

THE IN A HURRY SERIES

Astronauts *in a Hurry*

What it does to a human body and mind

Max Brocklesby

BOOKSINAHURRY.COM

Contents

The Whole Thing in One Page 4

Why You Should Care 6

The Core Ideas 8

How It Actually Works 20

What People Get Wrong 30

Use It 35

Terms 40

Go Deeper 44

Notes and Sources 45

Bibliography 51

The Whole Thing in One Page

The public image of an astronaut is a person released from ordinary life: floating, looking down at Earth, performing graceful work in a place where weight has vanished. The body experiences something less poetic. Space removes a set of signals that have trained most humans since infancy, then asks the same person to remain strong, alert and coordinated for the moment those signals return.

Orbit is not a place without gravity. It is continuous free fall. The spacecraft, the astronaut and everything loose inside are falling around Earth together, so the floor stops pushing upwards and the body loses its normal load. Muscles no longer need to hold the head and trunk upright. Bones receive fewer forceful strains. Blood no longer forms the familiar gradient from head to feet. The inner ear cannot use the weight of tiny sensory structures to define down. The body begins to regulate for the new conditions. Some changes restore function; others are side-effects, while radiation is exposure rather than adaptation.

That mismatch explains most of the subject. Conflicting sensory signals can produce nausea and disorientation; the brain reweights them until floating becomes ordinary. Fluid moves towards the chest and head, prompting the circulation and kidneys to adjust, while the return to upright gravity may bring dizziness or faintness. Muscle size, power and endurance can fall; bone remodelling shifts towards loss in heavily loaded regions; the eye and tissues behind it may change in a pattern called spaceflight-associated neuro-ocular syndrome. Sleep must be protected against strange schedules, noise, light and work. Immune signals, microbes and metabolism alter within a closed habitat.

Then there is radiation, which is not another version of deconditioning. Earth's magnetic field traps some particles and deflects others. Beyond its protection, solar eruptions and high-energy galactic cosmic rays become greater concerns. Their effects depend on particle type, energy, timing and shielding. A Mars risk cannot be compressed into one neat dose or one

confident prediction.

The mind is no passenger. Astronauts work inside small, international crews under surveillance, danger and dependence on distant specialists.

Selection, training, routine, privacy and ground support have made current crews strikingly resilient. That success does not prove isolation is harmless.

A Mars crew will receive advice late, lose rapid evacuation and have to diagnose technical, medical and interpersonal trouble with less help.

Countermeasures therefore create a partial substitute Earth. Loading straps pull runners onto treadmills. A resistance machine makes force without iron plates. Timed light protects sleep and circadian alignment. Medical monitoring, food, communication, shielding and rehearsal replace conditions that the planet normally supplies for free. They work unevenly, consume time, mass and power, and cannot recreate gravity across every waking hour.

Responses also differ sharply between people. A mission average can hide one crew member who retains capacity and another who crosses an operational threshold. The central mistake is to judge each change only by whether it harms the astronaut while floating. Some changes are useful adaptations to orbit; others are maladaptive costs or direct injuries. Even a useful change may reveal its price at the next transition: re-entry, landing, emergency escape, a lunar surface, Mars, or home. Space changes the body inside the world it occupies, while the mission requires enough reserve to leave.

That is the book.

Why You Should Care

The revealing part of a long space mission is not the first weightless somersault. It is the first attempt to stand afterwards. The crew member who could guide a large laboratory rack with one hand once it was moving may return to a world where the head again weighs several kilograms, blood is pulled towards the legs, balance signals disagree and every step can become a calculation. Recovery teams are waiting because landing is a physiological event as well as an engineering one.

That reversal makes astronauts useful far beyond spectacle. Spaceflight is one of the few experiments in which a healthy adult enters a radically altered environment, is measured before, during and after it, then crosses back into the original condition. Researchers can watch systems change on different clocks. Sensorimotor changes begin within minutes. Fluid distribution shifts within hours. Muscle and cardiovascular capacity can change across weeks. Bone structure, vision and some molecular measures may recover slowly or incompletely. The person is not a bag of separate organs. One environmental change travels through the whole system.

This matters because much of the body's response is regulated rather than random. Unused tissue is expensive to maintain. A circulation that no longer needs to lift blood from feet to brain can reduce capacity. A brain whose old definition of down has become unreliable should favour other cues. Bone that receives little strain need not preserve the same architecture. Calling all of this damage misses the mechanism. Calling it harmless adaptation misses direct hazards and the mission. The body adjusts to present conditions, while the astronaut must remain ready for those ahead.

That is a general lesson about health, work and design. Fitness is always fitness for something. A capability maintained by constant environmental demand can disappear when the demand does. A system can function well in one steady state and fail during transition. A countermeasure should be judged by the task it preserves, not by whether a biomarker looks reassuring. Space makes these principles visible because there is nowhere

for the consequences to hide.

The mind adds a second reason to care. Popular accounts swing between two fantasies: astronauts as unbreakable heroes, or confinement as a machine that inevitably produces madness. The evidence supports neither. Professional crews have usually worked with discipline under severe pressure, helped by selection, training, clear roles, private space, meaningful work, communication and large teams on Earth. Yet those protections are part of the result. Remove timely ground support, lengthen missions, reduce privacy or place an unresolved conflict inside a crew that cannot separate, and the system changes.

Space medicine also forces an unusually honest bargain with risk. No mission can remove every hazard, and waiting for complete evidence would prevent the missions that could produce it. The defensible response is neither to promise safety nor to romanticise danger. It is to state what is known, expose what remains uncertain, build margins around the uncertainty and give the crew enough information to consent to the residual risk. That is human research, occupational medicine and ethics meeting inside one vehicle.

The limits matter. Astronauts are few, unusually healthy and heavily supported. A six-month station expedition is not a three-year voyage away from Earth. Even a long station mission retains nearby help and some magnetic protection.

That uncertainty is not a reason to shrug. It tells engineers where to spend mass, clinicians what to monitor, crews what to rehearse and mission planners which rescue assumptions they have quietly imported from Earth orbit. Human exploration is possible because the astronaut is treated as part of the spacecraft. The deeper fascination is that the spacecraft must also be treated as part of the astronaut.

The Core Ideas

Gravity Is a Daily Training Load

Gravity is usually described as a force that keeps people on the ground. For the body, the more important fact is the ground pushing back. Every time you stand, walk, climb or arrest a fall, the floor sends force through feet, legs, hips and spine. Muscles maintain posture. Bones bend by tiny amounts. Blood must be returned from below the heart. The brain predicts how much effort will move a limb whose weight is familiar. Earth supplies a training programme that runs from waking to sleep without appearing on a calendar.

An orbiting astronaut has not escaped gravity. At the height of a space station, Earth's pull remains strong. The station is moving sideways fast enough that, as it falls, the planet curves away beneath it. Crew, vehicle and loose objects share the fall. Because no supporting surface presses continuously against the body, the result feels weightless and is called microgravity. The small residual accelerations matter for experiments, but they do not restore the loading pattern of standing on Earth.

Lying in bed removes much upright work and shifts fluids, which is why head-down bed rest is useful as an analogue. It still leaves ordinary gravity acting across the inner ear. Free fall removes a wider bundle of cues. That missing load changes the signals controlling tissue maintenance. Muscle that rarely produces high force tends to shrink; bone receiving less strain can lose material. These responses are often described as deterioration, which captures their cost but hides their dependence on conditions. The body has no department that keeps unused capacity aside because the flight plan will need it later.

That distinction matters because adaptation and mission fitness are different questions. A smaller postural muscle can be adequate for moving through a module by fingertips. A reduced blood volume can serve a body whose fluids no longer pool in the legs. A sensory system that stops trusting gravity can orient well inside a spacecraft. None of those changes needs to cause

obvious trouble in stable orbit. The bill arrives when the environment changes again.

Landing asks for capacities that may have been economical to discard. The astronaut may need to tolerate acceleration, control the head and eyes, stand, walk on uneven ground, leave a damaged vehicle or perform work in a pressure suit. On Earth, recovery staff can help. On Mars, nobody is waiting outside with a chair and a medical team. The standard for preservation therefore cannot be comfort while floating. It must be readiness for the hardest credible task after the next transition.

Gravity is not the only load. Exercise machines can create force, suits can resist movement, and hands and shoulders work hard during space tasks. Responses vary with mission length, age, sex, starting condition, equipment, adherence and individual biology. Partial gravity may supply some useful stimulus, but nobody has lived for months at lunar or Martian gravity, so its protective value remains unknown. The broad rule survives those differences: a capacity sustained by repeated demand tends to diminish when that demand disappears. Human spaceflight is the attempt to preserve it in advance for a world that is temporarily absent.

The Brain Must Rebuild Up and Down

On Earth, down arrives through several channels that normally agree. The eyes see vertical walls and a stable horizon. Pressure under the feet marks support. Muscles and joints report the position of the limbs. In the inner ear, semicircular canals detect rotation while the otolith organs respond to linear acceleration and the persistent pull of gravity. The brain combines these signals into a working estimate of orientation. It feels immediate because the calculation has been rehearsed since infancy.

Microgravity breaks the agreement. The otoliths still respond when the head accelerates, but they no longer receive the familiar steady gravitational reference. A movement that once meant tilting may now produce a pattern the brain interprets badly. Vision can say the cabin is stable while the vestibular system reports something less coherent. The result may be space

motion sickness: nausea, malaise, headache, reduced appetite and sometimes vomiting during the first days. Even a highly trained astronaut can become a passenger inside a sensory argument.

The useful response is sensory reweighting. Vision and touch gain authority. A wall becomes a floor when the feet are placed against it, then becomes a wall again when the crew member turns. Equipment is usually arranged with a shared local up because conventions reduce errors even when physics does not require one. Astronauts learn to move the head differently, anticipate the consequences of pushing off and read body position through contact with handrails and surfaces. Floating stops feeling like falling because the brain changes its prediction.

