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For the U.S., a defensive shift away from monolithic satellites has proved harder than envisioned. PAGE 18

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ARTIFICIAL GRAVI

ITY'S ATTRACTION

NASA astronaut **Catherine "Cady" Coleman** participated in an experiment to study the effects of long space flights on the cardiovascular system while she was on the International Space Station in 2010-11.

NASA

Some spaceflight experts are concerned that the exercise techniques pioneered aboard the International Space Station won't be enough to counteract the effects of years in microgravity during missions to the region around the moon and to Mars. Adam Hadhazy spoke to scientists leading the renaissance of interest in artificial gravity concepts.

BY ADAM HADHAZY | adamhadhazy@gmail.com

The prospect of floating, exhilaratingly unbound, in microgravity has long drawn people to space exploration, but now that some astronauts and cosmonauts have spent upward of a year in space, it turns out that the thrills of weightlessness do not come scot-free.

Living in a near lack of gravity can trigger a daunting range of ailments. A mere sampling: Muscle atrophy. Bone deterioration. Weight loss. Bodily fluid redistribution. Balance problems. Cardiovascular dysfunction. Anemia. Kidney stones. Trouble sleeping. Nasal congestion. Weakened immune systems. And, to add insult to injury, increased flatulence.

Countermeasures including astronaut exercise regimens and nutrient supplementation have been increasingly deployed on the International Space Station over the last decade and a half. These measures have reduced some of the negative effects, but space medicine practitioners are not entirely sure how explorers will be affected by even longer exposure to microgravity. Even now, they have no solution for an impairment of vision, thought to arise from the pressure buildup of fluid in spacefarers' heads. With space agencies and the private sector firmly setting sights on journeys to Mars lasting two years or more, a comprehensive remedy for this and other gravity-related impacts is in higher demand than ever.

The most logical of silver bullets: artificial gravity, induced by rotation. Some concepts call for astronauts to live and work in a cylindrical or wheel-shaped, revolving spacecraft or portion of their space vehicle. Other setups could see astronauts spend time or even sleep in spinning centrifuges, and then work in conventional, microgravity modules. Whichever way, the goal is to deliver astronauts to their extraterrestrial destinations healthy and ready to explore. Accordingly, the voguish systems are being freshly reassessed for future missions. In 2014, NASA restarted its moribund artificial gravity research program, and aerospace companies are giving the idea serious consideration.

"Artificial gravity does not countermeasure for just one thing; it addresses all physical systems," says Gilles Clement, the lead scientist for artificial gravity in the Human Health Countermeasures Element of the Human Research Program at NASA's Johnson Space Center in Houston.

"We think about long durations in the exploration of space as a way to expand our planet to other planets," Clement adds. "We bring food and air — why not take gravity with us?"

