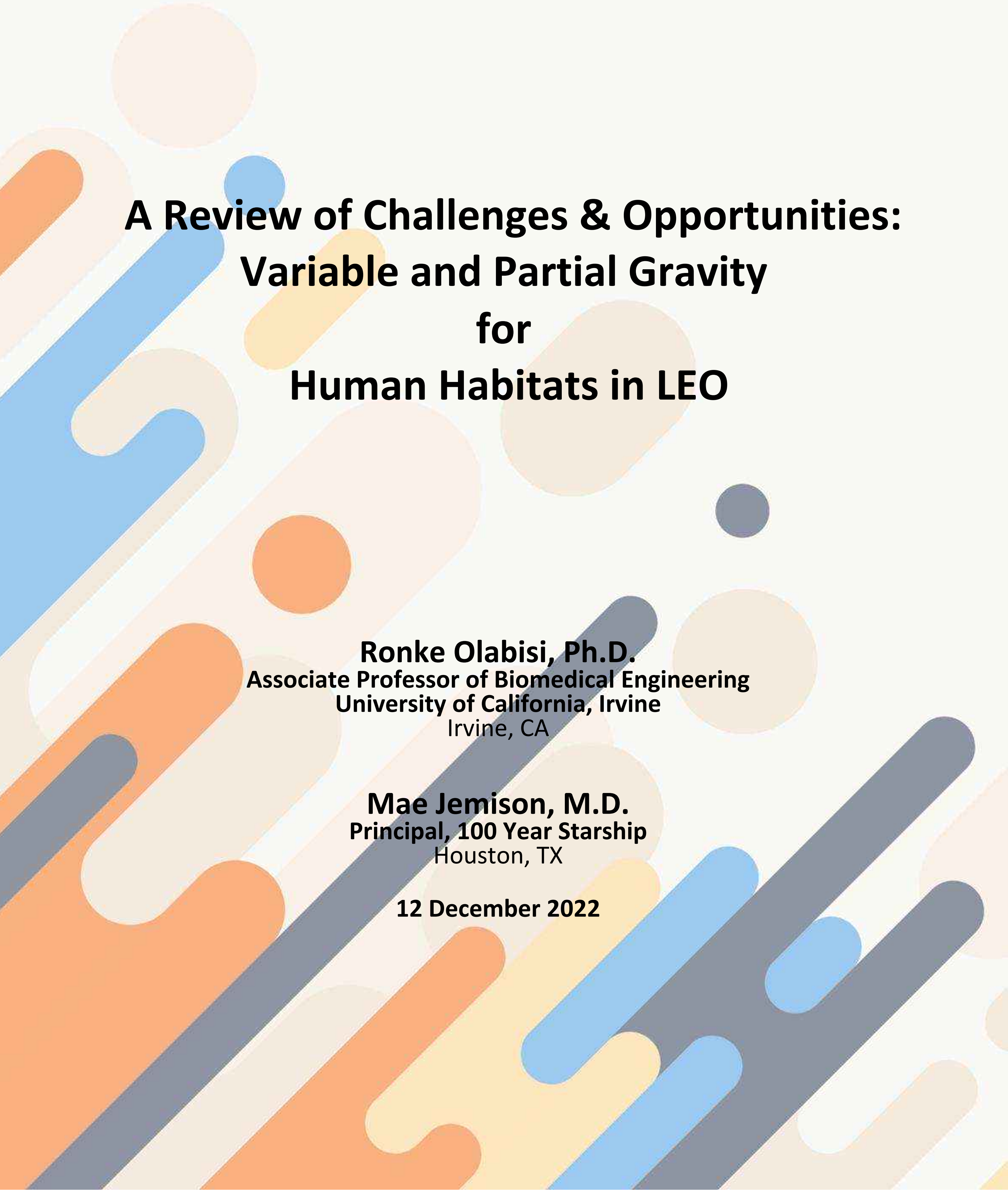

# A Review of Challenges & Opportunities: Variable and Partial Gravity for Human Habitats in LEO

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**12 December 2022**

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# OVERVIEW

The environment encountered in space presents significant unrealized and unrecognized opportunities for research, manufacturing, discovery, and industry. And that environment poses stiff challenges that hinder the realization of potential opportunities. Balancing the tension between the advantages and hurdles of operating in a weightless environment is particularly acute with human habitation. Gravitational variability—from microgravity (µg) to hypergravity—is one of the most notable and potentially exploitable for operations, research, and manufacturing.

This report reviews the literature and discusses the implications for creating artificial variable gravity habitats for humans in Low Earth Orbit (LEO) and cis-lunar space.

Artificial gravity through rotation was first proposed in 1883, by the Russian rocket scientist Konstantin E. Tsiolkovsky. Decades before space flight was a reality, designs for artificial gravity systems using rotational structures were proffered as many experts believed that humans would not be able to survive in the weightlessness of space. However, today we know humans can survive in zero G. The overwhelming majority of human space experience has been in weightlessness, which does have definite damaging effects on human physiology and performance if left unaddressed by countermeasures.

Rotational artificial gravity structures are being proposed as single solutions to long duration and interplanetary space travel. It is also a consideration for accommodating everyone—from professional crew to researchers to tourists—to protect health, facilitate operations and optimize time on orbit.

Major challenges to successfully designing, building, and operating rotating artificial gravity habitats is that ground-based studies of humans in rotational artificial gravity are hindered by the fact that Earth's gravity is always present, so studies may not translate to space; however, these studies do provide data to guide development. The reality is that there is little direct human evidence that artificial gravity will protect human health, but animal studies combined with ground-based studies provide important clues. Including the possibility that continuous, full 1 G Earth gravity may not be required to be an effective single solution countermeasure; intermittent 1 G or even 0.5 G may be effective. Further, the design and maintenance of equipment and the habitat may benefit from artificial gravity because dust, crumbs, etc. settle to the floor.

Coriolis acceleration produces unexpected sensations and actual movement of objects in unexpected ways and must be addressed by engineering, architectural, and human factors design to successfully live and operate in a rotating environment. Ground based studies do provide helpful direction for designs.

Factors critical to achieve a successful design recognize that human operations in artificial gravity inside a rotating structure must be approached with the same rigor and meticulousness as is applied to the engineering, launch, assembly, and maintenance of structures in this dynamic environment.

This study is authored by the Olabisi Lab at the University of California, Irvine in collaboration with the 100 Year Starship in Houston, Texas.

## 1. LIVING IN SPACE

Space—an isolated, confined, and extreme (ICE) environment—induces significant changes and adaptations in a variety of living organisms, from complex multicellular plants and animals to simple single-celled organisms (Adamovich et al, 1980; Gurovsky et al, 1980; Jemison, Olabisi, 2021; Kiss, 2014; Thombre et al, 2022). Many of these adaptive changes resemble pathophysiological changes here on Earth. For example, significant muscle atrophy and bone resorption resemble accelerated aging of the musculoskeletal system (Clément et al, 2015; Clément et al, 2016; Lang et al, 2006; Larina et al, 2017; Mulder et al, 2014; Swift et al, 2013; Symons et al, 2009) and aspects of cardiovascular deconditioning mimic varied heart disease processes (Charles et al, 1999; Powers, Bernstein, 2004). However, rather than years, these adaptations occur on a timescale of weeks to months. Some of the adaptations plateau or resolve in days to weeks, while others continue to progress throughout time in space.

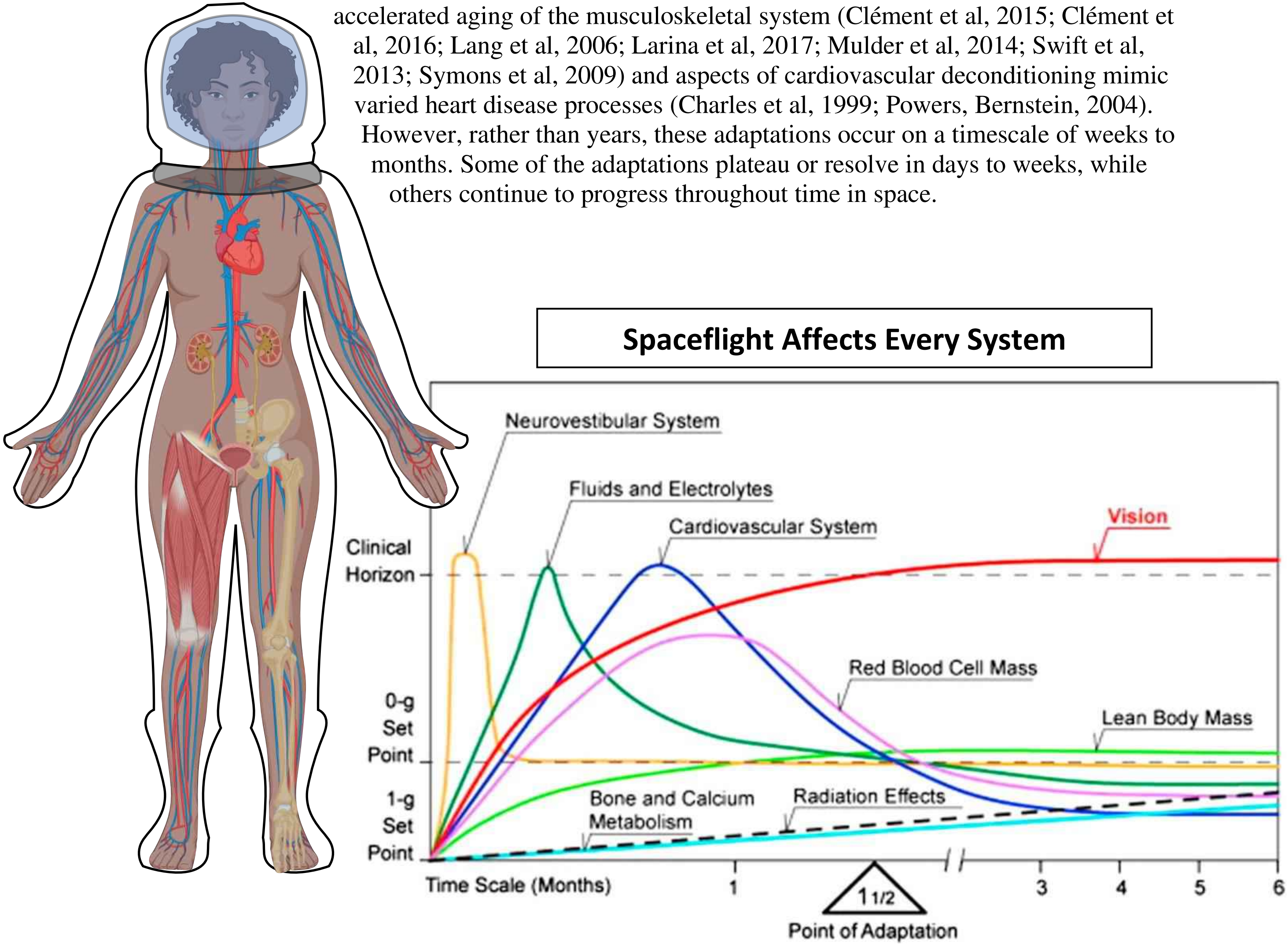


**Figure 1:** Time course and types of physiological changes in response to microgravity.

The vast majority of human space experience has been in weightlessness, so knowledge and research around adaptation to and function in space has most commonly been from the perspective of the impact of weightlessness. Weightlessness can have a detrimental impact to human functioning during and post spaceflight. And the resulting effects can further extend to space habitat systems. Actions taken to protect crew health and function that counter or negate the deleterious short- and long-term impact of space environments are called countermeasures. Countermeasures may be behavioral, exercise, facilities designs, pharmacological, or adaptive technologies (e.g., glasses for Spaceflight Associated Neuro-Ocular Syndrome (SANS)).