Movement depends on more than balance. The eyes must remain stable while the head turns, the hand must meet an object whose inertia remains but whose weight has gone, and force must be stopped before it sends the worker away from the task. Training teaches these couplings on Earth, but no simulator reproduces them continuously. This is adaptation at its cleanest, and it exposes the transition problem. The new model works in orbit. On return, gravity restores the old signal before the nervous system has restored the old weighting. The head can feel unstable, vision may seem to move during walking, balance narrows and coordinated movement demands attention. NASA treats the hours around gravity transitions as a period of high operational risk because manual landing, emergency exit and early surface work may occur before readaptation is complete.

The brain also changes physically. Scans before and after flight have shown shifts in fluid spaces and changes in regions involved in sensorimotor control. A changed image need not mean damaged intelligence. The practical test is what the person can do. Can they keep a display steady in view while moving their head, guide a hand to a control or walk without losing balance? Imaging and performance tests answer different parts of that question.

The brain does not carry one permanent map of the world. It predicts from repeated signals and revises when prediction fails. Space proves the

flexibility. Landing proves the price.

The Circulation Moves North

Stand up on Earth and gravity creates a column of fluid. Pressure is higher below the heart, lower above it, and blood tends to pool in the legs. Veins, muscle contractions, breathing and reflex changes in heart rate and vessel tone keep enough blood returning to the chest and brain. The system performs this correction whenever the body is upright. Lying down weakens the gradient. Free fall removes the persistent direction almost entirely.

Fluid then redistributes towards the chest and head. The face can look fuller, the nose can feel congested and the legs lose some of their usual volume. Sensors in the central circulation encounter a state that resembles excess filling, even though no water has been added to the body. Hormonal and kidney responses help reduce plasma volume. Over time, the heart, blood vessels and autonomic reflexes operate under a different demand. The adaptation can be adequate in orbit and exposed on landing, when gravity again draws blood towards the legs.

Orthostatic intolerance is the failure to tolerate that upright challenge. The person may feel light-headed, weak or close to fainting because blood pressure and cerebral flow are not being defended well enough. It has no single cause. Lower circulating volume, altered vessel responsiveness, reduced muscle pumping, heat, dehydration and sensorimotor disturbance can combine. This is why a return crew is assessed as a system rather than told to stand up and be brave.

The headward shift also reaches the eye and tissues around the brain. Some long-duration crew members develop spaceflight-associated neuro-ocular syndrome, or SANS. The optic disc, where the nerve carrying visual information leaves the eye, may swell. The choroid, a blood-vessel layer behind the retina, may develop folds. The back of the eyeball can flatten, and altered eye shape can shift focus so that near work becomes harder. These are changes to the structures through which seeing happens, not just tired eyes. Astronauts can image their own eyes in orbit while

specialists guide and interpret from Earth.

The tempting explanation is that fluid raises pressure inside the skull and presses on the eye. That account is too neat. SANS does not match any one terrestrial disorder. Headward fluid movement and venous congestion are central suspects, while anatomy, carbon dioxide, sleep, pressure regulation and individual susceptibility may contribute. NASA changed the older name, which centred presumed intracranial pressure, because the mechanism had outrun the label.

The veins add a less familiar hazard. Ultrasound has revealed stagnant or reversed flow in the internal jugular vein, which drains blood from the head, in some crew members. A clot has required treatment in orbit. This is a warning to watch a particular pathway, not a prediction that every headward fluid shift produces thrombosis. Nor does a comfortable astronaut necessarily have unchanged vessels or eyes. Symptoms and structural measures do not always move together; monitoring can find a problem before the crew member has a reason to report one.

Countermeasures try to restore the missing gradient. Lower-body negative pressure encloses the legs and applies suction, drawing blood away from the head and challenging the circulation. Thigh cuffs, exercise, hydration strategies and landing preparation target different parts of the pathway. None converts orbit into Earth. The deeper lesson is that circulation depends on geometry. Change the direction of the field and the body's internal map of volume changes with it.

Unused Structure Is Spent

The astronaut's exercise area looks like a gym designed by someone who has removed weight from the concept. A treadmill needs loading straps and elastic resistance to keep the runner on the belt. A cycle ergometer provides resistance without needing the rider to support body weight. The Advanced Resistive Exercise Device, known as ARED, uses vacuum cylinders and flywheels to imitate the force of heavy lifting. Its size is evidence of the problem: replacing an invisible planet takes machinery.

Muscle responds to force, speed, length and repetition. In microgravity, the postural and lower-limb muscles lose much of the low-level work that filled ordinary life, while movement around the station can be accomplished with small pulls. Without sufficient countermeasure, muscle size, strength, power and endurance can decline. Aerobic capacity can fall as blood volume, cardiac function and peripheral tissues adapt. Modern station exercise has improved the picture. Crews who follow the schedule with capable equipment return, on average, with small losses in measured aerobic fitness. That is a countermeasure success, not proof that the environment has stopped acting.

The spine illustrates how unloading redistributes rather than removes mechanical stress. Without ordinary compression, spinal length can increase and back discomfort is common, while discs and supporting muscles experience unfamiliar conditions. A taller measurement after launch is not free growth. It is another sign that structures are carrying load differently. Bone presents a slower and less forgiving problem. Bone is living tissue. Osteoclasts remove material and osteoblasts form it, with mechanical strain among the signals shaping the balance. Unloading is greatest in regions that normally bear weight, such as the hip and lower leg. Areal bone mineral density from a scan is useful, but it cannot fully describe three-dimensional structure, trabecular connections or strength. Research following astronauts after long missions has found that some measures remain below baseline after a year, with recovery differing by site and person.

The loss matters least while the crew is floating and more when loads return. A bone does not fracture because a scan number crossed a line. It fractures when an applied load exceeds local strength. A deconditioned astronaut may face a hard landing, an awkward fall, a heavy suit or prolonged surface work. That turns muscle, balance, vehicle design and bone architecture into one risk. NASA's recent bone assessment notes that no in-flight bone fracture has occurred, while refusing to treat that history as proof that exploration fracture risk is absent.

Bone mineral released during resorption also enters the circulation and urine, contributing to renal stone risk. Hydration, food, exercise and, in selected settings, medication become linked. A kidney stone is painful on Earth and potentially disabling in a vehicle where imaging, procedures and evacuation are limited. Space medicine repeatedly converts a modest physiological change into an operational question by removing ordinary treatment options.

Exercise is powerful because it supplies specific signals. It is limited for the same reason. A short bout of high force cannot reproduce hours of standing, walking, turning and carrying. The loading straps can become uncomfortable before they reproduce Earth-like force. Equipment can fail. Time spent setting up, exercising, cleaning and stowing competes with science, maintenance and sleep. A compact exploration vehicle may not carry a machine as capable as ARED.

There is no single rate at which an astronaut becomes weak or loses bone. The robust conclusion is structural: use falls, maintenance signals change, countermeasures preserve different capacities with different success, and recovery runs on several clocks.

The Shield Is Part of the Body

On Earth, protection is so large that it disappears into the background. The atmosphere removes much incoming radiation and Earth's magnetic field deflects many charged particles. Air is renewed by an ecosystem. Heat, waste, water and microbes are handled by systems spread across a planet. In space, the boundary between physiology and engineering moves outward. A pressure shell, scrubber, filter, water loop and radiation shelter perform work that the environment once did.

Space radiation is a family of exposures. Trapped particles occupy regions shaped by Earth's magnetic field. Solar particle events can send large numbers of energetic particles over hours or days. Galactic cosmic rays arrive from beyond the Solar System, including high-energy heavy ions that are rare at ground level and hard to stop. Low Earth orbit retains some

magnetic protection. A voyage to the Moon or Mars changes the mixture, duration and options for retreat.

One dose number cannot preserve all that information. Absorbed dose records energy deposited per unit mass and is measured in gray. Equivalent and effective dose, expressed in sieverts, apply radiation and, for effective dose, tissue weightings. Those weightings carry assumptions. Particle charge and energy influence the pattern of ionisation through tissue. Dose rate affects the time available for repair. The organ crossed matters. Age, sex and individual biology alter estimated lifetime risk.

Shielding helps, but more material is not an unlimited answer. Hydrogen-rich materials are useful, and a solar event shelter can be built by placing water, food and other mass around a small refuge. Galactic cosmic rays are harder. High-energy particles can pass through shielding and generate secondary radiation when they strike it. Mission planners therefore combine vehicle design, forecasting, monitoring, operational shelter and career exposure limits rather than promise a wall that makes deep space ordinary.

Cancer is the principal long-term outcome in current radiation-risk models, yet even that remains an estimate rather than a scheduled event. Radiation may also affect the cardiovascular system, central nervous system, lens and other tissues. Cell and animal studies help explain possible effects where human evidence is sparse. A laboratory result in a mouse is not a measured probability for a Mars crew.

Pressure and oxygen sit in the same engineered boundary. A cabin atmosphere must support consciousness and work while limiting fire risk, decompression risk and the cost of carrying gas. A spacesuit becomes a one-person atmosphere whose stiffness alters movement and fatigue. The closed habitat adds quieter exposures. Carbon dioxide must be removed continuously. Trace chemicals, dust, humidity and heat need control. Microbes from people and cargo enter an ecosystem with no soil, weather or large volume to dilute them. Immune markers and latent-virus activity can change during flight, shaped by stress, sleep, radiation, altered gravity and the microbial environment. That does not mean the immune system

switches off. It means host, habitat and microbes form a coupled system.

The same coupling governs medicine. Medicines can lose potency during long storage, although temperature, packaging, repackaging and shelf life complicate what can be blamed on spaceflight. Spaceflight physiology may alter how the body absorbs, distributes and responds to a medicine, but human in-flight data are too sparse to predict the direction or the right dose reliably. Far from Earth, a familiar illness meets unfamiliar diagnostics and no rapid resupply. The shield is therefore more than armour. It is the full engineered boundary that decides which physical, chemical and biological conditions reach the person. In human spaceflight, part of the body has bolts, pumps and software.