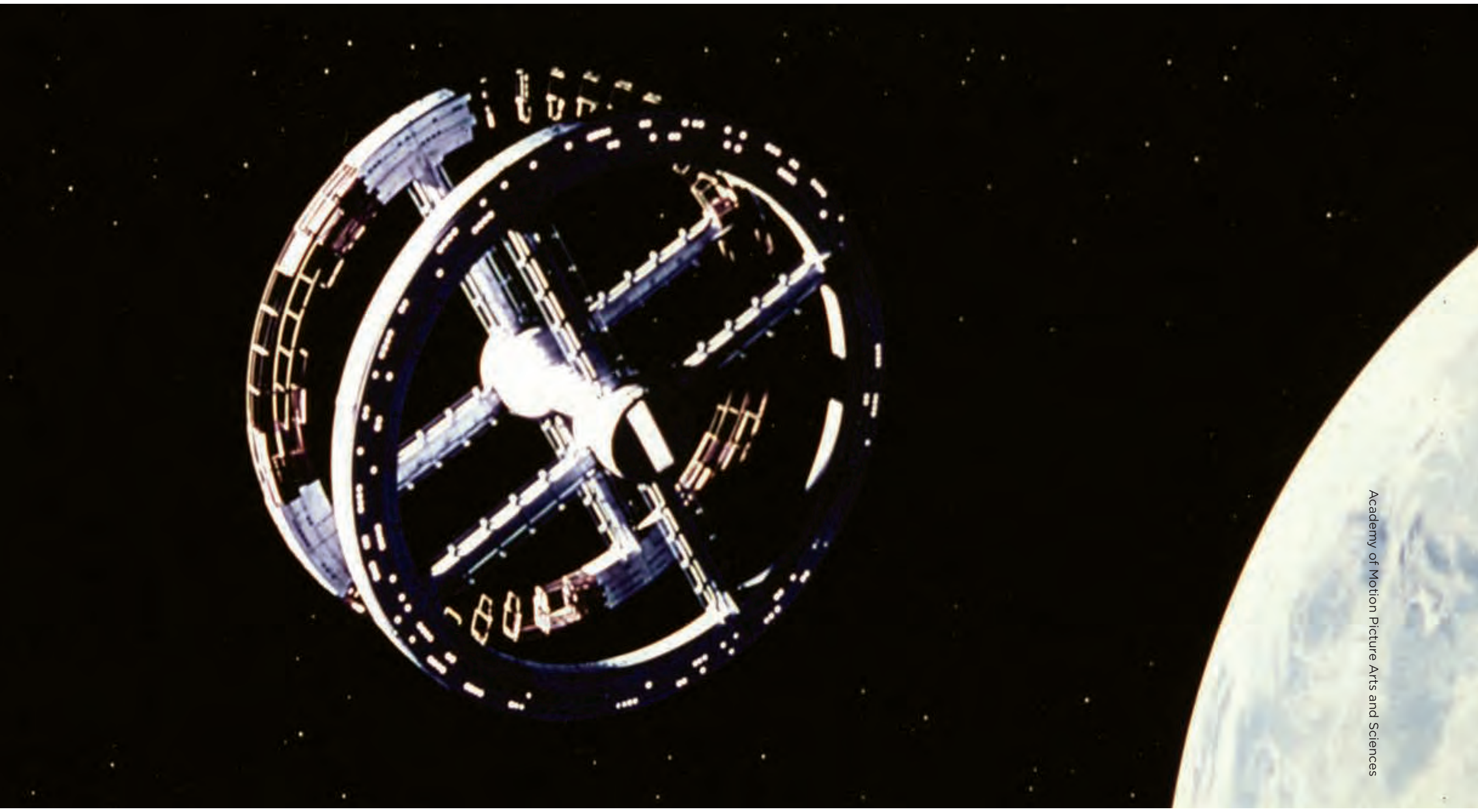
Gravity's hold on us

The idea of artificial gravity goes back to an 1883 description by the Russian rocket scientist Konstantin Tsiolkovsky, who famously remarked: "Earth is the cradle of humanity, but one cannot remain in the cradle forever." By the dawn of the Space Age, seven decades later, engineers took artificial gravity as a given in their visions for huge, wheel-shaped outposts on the final frontier. Stanley Kubrick's 1968 film "2001: A Space Odyssey" and Arthur C. Clarke's novel of the same name further popularized the concept, depicting a revolving space station and astronaut living area on a vessel outbound to Jupiter.

The principle at work behind these notions of artificial gravity is centripetal force, which acts on an object moving in a curved path. A familiar demonstration is how water will stay at the bottom of a bucket when spun outward horizontally by a person twirling in place. The bucket's bottom pushes toward the rotation axis, just as the hull of a spinning spaceship, or the footrest in a centrifuge, pushes "up" against an astronaut's feet, mimicking the gravitational effect we experience living on a massive planet.

The amount of artificial gravity produced in this manner depends on three things: the mass of the object being rotated, its radius from the center of rotation, and the rotation rate. Increasing any of those factors ups the overall centripetal force. As such, creating a desirable apparent gravity for a human inside a vessel, whether a spacecraft or an onboard centrifuge, is a tradeoff between radius size and rotation rate.

