the search conditions are not described as uniform across databases.

Supplementary Table 1. Instruments by construct: acquisition, what each resolves, and what it does not

Acquisition detail is taken from the Methods and appendices of the thirteen full texts. The final column grades measurement-property evidence by what each source cited for its own charted outcomes, in full, partially, or not at all, and records whether evidence was cited without judging its adequacy, as described in the Methods.

Construct	Instrument and acquisition, as named by the source	Sources (results)	Resolves	Does not resolve	Measurement-property evidence cited
Whole-limb muscle volume	3-T MRI (Philips Ingenia) whole-body and leg volume, gluteals, quadriceps, adductors, hamstrings	Shur 2024 (1)	Summed volume of a muscle group along a limb	Individual muscle region within muscle composition	None
Mean axial CSA per muscle	Axial spin-echo T2 MRI, 3 T (GE Signa Horizon LX) TR 2,000 ms, TE 51 ms, 10 mm slices, 10 mm gap, 512 × 512 ankle mortise to iliac crest manual ImageJ tracing by one researcher, verified by two	Scott 2020 (2)	Muscle-by-muscle area averaged along length grouped and single-muscle regions of interest	Volume fat fraction anything outside the imaged segment	Full, inter-experimenter CV 2.8–3.8%, ICC 0.946–0.986
Segmental volume by intervertebral level	T1-weighted Dixon MRI 64 transverse slices, T12 to sacrum, 4 mm, TR 7.02 ms, TE 2.46/3.69 ms semi-automated Matlab region of interest, four medial-to-lateral quartiles per muscle	De Martino 2022 (2)	Level-specific and mediolateral distribution of lumbopelvic volume	Limb muscles contractile function	Partial, method reliability cited to prior work, no coefficient in the paper
Level-specific CSA (multifidus L2–L5)	B-mode ultrasound, 5-MHz convex array (GE LOGIQ e) prone bilateral transverse images, level identified by palpation of the spinous processes borders traced on the device after acquisition	Hides 2016 (1) Hides 2021 (2, including contraction)	Single-level paraspinal CSA at the bedside	Volume deep or overlapping structures force	Full for both, Hides 2016: intra-rater $ICC_{1,1}$ 0.83–0.99, inter-rater $ICC_{2,1}$ 0.88–0.99. Hides 2021: intra-rater $ICC_{1,1}$ 0.83–0.99 and inter-rater $ICC_{2,1}$ 0.88–0.99 for the multifidus, transversus abdominis and internal oblique measures multifidus at rest ICC 0.84–0.99 across the four vertebral levels mean intra-rater ICC 0.95 and inter-rater ICC 0.95 against an

Construct	Instrument and acquisition, as named by the source	Sources (results)	Resolves	Does not resolve	Measurement-property evidence cited
					expert for the contraction measure
Anterolateral abdominal thickness	B-mode ultrasound, supine with the abdominal wall relaxed transverse image on a line midway between the inferior angle of the rib cage and the iliac crest, right side linear thickness of transversus abdominis and internal oblique (external oblique also in Hides 2021) at rest and on contraction	Hides 2016 (1) Hides 2021 (1)	Layer-by-layer thickness contraction as thickness change	CSA or volume force	As above Hides 2021 reports intra-rater agreement of 0.83–0.98 at rest and 0.97–0.98 contracted
Paraspinal fat content	Chemical shift lipid/water Dixon MRI fat and water in-phase/out-of-phase, quartile-wise reporting	De Martino 2022 (1)	Fat fraction by muscle, level and quartile	Fibrous or connective content force per unit area	Partial, as above
Intramuscular collagen-1	Anti-collagen-1 immunoreactivity on soleus biopsy cryosections area pixel intensity in arbitrary units per 400 µm² field, 100 myofibres per cryosection	Schoenrock 2018 (1)	Presence and relative intensity of the collagen-1 network in one muscle	Whole-muscle burden repeat measurement without re-biopsy	Partial, operator training reported, no coefficients
Passive tone, stiffness, elasticity, relaxation	MyotonPRO hand-held digital palpation 22 skin-marked points (11 bilateral: upper trapezius, anterior deltoid, longissimus Th12, multifidus L4–5, rectus femoris, infrapatellar tendon, medial gastrocnemius, soleus, tibialis anterior, Achilles tendon, plantar fascia) frequency [Hz], stiffness [N/m], log decrement, relaxation [ms]	Schoenrock 2018 (1)	Damped-oscillation mechanics of a superficial tissue column, passive	Force torque area volume deep muscle shear modulus	Partial, as above
Myofibrillar protein synthesis	Oral D_2O tracer with serial vastus lateralis microbiopsy (Bard Monopty, 12 g / 10 cm) 3-methylhistidine tracer for whole-body breakdown	Shur 2024 (1)	Cumulative fractional synthetic rate over an interval	A state at a time point site-specific size change	None
Maximal strength	1RM squat and bench press on a Smith machine, ESA Astronaut Fitness Assessment	Petersen 2017 (1)	Whole-body multi-joint maximal lift, as an estimate	The lift itself joint-specific torque velocity	Partial, protocol sources cited, no coefficients the one instrument in