A Mind Flies Inside a Crew

The lone astronaut is one of the subject's persistent fictions. Even when a crew member works alone in a module, performance depends on other people: crewmates, flight controllers, doctors, engineers, family, trainers and planners. A decision may begin in orbit, be checked in Houston, discussed with another control centre and returned as a procedure. The mind that flies is distributed across a social and technical network.

Space can strain that network. The work is consequential, schedules are dense, privacy is scarce and small irritations cannot be escaped by going home. Noise, light, alarms and operational demands can erode sleep. International crews may differ in language, hierarchy, humour and preferred ways of handling disagreement. A person can be lonely while never being alone. The view from the window does not cancel fatigue or resentment.

Yet the record is not a procession of breakdowns. Astronauts are selected for emotional stability, judgement and teamwork, then trained together through emergencies until useful behaviour is rehearsed. Missions provide routines, exercise, private communications, psychological support and meaningful work. Crews have usually sustained high performance under conditions that would be difficult for almost anyone. Their resilience is real. It is also supported.

The window can also help. Astronauts photograph Earth for research, and many choose to spend off-duty time doing the same thing from the station's cupola. NASA reports benefits to well-being from the activity. The human being whose attention is constantly claimed by checklists can choose something to look at. That is a different kind of relief from merely finishing work. The view offers something rewarding that is neither a task to complete nor a symptom to manage.

What happens to thinking is less cinematic. Sleep loss, workload, illness, carbon dioxide, stress and altered sensory processing can affect performance. A 2024 study followed twenty-five professional astronauts on roughly six-month station missions and found no systematic decline across cognition as a whole. Particular tests and mission phases did show differences in processing speed, visual working memory, sustained attention and risk behaviour. Accuracy and speed can move separately. Taking longer to get the right answer may be a sensible adjustment, until a docking manoeuvre or an unfamiliar alarm removes the spare seconds.

Privacy is a countermeasure, not a luxury label. A personal compartment, a family call without an audience and time without public performance provide relief that another productivity target cannot. Meaningful work can sustain morale; pointless or endlessly interrupted work can drain it. Teams have failure modes of their own. Withdrawal and reduced information sharing may be harder to notice than an argument. A crew can remain polite while coordination degrades. Ground control can become part of the tension when priorities conflict or instructions feel intrusive. Clear authority matters, but so does the trust to challenge it and reveal a mistake early.

Distance changes the architecture. Near Earth, conversation is close to live and specialists can guide a procedure step by step. At Mars, one-way communication can approach twenty minutes, so a question and answer may take most of an hour. The ground can advise only after the moment has moved on. Crews need deeper technical and medical competence, decision rights, local records and tools that support rather than distract. Mission Control becomes a correspondent, not an extra brain in the room.

The psychological unit of spaceflight is therefore neither the heroic individual nor the crew alone. It is person, crew, habitat, task and ground arranged over time. Change one connection and the mind experiences a different mission.

Countermeasures Build a Substitute Earth

The straps on a treadmill tell you what a countermeasure is for. On Earth, gravity keeps the runner on the belt. In orbit, equipment must supply that contact, or the first stride would launch the runner away. The machine puts back one missing condition. It does not put back a planet. Most space medicine has this shape: identify a function the environment no longer supplies, then restore enough of it to keep a person capable.

The collection can look like a medical shopping list, but it is better understood as a substitute Earth. The planet provides gravity across the whole body, a twenty-four-hour light cycle, room to separate, an atmosphere, microbial exchange, abundant water, hospitals and rapid help. A spacecraft replaces selected functions with machines, schedules, procedures and people. The imitation is expensive and incomplete.

This makes countermeasure design an allocation problem. Mass used for an exercise device cannot be used elsewhere. Power for environmental control must be generated and rejected as heat. Crew time spent on two hours of physical training is unavailable for maintenance or sleep. A protective shelter large enough for comfort may be too heavy. Medical equipment that can diagnose every rare condition would overwhelm the vehicle. The relevant question is not whether a countermeasure helps. It is which capability it preserves, for which mission phase, at what cost and with what failure mode.

Exercise shows why averages are insufficient. A programme can preserve mean aerobic capacity while one individual loses more than expected. It can maintain muscle strength yet leave bone microarchitecture altered. The hardware can work in a spacious station and become unusable in a small transit vehicle. Adherence can be high during routine operations and

collapse during an emergency month. Preservation needs thresholds tied to tasks: climb a ladder in a suit, carry a load, rise after a fall, perform cardiopulmonary resuscitation, control a landing or leave a cabin quickly.

Sequence is decisive. Launch imposes acceleration, vibration, restraint and workload. Free fall rewards a lighter, fluid-shifted, visually guided body. A lunar landing restores one-sixth of Earth gravity; Mars restores a little over one-third; return restores the full field. Each transition arrives with its own tasks. A system tuned for the cruise may be poorly prepared for the surface, while a programme that protects landing capacity may consume resources needed to survive the cruise.

Artificial gravity offers a different strategy: rotate all or part of the vehicle so motion creates a sustained inward acceleration. It could act across more systems and more hours than exercise. The engineering and physiology remain joined. Short-radius rotation produces large head-to-foot gradients and provocative motion cues; large-radius designs demand more structure and mass. The other blank is natural partial gravity. Humans spent only brief periods on the Moon, and no one has lived in Martian gravity. One-sixth or a little over one-third of Earth gravity might preserve some muscle, bone, balance and circulation, or sit below useful thresholds for important tissues. Both options are testable design choices, not settled medical facts.

Deep space also removes rescue. A station crew can receive supplies and return in days under many scenarios. A Mars crew must manage illness, equipment failure and interpersonal strain with delayed advice and finite stock. Countermeasures must become maintainable, diagnosable and repairable by the people using them. Monitoring should detect loss early without turning every waking hour into surveillance and every biological fluctuation into disease.

The final standard is capability across transitions. A successful mission does not produce a person perfectly adapted to weightlessness. It carries a human through several hostile states while preserving enough reserve for the next one. Core systems, crew selection and medicine all answer the same question: what must this person still be able to do when the

environment changes without permission? Countermeasures build a substitute Earth because human regulation never pauses, hazards continue and the next world will not wait for readaptation to finish.

How It Actually Works

Before the hatch closes

Astronauts practise spacewalk tasks in a swimming pool. In neutral-buoyancy training, suited trainees rehearse with tools and tethers while divers and controllers support the work. Buoyancy offsets weight, although water's resistance makes movement unlike free fall. The pool is useful because a task can be made familiar before it becomes dangerous. Staying attached while handling equipment, communicating clearly and keeping track of the next action all need to become habits. Courage is a poor substitute for knowing where the tether goes.

The same principle runs through emergency training. Operating in a pressure suit, responding to fire or decompression and solving problems with the few people who will share the vehicle are practised before launch. The exercise is larger than knowing the correct answer. Crew members need to know who acts, who checks, how to pass information and what to do when the first plan fails. A procedure has to survive noise, fatigue and competing demands, not just a written examination.

Medical preparation establishes what this particular body can do. Bone and muscle scans, blood and urine samples, cardiovascular tests, eye imaging, balance tasks and cognitive tests create a preflight baseline. Later, a change can be compared with the same person before the mission rather than with an imaginary average astronaut. Selection has already excluded many health risks; measurement helps catch those that emerge despite it. Neither can promise how every system will respond after months away from Earth.

The mission also begins before ignition. Travel, quarantine, schedule changes, public duties and anticipation can alter sleep and stress.

Equipment, experiments and personal countermeasures have already been chosen, so later physiology is partly the consequence of decisions made when the spacecraft was still a drawing. An exercise device too large for the vehicle, a medical test without trained operators or a lighting plan that conflicts with operations cannot be improvised into existence after launch.

The ride uphill

Launch compresses danger into minutes. The crew lies restrained while acceleration rises, vibration crosses the body, noise fills the cabin and displays demand attention. The direction of acceleration matters because blood and tissues respond differently when force runs from chest to back than from head to feet. Seats, suits and vehicle profiles are designed around those loads. Healthy astronauts can tolerate them, but tolerance is not the same as ease.

Acceleration is experienced as apparent weight because the seat must redirect the body with the vehicle. A force through chest and back is tolerated differently from a force pulling blood from brain towards feet. Duration, onset rate, restraint, breathing and body position all matter, which is why one peak g value cannot describe the human ride.

Workload is part of the exposure. A crew member may need to monitor systems and prepare for an abort while feeling heavy, hot or nauseated. Then the engines stop and the supporting force disappears. Objects lift. The head and limbs no longer require the expected muscular effort. Fluids begin to redistribute, and the vestibular system loses the gravitational reference it was using moments earlier.

This sudden change is why a mission cannot be understood as a long block called space. The first transition has happened before the crew has slept, eaten properly or learnt how this particular body will respond.

The first floating hours

The quickest lesson is that momentum has survived. A gentle push can carry a person farther than intended; stopping requires another contact. Arms replace legs as the main means of travel. Loose objects continue until captured by a surface, filter or crewmate. The cabin is three-dimensional, yet labels, lights and workstations preserve a common orientation because shared conventions prevent mistakes.

For some crew members, the first days bring space motion sickness. Head movement may aggravate symptoms, so experienced practice includes moving deliberately and protecting critical work while the brain adapts. Medication can help, though sedation or other effects matter when the user must perform. Symptoms vary enough that mission planners cannot assume either illness or immunity.

Ordinary acts expose the new physics. Washing uses captured droplets and airflow rather than a falling stream. Crumbs and tools must be controlled because the cabin ventilation will eventually collect what the crew does not. Smell can seem muted when the nose is congested, influencing appetite. Swallowing still works because muscular contractions move food through the oesophagus; gravity was helpful at the table, not the engine of digestion.