During early astronautic decades, numerous studies examined these tradeoffs. The studies involved everything from placing people in rotating

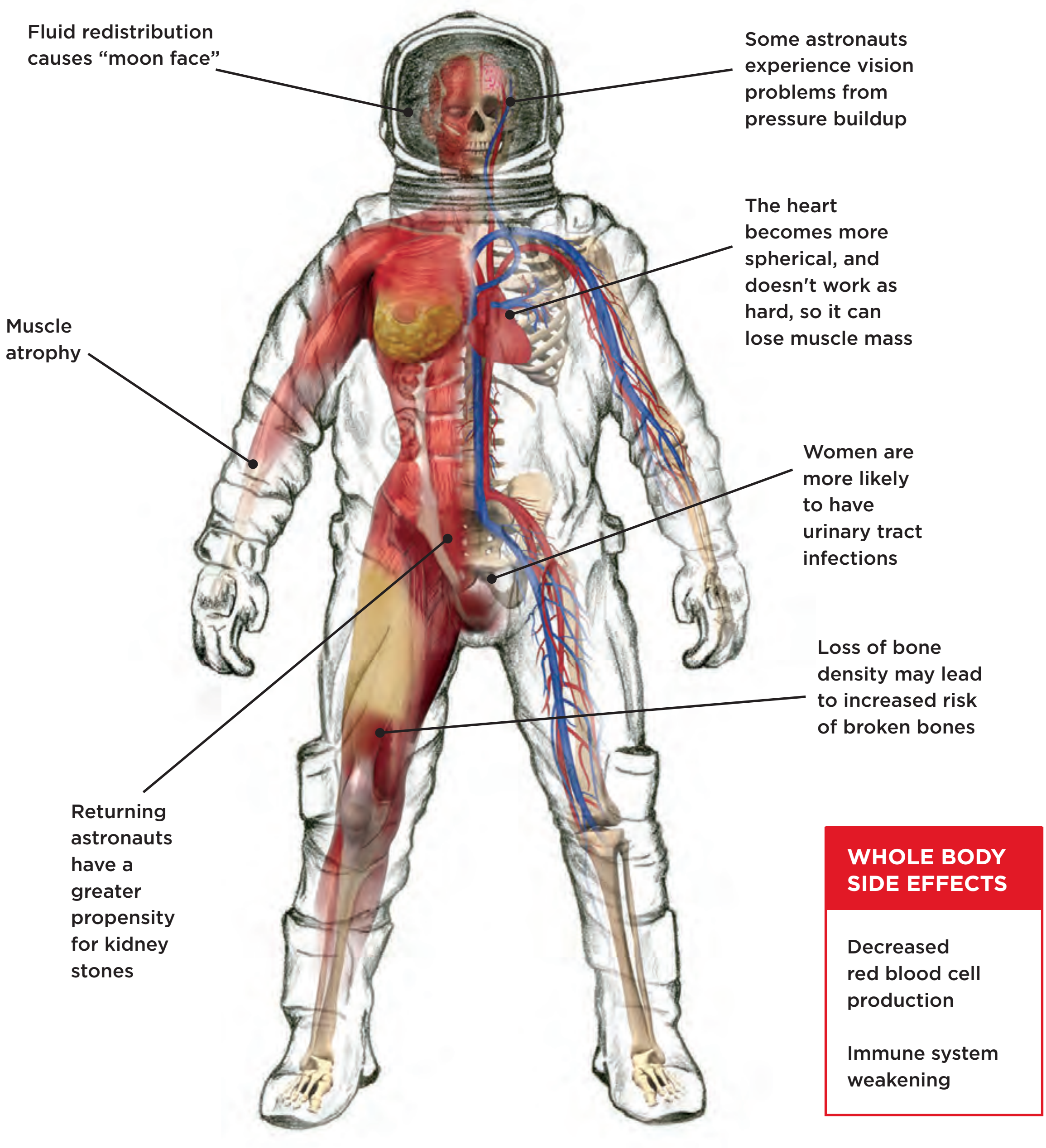


▼ **The space station** in 1968's "2001: A Space Odyssey" simulated gravity while revolving in low Earth orbit.