Construct	Instrument and acquisition, as named by the source	Sources (results)	Resolves	Does not resolve	Measurement-property evidence cited
	the value is calculated from two sets of up to 10 repetitions (Brzycki, 1993), not lifted			dependence effort-independent measurement	the set whose source cited an interpretive band for its own metric (5–10% day-to-day, Laughlin et al. 2015)
Muscular power	Countermovement, squat and drop jump, height [cm] and peak force [N], best of three trials, Templo software on a Kistler force platform	Petersen 2017 (1)	Stretch-shortening and concentric power expression	Which tissue property changed re-familiarisation effects whether a crew member willingly loaded the limb	Partial, as above
Hip flexibility	Sit and Reach, reaching forward on a standardised box [cm] Thomas Test, hip angle measurement [deg]	Petersen 2017 (1)	Composite hip and posterior-chain range of motion, on two instruments that in this study disagree (Results Table 3)	Muscular versus capsular versus neural contribution which of the two instruments to believe	Partial, as above
Core endurance	Ventral core endurance, holding a standardised position as long as possible [s] (ESA Astronaut Fitness Assessment)	Petersen 2017 (1)	Time-to-failure trunk endurance	Which trunk muscles carried the task motivation and pain tolerance	Partial, as above
Regional intramuscular fat fraction	3-T MRI, axial Dixon sequence automated computer-vision segmentation of lumbopelvic muscles. Lumbar muscles divided into eight tiles (superficial/deep and lateral/medial) gluteal muscles divided into anatomical regions.	Wesselink 2025 (1)	Muscle fat fraction by muscle and region, including spatial differences across lumbar vertebral levels and within individual muscles.	Muscle force or strength, contractile function, or direct histological evidence of fibrosis or connective-tissue changes.	Partial, automatic segmentation was compared with manual segmentation, with agreement analyses reported.
Hip bone mineral density (trabecular volumetric and total-hip areal BMD)	Quantitative computed tomography (QCT), GE LightSpeed VCT 64, for trabecular hip vBMD (g/cm^3) dual-energy X-ray absorptiometry (DXA Discovery or QDR-4500W-D) for total-hip aBMD. Both hips scanned. Preflight 30–45 d before launch first postflight scan within 5–22 d after return (R+5–22) R+1 yr conditional QCT at R+2 yr if QCT recovery was not within the least	Sibonga 2020 (2)	QCT resolves hip trabecular volumetric BMD and its recovery relative to preflight measurement DXA resolves total-hip areal BMD. The methods can show discordance between trabecular vBMD and aBMD recovery.	Does not establish that postflight reconditioning caused the observed bone recovery does not measure exercise dose-response or fracture incidence. R+2 yr QCT was conditional, not obtained for all astronauts.	Full for the measurement threshold reported: QCT least significant change 2.3% DXA least significant change 2.1%, based on the source's cited JSC precision testing. These are technology-specific measurement thresholds, not an MDC/MCID derived for the whole review or evidence of programme efficacy.