The toilet exposes the bargain more bluntly. With no reliable down to carry waste away, airflow must collect it. The crew member stays positioned while urine and solid waste follow separate collection paths; solids are contained for disposal. A familiar private act now depends on fans, seals and correct alignment. This is not incidental plumbing. A body still needs to empty itself, and a shared cabin needs the result to stay where it belongs. Even dignity has acquired a power supply.

The face and upper body begin to look and feel fuller as fluid moves headward. The sensation has often been compared with congestion. Central volume signals promote fluid and electrolyte adjustments, reducing the amount the circulation later has available when gravity returns. The change is not a single one-way transfer. Fluids occupy several

compartments, vessel tone changes and daily intake continues. The useful image is a new distribution followed by regulation, not blood permanently parked in the skull.

Sleep may be poor at the point when adaptation demands it most. The crew has crossed time zones, endured launch and entered a noisy machine with a dense schedule. A sleeping bag is tethered so the body does not drift into equipment. Without the pressure of a mattress, some people find the posture comfortable; others miss the cues that mark bedtime. Fans must keep air moving around the face because exhaled carbon dioxide does not rise away in a buoyant plume as it does on Earth.

The first week

Competence returns by repetition. The short trip across a module becomes easier, tools stay where intended, and meals demand less concentration. There is a trap in that improvement: the changes a person feels first are not the same changes that will cost most later. The inner ear can begin accepting the new arrangement while bone and muscle are only beginning to respond to reduced loading. Feeling at home in the cabin is welcome. It is not a certificate of readiness for landing.

Meanwhile, the circulation is revising. Plasma volume falls, autonomic control changes and the heart works in a body without the ordinary vertical gradient. Exercise begins early because waiting for measurable loss would waste time. The treadmill, cycle and resistance machine provide different demands, scheduled across the week and adjusted to the person. The target is not appearance. It is the ability to perform mission tasks and tolerate later gravity.

Samples and measurements turn the crew into both operators and participants. An astronaut may draw blood, preserve it, image an eye, fit sensors or guide ultrasound over their own vessels while a specialist watches from Earth. This arrangement expands what can be measured, but it also competes with work and rest.

The closed environment starts to acquire a biological signature. Skin,

airways and gut continue exchanging microbes with the habitat. Surfaces are cleaned, air and water are processed, and environmental sensors watch conditions that a city leaves to an enormous infrastructure. Human physiology now depends visibly on maintenance logs.

The long middle

After the novelty fades, a station mission becomes a working life. The crew conducts experiments, repairs equipment, exercises, eats, cleans, speaks with family and tries to sleep. The schedule is planned tightly because launch opportunities and research time are expensive. Yet efficiency has a limit. Unplanned maintenance, alarms, visiting vehicles or spacewalks can compress exercise and sleep, increasing several risks at once.

Muscle and aerobic adaptation depend on the accumulated pattern. Capable equipment and consistent use have reduced average losses compared with earlier eras, particularly for aerobic fitness. Bone remains harder to protect. High-force resistance work can preserve important features, but formation and resorption do not respond identically, and different skeletal sites change at different rates. Urinary calcium, hydration and stone risk sit downstream of the same process.

Eyes are monitored because SANS can develop without a simple dramatic symptom. Imaging can reveal optic-disc swelling, choroidal folds, globe flattening or retinal changes. Near vision may shift. A pair of stronger reading lenses can help function, but it does not explain the cause or prevent structural change. The study of SANS therefore links practical correction with a still-open physiological problem.

A case reported in 2020 shows how abruptly monitoring can become treatment. About two months into a six-month station mission, a research ultrasound revealed a suspected clot in an astronaut's neck vein. There had been no headache or worsening facial congestion to announce it. The astronaut repeated the scan with guidance from radiologists on Earth, who confirmed the clot. Treatment with anticoagulants followed, and the mission was completed. The patient was also the person operating the diagnostic

equipment. This was remote medicine without a colleague in the next room: the specialist could examine the images, but could not walk over to the bed. The case established a hazard to prepare for, not its frequency among future crews.

Most radiation exposure arrives without a useful warning. Astronauts have reported brief light flashes linked to particles passing through the visual system, but those flashes are no dose meter. Dosimeters record exposure while space-weather teams watch the Sun. In low Earth orbit, vehicle structure, operational limits and Earth's magnetic environment reduce parts of the hazard. Feeling well tells the crew little about the radiation accumulating through an otherwise ordinary day.

The immune system does not fail in one direction. Cell activity, inflammation, stress hormones and latent-virus reactivation can change, while most crew members remain capable of work. The combination matters more than any one marker. Poor sleep, heavy workload, radiation, altered nutrition and confinement can converge on the same person. A molecular difference may be an adaptive signal, a risk marker or noise. Meaning requires symptoms, timing and other measures.

The slower pressures are less conspicuous. Fatigue can change how work is done before anyone stops doing it. A checklist, a second pair of eyes and enough time to repeat a doubtful reading can absorb an error. Compress the schedule and the same slip may reach the next task. This is why performance cannot be inferred from a crew's calm appearance. The work may be going well because people and procedures are catching problems, not because there are none to catch.

The daily repair shift

Countermeasures occupy a substantial part of station life because they must be repeated. Resistive exercise asks muscles and bones for high force. Treadmill running supplies impacts and locomotor patterns through straps that pull the body towards the belt. Cycling challenges the cardiovascular system with less skeletal loading. The programme is individualised and monitored, while setup, loading, cleaning and stowage add to the visible workout.

Specificity governs the result. Cycling can protect aerobic capacity without restoring the sensory demands of walking. Heavy lower-body work can load the hip and spine without reproducing every direction of ordinary movement. Treadmill loading can become uncomfortable before it creates Earth-like force. More exercise also creates fatigue and heat that the vehicle must manage. The aim is enough useful signal, not the maximum tolerable punishment.

Other countermeasures are quieter. Lighting and schedule design help align sleep and circadian timing. Food supplies energy, protein, vitamins, minerals and hydration within storage and appetite constraints. Lower-body negative pressure challenges blood volume and vessel control while drawing fluid away from the head. Compression garments, medication and pre-landing fluid strategies target narrower pathways. Psychological support, private family contact and protected off-duty time preserve performance through social means.

Countermeasures can also interfere with one another. Exercise late in a shifted workday may delay sleep. Fluid strategies that support landing must fit kidney and cardiac constraints. A medicine that eases motion sickness may reduce alertness. Extra shielding can consume mass needed for food, water or exercise hardware. There is no independent health department inside the vehicle; every intervention enters the same budget.

Monitoring closes the loop. If strength, aerobic capacity, eye findings, sleep or symptoms move in the wrong direction, the programme can change. This

is easier in low Earth orbit, where specialists are available and equipment is extensive. An exploration countermeasure must work with less volume, mass, maintenance and guidance. A device that preserves health only while a team on Earth troubleshoots it live has not solved the Mars problem.

Coming home

Re-entry restores force before it restores competence. The crew is strapped in as the vehicle decelerates through the atmosphere. A body adapted to free fall now feels its head and limbs acquire weight. Vestibular cues change rapidly, and the circulation must defend blood flow under acceleration. Landing adds shock, noise and uncertainty. The astronaut has crossed from one operating model to another in minutes.

The first upright period is revealing. Reduced plasma volume, altered reflexes and weaker leg muscles can combine with heat and fatigue. Balance and gaze control may be unreliable. Recovery personnel assess symptoms, support movement and collect time-sensitive measurements. The purpose is not ceremonial care for fragile heroes. It is risk management during a known period of sensorimotor and cardiovascular readaptation.

Postflight measurements are collected quickly because some changes begin reversing as soon as gravity returns. That urgency can make landing day scientifically rich and personally exhausting. Blood draws, balance tests and imaging compete with nausea, travel and reunion. Ethical research design has to preserve the evidence without treating a tired crew member as equipment delivered with the capsule.

Recovery then separates into several clocks. Nausea and orientation may improve over hours or days. Gait and balance can need longer. Blood volume and aerobic function can return across days or weeks. Muscle strength is rebuilt through progressive loading. Bone density, structure and estimated strength may take months, and some measures can remain below preflight values at one year. Vision findings also differ in reversibility and timing.

Reconditioning cannot be a race back to the old programme. The returned

astronaut has high motivation, extensive support and a body whose systems have not all recovered together. Training progresses according to symptoms, movement quality and measured capacity. The same principle would be harder on another planet, where the crew may need to unload cargo, set up power and respond to faults before a rehabilitation phase has begun.

Beyond low Earth orbit

The station answers what trained adults can do for months in microgravity while close to Earth, under partial magnetic protection and with powerful support. Exploration changes every clause. Transit may be longer. Radiation is different. Resupply and evacuation recede. Communication becomes delayed. Exercise and medical systems must shrink. The crew may move from free fall into partial gravity, then back again.

The Moon supplies one-sixth of Earth's surface gravity, Mars a little over one-third. Those numbers describe weight, not biological sufficiency. A tissue may need a threshold, a pattern of movement or intermittent high force rather than a fixed fraction of Earth gravity. Brief lunar visits do not reveal what months of exposure would preserve. Partial gravity might reduce deconditioning, leave it largely unchanged for some systems or create a distinct adaptation that must later be reversed.

Radiation risk also stops resembling the station. A solar particle event may require the crew to interrupt work and shelter behind stored mass. Galactic cosmic rays continue through the mission and resist complete shielding. Risk models must combine particle physics, biology and uncertain human susceptibility. The absence of immediate sickness would say little about cancer or cardiovascular effects decades later.

Dust and surface operations add destination-specific hazards. Lunar dust is abrasive and electrostatically troublesome; Martian dust may carry chemical and respiratory concerns. Pressure suits restrict movement and impose metabolic work. A crew that arrives with reduced strength, balance or aerobic reserve must meet those environmental costs immediately. The

destination therefore multiplies the consequences of transit adaptation rather than providing a calm rehabilitation ward.