Historically, countermeasures have targeted *individual* systems, symptoms, or activities. For instance, exercise and individualized nutrition have been used to mitigate muscle and bone loss (Bloomberg et al, 2014; Hargens, Bhattacharya, Schneider, 2013); fluid loading to counteract the impact of cardiovascular deconditioning on return to Earth (Charles et al, 1999); or training to counter the microgravity-disoriented neurovestibular system (Lawson, Rupert, McGrath, 2016). Many of these countermeasures have been successful at reducing the adverse effects of microgravity, and in turn the concomitant health risks that arise with extreme and prolonged deconditioning. However, most of the countermeasures require both extensive equipment and crew time. Although some space-related alterations are thought to be due to galactic cosmic radiation, the lion's share of LEO adaptations are understood to be due to microgravity (Wade, 2005).

As such, a system that could generate a head-to-foot acceleration field (i.e., artificial gravity), could at once mitigate the entirety of the effects of microgravity on all physiological systems. Such artificial gravity could be achieved using rotational acceleration either through the use of short radius centrifuges, by rotating part of the spacecraft, or by rotating the entire spacecraft.

Artificial gravity systems could be used as countermeasures for weightlessness in multiple ways. The artificial gravity system could be deployed throughout the crew's entire stay in space (on orbit) or administered therapeutically at discrete advantageous times during the mission in low Earth orbit, on the lunar surface, during interplanetary travel, or on other planets.

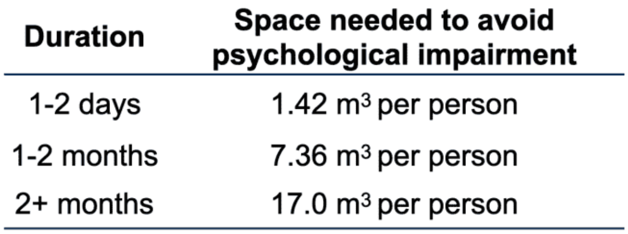
The potential technology within reach in the next decade or so for generating artificial gravity include continuous straight-line acceleration and some type of rotational system. Here we will primarily explore in depth the health and operational aspects of rotational systems.

To date, no space habitats have had artificial gravity except for the few experiments described in Section 6.1. However, in contextualizing the tasks involved in and the value of designing, deploying, operating, and maintaining artificial gravity habitats in space, it is constructive to review prior and current space habitats as well as the research and experiences of living and working in weightlessness.

## 2. PRIOR AND CURRENT HUMAN SPACE HABITATS

Throughout the decades of human space exploration, there have been capsules, shuttles, and space stations. The earliest spacecraft were designed purely from an operational perspective—namely, to safely bring its occupant(s) into space and to safely return them to Earth. As more was learned about the psychosocial impact of confined environments, crew size and cabin volume considerations were incorporated into mission designs (Morphew, 2001). Specifically, crew size was adjusted based on mission duration, payload capacity (e.g., food), oxygen and water requirements, carbon dioxide scrubbing capabilities, possibility of resupply, crew orientation to distribute forces, and the psychosocial impact of the cabin volume per person that would avert negative behavioral impacts (Clément, 2011; White, Averner, 2001).

**Table 1**: Habitability per person over time.



| Duration | Space needed to avoid psychological impairment |
|---|---|
| 1-2 days | 1.42 m$^3$ per person |
| 1-2 months | 7.36 m$^3$ per person |
| 2+ months | 17.0 m$^3$ per person |

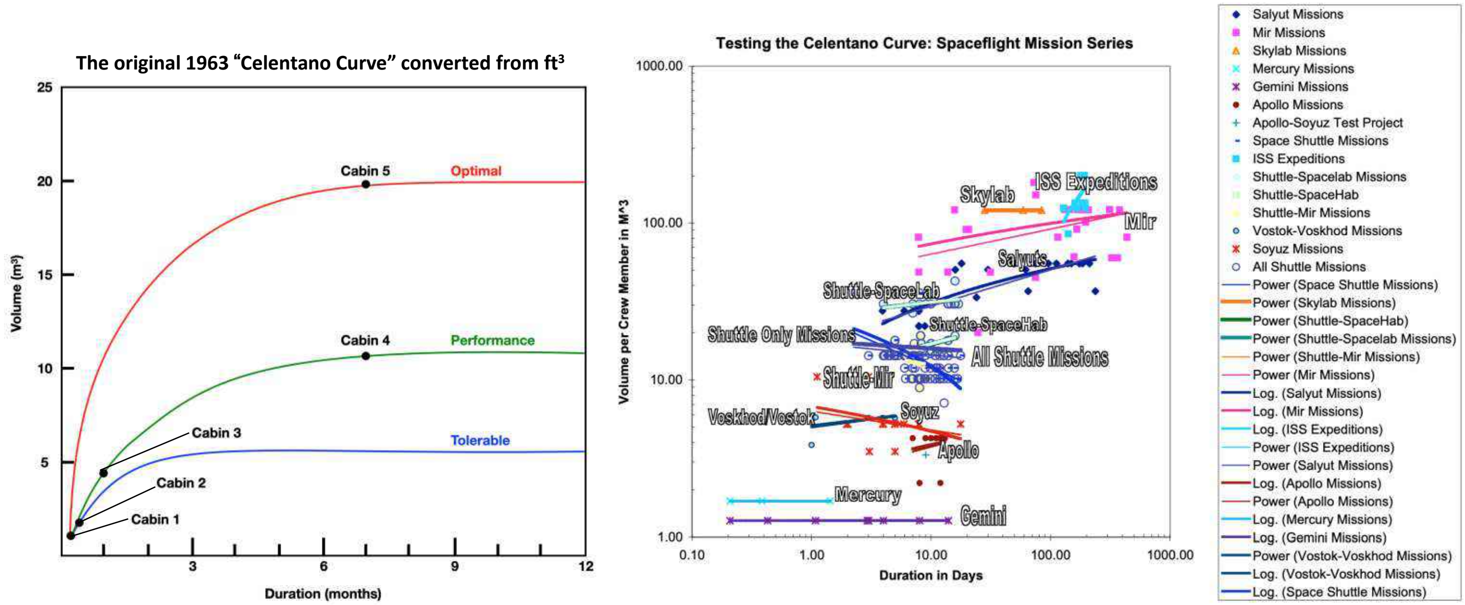
During the early part of crewed spaceflight, a set of curves was proposed that described an "Index of Habitability" (Celentano, Amorelli, Freeman, 1963). The purpose of the index was to predict a spacecraft's cabin volume necessary per crewmember to conduct a mission at "tolerable,

**Table 2**. Summary of Spacecraft Habitats

| Spacecraft Type | Category | No. of missions | Total Cabin Volume $m^3$ | Operational Date |
|---|---|---|---|---|
| Mercury | Capsule | 6 | 1.70 | 1961 |
| Gemini | Capsule | 10 | 2.52 | 1964 |
| Apollo CM with and w/o LM Capsule | Capsule | 11 | 12.81 | 1968 |
| Apollo LM | Lander | 7 | 6.66 | 1964 |
| Apollo-Soyuz | Capsule | 1 | 16.65 | 1975 |
| Vostok | Capsule | 6 | 3 | 1961 |
| Voskhod | Capsule | 2 | 5.74 | |
| Soyuz | Capsule | 42 | 9 | 1967 |
| Shenzhou | Capsule | 9 | 17 | 2003 |
| Space Shuttle | Shuttle | 135 | 71.5 | 1981 |
| Crew Dragon | Capsule | 34 | 9.3 | 2020 |
| Shuttle Spacelab/ SpaceHab | Shuttle | 25 | 213.5 | 1983 |
| Skylab | Station | 3 | 360.99 | 1973 |
| Salyut | Station | 17 | 110.5 | 1971 |
| Mir | Station | 25 | 362.7 | 1986 |
| ISS | Station | 67 | 402.26 | 2001 |
| Tiangong Space Station | Station | 3 | 110 | 2021 |
| Blue Origin | Capsule | 3 | 6 | 2021 |
| Virgin Galactic | Plane | 3 | 3 | 2018 |

performance, or optimal" levels (summarized in Table 2). However, the authors only examined 9 subjects divided across 3 conditions and the longest duration was 7 days. Critics of the paper have questioned the generalizability of the study and observed that for a sufficiently powered study, there should have been 10 subjects in each condition and rather than use 7 days to extrapolate to several months, the study should have included longer time points. Furthermore, the study was performed on Earth in gravity conditions, and its applicability to space may have additional limitations. When compiling all the space missions from 1961-2006, then overlaying the Celentano predictions with spacecraft that were built, as missions became longer, cabin space exceeded the prescribed values. "There is currently no method available to determine with absolute certainty, the amount of habitable space needed per crewmember for missions beyond LEO. Until better data is available, designers should plan on allocating a minimum of 16.99 $m^3$ (600 $ft^3$ ) of usable space per crewmember" (Allen et al, 2003; Cohen, 2008). As this recommendation itself was not evidence-based but an educated estimation, future spacecraft could also rely upon historical data to design cabin size.

Nevertheless, it is understood that for long duration missions, adequate habitable cabin space is especially important to crewmembers because it provides them some semblance of privacy (Ritsher, Kanas, Saylor, 2005). The Russian Salyut and Mir space stations had two larger rooms for crewmembers, with smaller corners of privacy up for grabs. Space shuttle crewmembers reported that the sleep stations occasionally flown afforded them some privacy that they valued. The Russian service module of the ISS contains private rooms for crew. Private space in long duration missions is considered by crewmembers to be critical to psychological health (Palinkas, 2007).



**Cabin A**: living volume = 5.7 m³, living space = 3.6 m², 1.2 m²/person, 3 subjects, 7 days duration (at, essentially, bed rest) = Tolerable (Cabins 1 and 2).

**Cabin B**: living volume = 42.5 m³, living space = 13.9 m², 3.5 m²/person, 4 subjects, 7 days duration (at sedentary activity level) = Performance (Cabin 4).

**Cabin C:** living volume = 45.3 m³, living space = 37.2 m², 18.6 m²/person, 2 subjects, 4 days duration (at average office worker activity level) = Optimal (Cabin 5).