Academy of Motion Picture Arts and Sciences

Effects of spaceflight

Humans suffer a variety of side effects when exposed to microgravity. Here are some research findings:



Source: NASA; “Artificial Gravity for Low Earth Orbit (ISS) & Deep Space Exploration,” AIAA Space 2016

DLR

rooms on Earth to centrifuging animals in space aboard satellites to spinning a Gemini capsule in 1966 while tethered to another spacecraft, bola-style, generating a temporary whisker of artificial gravity for the crew.

Among the broad, albeit indirect, takeaways from these forays: humans could likely tolerate a space station, say with a 100-meter radius rotating perhaps three times a minute without experiencing sensorimotor trouble like dizziness and nausea. This rate would produce force equivalent to the 1 G of gravity we feel on Earth. Deriving 1 G from a small centrifuge, though, would mean spinning significantly faster, up to an uncomfortable 10 revolutions per minute. Plus, the well-spun occupants would have difficulty adapting to low gravity after a session ended.

Early studies of artificial gravity suggested that it "created more problems than it solved," Clement says. At the time, there wasn't the awareness there is today of the need to address the myriad medical issues that arise for humans when they are in microgravity for months or years.

Moreover, the missions then at hand, and until recently, never truly demanded it. Indeed, astronauts seemed to get by well enough on the Apollo missions to the moon. After a few days, spacegoers recovered from the disorientation, nausea and headaches of "space sickness" that marked their transition to microgravity, as well as back to the 1 G environment upon terrestrial return. Eating food and going to the bathroom in space, while tedious at first, soon became manageably routine.