Distance shifts responsibility into the cabin. A medical problem may have to be diagnosed with limited imaging, finite medicines and no evacuation. A technical failure may demand a decision before Earth can answer. Psychological support cannot depend on live conversation. The crew needs autonomy without isolation from expertise, which means better procedures, local data, decision aids and pre-agreed authority.

A deep-space mission is therefore not the station extended on a longer timeline. It is a different human system. The central design question is whether person, crew and vehicle can preserve enough capacity across every transition, including the transition for which there is no rescue rehearsal.

How we know

Human spaceflight evidence is unusually direct and unusually small. Astronauts can be measured repeatedly before, during and after missions, but crews are medically selected, historically narrow and rarely assigned at random. A result from one vehicle, exercise system, cohort or mission length may not travel to another. Broader participation is improving the evidence, while short commercial trips and long professional expeditions remain different exposures.

Ground analogues isolate parts of the problem. Head-down bed rest and dry immersion reproduce unloading and fluid shifts; rotating rooms, parabolic flight and centrifuges test gravity transitions; Antarctic stations and sealed habitats study confinement. None combines microgravity, radiation, danger, meaningful work and distance in the way a mission does. Animal and cell experiments expose mechanisms at doses or scales that cannot be copied directly into a human prediction.

The Twins Study compared Scott Kelly during a long mission with his twin Mark on Earth and integrated many biological measures. Its strength was depth. Its limit was one flying individual. A 2026 surveillance study found

seven fractures among 242 astronauts within five years after flight, but without a matched ground cohort it could not establish an excess caused by spaceflight. That is the central evidence discipline: observation can identify a possible outcome before it measures causation or rate. Precise Mars outcomes remain forecasts built from incomplete pieces.

What People Get Wrong

“There is no gravity in orbit”

The phrase zero gravity is convenient and wrong in the way that matters. A space station remains deep inside Earth’s gravitational field. Crew and vehicle feel weightless because they are falling together while moving sideways fast enough to keep missing the surface. Nothing inside needs continuous support, so scales read zero and dropped objects do not drop towards the floor.

The error survives because weight and gravity feel identical on Earth. Stand on a floor and the force you notice is the floor pushing up, yet you name the sensation after gravity. Orbit removes that support force while retaining gravity. This distinction explains why the station does not drift away and why a spacecraft cannot hover there without motion.

Short parabolic flights create brief weightless intervals because the aircraft and occupants follow the same falling arc. The sensation comes from shared acceleration, not distance from Earth.

It also sharpens the biology. The body is responding mainly to lost loading, altered fluid geometry and changed sensory cues, not to gravity being switched off. Small accelerations from movement, equipment and atmospheric drag remain, hence microgravity. The correct model is continuous free fall. Once that is clear, weightlessness stops being magic and becomes an environmental signal.

“Space only makes astronauts weak”

Weakness is visible, so it becomes the summary. Muscle, aerobic capacity and bone can decline, and those changes matter. They are still one part of a broader reorganisation that includes balance, eye structure, fluid volume, sleep, immune signalling, microbial ecology, sensory prediction and team performance.

The weakness model also implies passive decay, as though the body were a machine rusting in storage. Some of the response is regulated and economical. A postural muscle receives less work. The circulation encounters no sustained upright gradient. The brain revises how it combines vestibular and visual cues. Those adaptations can improve function in orbit while reducing reserve for landing. Other changes are unwanted side-effects, and radiation or toxic exposure can injure tissue without helping the body fit its environment.

A changed marker still does not prove illness. Some molecular shifts reverse quickly, some persist and some have uncertain functional meaning.

The correction matters because treatment follows the model. Strength exercise alone cannot prevent motion sickness, protect sleep, provide radiation shielding or train a crew for delayed communication. Mission medicine first asks whether a change is an adjustment, a side-effect or an injury, then asks what current or future task it threatens.

“Two hours of exercise cancels microgravity”

The station exercise programme is substantial, and its successes are easy to overread. Modern hardware and disciplined training can preserve average aerobic capacity and important muscle functions far better than earlier missions. High-force resistance work has improved skeletal outcomes. None of this means the astronaut spends the rest of the day in an Earth-equivalent body.

A session supplies selected forces for selected tissues. The treadmill loading system cannot reproduce every direction and magnitude of walking.

Cycling challenges the heart and legs with little impact loading. ARED can create heavy resistance, yet it does not restore the low-level muscular work, fluid gradient, balance demands and ordinary movement that gravity provides across the day. Comfort, hardware limits and crew time constrain the dose.

The scheduled block also includes setup, adjustment and stowage, so a timetable entry is not a pure measure of muscular work. Quality and loading matter beside duration.

Exercise should therefore be judged by retained capability and tissue-specific outcomes, not by hours completed. A programme may protect one measure while another changes. Exploration vehicles may carry smaller equipment than the station. The achievement is partial replacement of a planet, repeated almost daily. Calling it cancellation understates both the engineering and the remaining risk.

“A puffy face explains the eye changes”

The headward fluid shift makes an attractive story: fluid rises, pressure in the skull increases and the back of the eye is compressed. The visible face and the old name for the syndrome encouraged that account. It offers one cause, one pathway and an obvious target.

SANS has refused to be that tidy. Astronauts can show optic-disc swelling, choroidal folds, globe flattening, retinal changes and altered refraction in different combinations. The syndrome has no exact terrestrial equivalent, and symptoms do not match structural findings perfectly. Direct in-flight intracranial-pressure data are limited. Venous congestion, cerebrospinal-fluid dynamics, anatomy, carbon dioxide, sleep and other individual factors may interact.

The uncertainty is operational rather than academic. A crew still needs reading correction, surveillance and thresholds for action while researchers continue to separate contributing pathways.

Headward fluid movement remains central, but central is not complete. The

correction matters because a countermeasure aimed only at general pressure may miss the relevant pathway or help some people more than others. SANS is also a warning about names. A label that embeds a mechanism can make a hypothesis feel settled long after the evidence has moved on.

“Radiation is one dose with one outcome”

Radiation is often reduced to a number followed by a comparison with medical imaging. That can orient scale, but it can also erase the features that control risk. Trapped particles, a solar particle event and galactic cosmic rays differ in energy, composition, timing and response to shielding. The same absorbed energy can be distributed through tissue in different microscopic patterns.

Outcomes also occur on different clocks. A large solar event can create an acute operational hazard if shelter is inadequate. Cancer risk is estimated across later life. Cardiovascular, lens and nervous-system effects have different evidence bases. Age, sex, organs exposed and individual susceptibility alter modelled risk. Heavy shielding can reduce some particles while producing secondary radiation from high-energy impacts.

A chest X-ray comparison can therefore be numerically tidy and biologically crude. It may orient a lay reader while hiding the mixed particle field and long exposure.

The correct question is not what the dose is. It is what field produced it, over what time, through which shielding, to which tissues and for which outcome. This is why an exact Mars risk remains uncertain despite excellent physics. The number is necessary. It is not the whole exposure.

“Isolation makes crews fall apart”

Put several people in a small volume for months and fiction supplies the ending. Conflict grows, judgement fails and the crew turns on itself. Real crews have had tension, mistakes and periods of strain, but human spaceflight is not a reliable machine for producing psychological collapse.

The dramatic model ignores selection and support. Astronauts are screened, trained and given clear roles. They rehearse emergencies, communicate with specialists, exercise, maintain family contact and perform work they regard as meaningful. Privacy and off-duty time are designed rather than left to chance. These conditions help explain why crews have usually functioned well.

Good selection can also hide fragility in the system: trained, adaptable people and extensive support may prevent strains that would overwhelm a less prepared crew.

The opposite conclusion is equally poor. Success on the station does not prove confinement harmless or predict Mars. Communication delay, smaller support teams, longer duration, less resupply and no rapid evacuation alter the social system. Conflict may also appear as silence, subgrouping or withheld information rather than shouting. The useful unit is person, crew, habitat and ground. Isolation is one pressure inside that arrangement, not a destiny.

“The space station tells us what a Mars mission will do”

The International Space Station supplies humanity’s most extensive long-duration evidence in orbit, so its findings are often stretched into a Mars forecast. The temptation is understandable. It mistakes evidence from one kind of mission for an answer about another.

Station crews live in microgravity for months, but they remain in low Earth orbit, partly protected by the magnetic field. Communication is close to live. Cargo arrives. Medical evacuation may be possible. Exercise machines are large, power is abundant by spacecraft standards and a vast ground organisation helps solve problems. A Mars mission changes radiation, duration, volume, maintenance, autonomy and the sequence from microgravity to partial gravity.

Even mission duration can mislead. Six months on a supplied station and six months in a small outbound vehicle share a calendar while differing in

autonomy, stakes and escape.

Imagine the same pump fault in two vehicles. On the station, a specialist can follow the crew's description as they work. Far from Earth, a reply may arrive after the next decision is due. A procedure built around live supervision now asks more of the person holding the tool. The hardware fault is similar; the human task is not.

Use It

Ask which Earth signal disappeared

When a system changes in space, begin with the missing input rather than the damaged organ. Muscle responds to force. Bone responds to strain and endocrine context. The circulation responds to pressure gradients and volume. The vestibular system responds to acceleration patterns. Sleep responds to light, timing, opportunity and arousal. Removing gravity changes several inputs at once, while confinement and radiation add others.

This question prevents a tour of symptoms from becoming a fact pile. Puffy faces, reduced plasma volume and post-landing dizziness belong to one altered geometry. Muscle loss, bone remodelling and renal-stone risk share a loading pathway without being interchangeable. Motion sickness and balance errors arise from conflicting sensory predictions rather than weak will.

Carry the lens back to Earth. When a capacity declines after bed rest, immobilisation, remote work or a changed routine, ask what repeated demand used to maintain it. Capacities maintained by repeated demand often weaken when that demand disappears. The answer is often a missing signal, not a moral failure. Restoring the demand may be more effective than adding motivation to an environment that no longer asks for the capacity.