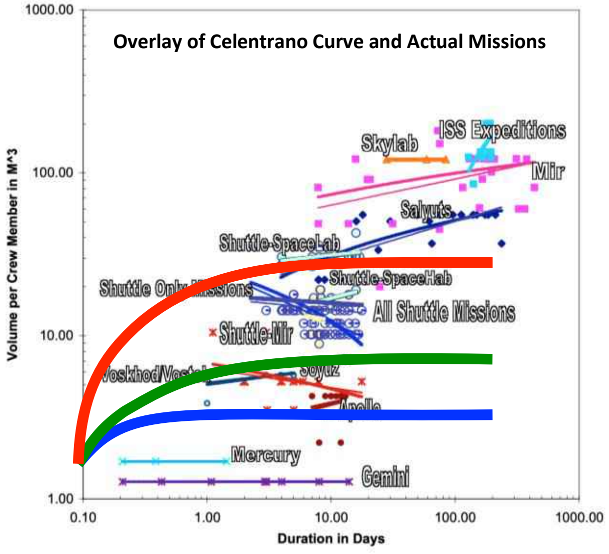
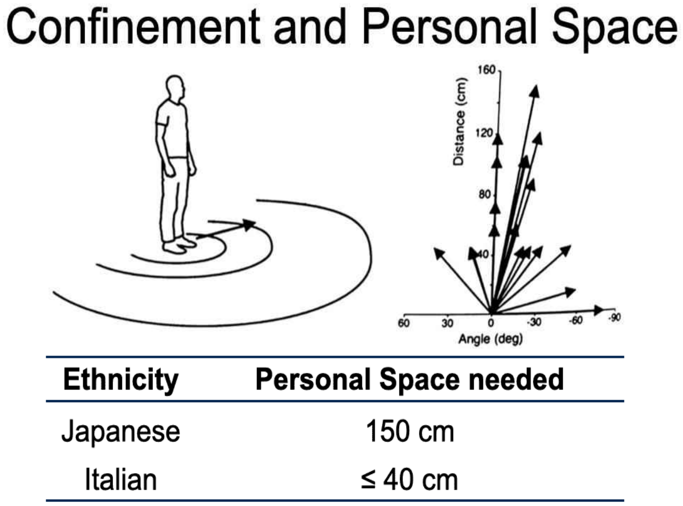


**Figure 2:** Predicted vs actual habitat size per person.

In addition to cabin volume per person, the nationality of the crew must be considered. The average personal distance in which individuals feel comfortable in varies from culture to culture. Latin Americans, French, and Arabs interact at closer distances than people from the US, the English, Swedish, or Germans. The angle at which people face one another during conversation is also cultural. During a study, subjects were interviewed under false pretenses (Clément, 2011). The subject of the interview was trivial, the study designers were in actuality measuring the distance and angle between subjects and the interviewer. Depending on the culture of the interviewee, they might have faced the interviewer directly, or turned away while speaking. Additionally, depending on the culture of the interviewee, the direction the interviewer faced may be perceived as polite behavior, or extremely rude. In an international setting such as the International Space Station, it is important that crews understand these differences or they can lead to conflict.



| Ethnicity | Personal Space needed |
|---|---|
| Japanese | 150 cm |
| Italian | ≤ 40 cm |

**Figure 3:** Mean Distance and Angle Between Two Individuals During a Seated Interview, from a population of 23 students from 13 different countries.

## 3. IMPACT OF MICROGRAVITY ON PHYSIOLOGICAL SYSTEMS

Immediately upon entry into space, microgravity begins to affect every single physiological system in the body. In brief, it causes the following:

1. Space Adaptation Syndrome: a complex of symptoms beginning within hours on orbit that includes nausea, headache, fatigue, vomiting, loss of appetite, sinus congestion, pallor and generalized discomfort (Kornilova, Kozlovskaya, 2003).
2. A headward shift or redistribution of body fluids from the lower extremities to the upper body begins immediately and contributes to a variety of physiological changes including (Clément, 2011; Diedrich, Paranjape, Robertson, 2007; Norsk et al, 2015; Williams et al, 2009):
   a. Headaches, visibly swollen faces, sinus congestion (Norsk, 2020);
   b. Reduction in total circulatory blood volume due to baroreceptors (blood pressure and volume sensors) in the neck and heart triggering excretion of what is sensed as “excess fluid” in efforts to return upper body fluid levels to normovolemia. Unfortunately, this leaves the body overall in a hypovolemic state when compared to Earth normovolemic levels. Stabilizing within 2 weeks, this relative hypovolemia can result in orthostatic intolerance—fainting upon return to Earth (Norsk, 2014; Norsk et al, 2015);
   c. Baroreflex dysfunction (Norsk, 2020; Norsk et al, 2015);
   d. Visual changes due to Spaceflight Associated Neuro-Ocular Syndrome (SANS) (Aleci, 2020; Mader et al, 2011);
3. Cardiovascular system changes and deconditioning (Charles et al, 1999; Norsk, 2020);
4. Disuse atrophy of muscles, including the heart (Clément, 2011);
5. Resorption of weight-bearing bones, which can lead to:

    a. Increased fracture risk, particularly when re-entering a gravity environment (Swaffield, Neviaser, Lehnhardt, 2018);
    b. Fracture healing impairments (Androjna et al, 2012);
    c. Increased risk of developing kidney stones due to the excess calcium excretion (Pietrzyk et al, 2007; Simon et al, 2016);
6. Circadian disruption (Clément, 2011);
7. Sensorimotor and neurovestibular dysfunction (Fuller et al, 2002; Lawson, Rupert, McGrath, 2016);
8. Reproductive changes (Lei et al, 2019);
9. Immunological suppression (Crucian et al, 2018);
10. Wound healing delays (Riwaldt et al, 2021);
11. Microbiome alterations (e.g., gut, skin, and body flora composition and pathogenicity) (Morrison et al, 2021; Voorhies et al, 2019); and
12. Cognitive deficits and diminished reflex responses/plasticity (Benvenuti, Bianchin, Angrilli, 2011).

Both the progression and duration of these adaptations vary widely. For instance, some adaptations happen immediately while others take months to appear. Some adaptations stabilize to a constant set point, e.g., a zero-gravity set point. For example, an individual will have a certain lean body mass in Earth’s gravity and a different lean body mass in zero gravity (Schneider, Ploutz-Snyder, et al, 2016). Other adaptations will continue to progress throughout the duration spent in microgravity. There remains uncertainty whether many of these changes are disruptions to the normal homeostatic mechanisms or an appropriate response to an extreme stimulation. Nevertheless, a number of these adaptations can be well tolerated in space. However, most become problematic during the return to gravity environments. For instance, astronauts returning to Earth from the ISS must be carried. Should the mission require astronauts to land on Mars following travel from Earth, being carried will not be an option. The following discussion briefly delineates the impact of microgravity on several physiological systems.

## 3.1 Space Adaptation Syndrome

Space Adaptation Syndrome, sometimes called “space motion sickness”—though one of the earliest onset adaptations to space and most easily noticed symptom complexes—was recognized later in U.S. astronauts than Soviet cosmonauts (Homick, Reschke, Vanderploeg, 1984).

The Soviets first noticed what would come to be called Space Adaptation Syndrome with Gherman Titov, Yuri Gagarin’s successor. Titov achieved two records. First, at 25 years old, Titov became the youngest person in space (a 50-year-old record that stood until 2021 when Dutch 18-year-old Oliver Daemen launched aboard Blue Origin). Second, he became the first person in history to vomit in space. As he was also the first person to spend more than two hours in space, his nausea was related to the extended time he spent in the spacecraft (25 hours) (Ortega, Harm, Reschke, 2019). At the time Soviet scientists and physicians did not know the cause and suspended the Soviet human spaceflight program for a year. The U.S. space program did not recognize Space Adaptation Syndrome until later, most pointedly in the Skylab program when astronauts over an open microphone were overheard discussing amongst themselves what to do with a full emesis bag—as though it were routine (Lindsay, 2001). For fear of being grounded, astronauts often underplayed its impact.

### *3.1.1 The Neurovestibular System*

The sensory systems that coordinate information to report position to the brain are the visual, somatosensory, and vestibular systems. In sighted people, in most situations, the visual system processes the bulk of external positional information, which is then integrated with the somatosensory and vestibular systems to determine positional status. The visual system comprises the eyes; the somatosensory system comprises tactile and proprioceptive inputs, primarily from skin and musculoskeletal mechanoreceptors; and the vestibular system includes the otolith organs and semicircular canals of the inner ear. The mismatch between the input from these systems—visual, vestibular, and somatosensory—while adjusting to weightlessness is believed to cause Space Adaptation Syndrome, which is compounded by a headward shift in the body's fluids (Homick, Reschke, Vanderploeg, 1984; Ortega, Harm, Reschke, 2019; Young et al, 2003).

The physiology of the vestibular system is key to motion sickness on Earth. In addition, as will be described later, the vestibular system is responsible for the challenges to human health and function in artificial gravity that is generated by a rotating environment. Therefore, the vestibular system is discussed in some detail here.

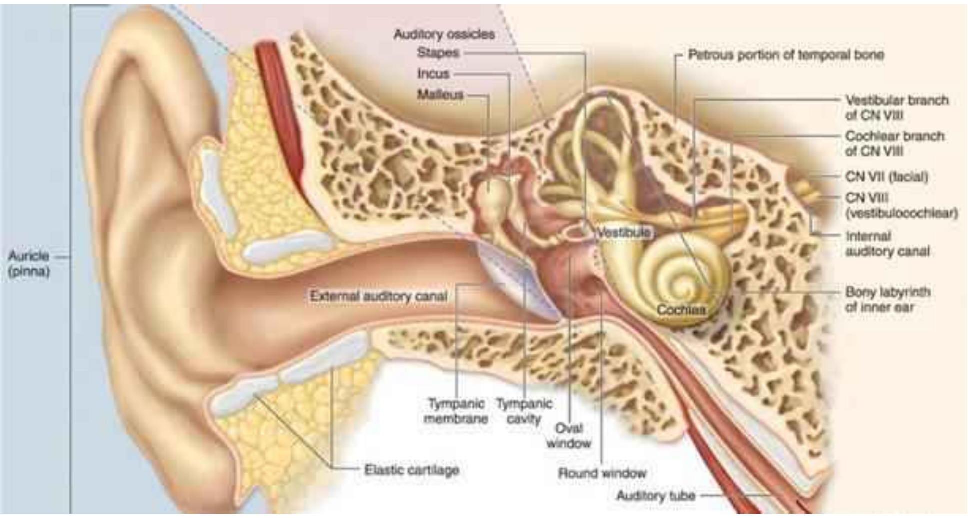
The otolith organs, the saccules (sagittal direction) and utricles (horizontal direction), sense linear acceleration (Ekdale, 2016; Hayes et al, 2013). The anterior, posterior, and horizontal semicircular canals detect angular velocity of the head. The nerves that report this information to the brain are called hair cells.