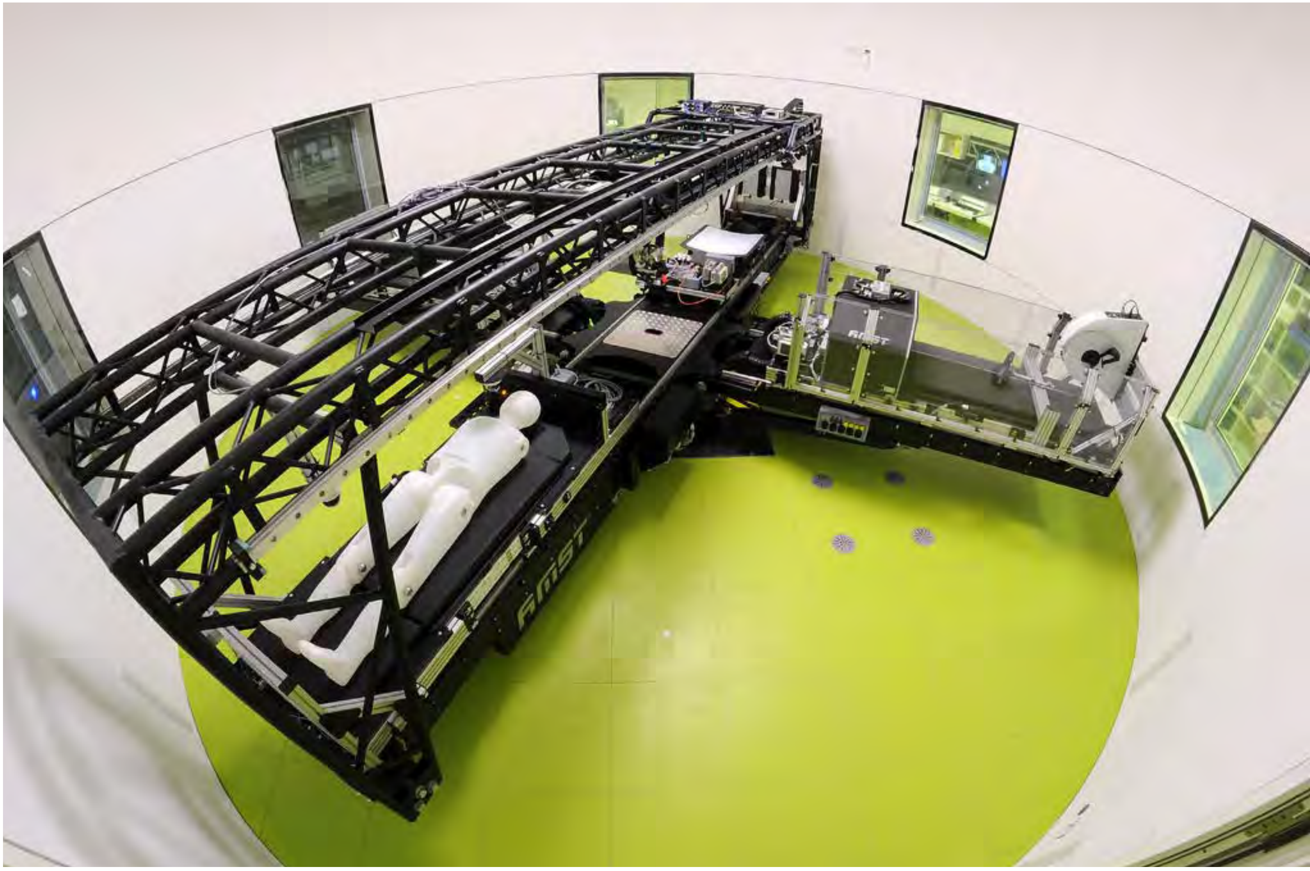
A weighty matter

Deeper concerns emerged, however, with the prolonged periods of weightlessness undergone onboard the Skylab space station in the 1970s, as well as the Soviet Union and Russian Mir station starting a decade later. The chief problems of bone- and muscle-mass loss were investigated during space shuttle flights, though these lasted at most only two weeks. As humans took up residence in the International Space Station in late 2000, medical testing technology advances began laying out the scope of zero G's ravages.

In parallel, progress in diet, nutrient supplementation and heavy resistive exercise began to peg artificial gravity again as a bridge too far. The deployment of treadmills, stationary bikes, and the equivalent of a gym apparatus for doing daily exercises such as squats, dead lifts and calf raises made ISS life far less deleterious.

"We've got an advanced countermeasures suite up there," said astronaut Michael Barratt in comments to an audience at the AIAA SPACE 2016 Forum

▲ **A researcher straps a subject into the short-arm centrifuge** at the DLR Institute of Aerospace Medicine in Cologne, Germany, where scientists are researching the effects of artificial gravity.



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▲ **When the short-arm centrifuge spins a person**, it creates artificial gravity that forces blood back toward their feet. The device is at the DLR's ":envihab," short for enviroment and habitat.

in Long Beach, California, in September. "We are now preserving bone and muscle and aerobic fitness better than any time in history. So what used to be a huge enemy is something we have a solution for."

It so happens that Barratt's six-month stay on the ISS in 2009 is what first hinted at why artificial gravity might prove necessary aloft after all. After he and another crew member developed nearsightedness, examinations revealed optic nerve swelling and changes in their eyeballs' shapes. Those ocular problems are linked to fluid shifts into the head during long stints in space. The condition, dubbed visual impairment and intracranial pressure syndrome, or VIIP, appears to worsen over time. If unaddressed, it might leave humans on a Mars mission unable to see. Fully 90 percent of astronauts acquire VIIP to some degree; previous generations of astronauts had also noted vision problems, but the issue had never been pursued. "We've been flying in space for 50 years and we missed this," said Barratt in Long Beach. The discovery begs another alarming question, Barratt added: "What else are we missing?"

The hope is that VIIP, as well as other as-yet-unknown ailments kindled by chronic weightlessness, can be corralled by keeping fluids more normally distributed in the body — which exercise unfortunately cannot do. With NASA on a mid-2030s timetable for a possible mission to Mars, perhaps with a long layover at the moon or an asteroid, artificial gravity's scattershot history of research is ripe for a re-evaluation.

"Research was distributed and uncoordinated across numerous government and research organizations," says Clement. "Now that there are plans to send humans to Mars, using artificial gravity as an integrated countermeasure is logical and practical."