Construct	Instrument and acquisition, as named by the source	Sources (results)	Resolves	Does not resolve	Measurement-property evidence cited
	significant change at R+1 yr.				

Note. De Martino et al.'s segmental-volume row carries two charted results (multifidus, and erector spinae with quadratus lumborum and psoas major), matching the two rows of Table 3. Scott et al.'s knee extension and flexion strength on an isokinetic dynamometer (Biodex System 4) was measured before bed rest and at two recovery time points but no torque values were published. It is recorded as measured but not reported and does not appear as a row.

Charting decisions behind Tables 1, 3 and 5. Hides et al. 2016 is entered with no programme start because that source never stated when rehabilitation began. Its R+1 is an ultrasound assessment day, the assessments at R+1 and R+14 bound the first phase without dating its start, and the last-measurement column of Table 5 is computed from the end of the three-week first phase, which the source did state. Hides et al. 2021, from the same group, stated its start explicitly and is charted accordingly, but is charted as not reporting supervision, because the sentence naming the ESA physiotherapist and sports scientist describes the in-flight period and is given once, in the conditions-during-exposure column. Petersen et al. stated two recovery-phase session durations. Ninety minutes is the programme template in the appendix that sets out the phases, and 120 minutes is what this crew member's own daily schedule sums to on eight of its twelve tabulated days, with the text describing daily two-hour sessions. One is what the programme prescribes and the other what one person received, the source did not say which a reader should use, and the in-flight figure in that source is also 2 h, so the recovery figure is distinguishable from the exposure figure only by the sentence it comes from. The field is counted as reported. Scott et al. reported the duration of the aerobic component and no total session duration, so the field is charted as not reported. On day 11 the 45-minute walk is one of twenty-six items prescribed for that day, no row, column or footnote of eTable 1 carries a total, and the word "session" does not appear in the main text. The muscles Scott et al. recorded as recovered are counted two ways by that source, and both counts are recorded in Table 3. De Martino et al. randomised participants across three artificial-gravity arms crossing 1:1 with the two reconditioning programmes, so one third of that sample received no artificial gravity. Schoenrock et al.'s BDC entry has been removed from the myotonometry time points because that source's Methods place the first measurement at HDT+1 and every figure legend names HDT+1 as the baseline, while BDC is when the 22 points were identified and marked on the skin. The biopsy row is unaffected, since its BDC−5 baseline is a genuine pre-exposure measurement. Shur et al.'s own day numbering is internally inconsistent. Its supporting information placed the final experimental visit on the morning of day 7 and then stated that the study ended after a final scan on day 8, and both statements are recorded. On either, the final scan is R+4 in days from the end of unloading. Were the hip-flexibility result of Petersen et al., whose two instruments disagree, counted as one result per instrument, Table 2 would show 33 results and 34 assignments, functional performance 4 results from three studies and spaceflight 13 results, with no other cell changed. Spine carries no result on either charting form. The studies once recorded against it at study level measured lumbar musculature, which is charted under postural muscles, and no included study measured spinal shape, spinal bone mineral density or the intervertebral discs. One outcome was measured but not reported and is excluded from the results count. That study assessed knee extensor and flexor strength on an isokinetic

dynamometer before bed rest and at two recovery time points and published no values for it, only a correlation with muscle size. The background pool contains no group corresponding to orthostatic intolerance or aerobic capacity, and its cartilage group is filed as cartilage and connective tissue, which is broader than the report's row. Classified on spaceflight evidence alone, no cell of Table 2 changes.

Supplementary references

S1. Brzycki M. Strength testing, predicting a one-rep max from reps-to-fatigue. J Phys Educ Recreat Dance. 1993;64(1):88–90. doi:10.1080/07303084.1993.10606684.