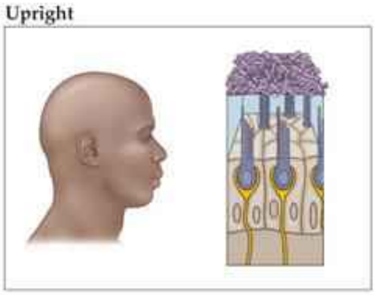
In otolith organs, hair cells are located inside a structure called the macula and in the semicircular canals, hair cells are within the cupula. All macula hair cells are covered by a gelatinous mass containing denser structures made of protein and calcium carbonate called otoliths. Because these otoliths are so much heavier than the gelatinous mass, they respond to acceleration or gravity by moving the entire mass towards the direction of that acceleration or gravity, and in doing so displace the hair cells. When these hair cells are displaced, the brain perceives it as movement. In this way, otolith organs act as accelerometers. The macula of the utricle is located horizontally while that of the saccule is positioned vertically. Together, they can report any acceleration or head position (in a gravity field) to the brain. In contrast, the semicircular canals provide information about angular velocity. The semicircular canals are 3 interconnected hollow loops about the size of a dime. Each loop provides the brain with information about roll, pitch, and yaw of the head. They are positioned at right angles to one another in the 3 planes of space. The semicircular canals and otolith organs are interconnected, allowing them to coordinate a unified signal to the brain. These signals are then further integrated with visual and proprioceptive inputs.

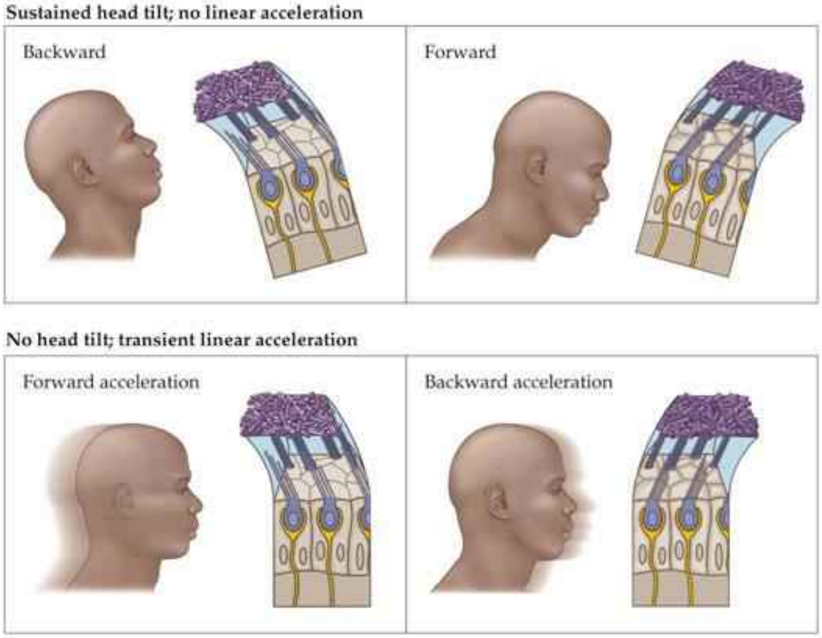
Microgravity alters many of these input signals, leading the brain to misinterpret the signals and respond inadequately or inappropriately  (Kornilova, Kozlovskaya, 2003; Lawson, Rupert, McGrath, 2016). These misinterpreted signals result in a variety of symptoms, including appetite loss, headache, nausea, pallor, vertigo, vomiting, lethargy, and sinus congestion, among others. Because many of its symptom are similar to motion sickness, this response has been called space motion sickness, but unlike conventional motion sickness, antiemetic drugs have limited efficacy suppressing the symptoms of space motion sickness (Lackner, DiZio, 2006). As described above, it is more properly known as Space Adaptation Syndrome and it is very prevalent, with approximately 60–80% of astronauts developing the symptoms within hours to 2 days after launch (Eyal, Derendorf, 2019; Hodkinson et al, 2017). Effective countermeasures against space motion sickness are considered important because it impairs the astronauts' operational performance.

For fear of being grounded, Apollo astronauts largely attributed their symptoms to illnesses. For instance, Wally Schirra complained that he had a head cold (Burgess, 2016). Fellow astronauts Donn Eisele and Walter Cunningham complained of similar cold/flu symptoms and Apollo VIII—IX astronauts all complained of gastrointestinal distress, now widely regarded as actually having been space sickness (Johnston, Hull, 1975). On Apollo VIII, commander Frank Borman vomited. As mentioned above, when the astronauts forgot to turn off their microphone in the early 1970s during a Skylab mission and were overheard discussing the emesis bag, this was the first confirmation about the ubiquity of the problem, and at this point NASA scientist Millard F. Reschke began to research it.

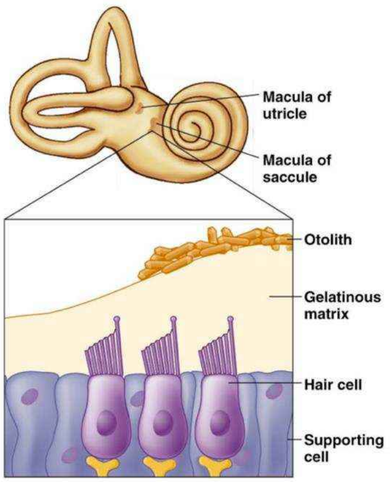
# The Human Inner Ear and Vestibular System Organs

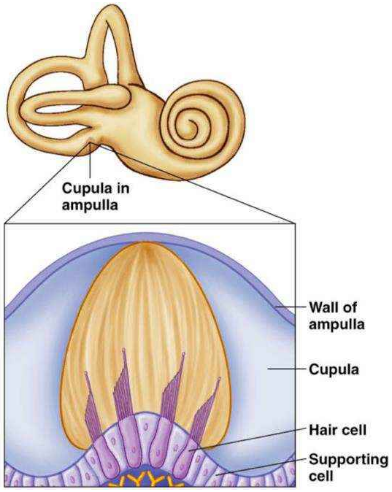






## Linear Head Movement and Otoliths





## Semicircular Canals and Otoliths with Hair Cells

**Figure 4:** Form and function of the vestibular organs.

He said, “It was clear that it was motion sickness. I say motion sickness, because it became more prevalent, the larger the volume of the space craft was. If you have a small space craft you can’t move around very much and if you can’t move around, you typically don’t begin to get terribly ill … the brain is very good at adapting and says, ‘I’ve got to make up the difference somehow.’ The period of adaptation, when the brain is trying to do this, is when motion sickness is probably going to be the most prevalent and that is typically when the person has just gone into space. It may last a day, it may last 2 or 3 days. In some cases, adaptation has never taken place and people are sick for the entire flight, but typically it resolves and within 2 or 3 days people are feeling fine.”

Conventional motion sickness is more likely to occur when there is a vestibular/ocular conflict, which is in turn more likely to occur when there is more room to move. Methods to stave off vomiting in space include anti-emetic drugs, avoiding excessive head movement, and biofeedback programs (Homick, Reschke, Vanderploeg, 1984; Lackner, DiZio, 2006; Mouloua, Smither, Kennedy, 2008; Ortega, Harm, Reschke, 2019). Wearable portable biofeedback machines alert astronauts when their bodies are beginning to show signs of motion sickness that they would otherwise be unaware of. Through exercises, astronauts learn how to normalize metabolic functions that weightlessness might otherwise skew into the nausea zone.

The exact mechanism of Space Adaptation Syndrome remains unknown. The leading hypotheses behind the cause of space motion sickness are a sensory conflict due to microgravity-induced alterations to sensory organs and fluid shift effects.

### *3.1.2 Leading Hypotheses of the Cause of Space Adaptation Syndrome*

The sensory conflict hypothesis posits that without gravity, tilt-related signals from otolith organs are muted (Thornton, Bonato, 2013). Without gravity, the otolith organs of the inner ear cannot provide the neurovestibular system information on head position and which way is up. Along with the semicircular canals, the vestibular system uses the otolith organs to control eye movements during motion. The vestibular system provides the brain with information about the position and motion of the head, and the brain then directs the oculomotor center to move the eyes. This involuntary control is called the vestibular ocular reflex and it works as a biological steady-cam making small adjustments to permit activities such as visual pursuit or rapid movement without seeing a motion blur. Microgravity alters the vestibular system, which struggles to adapt. Microgravity also causes a phenomenon known as “retinal slip” (Reschke et al, 2002; Somers et al, 2002). The eyeballs lag in their movements, causing images to race across the retina, producing a motion blur. The vestibular system is now further taxed by the vestibular ocular reflex’s efforts to compensate for this retinal slip. The more astronauts move their heads around, the more the vestibular ocular reflex struggles to function properly and the more it fails. In essence, this loss of otolith-tilt information causes a conflict between actual and anticipated signals from sensory organs that determine spatial orientation. As unusual sensory conflicts induce conventional motion sickness, it follows that microgravity-induced sensory conflicts induce space motion sickness.

The fluid shift hypothesis posits that Space Adaptation Syndrome derives from the headward fluid shift, which in turn results from the loss of Earth-normal hydrostatic pressure gradients upon entry into microgravity (Jennings, 1990). Among other things, this fluid shift is thought to increase the intracranial pressure, the cerebrospinal fluid pressure, and/or the inner ear fluid pressure, altering the response properties of the vestibular receptors and inducing space motion sickness.

It is likely that both sensory conflict and headward fluid shift contribute, and larger crew cabin volumes may exacerbate the problem by permitting excessive head movements by the crew.

### 3.2 Headward Fluid Shift

On Earth, there is generally more blood in the vasculature of the lower body. That is because in a weighted environment, e.g., 1 G, liquids pool toward bottom of a closed, elastic container; and the vasculature is essentially a closed elastic container, albeit with some key differences. This pooling is caused by gravity, which induces a hydrostatic gradient whereby pressure increases with depth due to the weight of the fluid above. On Earth, the body counteracts this tendency of body fluids to pool in the lower body, returning blood to the thorax through the innate elasticity of the vasculature and mild compression in the resting muscle tone of the extremities. In addition, major shifts of blood volume in the extremities—for example upon standing—are regulated through active constriction or dilation of blood vessels via the autonomic nervous system. This maintains normal blood pressure and fluid distribution.

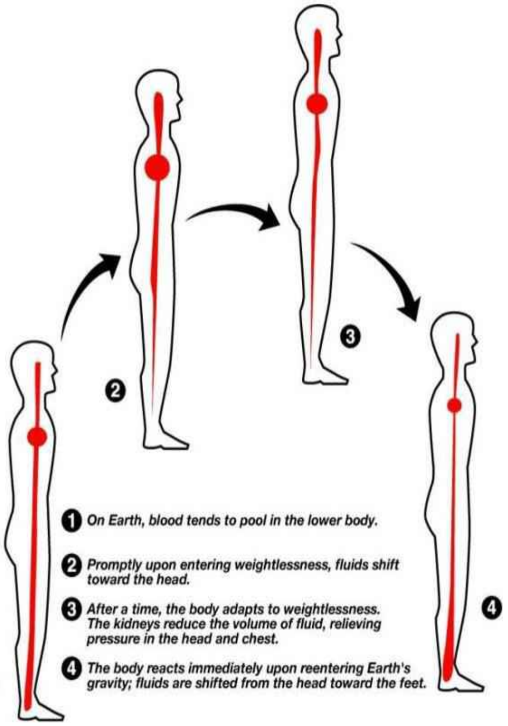


**Figure 5:** Blood distribution on Earth and in space.

In microgravity, fluid will redistribute throughout a container based on the elasticity of the container. In the human body in space, this results in a significant (1-2 liters) and extremely rapid headward fluid shift and subsequent fluid volume depletion (Drummer et al, 2000). For example, on day one of microgravity exposure the circulatory blood volume decreases by 17% (Watenpaugh, 2001). The shifting fluid dynamics usually stabilize within two weeks to a weightlessness steady-state or "zero-G set point" (Marshall-Bowman, Barratt, Gibson, 2013; Simanonok et al, 1994). Multiple factors are probably in play—such as a mechanically-induced fluid transfer from intravascular to interstitial to intercellular spaces[1]; diuresis mediated by baroreceptors and volume receptors in the neck, cardiac atria, and pulmonary vasculature (Norsk, 2014); and the attendant stress of spaceflight with short and long term endocrine system responses (Leach, Johnson, Cintron, 1988). The fluid shift results in increased pressure in the head, leading to puffiness of the face, a feeling of fullness or heaviness in the head, nasal stiffness, papilledema (optic disc swelling due to intracranial hypertension), jugular vein dilatation, and headaches (Clément, 2011; Mader et al, 2011; Norsk et al, 2015; Simanonok et al, 1994). Some astronauts have described microgravity-induced headaches as the worst headache of their lives—and these headaches may last for 3-5 days.