Separate adaptation from retained capability

Classify the change before judging it. Some responses restore function under current conditions, some are side-effects of altered regulation, and some are injuries from exposure. An adaptation should then be judged against its present environment. Reduced postural muscle may be efficient in free fall. Sensory reliance on vision may make movement safer in a spacecraft. Lower fluid volume may suit a circulation without an upright column. Calling those responses bad by definition confuses Earth fitness with universal fitness.

Mission planners need a second judgement: what must survive for the next phase? A useful orbital adaptation can undermine landing, surface work or emergency escape. The same split appears elsewhere. A business optimised for stable demand can become brittle during a shock. An athlete adapted to one event may lose a neglected capacity. A person comfortable in one routine may struggle at transition.

Ask two questions separately. Does the change help under current conditions? What future task will it make harder? The first explains the system. The second protects it from becoming trapped by its own success. Good design sometimes preserves an apparently inefficient reserve because the next environment will value it.

Design for transitions, not the comfortable middle

Many vulnerable moments occur before a system has settled, while signals, loads and rules are changing. Space motion sickness is concentrated after entering free fall. Balance and orthostatic problems appear after gravity returns. A Mars crew may face demanding surface tasks before circulation, muscles and orientation have adjusted.

Design reviews often focus on the long cruise because it occupies the most days. The astronaut model reverses the emphasis. List every transition, the time available for adaptation, the tasks required during that interval and the support that disappears. Then test the weakest combination. The person who is safe after three days of recovery may still be unsafe when the hatch

must be opened in thirty minutes.

This lens applies to surgery, shift changes, software migrations, company handovers and travel. A steady state can be sound while the route into it is dangerous. Protect the crossing, not merely the destination. Recovery time, fallback authority and a lower first workload may matter more than improving the final steady state.

Keep the dimensions of dose separate

Radiation teaches the cost of compressing exposure into one number. Total energy matters, but so do particle type, dose rate, tissue, shielding and time. Exercise has the same structure. Force, duration, frequency and movement pattern produce different adaptations. Sleep opportunity, timing and continuity cannot be replaced by one nightly score.

Whenever a claim says more is harmful or less is safe, ask which dimension moved. A concentrated exposure may differ from the same total spread across months. An average can hide peaks. A whole-body value can hide one organ. A mission total can hide the solar event that determines the emergency plan.

This is not an argument against summary measures. Decisions need compression. It is a rule for knowing when compression has become misleading. Keep the dimensions that change mechanism or consequence, and refuse comparisons built from incompatible measures. A clean chart is no compensation for merging quantities that answer different questions.

Draw the whole human system

For mission planning, the person inside the vehicle is only part of the picture. The operational human system includes crew, habitat, interfaces, schedule, ground control, family communication, medical support and authority. A cognitive error may begin with poor sleep caused by noise, continue through a confusing display and become serious because a crew culture discourages challenge. Labelling the astronaut inattentive would describe the final link and miss the system.

Draw who supplies memory, diagnosis, emotional regulation and permission. On the station, ground teams hold enormous expertise and can often converse in near real time. At Mars, delay moves those functions towards the crew and local tools. The same people may appear equally capable while the network around them has lost resilience.

Use this lens in any high-stakes team. Before retraining an individual, inspect the information, incentives, environment and response time around them. Human performance is produced, not carried intact from room to room. A resilient worker in one network can become exposed when information, rest or authority is removed.

Turn uncertainty into architecture

The honest sentence about partial gravity is that nobody knows whether months at lunar or Martian gravity will protect each human system enough. That uncertainty should not end the discussion. It should change the mission.

Uncertain risks can be bounded through margins, monitoring, reversibility and staged exposure. Build a habitat that can increase exercise loading. Carry sensors that detect loss before a task fails. Give the crew authority to alter schedules. Place water and stores so they can become a radiation shelter. Rehearse medical decisions under delayed communication. Test smaller steps before committing to the longest one.

The alternative is to demand a precise forecast from evidence that cannot supply it, then hide the guess inside a confident number. Good architecture marks where knowledge ends and makes the system less dependent on being right. Spaceflight is full of unknowns; it need not be full of unacknowledged assumptions. A visible uncertainty can be monitored and managed. A hidden one becomes a surprise.

The limits

Space medicine offers mechanisms, not personal diagnosis. Dizziness, vision change, sleep loss, anxiety, muscle weakness and abnormal laboratory results have many causes on Earth. An astronaut is screened, monitored and supported through protocols that do not transfer into a self-treatment plan. Lower-body negative pressure, prescription drugs, fluid loading and radiation limits belong inside specialist systems.

The crews described here are medically selected and heavily supported. They cannot stand for people on different missions, including short commercial flights with different physical demands.

The book also cannot tell us whether a particular exploration mission is ethically acceptable. Risk depends on purpose, alternatives, consent, uncertainty, rescue, fairness and who bears long-term harm. Technical feasibility does not settle that judgement. The proper limit is not timidity. It is refusing to convert incomplete evidence into either a promise of safety or a romance of sacrifice.

The one thing to keep

Keep the transition.

The first attempt to stand after landing should now look different. It is neither an embarrassment nor evidence that humans cannot live in space. The body has spent months working in another set of conditions. Gravity has returned at once; readiness has not. The people helping the astronaut out of the vehicle are part of the mission, just as surely as the people who launched it.

Adaptation has no knowledge of the mission plan. It does not preserve leg strength because Mars is coming or retain an Earth-ready blood volume out of loyalty to home. It responds to present signals. A body can fit orbit better while becoming less ready to leave, and an exposure can cause harm without fitting it at all.

That changes how to see any human system. Stop asking whether it is

adapted in the abstract. Ask what environment trained it, what capability that environment stopped requesting and which transition will expose the difference. Then build the missing demand back in before it is needed.

That is what the spacecraft must carry home: not merely a living passenger, but a person with enough strength, balance and judgement for the world outside. Some of that capacity survives through exercise, some through protection, some through help from other people. The body answers the environment it is in. Human foresight has to answer for the one it will meet next.

Terms

Microgravity. The condition in which objects experience tiny residual accelerations while sharing orbital free fall. It produces practical weightlessness without implying that Earth's gravitational pull has disappeared. Mass and inertia remain, so a moving object still resists changes in motion.

Free fall. Motion governed mainly by gravity, with no continuous supporting force. An orbit is free fall around a curved planet rather than a stationary place above it. Thrust, drag or contact interrupts the shared fall.

g. A unit referenced to Earth's surface gravitational acceleration. It describes acceleration or apparent loading, not a substance inside the body. Direction, duration and rate of onset alter tolerance. One g is the familiar Earth reference.

Loading. Force applied to tissue through posture, movement, exercise, acceleration or impact. Muscle and bone respond to the size, direction, rate and repetition of that force. Background loading across a day also matters.

Deconditioning. Loss or alteration of a capacity when its usual demand is reduced. In space it may involve cardiovascular, muscular, skeletal or sensorimotor systems, each on a different timetable. The term does not by itself mean disease.

Countermeasure. An intervention intended to prevent, reduce or monitor a spaceflight risk. Exercise, lighting, shielding and lower-body negative pressure target different missing environmental functions. Effectiveness is judged against a defined risk or task.

Space motion sickness. Nausea, malaise and related symptoms during early adaptation to altered gravity. Sensory conflict contributes, but individual susceptibility and mission conditions create wide variation.

Vestibular system. Inner-ear organs and neural pathways that help estimate head motion, orientation and balance. Microgravity changes the signals from which that estimate is constructed. Vision, touch and proprioception help resolve the new pattern.

Semicircular canals. Three fluid-filled canals in each inner ear that detect head rotation. They still function in orbit, though their signals must be interpreted without the familiar gravity reference.

Otolith organs. The utricle and saccule, which detect linear acceleration and gravity through weighted sensory structures. Free fall removes the steady component that normally helps define down.

Proprioception. Information from muscles, tendons and joints about body position and movement. In microgravity it combines with touch and vision to replace some lost gravitational cues.

Sensory reweighting. The brain's adjustment of how much it trusts vision, vestibular input, touch and proprioception. It supports adaptation in orbit and can complicate readaptation after landing. The change is learned largely outside conscious control.

Cephalad fluid shift. Redistribution of blood and other fluids towards the chest and head when the persistent head-to-foot gravity gradient is removed. Cephalad means towards the head. The phrase describes redistribution and regulation, not all body fluid collecting in one place.

Plasma volume. The amount of liquid in blood, excluding blood cells. It commonly falls during spaceflight, contributing to the challenge of

maintaining circulation when upright gravity returns.

Baroreflex. Rapid cardiovascular control using pressure sensors, heart rate and vessel tone to stabilise blood pressure. Altered demand in space can reduce performance during later upright stress.

Orthostatic intolerance. Difficulty maintaining circulation and function while upright. After spaceflight it may appear as light-headedness, rapid heart rate, weakness or near-fainting during gravity readaptation.

Antigravity muscles. Muscles used heavily to maintain posture and oppose gravity, especially in the legs, hips and trunk. Their ordinary background work drops sharply during free fall.

Bone remodelling. Continuous removal and formation of bone tissue. Mechanical strain, hormones, nutrition and other signals influence whether structure is maintained, added or lost.

Bone resorption. Breakdown of bone by cells called osteoclasts, releasing minerals into the circulation. Increased resorption during unloading contributes to skeletal and renal-stone concerns.

ARED. The Advanced Resistive Exercise Device on the space station. Vacuum cylinders and flywheels create high forces without ordinary weights, allowing squat, deadlift and related movement patterns. Restraints transmit the force to the body.

SANS. Spaceflight-associated neuro-ocular syndrome, a variable cluster of eye and brain findings during or after flight. Several mechanisms may contribute; their relative importance remains unresolved. Findings and symptoms vary between crew members.

Ionising radiation. Radiation energetic enough to remove electrons from atoms and damage biological material. Space fields include particles whose energies and tissue tracks differ from common terrestrial exposures. The crew usually cannot feel the exposure as it occurs.