Making headway

In February 2014, NASA gathered participants from space agencies worldwide at an artificial gravity workshop at Ames Research Center in Moffett Field, California. From that starting point, Clement is coordinating international efforts to develop a research road map with enough lead time to affect next-generation mission designs.

Among scientists' key questions: How much gravity must a person be exposed to in order to stay healthy — the so-called G dose-response relationship? "We know how people work in 1 G and we know a lot about how people respond to zero G, but there's almost no data in between," Clement says. It could be that, say, just a low dose of 60 percent of Earth's gravity, provided by a slowly spinning centrifuge while its occupant soundly sleeps, may suffice in warding off VIIP and other nasties.

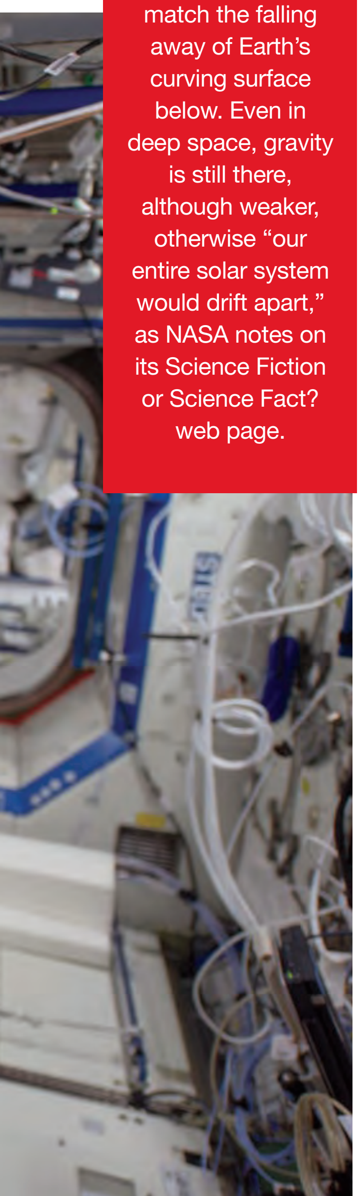
To fill the knowledge gap, NASA, the European Space Agency and other organizations have over the last couple of years announced a series of grants to study the physiological effects of varying gravity levels and intervals on cell cultures and animals, on Earth and in space. Humans, meanwhile, will partake in new studies at the DLR Institute of Aerospace Medicine in Cologne. Subjects in a facility called ":envihab," short for environment and habitat, will endure 60 days of bed rest with a 6-degree tilt down toward their heads, an orientation that mimics some of the physiological strain of weightlessness. Intermittently, subjects will go inside a horizontally spinning, 3.8-meter centrifuge to receive varying gravitational doses.

Other, no-less-intrepid participants will climb aboard NASA's McDonnell Douglas C-9B and outside contractor Zero Gravity Corp.'s Boeing 727 for new runs of the agency's "Vomit Comet" program, in which sudden drops in aircraft altitude induce periods of varying weightlessness lasting about 25 seconds. Researchers assess subjects' sensorimotor and perceptual systems, as well as rapid cardiovascular responses, during these brief windows that are repeated dozens of times over the course of a flight session, thus better gauging minimal G levels for comfort and countermeasure purposes.

Still, for all these gains, what will ultimately be needed are tests on astronauts inside a cosmic centrifuge. "We must validate in space," says Clement. "It's impossible to [fully] simulate on Earth." At present, no plans are afoot for putting a human-rated centrifuge on the ISS. The last effort, the Centrifuge Accommodations Module, got the ax in 2005 before it ever reached orbit. ISS cost overruns and concern over the centrifuge's vibrations interfering

▼ **NASA astronaut Karen Nyberg** looks into a fundoscope, a device that images the back of the eye, so that researchers can monitor any effects of microgravity on her eyes during her 166 days on the International Space Station.