This headward fluid shift may also cause an increase in intraocular pressure (Aleci, 2020; Mader et al, 2011; Marshall-Bowman, Barratt, Gibson, 2013). While the leg volume decreases by up to 1 liter, the forehead subcutaneous tissue becomes up to 7% thicker than when in a preflight supine position (Reynolds, 2020). With the 1-2 liter shift of fluid from the legs, the blood volume in the pulmonary capillaries increases by about 25% and the cardiac output increases (within 24-48 hours) by 18-26% (Iwase et al, 2020).[2] Upon stabilization at the zero-G set point, many of the symptoms (e.g., facial puffiness or jugular vein dilatation) improve or resolve.

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[1] The shift from intravascular to interstitial spaces is driven by two phenomena. First, there is a transmural pressure that is significantly reduced by the absence of gravity-induced compression, especially of the thorax cage (Noskov, 2013; Watenpaugh, Hargens, 1996). Second, fluid shifts from the intravascular to muscle interstitial spaces because the muscle tone required to maintain body posture is reduced, thereby permitting fluid influx (Iwase et al, 2020).

[2] Since the heart rate remains relatively unchanged or even decreases, the increase in cardiac output is caused by increase in stroke volume (cardiac output = heart rate x stroke volume). In turn, the increase in stroke volume is due

### 3.3 Cardiovascular System

The response of the cardiovascular system's adaptation to weightlessness has both rapid and gradual components. Fluid shifts and reduced circulatory volume essentially begin with launch. The fluid shift-induced increases in venous return, cardiac output, and stroke volume triggers autonomic nervous system responses and, eventually, changes in the endocrine control of the cardiovascular system (Antonutto, Di Prampero, 2003; Charles et al, 1999; Leach, Johnson, Cintron, 1988; Norsk, 2020; Powers, Bernstein, 2004; Watenpaugh, Hargens, 1996).

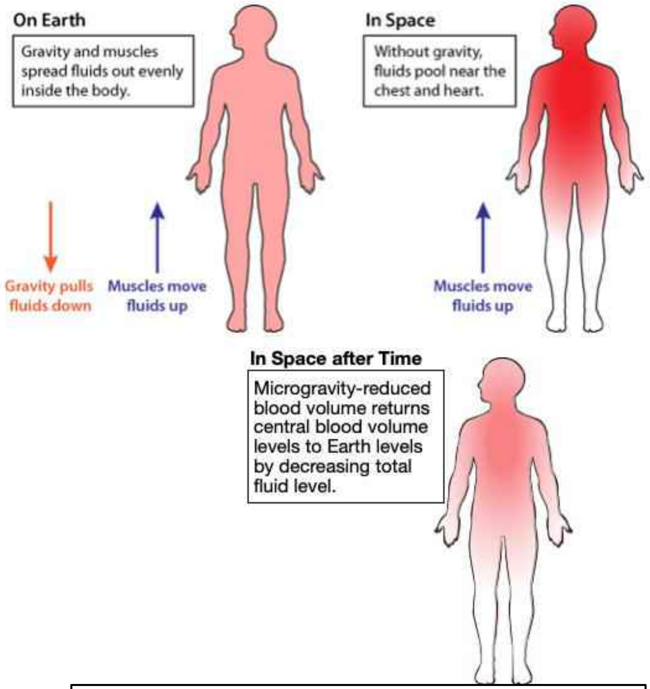

**Figure 6:** Interstitial fluid distribution on Earth and in space.

The autonomic nervous system maintains a stable blood pressure in response to continual short-term perturbations, such as rapidly rising from rest, which abruptly induces hypotension. The lowered blood pressure is due to a rapid gravity-driven drop of blood volume from the upper body to the lower body caused by the positional change. To maintain blood pressure the autonomic nervous system, rapidly causes a temporary increase in heart rate, stroke volume, and vasoconstriction by activating sympathetic nerve activity. In microgravity, the autonomic system initially acts to reverse increases in blood pressure (sensed by neck and thorax baroreceptors due to the headward fluid shift) by suppressing sympathetic activity, thus reducing the heart rate and suppressing muscle sympathetic nerve activity (e.g., resting muscle tone) (Mandsager, Robertson, Diedrich, 2015; Shankhwar, Singh, Deepak, 2021). Over the time course of cardiovascular adaptation, the autonomic nervous system activates parasympathetic nerve functions such as suppressing vasopressin, increasing α-natriuretic peptide secretion, and inhibiting the renin-angiotensin-aldosterone system, all of which facilitate urination (Iwase et al, 2020). In this way, a large volume of the shifted fluid is excreted—10-15% of the circulatory volume—to achieve a normotensive state.

The loss in circulatory volume causes an increase in the hematocrit levels (ratio of red blood cells to plasma in the blood), which in turn suppresses the hormone erythropoietin and results in decreased red blood cell production and volume (Iwase et al, 2020). The reduction in the circulatory plasma volume plus the decrease in erythrocyte volume sum to an overall 11% reduction in the total blood volume (Prisk et al, 1993). This ~11% reduction represents the 0-G setpoint (Diedrich, Paranjape, Robertson, 2007). The volume of blood shifted towards the heart, the "central blood volume," has been reduced to roughly the same central blood volume that would be present on Earth when standing.

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to the increased fluid load caused by the fluid shift (Antonutto, Di Prampero, 2003; Shankhwar, Singh, Deepak, 2021; Tanaka, Nishimura, Kawai, 2017).

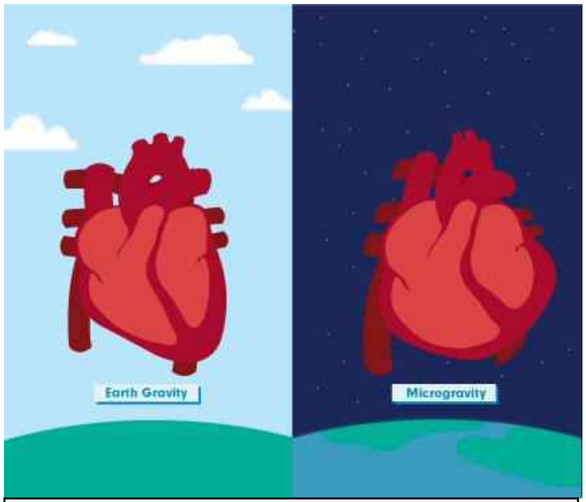


**Figure 7:** The heart becomes more spherical in space.

Stroke volume is directly related to the forcefulness of the heart's contraction—its contractility—and the volume of blood in the heart chambers available to be pumped. The greater the stroke volume, the greater the cardiac output (e.g., liters of blood pumped per minute). The heart's large pumping capacity is necessary to maintain arterial pressure against gravity and deliver blood to the brain. Without the requirement to pump against gravity, cardiac muscle atrophies by 8-10% after 10 days in microgravity (Diedrich, Paranjape, Robertson, 2007). As noted earlier, on Earth, standing from a supine position causes blood to drop towards the feet, lowering the blood volume available for the heart, hence lowering the stroke volume, and thus lowering the cardiac output. To maintain cardiac output—and consciousness—the sympathetic nervous system increases the heart rate and stimulates vasoconstriction increasing vascular resistance, slowing the drop of blood from the trunk towards the feet. Nearly 100 astronauts who had been on orbit for 9-14 days and could not stand for 10 minutes were all found to have significantly reduced vasoconstriction responses (Tanaka, Nishimura, Kawai, 2017). There is a limited amount that the vasculature can constrict and since vascular resistance is already elevated after spaceflight, it is not clear whether the reduced vasoconstrictive response was due to the vessels having constricted to their limits. Further, the relative hypovolemia upon return to 1 G (Earth), may not provide enough blood volume for vasoconstriction to be fully effective.

In microgravity the heart becomes more spherical (May et al, 2014; Summers et al, 2010). The shape of the heart on Earth is determined by several factors, including the amount and quality of cardiac muscle; the pericardium, a connective tissue sac that contains and protects the heart; and gravity. The heart's change in shape in weightlessness may be due in part to a loss of muscle mass in the left ventricle, the major pumping chamber of the heart that distributes blood throughout the body. Cardiac studies unrelated to spaceflight have demonstrated that spherical heart shapes are less efficient (May et al, 2014; Schneider, Charles, et al, 2016)—a spherical heart must expend more energy to pump the same amount of blood. The lack of a gravity-assist to drive blood to the lower extremities, the decreased muscle activity in the legs that would normally aid in the venous return of blood, and the change in shape, all result in a smaller, more spherical heart beating faster to maintain cardiac output. Whether these changes are unhealthy in space or merely adaptive for the space environment is not clear, but astronauts have been shown to lose a quarter of their aerobic capacity after only 2 weeks in space (Shen, Frishman, 2019). Electrocardiogram monitoring of astronauts engaged in extravehicular activities indicates that the microgravity-adapted heart may be more susceptible to arrhythmia (Schneider, Charles, et al, 2016).

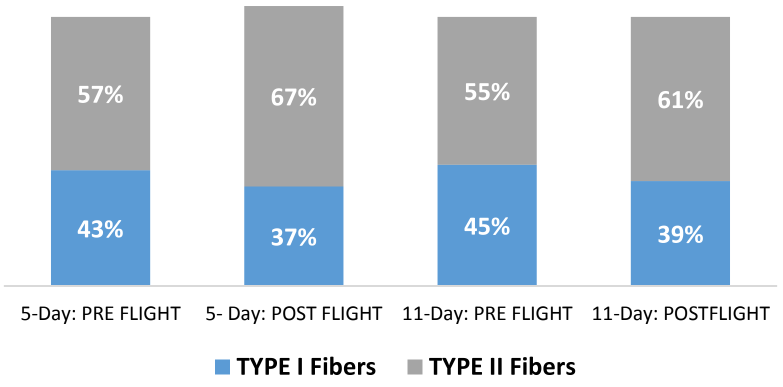
### 3.4 Skeletal muscles

Muscle atrophy occurs very quickly, and has been reported to occur between 5-11 days in space (Gao et al, 2018). The muscle most affected are the "anti-gravity muscles" that are used for locomotion in 1 G and/or to hold the body erect—the leg and back muscles. The most prominent muscle volume loss in the lower extremities is in the calf muscles. This loss is partly attributable to the headward fluid shift as well as to pronounced muscle atrophy.