Absorbed dose. Energy deposited by ionising radiation per unit mass of

material. It is measured in gray and does not by itself capture particle quality or biological outcome.

Gray. The SI unit of absorbed dose, equal to one joule of radiation energy deposited per kilogram. Identical gray values can produce different biological effects.

Sievert. The SI unit for weighted radiation-dose quantities, including equivalent and effective dose. Such quantities support radiation protection; they depend on models rather than counting injuries directly.

Linear energy transfer. Energy deposited by radiation along its path through material. High-LET particles create dense ionisation tracks that can be biologically difficult to repair.

Galactic cosmic rays. High-energy particles arriving from beyond the Solar System. They include heavy ions, penetrate spacecraft deeply and are difficult to eliminate with practical shielding.

Solar particle event. An episode in which the Sun accelerates energetic particles towards space. Warning, monitoring and a shielded refuge can reduce crew exposure during a major event.

Circadian rhythm. A roughly twenty-four-hour biological cycle affecting sleep, alertness, temperature and other functions. Light, schedules and mission operations can align or disrupt it.

Earth-independent operations. Work performed when distance and communication delay prevent immediate ground guidance. Crews need greater local knowledge, authority, diagnosis and repair capacity as Earth recedes.

Go Deeper

For the human detail: Mary Roach, *Packing for Mars: The Curious Science of Life in the Void* (W. W. Norton, 2010). Roach reports from the less dignified edge of human spaceflight: motion sickness, hygiene, food, confinement, testing and the problem of taking an Earth animal into a small machine. It is the most inviting next read here because the humour rests on reported practice rather than awe. The science and programmes predate much of the current station evidence, so use it for the questions, experiments and physical reality, then check present risk conclusions against newer sources. Its lasting value is the refusal to separate bodily embarrassment from engineering seriousness.

For the lived mission: Scott Kelly with Margaret Lazarus Dean, *Endurance: A Year in Space, a Lifetime of Discovery* (Alfred A. Knopf, 2017). Kelly's account connects training, station routine, fatigue, maintenance, family separation and return to Earth across a career rather than one dramatic flight. Read it for the difference between an astronaut's daily workload and the edited public image. A memoir supplies perception, sequence and texture, not a representative medical sample. Kelly's long mission later became one half of the Twins Study, but his experience cannot stand for every crew member. Pair it with the research to see where a vivid case illuminates a mechanism and where it cannot estimate a rate.

For the technical field: Ethan Waisberg, Joshua Ong and Andrew G. Lee, eds., *Fundamentals of Space Medicine and Clinical Technology* (Elsevier, 2025). This large multi-author reference covers physiology, clinical risks, monitoring and emerging technologies with far greater depth than a one-hour book can carry. It is the route into SANS, radiation, cardiovascular adaptation, surgery, diagnostics and terrestrial applications. The reward is breadth and currency; the warning is that chapters vary in emphasis and assume biomedical knowledge. Use it to follow a mechanism, not as a book to read straight through. Begin with the organ system or mission hazard that this book left most unresolved for you.

For the ethical problem: Institute of Medicine, *Health Standards for Long Duration and Exploration Spaceflight: Ethics Principles, Responsibilities, and Decision Framework* (National Academies Press, 2014). The report asks what should happen when an exploration mission cannot meet existing health standards or when uncertainty prevents a reliable standard from being set. That is the hidden question beneath radiation limits, rescue, consent and acceptable loss. It separates technical risk estimation from the decision to expose a crew. The prose is institutional, but the framework prevents courage, scientific value and employer responsibility from being collapsed into one heroic story.

Notes and Sources

Important scientific, medical and operational claims were reviewed against sources available on 5 September 2026. NASA Human System Risk records provide the main current synthesis, with original studies used for specific findings. Evidence from supported low-Earth-orbit crews is distinguished from predictions for longer, Earth-independent missions. The notes identify the studies and limits that materially shape the account; they are not a claim that every sentence has been independently tested.

The Whole Thing in One Page and Why You Should Care

The overall model combines NASA's current human-system risk architecture with Gilles Clément's account of adaptation across gravity transitions. The three-way distinction among regulated adjustment, unwanted side-effect and direct exposure injury is an authorial synthesis used to prevent every spaceflight change from being called either damage or adaptation. The distinction between useful adaptation in one environment and retained capability for the next is also a synthesis, not a NASA slogan. NASA's risk records support the linked treatment of altered gravity, radiation, isolation, distance and the closed habitat. The ethical discussion follows the Institute of Medicine framework for missions whose hazards exceed existing evidence or health standards.

The Core Ideas

Gravity, free fall and loading

The free-fall account follows standard orbital mechanics and space physiology. NASA's sensorimotor, bone, aerobic and exercise records support the claim that removing continuous support and ordinary movement alters several systems at once. Head-down bed rest is treated as a partial analogue because it reproduces unloading and headward fluid shift while retaining gravity, contact pressure and a terrestrial environment. No claim is made that one bed-rest result predicts an astronaut outcome exactly.

Sensorimotor adaptation and cognition

NASA's Sensorimotor Risk record supports the description of vestibular conflict, space motion sickness, sensory reweighting and the operational vulnerability around gravity transitions. Structural brain findings are described without treating imaging change as cognitive injury. Dev and colleagues followed 25 professional astronauts on roughly six-month International Space Station missions. Their 2024 study found no systematic decline across cognition as a whole, with phase-specific changes in selected measures. The manuscript preserves that population, duration and level of certainty rather than extending the result to Mars.

Fluids, circulation and SANS

NASA's cardiovascular and SANS risk records support the headward-fluid-shift account, postflight orthostatic risk and the statement that SANS remains mechanistically unresolved. Lee and colleagues provide the neuro-ophthalmic review used for the range of findings and the caution against one-pressure explanations. Marshall-Goebel and colleagues studied 11 long-duration crew members, finding stagnant or retrograde left internal-jugular flow in several and an occlusive thrombus in one. The text uses this as evidence that the hazard can occur, not as a stable population rate. The treated case described in the mission sequence is reported by Auñón-Chancellor and colleagues in 2020; that is the publication year, not a disclosed mission date. The treating clinician's account, issued by UNC Health Care, corroborates treatment and safe return. Hughson and colleagues support the broader cardiovascular account.

Muscle, bone, aerobic capacity and renal stones

NASA's bone, aerobic, exercise and renal-stone records support the tissue-specific treatment of deconditioning and countermeasures. Stavnychuk and colleagues' 2020 meta-analysis supplies broader context on variation in bone loss across sites and missions. Gabel and colleagues followed 17 astronauts and found incomplete average recovery of several distal-tibia measures one year after long-duration flight, with differences by mission duration and individual. The text does not equate one scan measure with fracture or claim one fixed rate of loss. NASA's 2025 bone risk record reports no in-flight bone fracture and warns that this history does not characterise future exploration risk. Fiedler and colleagues report seven fractures among 242 astronauts within five years after flight. The small surveillance cohort had no matched ground group, so it cannot establish a causal excess. The paper's text and table disagree on how many fractures fell within two years; that subcount is not used here.

Radiation, atmosphere, microbes and medicines

NASA's Radiation Carcinogenesis risk record and Durante and Cucinotta support the distinction among trapped particles, solar particle events and galactic cosmic rays, together with the limits of passive shielding against high-energy heavy ions. The FDA's radiation-quantities guidance distinguishes absorbed dose in gray from equivalent and effective dose in sieverts; equivalent dose uses radiation weighting, while effective dose also includes tissue weighting. The manuscript does not convert animal or cellular effects into human Mars probabilities. NASA technical briefs and current Human Health and Performance records support the sections on carbon dioxide, environmental control, immune and microbial interactions, drug storage and altered medicine effectiveness. NASA states that spaceflight factors and long resupply intervals can make products ineffective or toxic and that pharmacokinetics or pharmacodynamics may differ, but the retained body text makes no directional dose claim because human in-flight evidence is sparse. The celestial-dust treatment follows NASA's current dust risk record and its 2026 work on preliminary Martian dust limits; no authentic airborne Martian dust has yet been returned for toxicology. Light flashes associated with particle passage are documented in Avdeev and colleagues' Mir observations (2002). They are not a reliable measure of personal exposure; the narrative does not assign one mechanism to every reported flash.

Sleep, cognition and crews

NASA's sleep, behavioural-health, team and Earth-independent-operations records support the treatment of workload, circadian disruption, privacy, meaningful work, crew composition, ground support and delayed communication. Barger and colleagues supply the large operational study of sleep deficiency and hypnotic use around shuttle and station missions. NASA's 2024 account of Crew Earth Observations supports the description of off-duty photography and reported well-being benefits. This is not presented as a universal therapeutic effect. The manuscript avoids claiming that confinement alone predicts breakdown. It also avoids treating successful professional crews as evidence that selection, support and mission architecture do not matter.

Countermeasures, partial gravity and deep space

NASA's exercise overview and current risk records support the specificity and resource cost of exercise, lower-body negative pressure, lighting, schedule design, shielding, monitoring and medical preparation. No human population has lived for months in lunar or Martian gravity. Claims about partial gravity and artificial gravity are therefore framed as design hypotheses and research questions. The Moon and Mars gravity fractions are physical values; their sufficiency for each tissue or task is unknown.

Mission sequence and evidence

The mission sequence is a synthesis of the evidence above, arranged from baseline measurement through launch, early adaptation, long-duration operations, landing and exploration. Baseline and repeated-measures language reflects the practical strength of astronaut studies, while the cautions address selection, practice effects, changing hardware and the lack of random assignment. Garrett-Bakelman and colleagues provide the NASA Twins Study example: unusual biological depth in one flying twin, with no permission to estimate a population rate. Examples of self-ultrasound, eye imaging, exercise setup and environmental maintenance are documented station practices rather than invented scenes.