Is there such a thing as zero gravity? The short answer is no, though even experts utter the term for the sake of simplicity. Technically speaking, objects in Earth orbit experience "microgravity," which is a state of continuous free-fall around the planet. The objects are traveling fast enough that they match the falling away of Earth's curving surface below. Even in deep space, gravity is still there, although weaker, otherwise "our entire solar system would drift apart," as NASA notes on its Science Fiction or Science Fact? web page.



with delicate on-orbit experiments, like crystal growing, that require pristine microgravity, doomed the endeavor.

Clement flatly believes there is "no hope" of flying a human-rated centrifuge to ISS, whose operations are anyway slated to cease in 2024. Instead, he is looking ahead to the mid-2020s to NASA's "deep space habitats," proposed to take crews out of low Earth orbit into cislunar space, between the Earth and the moon, in preparation for an eventual mission to Mars.

Escaping Earth's orbital clutches

Several companies received two-year NASA grants, estimated to cost $65 million, in August 2016 through the public-private Next Space Technologies for Exploration Partnerships, or NextSTEP, initiative. The companies will develop ground prototypes of deep space habitats. A centrifuge might just find its way into the proposals or even a finalized mission, Clement says, fingers crossed.

Lockheed Martin and Orbital ATK, two recipients, do not look to be considering artificial gravity research — or operational — options at present. But there are indications Boeing is. Space Exploration division engineers presented a paper at the Long Beach event explaining how the company has nine patents pending on designs to address technical challenges of artificial gravity systems. In this vein, Boeing is conducting studies on potential centrifuge designs.

Bigelow Aerospace, another NextSTEP recipient, has not announced specifics for its cislunar habitats, though the high volumes of its hallmark inflatable modules do leave the door open for centrifuges. Ditto for Sierra Nevada Corp., whose proposed habitat made of multiple Dream Chaser spacecraft cargo modules could afford ample real estate for experimentation.

The idealistic covers of classic sci-fi novel notwithstanding, a paradigm shift to a rotating spacecraft, or spacecraft module, is not really in the cards. Budgetary, design and operational hurdles are clear and present — as is astronaut trepidation. "It's not easy to build Stanley Kubrick's space station that spins," Barratt, the astronaut, said in Long Beach. "Astronauts fear artificial gravity. Why? Because we don't like big, moving parts. They break."

Nevertheless, seed money is out there from NASA, including $500,000 for a study looking into how robots might build a lightweight plastic, expandable spacecraft that would rotate on its way to Mars. Back in 2011, NASA engineers boldly proposed the $3.7 billion Nautilus-X, a long-duration crew vehicle that would have included a large, rotating wheel section to give astronauts partial Earth G while sleeping.

"WE BRING FOOD AND AIR — WHY NOT TAKE GRAVITY WITH US?"

– Gilles Clement, NASA's Johnson Space Center

For the foreseeable future, centrifuges will therefore be the focus. Astronauts might enter a centrifuge for gravity-dosing sessions during working hours, or perhaps sleep in one. The challenge is that the necessary revolutions-per-minute for adequate medical countermeasures might be uncomfortable physically and perceptually, with even a stray, sideways glance potentially causing motion sickness. Barratt, for one, has concerns. "From an engineering standpoint, [a centrifuge is] a more practical solution," he said. "From an astronaut's perspective, it's a nightmarish form of countermeasure."

Even if space agencies do not soon go whole hog for centrifuges, their ongoing efforts to characterize G levels for human health will help set the stage for the main rationales behind the gyrating devices: Mars. The Red Planet's gravity is just 38 percent of Earth's — right in that scientific no-man's-land between 1 and zero G, meaning how explorers will fare in the world's weak embrace is an open question. "We know nothing about Martian G," says Clement.

There is room for optimism. Mars' gravity might itself serve as a sufficient countermeasure, letting astronauts forego lugging gym equipment or a heavy centrifuge down to its ruddy surface. Humans may be more prepared to take on Mars than we realize. And with artificial gravity and other countermeasures in place, even more exotic solar system destinations with partial Earth gravities — asteroids, Europa, Titan — will increasingly become within our species' grasp.

"From a teleological standpoint, until we develop interstellar travel, everything of interest to us involves zero to 1 G," said Barratt. "We need to operate in that band." ★