Microgravity-induced muscle atrophy affects muscle types differently (Fitts, Riley, Widrick, 2000; Shackelford, 2019). Muscles types are characterized by one of the main proteins that comprise them, the myosin heavy chain, which is present in several isoforms. Human muscle generally contains slow-twitch muscle fibers (type I) and two types of fast-twitch fibers (type IIa and IIb). Type I slow-twitch fibers rely on oxidative metabolism and are hence aerobic, providing endurance and steady power. Type II fast-twitch fibers rely on glucose metabolism and are hence anaerobic, providing explosive power, but fatigue easily. Although muscle is a mix of these muscle types, a greater proportion of one fiber type will comprise a muscle depending on that muscle's function. One of the calf muscles, the soleus, contains primarily the type I slow-twitch oxidative muscle fibers. Another calf muscle, the gastrocnemius, mostly contains type II fast-twitch glycolytic fibers. Muscles responsible for maintaining posture—antigravity muscles—are largely comprised of type I slow-twitch muscle fibers while muscles responsible for movement and locomotion have many type II fast-twitch myofibers.

Without gravity, antigravity muscles atrophy more than locomotion muscles. Specifically, the order that muscles atrophy from greatest to least has been reported as: atrophy in soleus type I > soleus type II > gastrocnemius type I > gastrocnemius type II (Gao et al, 2018). This is when considering the whole muscle. When examining the individual fibers, although both muscle types atrophy, type II fast-twitch muscle fibers exhibit greater atrophy than type I slow-twitch muscle fibers (Edgerton et al, 1995; Widrick et al, 1999). In addition, type II fibers begin to replace type I fibers. Thus, there are more small-diameter type II muscle fibers than the larger-diameter type I muscle fibers and in terms of the whole muscle, type I muscles therefore atrophy more.

**Figure 8. Changes in Muscle Fiber Composition Pre & Post Flight**
**During 5 Day & 11 Day Spaceflight Missions**



In 1995, astronauts were biopsied before and after either a 5-day mission (3 astronauts) or an 11-day mission (5 astronauts) (Edgerton et al, 1995). Five days in space caused the proportion of type I fibers to change from 43% (preflight) to 37% (postflight), and that of type II fibers to change from 57% to 67%. Eleven days of space decreased the proportion of type I fibers from 45% to 39% and that of type II fibers from 55 to 61%. The fiber type changes are caused by a combination of increased protein breakdown and decreased protein synthesis, with the latter observed after only 3 hours in space. Microgravity also influences the genes regulating protein synthesis. The genetic influence of atrophy is supported by the fact that muscle atrophy continues for 4 days following landing. It is possible that there is a delay in restarting the genes regulating protein synthesis. However, it is also possible that muscle damage occurs with the sudden weight bearing after extended weightlessness.[3]

### 3.5 Bone

Wolff's Law describes how bone optimizes its biomechanical properties to meet its loading environment; in a weightless environment, most bone is extremely unloaded. Skeletal unloading results in dramatic bone resorption (Clément, 2011). Since calcium is stored in the skeletal system, this results in the calcium

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[3] Interestingly, the fiber type changes that occur in humans are opposite to those that occur in rats, with type I fibers more affected by microgravity. In rats, 14 days of spaceflight decreased type I slow-twitch muscle fibers by 30% and type II fast-twitch fibers by 15% (Ohira et al, 1992).

being released into the blood stream. Calcium is essential in bone structure and also plays such a critical role in a variety of other functions that its absence is incompatible with life (Iwase et al, 2020; Theobald, 2005). For instance, calcium is required for blood coagulation, cell permeability, the contraction of cardiac and skeletal muscles, hormonal signaling, and neural transmission. In an Earth gravity environment, serum calcium is maintained at 8.4-10.2 mg/dL by ingesting calcium through diet, then absorbing it into the blood from the small intestine (300 mg/day); by depositing blood serum calcium into the bone or releasing calcium from the bone into the blood (500 mg/day); or excreting calcium from the diet into the feces or from the blood into urine through the kidneys (150 mg/day) (Iwase et al, 2020).

Within several days of spaceflight, urinary calcium excretion increases by 60-70%, putting astronauts at increased risk for kidney stones (Buckey, 2006). Reflecting Wolff's law, bone mineral density decreases in weight bearing bones, such as the femur, heel, bones of the hip, pelvis, and spine, while increasing in bones that are under increased loading such as the skull and arm, which endure increased intracranial pressure and locomotion duties, respectively (Buckey, 2006; Clément, 2011). Astronauts lose an estimated ~1-3% of bone per month (Buckey, 2006; Clément, 2011). Thus, long duration missions put astronauts at risk of osteopenia or osteoporosis, in turn putting the astronaut at an increased fracture risk. A fracture off-world could be disastrous for the mission and potentially life threatening, depending on severity and possible complications. Fracture risk models predict that long duration astronauts are at high risk of fractures to the hip and wrist (Nelson et al, 2009). In fact, long-duration astronauts have suffered post-flight fractures, though none during space missions (Ramachandran et al, 2018).

### 3.6 Visual and Ocular System

Changes to visual perception and the ocular system occur in weightlessness. As discussed previously, incorrect signaling from proprioceptors and the vestibular system can lead to visual processing problems in weightlessness. In addition, microgravity can lead to pathological changes in the eye that impair vision.

Short-duration microgravity exposure (under 2 weeks) has caused ocular changes such as hyperopic shift, when the axial length of the eye is shorter than the focal length (Mader et al, 2011). With longer duration missions, more severe ocular changes such as optic disc swelling were observed (Mader et al, 2011). Initially presumed to be due to elevated intracranial pressure, it was termed visual impairment and intracranial pressure (VIIP) syndrome. However, since the role of elevated intracranial pressure had not been established, the phenomena was renamed Spaceflight Associated Neuro-ocular Syndrome (SANS).

A great deal still remains unknown about SANS and a clinical definition for it has yet to be accepted (Aleci, 2020; Mader et al, 2011; Marshall-Bowman, Barratt, Gibson, 2013). Nevertheless, most literature defines SANS according to a combination of clinical and radiographic findings, including the appearance of choroidal and retinal folds, focal areas of ischemic retina, globe flattening, hyperopic refractive error shift, and/or optic disc edema. Several papers compare SANS to terrestrial pathologies such as idiopathic intracranial hypertension, pseudotumor cerebri and/or radiation associated neuro-ocular changes (Paez, Mudie, Subramanian, 2020). However, continuing research has revealed that SANS and the other terrestrial pathologies are more different than alike, with only disc edema shared between them.[4].

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[4] For instance, the female:male ratio for idiopathic intracranial hypertension is 9:1, while for SANS it is 0:10, with the caveat that although no female astronauts have been diagnosed with SANS (as of 2020), ocular changes have been detected in both sexes (Lee et al, 2020). While the idiopathic intracranial hypertension and pseudotumor cerebri cause frequent and severe headaches, vision to be obscured transiently, and tinnitus that is synchronous with the pulse, the only symptom of SANS is typically vision complaints with near vision better than far vision (Kesserwani, 2021). In SANS the disc edema seems to occur mostly in the right eye with terrestrial pathologies occurring in both. Additionally, in SANS choroidal (the vascular layer of the eye) folds appear first, while in terrestrial pathologies retinal folds appear first. Further, these folds are linear in SANS and concentric around the optic nerve head in terrestrial pathologies.

Although many of the changes characterizing SANS have resolved following the return to Earth, some of the vision changes have persisted for over 7 years. However, all documented ocular changes have been correctable with corrective lenses.

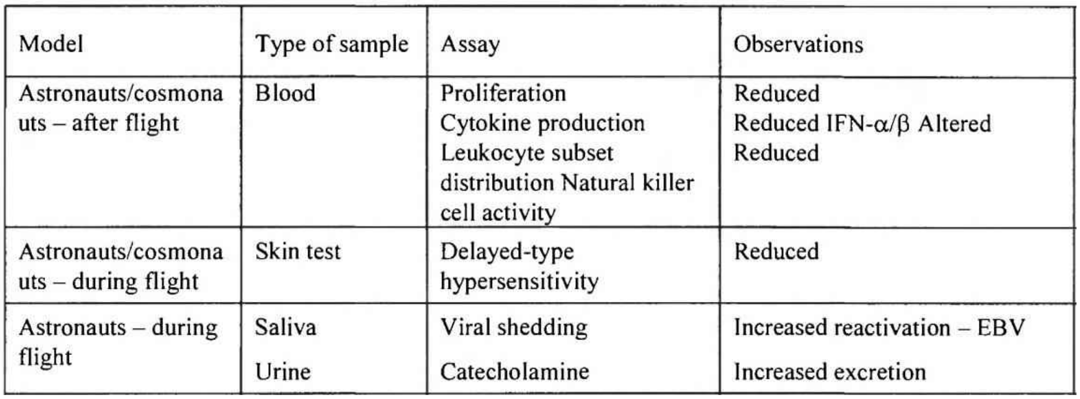
### 3.7 Wound Healing

Wound healing is known to be delayed in weightlessness; however, the precise mechanisms are not known (Farahani, DiPietro, 2008; Morbidelli, Genah, Cialdai, 2021; Riwaldt et al, 2021). Appropriate wound healing requires a complicated coordination of immune cells, soluble factors, and skin cells, all of which are individually impacted by microgravity. Wound healing is also delayed by subclinical hypovolemia, a state which astronauts remain in during weightlessness due to fluid-shift induced blood volume losses. While animal experiments have shown that treatments that work for chronic wounds also accelerate microgravity-impaired wounds (Cialdai et al, 2020), the full impact of spaceflight on wound healing has yet to be described.

### 3.8 Immune System

The immune system is an extremely critical and complex system that protects the body against microbial and toxic external assaults and also monitors and defends against potential internal assaults such as cancer. The immune system is embedded in all organ systems, particularly the gastrointestinal system and is intertwined with wound healing as well as modulated biofactors such as cytokines, chemokines and hormones circulated in the blood.

**Table 3.** Effects of space flight and space flight conditions on the immune system of humans (Sonnenfeld, Butel, Shearer, 2003).



| Model | Type of sample | Assay | Observations |
|---|---|---|---|
| Astronauts/cosmonauts – after flight | Blood | Proliferation<br>Cytokine production<br>Leukocyte subset distribution Natural killer cell activity | Reduced<br>Reduced IFN-α/β Altered<br>Reduced |
| Astronauts/cosmonauts – during flight | Skin test | Delayed-type hypersensitivity | Reduced |
| Astronauts – during flight | Saliva<br>Urine | Viral shedding<br>Catecholamine | Increased reactivation – EBV<br>Increased excretion |

Microgravity reduces the numbers of T-lymphocytes (T-cells), natural killer lymphocytes (natural killer cells), peripheral blood monocytes, and neutrophils, which are all important to the optimal functioning of the immune system on Earth (Crucian et al, 2018; Sonnenfeld, Butel, Shearer, 2003). Moreover, leukocyte function is affected by microgravity, with neutrophil adhesiveness increased (ElGindi et al, 2021; Lin et al, 2020). Microgravity increases the level of adhesion molecules expressed on the surface of neutrophils and enhances their chemotactic responsiveness by 10-fold. In monocytes, simulated microgravity has been demonstrated to impair their locomotion, affecting their ability to migrate to sites of foreign invasion (Ludtka et al, 2021). Microgravity also disrupts cytokine and chemokine production and/or function (e.g., IFN-α/β TNF-α), impairing the ability to recruit immune cells (Sonnenfeld, Butel, Shearer, 2003).