ESA's account of astronaut candidates in neutral-buoyancy training documents suited practice with tethers, tools, divers and controllers. Its daily-life account and NASA's crew-systems description support airflow-based waste collection. These are documented practices, not reconstructed private scenes. The anonymous thrombosis patient is not assigned a name, dialogue, motive or undisclosed flight date. The pump-fault comparison in the Mars misconception is explicitly hypothetical, not an account of an incident.

What People Get Wrong

The seven corrections are built from the same sources rather than from manufactured claims. Zero gravity is corrected to shared free fall. Weakness is widened into regulated adjustment, unwanted side-effect and direct injury across several systems. Exercise is described as partial replacement rather than cancellation of microgravity. SANS is separated from a single intracranial-pressure story. Radiation dose is separated from field, timing, tissue and outcome. Crew resilience is linked to selection and support. Station evidence is bounded to low Earth orbit rather than treated as a completed Mars experiment.

Use It

The practical lenses are the author's synthesis of the book's mechanisms. They are not clinical advice, a personal radiation standard or a mission-certification method. The transition lens follows directly from the mismatch between adaptation in free fall and required performance after landing. The dose lens follows the measurement incompatibilities visible in radiation, exercise and sleep. The whole-system lens follows NASA's treatment of person, crew, habitat, task and ground as interacting contributors to risk.

Terms

Definitions follow standard usage in space medicine, physiology, radiation protection and human factors. Some terms, including deconditioning, dose and Earth-independent operations, have narrower technical definitions in particular programmes. Entries are operational guides to this manuscript, not claims that one convention governs every discipline.

Go Deeper

Publisher and institutional records were checked for all four recommendations. Mary Roach's *Packing for Mars* was published by W. W. Norton in 2010. Scott Kelly and Margaret Lazarus Dean's *Endurance* was published by Alfred A. Knopf in 2017. Ethan Waisberg, Joshua Ong and Andrew G. Lee's edited *Fundamentals of Space Medicine and Clinical Technology* was published by Elsevier in 2025. The Institute of Medicine report was published by the National Academies Press in 2014.

Bibliography

Original research and reviews

Avdeev, S., V. Bidoli, M. Casolino, et al. "Eye Light Flashes on the Mir Space Station." *Acta Astronautica* 50, no. 8 (2002): 511-525. DOI: 10.1016/S0094-5765(01)00190-4.

Auñón-Chancellor, Serena M., James M. Pattarini, Stephan Moll and Ashot Sargsyan. "Venous Thrombosis during Spaceflight." *New England Journal of Medicine* 382, no. 1 (2020): 89-90. DOI: 10.1056/NEJMc1905875.

Barger, Laura K., Erin E. Flynn-Evans, Alan Kubey, Lorcan Walsh, Joseph M. Ronda, Wei Wang, Kenneth P. Wright Jr and Charles A. Czeisler. "Prevalence of Sleep Deficiency and Use of Hypnotic Drugs in Astronauts Before, During, and After Spaceflight: An Observational Study." *The Lancet Neurology* 13, no. 9 (2014): 904-912. DOI: 10.1016/S1474-4422(14)70122-X.

Dev, Sheena I., Alaa M. Khader, Sydney R. Begerowski, Steven R. Anderson, Gilles Clément and Suzanne T. Bell. "Cognitive Performance in ISS Astronauts on 6-Month Low Earth Orbit Missions." *Frontiers in Physiology* 15 (2024): 1451269. DOI: 10.3389/fphys.2024.1451269.

Durante, Marco, and Francis A. Cucinotta. "Physical Basis of Radiation Protection in Space Travel." *Reviews of Modern Physics* 83, no. 4 (2011): 1245-1281. DOI: 10.1103/RevModPhys.83.1245.

Fiedler, Benjamin, Nathaniel Grey Loyd, Joshua Morrow, Nick Cione, Abdullah Ghali, Brenden Ronna and Adil Shahzad Ahmed. "Spaceflight and Fractures: 5-Year-Fracture Incidence Upon Return From Spaceflight." *Wilderness & Environmental Medicine* (2026). Advance online publication. DOI: 10.1177/10806032261446640.

Gabel, Leigh, Anna-Maria Liphardt, P. A. Hulme, et al. "Incomplete Recovery of Bone Strength and Trabecular Microarchitecture at the Distal Tibia 1 Year After Return from Long Duration Spaceflight." *Scientific Reports* 12 (2022): 9446. DOI: 10.1038/s41598-022-13461-1.

Garrett-Bakelman, Francine E., Manjula Darshi, Stefan J. Green, et al. "The NASA Twins Study: A Multidimensional Analysis of a Year-Long Human Spaceflight." *Science* 364, no. 6436 (2019): eaau8650. DOI: 10.1126/science.aau8650.

Hughson, Richard L., Andrew D. Robertson, Philippe Arbeille, J. Kevin Shoemaker, James W. E. Rush, Katelyn S. Fraser and Danielle K. Greaves. "Increased Postflight Carotid Artery Stiffness and Inflight Insulin Resistance Resulting from 6-mo Spaceflight in Male and Female Astronauts." *American Journal of Physiology: Heart and Circulatory Physiology* 310, no. 5 (2016): H628-H638. DOI: 10.1152/ajpheart.00802.2015.

Lee, Andrew G., Thomas H. Mader, C. Robert Gibson, William Tarver, Pejman Rabiei, Roy F. Riascos, Laura A. Galdamez and Tyson Brunstetter. "Spaceflight Associated Neuro-Ocular Syndrome (SANS) and the Neuro-Ophthalmologic Effects of Microgravity: A Review and an Update." *npj Microgravity* 6 (2020): 7. DOI: 10.1038/s41526-020-0097-9.

Marshall-Goebel, Karina, Steven S. Laurie, Irina V. Alferova, et al.
"Assessment of Jugular Venous Blood Flow Stasis and Thrombosis During Spaceflight." *JAMA Network Open* 2, no. 11 (2019): e1915011. DOI: 10.1001/jamanetworkopen.2019.15011.

Stavnychuk, M., N. Mikolajewicz, T. Corlett, M. Morris and S. V. Komarova.
"A Systematic Review and Meta-Analysis of Bone Loss in Space Travelers." *npj Microgravity* 6 (2020): 13. DOI: 10.1038/s41526-020-0103-2.

Books and institutional reports

Clément, Gilles. *Fundamentals of Space Medicine*. 2nd ed. New York: Springer, 2011.

Institute of Medicine. *Health Standards for Long Duration and Exploration Spaceflight: Ethics Principles, Responsibilities, and Decision Framework*. Washington, DC: National Academies Press, 2014.

Kelly, Scott, with Margaret Lazarus Dean. *Endurance: A Year in Space, a Lifetime of Discovery*. New York: Alfred A. Knopf, 2017.

Roach, Mary. *Packing for Mars: The Curious Science of Life in the Void*. New York: W. W. Norton, 2010.

Waisberg, Ethan, Joshua Ong and Andrew G. Lee, eds. *Fundamentals of Space Medicine and Clinical Technology*. 1st ed. Elsevier, 2025.

European Space Agency. "Astronaut Candidates in Pool." Accessed 5 September 2026.

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Astronaut_candidates

European Space Agency. "Daily Life." Accessed 5 September 2026.

https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Astronauts/Daily_Life

Gaskill, Melissa L. "Mental Well-Being in Space." NASA, 15 August 2024. Accessed 5 September 2026.

<https://www.nasa.gov/missions/station/iss-research/mental-well-being-in-space/>

University of North Carolina Health Care. "UNC Expert Helps Treat

Astronaut's Blood Clot during NASA Mission." 2 January 2020. Institutional release reproduced by Phys.org.

<https://phys.org/news/2020-01-unc-expert-astronaut-blood-clot.html>

US Food and Drug Administration. "Radiation Quantities and Units."

Accessed 5 September 2026.

<https://www.fda.gov/radiation-emitting-products/medical-x-ray-imaging/radiation-quantities>

National Aeronautics and Space Administration. "Crew Systems." Orion reference guide, updated 4 September 2026. Accessed 5 September 2026.

<https://www.nasa.gov/reference/crew-systems/>

Current NASA risk and technical records

The risk records below are indexed at

<https://www.nasa.gov/hhp/human-system-risks/>

National Aeronautics and Space Administration. "5 Hazards of Human Spaceflight." Human Research Program. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Altered Sensorimotor/Vestibular Function Impacting Critical Mission Tasks, Human Health, and Long-Term Health." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Bone Fracture Due to Spaceflight-Induced Changes to Bone." Human System Risk record, Revision C, approved 9 June 2025. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Cardiovascular Adaptations Contributing to Adverse Mission Performance and Health Outcomes." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Spaceflight Associated Neuro-Ocular Syndrome." Human System Risk record, webpage

updated 16 September 2025. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Radiation Carcinogenesis." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Performance Decrements and Adverse Health Outcomes Resulting from Sleep Loss, Circadian Desynchronization, and Work Overload." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Adverse Cognitive or Behavioral Changes and Psychiatric Disorders Leading to In-Mission Health and Performance and Long-Term Health Effects." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of In-Mission Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation Within a Team." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Adverse Mission Outcomes Due to Earth Independent Human-Systems Operations." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Ineffective or Toxic Medications During Long-Duration Exploration Spaceflight." Human System Risk record, webpage updated 11 March 2025. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Renal Stone Formation." Human System Risk record. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Risk of Adverse In-Mission Health and Performance Effects and Long-Term Health Effects Due to Celestial Dust Exposure." Human System Risk record, updated 17 September 2025. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Establishing Crew

Exposure Limits of Martian Dust." 21 July 2026. Accessed 5 September 2026.

National Aeronautics and Space Administration. "Microbiology." Human Health and Performance, webpage updated 15 July 2026. Accessed 5 September 2026.

National Aeronautics and Space Administration. *OCHMO-TB-004 Carbon Dioxide*. Office of the Chief Health and Medical Officer technical brief. Accessed 5 September 2026.

National Aeronautics and Space Administration. *OCHMO-TB-031 Exercise Overview*. Office of the Chief Health and Medical Officer technical brief. Accessed 5 September 2026.