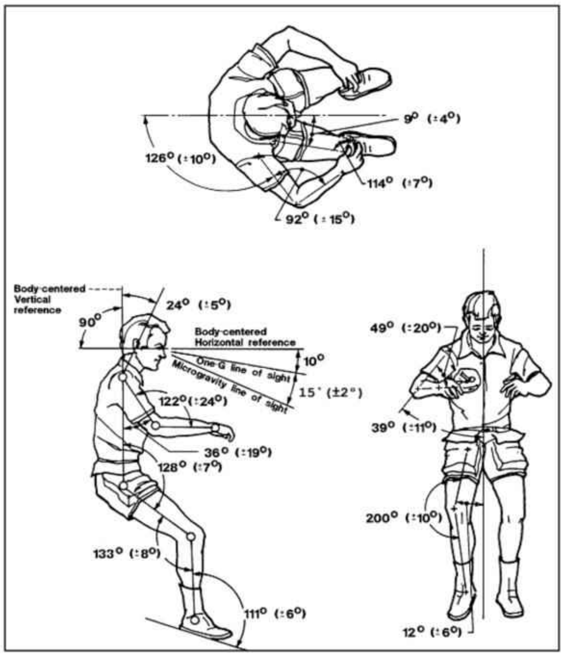
While the mechanisms of these spaceflight-induced immune alterations are still being described, it is likely a multifactorial process that includes microgravity, neuroendocrine factors, nutrition, radiation, sleep disruption, stress, etc. This likelihood is supported by the fact that many of the alterations observed in space could be induced by one or more factors present in the space environment. For instance, in rats, the changes in lymphocyte subset ratios induced by spaceflight could be induced by radiation alone and the spaceflight reduction in certain cytokines were induced by hindlimb unloading (Sonnenfeld, Butel, Shearer, 2003). Regardless of the underlying etiology, the impairment of both the cellular (e.g., lymphocyte) and humoral (e.g., cytokines/chemokines) immune systems greatly impacts the body's ability to resist infection in the space environment.

This is important since microgravity causes bacterial cell membranes to become thicker and less permeable, as well as increases bacterial resistance, virulence, and pathogenicity, which reduces the effectiveness of antibiotics (Graebe et al, 2004; Kim, Rhee, 2018; Mauclaire, Egli, 2010). Additionally, considering that cosmic radiation is mutagenic and natural killer cells seek and destroy genetically mutated cells while the cytokine TNF-α instructs them to self-destruct, the loss of natural killer cells and limited functionality of TNF-α represent compromised defenses against infections and tumors. These compromised defenses may increase the likelihood of astronauts developing cancers.

### 3.9 Miscellaneous Changes — Taste, Digestion, and Proprioception

Microgravity impairs the senses of smell and therefore, taste as well. On Earth, gravity drains the sinuses as they are continually producing mucus, which empties through a combination of drainage through the nose or down the throat. In microgravity, mucus accumulates and causes the symptoms of a minor cold—headache, stuffy nose, and a diminished sense of smell and taste (Alexander, 2021; Benninger et al, 2009; Buckey, 2006; Clément, 2011). Astronauts either blow their noses often or learn to live with the clogged sinuses, as nose blowing drains nasal passages but does not drain sinus cavities. This diminishes smell, resulting in foods tasting bland and increasing the desire among many astronauts for spicy or stronger flavors, such as horseradish, wasabi, mustard, and hot sauce (Obrist et al, 2019; Taylor et al, 2020).

There are also changes in digestion. The ability of the intestines to digest food was reduced and its ability to empty was accelerated (Buckley et al, 2011; J.-Q. Yang et al, 2020). It is believed that the permeability of the gastrointestinal tract and that the function of intestinal mucosal cells is impaired by microgravity, reducing the efficacy of the mucosal barrier (J.-Q. Yang et al, 2020). The increased intestinal permeability combined with the microgravity-increased pathogenicity of bacteria and other microorganisms causes a vicious cycle that increases the susceptibility to intestinal infection (J.-Q. Yang et al, 2020). The specific mechanisms for these changes are currently unknown. In addition, without gravity, digestive gasses do not float upwards. Therefore, belching is diminished. Thus, a disproportionate amount of gas is expelled by peristalsis, resulting in flatulence that is driven out "very effectively with great volume and frequency," according to astronaut Joe Kerwin (Bullock, 2006).

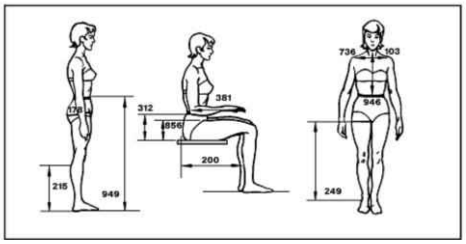


Note: The segment angles shown are means. Values in parentheses are standard deviations about the mean. The data was developed in Skylab studies and is based on the measurement of 12 subjects.

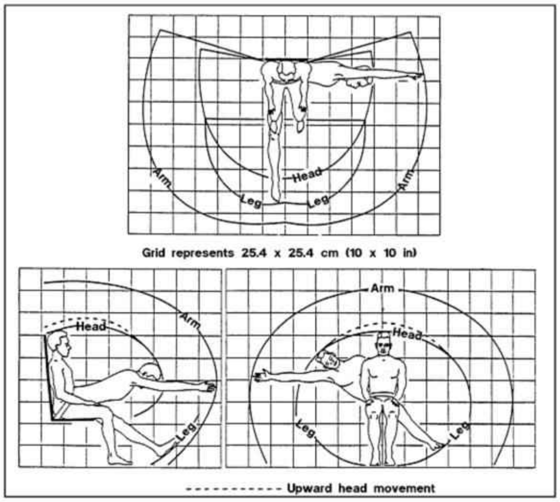
**Figure 9:** Microgravity neutral body position.

Without the need to stand against gravity, the body assumes a neutral body position (Andreoni et al, 2000; Wang, Zhang, Feng, 2017), which is somewhere between the standard anatomical position (standing erect) and the fetal position. This posture can affect reach and coordination, which are also independently affected by microgravity. Proprioception, recognizing position of the body and limbs, relies on a complex interplay of sensory nerves in the muscles, tendons, and joints that—in addition to otolith organs— are often collectively termed graviceptors (Barbieri et al, 2008). These graviceptors in the limbs send positional information to the brain, which integrates it. Proprioception uses gravity-induced stresses to assess position. In microgravity, those stresses are absent and the astronaut limbs often float into unexpected positions, surprising the astronaut (Berger et al, 1998). Additionally, in microgravity, the muscular effort required to perform a task is often overestimated, and astronauts still adjusting to the microgravity environment may overreach in reach and grab tasks (McIntyre, Berthoz, Lacquaniti, 1998; Mulavara et al, 2010).

Finally, some of the same signals involved in proprioception are involved in the urge to urinate. On Earth, gravity induces a hydrostatic gradient, thus pressure near the lower part (the neck) of the bladder increases. When the bladder is approximately two-thirds full the urge to urinate arises. In microgravity, there is no hydrostatic gradient and rather than collect at the bladder neck, urine adheres to the bladder wall (Baran, Erkoç, Ötünçtemur, 2022). Thus, the bladder may reach maximum capacity before an urge is felt, at which point urination may happen suddenly and spontaneously. Conversely, urine retention has also occurred repeatedly on orbit, with astronauts unable to void without catheterization (Stepaniak, Ramchandani, Jones, 2007).



Strike reach data



These figures show the envelope that the body extremities (arms, legs, head and torso could strike when seated person is subjected to 4-G acceleration either fore and aft or side to side.

**Figure 10:** Typical anthropometric data.

## 4. IMPACT OF MICROGRAVITY ON HUMAN ACTIVITIES

The impact of microgravity on crew activities may vary depending on whether the astronaut is on a long- or short-duration flight, with the former associated with work monotony stress and the latter extreme time pressure stresses (Flynn, 2005; Sandal, Leon, Palinkas, 2006). Efforts are made to optimize crew schedules preflight to fit as many experiments and operational tasks as possible during the mission based on adjusting terrestrial work times. Nevertheless, ground-based schedules rarely reflect the reality on orbit. The astronaut's "workday" is intended to be limited to 8.5 hours, but on the ISS, exercise[5] extends the duration of required activities to 11 hours per day.

The time estimated to complete an activity in 1 G generally underestimates the actual time needed to complete it in 0 G (Flynn, 2005). Movement and handling of equipment is generally slower and must be

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[5] Even ground exercise times do not translate simply to orbit exercise time. Due to the high intensity and duration of exercise required, astronauts perspire a great deal. In a gravity environment, perspiration rolls downwards and away from the body. In a microgravity environment, perspiration does not roll but remains on the body in tiny domes above the sweat glands. What does not evaporate may be flung off by a sudden movement. Perspiration must therefore be completely toweled off, adding time to the task of exercising (Flynn, 2005).

more purposeful to account for lack of gravity—one cannot "set objects down" or rely on them "to fall". In addition, on the ISS it is not completely uncommon for necessary equipment to be stowed incorrectly and thus difficult to locate, and located equipment may be malfunctioning, all of which lengthen the time to complete tasks. Schedules are also disrupted by contingency repair operations. Each unexpected task adds to the astronaut workload, increasing the risk of task saturation. Task saturation carries the risk of overuse injuries if the task is prolonged and physical or task saturation may result in a decline in attention to detail, both of which increase the risk of error. The difference in expectation of task completion on orbit and on ground have caused tension between ground managers and mission crews, adding psychosocial stress. Optimizing the workspace can increase efficiency and reduce task-related stress.

Researchers in the field of human factors, also known as ergonomics, endeavor to optimize the workplace, specifically the interface between humans and the technology (tools, furniture, equipment, "rooms" or compartments) they must use. Technology and work environments are designed around anthropometric data, which is a collection of measurements of the human body divided by sex, race, and percentile. Body segments are used to determine parameters like reach when designing a workstation, or extension when designing clothing. In space, human factors design on Earth and on-orbit must accommodate for space and microgravity related changes, namely:

1. Height Increase — Stature increases approximately 3% due to spinal decompression and lengthening,
2. Neutral Body Posture — The relaxed body in microgravity immediately assumes a characteristic neutral body posture,
3. Body Circumference Changes — Body circumference changes occur in microgravity due to the headward fluid shift,
4. Mass Loss — The total mass of the body decreases by 3% to 4%. This is due primarily to loss of body fluids and, to a lesser extent, atrophy and loss of the mass of muscles that were used in 1 G (Rajulu, 2018).

Additionally, space human factors must incorporate the ability to access a third dimension—the ceiling. When designing human-technology interfaces, human factors engineers often use computer models to enter anthropomorphic data and optimize the technology. When using such computer models to design workstations for use on the space station, these models could accurately predict experimental data obtained at 1 G. However, in the microgravity environment, the comuter predictions failed because they were based on the assumption that the neutral body posture was the same for all the subjects (Whitmore et al, 1992). A range of microgravity neutral body postures were exhibited by subjects during microgravity. Hence, designs that relied on a "standard" microgravity neutral body position would not be optimal. These standard neutral body positions were originally obtained from Skylab astronauts who were all white men, most of whom were between 5'9" and 5'10" plus two outliers who were 5'6" and 6 '(Mount, Whitmore, Stealey, 2003),. In contrast, once women were included, the range of astronaut heights increased from 5'4" to 6'4". Standard anthropometric data is taken from a large population and human factors design aims to accommodate as many people as possible; in contrast, space human factors must accommodate all astronauts. Towards that end, the Anthropometry and Biomechanics Facility routinely takes a full set of anthropometric and strength measures as well as full body scanning of all astronauts (Peacock, Rajulu, Novak, 2001). The astronaut population is relatively small in number and these precise spatial and strength measures are essential for both design as well as safety and may potentially be used to update anthropometry data for the microgravity neutral body position.

While workplace designs that relied on outdated microgravity neutral body postures are suboptimal, designs based on 1-G predictions are no better. Nor should crewmembers be expected to maintain a 1-G posture in a microgravity environment. Maintaining certain 1-G postures in microgravity can produce stress when muscles must provide forces that are usually provided by gravity. For example, stooping and bending cause fatigue in microgravity (Wang, Zhang, Feng, 2017). Additionally, microgravity adversely impacts postural stability while crew members perform either high force tasks or precise tasks. Maintaining an appropriate posture for an extended period of time can lead to fatigue and reduced performance. Strategically placed foot restraints and handrails to aid in locomotion are essential to both maintaining comfortable postures and exerting the higher forces needed to manipulate and transfer large mass objects such as racks. Further, where possible, natural heights and angles of the microgravity neutral body posture must be accommodated by human factors design, such as:

1. Feet and Leg Placement — Foot restraints must be used and should be placed under the work surface. The neutral body posture is not vertical because hip/knee flexion displaces the torso backward, away from the footprint. In general, the feet and legs are positioned somewhere between a location directly under the torso (as in standing) and a point well out in front of the torso (as in sitting);
2. Foot Angle — Since the feet are tilted at approximately 111° to the shin, sloping rather than flat shoes or restraint surfaces should be considered;
3. Work Height — The height of the crewmember in microgravity is between sitting and standing height. A microgravity work surface must be higher than one designed for 1-G or partial-gravity sitting tasks;
4. Arm and Shoulder Elevation — Elevation of the shoulder girdle and arm flexion in the neutral body posture also make elevation of the work surface desirable;
5. Head Tilt — In microgravity the head is angled forward and down, a position that depresses the line of sight and requires that displays be lowered (Wang, Zhang, Feng, 2017).

In addition to these human factors design criteria, the actual design of the space station was constrained by the challenges of transporting its various comprising modules into orbit via Space Shuttle cargo bays. Furthermore, to optimize the efficiency of human operations and facilitate the ability to update hardware, thereby extending its use, the ISS was designed to be modular (Peacock, Rajulu, Novak, 2001). Standard hardware modules (e.g., boxes, racks, trays) can be exchanged with other modules elsewhere on the ISS. Without the contribution of gravity-based vestibular cues, the astronaut relies exclusively on visual cues. Unfortunately, the station's modularity gives everything a similar appearance, reducing any meaningful visual cues. Inadequate spatial orientation can lead to human user errors that can be stressful when under time pressure, or dangerous when in an emergency.

Microgravity also affects the crew's ability to function in an Extra Vehicular Activity (EVA) suits (Rajulu, 2018). Astronauts' strength and mobility are reduced subsequent to muscle atrophy, which affects their ability to work in an EVA suit. The EVA suit itself limits the astronaut's force output capability and strength. Pressurization of the suit adds a stiffness to it that astronauts must work against, and the hard shell-type suits alter the joint mobility, fundamentally changing the limitations and capabilities of the astronaut inside the suit. Training underwater in EVA suits is important for learning the tasks, but the underwater strength required is not comparable to that required in space and Earth-based analogous environments do not exist. In part, because water adds drag and buoyancy forces that are absent in space. Further, astronauts in training have not suffered microgravity-related changes. Additionally, astronauts must at times transport heavy masses in space that would not be possible on Earth. Information on how an astronaut might perform an EVA on Mars following months of microgravity only exists in computer models.

Such information may assist in preventing unexpected events. Although modern countermeasures such as exercise and nutrition have ameliorated many potentially adverse events, historically there have been ventricular arrhythmias following EVAs. Apollo 15 was the first of longer lunar landing missions intended to be more expedition-like and exploratory in nature. When the lunar crew rendezvoused with the orbiting Command Module, they were very tired. The already fatigued lunar crew had to also transfer equipment from the Lunar Module to the Command Module, a task intended for the rested Command Module pilot but altered because of over scheduling. Following the equipment transfer, Lunar Module pilot James B. Irwin had bigeminal ventricular premature contractions and atrial premature contractions (Johnston, 1975; Johnston, Hull, 1975). Further, he reported a brief loss of consciousness at the time the arrhythmia was noted. The Command Module pilot David R. Scott also experienced less severe arrhythmias, and the episodes in the two men were attributed to a deficiency in potassium. However, a Skylab astronaut subsequently had an episode of multifocal ventricular premature contractions following an extravehicular activity.

**Figure 11:** Trash aboard the ISS.

Finally, waste handling and stowage in a microgravity environment remains challenging. In a single year, four astronauts can generate 2,500 kilograms of waste. Currently, ISS astronauts place trash into bags then load it onto designated vehicles for short term storage, which either returns the trash to Earth or burns up in the atmosphere. This disposal method will not be available for missions to the Moon or Mars. Additionally, when these vehicles are delayed, trash can accumulate and impede adequate operational and emergency access to various parts of the station. Further, temporary stowage of equipment, laundry, material, tools, and trash creates a constrained but dynamic environment where access must nevertheless be maintained.

Countermeasures to combat the myriad physiological changes have included a daily exercise regimen while on orbit that is both time consuming and vigorous. Lower body negative pressure suits have been used to thwart the headward fluid shift. Pharmacological agents were used to allay muscle and bone wasting. Despite these interventions, after returning to Earth following long duration Mir flights, Russian cosmonauts could not walk normally for several days, suffered orthostatic intolerance, and exhibited musculoskeletal deterioration so severe it required over four weeks of rehabilitation before the crew returned to their baseline physiological status (Borowski, McCurdy, Packard, 2014). US astronauts returning from Mir after 4-6 months had similar symptoms. Although the physical ability to spend months in 0 G, then explore the surface of Mars in a ~115 lb. spacesuit was highly unlikely, countermeasures aboard the ISS continued to advance. With the recognition of SANS as a problem and no effective countermeasure on the horizon, artificial gravity is once again being seriously considered. In 2014, NASA restarted its artificial gravity program.

**Table 4.** Stressors of Long Duration Spaceflight (Morphew, 2001).

| Physiological/Physical | Psychological | Psychosocial | Human Factors | Habitability |
|---|---|---|---|---|
| Radiation | Isolation & confinement | High team coordination demands | High & low levels of workload | Limited hygiene |
| Absence of natural time parameters | Limited possibility for abort/rescue | Interpersonal tension between crew/ground | Limited exchange of info/comms with external environment | Chronic exposure to vibration and noise |
| Altered circadian rhythms | High-risk conditions & potential for loss of life | Family life disruption | Limited equipment, facilities and supplies | Limited sleep facilities |
| Decrease in exposure to sunlight | System & mission complexity | Enforced interpersonal contact | Mission danger & risk associated with: equipment failure, malfunction, or damage | Lighting & illumination |
| Adaptation to micro-gravity | Hostile external environment | Crew factors (i.e., gender, size, personality, etc.) | Adaptation to the artificially engineered environment | Lack of privacy |
| Sensory/perceptual deprivation of varied natural sources | Alterations in sensory stimuli | Mulitcultural issues | Food restrictions/ limitations | Isolation from support systems |
| Sleep disturbance | Disruptions in sleep (readjustment with crew changeovers) | "Host-Guest" phenomenon | Technology-interface challenges | |
| Space Adaptation Sickness (SAS) | Limited habitability (e.g., limited hygiene) | Social conflict | Use of equipment in microgravity conditions | |

## 5. IMPACT OF MICROGRAVITY ON HABITAT SYSTEMS

Space life support and habitat systems are comprised of the systems, process technologies, and equipment that create and maintain a livable environment within the pressurized cabin of crewed spacecraft (Perry, Sargusingh, Toomarian, 2016; Wieland, 1994). These systems must operate in microgravity and be compatible with cabin atmospheres of up to 34% oxygen by volume and pressures ranging from 1 atmosphere (14.7 psi / 101.3 kPa) to as low as 0.52 atmosphere (7.6 psi / 52.4 kPa). Long term operation of these systems in microgravity within a closed environment has led to issues that are not observed on Earth.

Skylab, Mir, and the ISS have all had significant microbial colonization (Novikova et al, 2006; Sielaff et al, 2019), likely indicating that this is a condition that occurs on spacecraft intended for long-duration missions. The interfaces of station parts and components are often infested with microbial life and biofilm formation. Biofilms are problematic for every system and affect both crew contact surfaces (e.g., acoustic blankets, exercise equipment, hand rails, panels, racks, Velcro) and food contact surfaces (e.g., table surfaces, utensils) (Singh et al, 2018). Biofilm formation on hardware surfaces can cause damage, costly repairs, and other serious technical issues. Investigations into the magnitude of the problem have revealed extensive microbial diversity and the evolution of several new bacterial species that do not exist on Earth (Bijlani et al, 2021). Because onboard equipment currently cannot monitor surfaces or air, systematic microbial monitoring of the ISS is only conducted for water (Khodadad et al, 2021). In essence, surfaces are cleaned to remove microbial infestation, but not assessed to determine the efficacy of the cleaning. A considerable amount of the astronauts' time is spent cleaning and performing other habitat maintenance duties.

Decontaminating these surfaces is further complicated by the fact cleaning supplies are constrained due to potential toxicities, storage, and weight. The pre-moistened wipes currently used to clean ISS surfaces are consumable intensive and although a preferable option would be reusable wipes with cleaning solutions prepared on orbit, this poses its own challenges. The ideal cleaning solution must be effective against a wide range of microbial life, such as bacteria that are fecal coliform, food-based, and/or iodine resistant (NASA SBIR, 2016). The solution should also be able to remove body oils, food, and particulate matter from surfaces. Finally, any cleaning solution will have direct contact with crew, and thus pose risks of direct off-gassing and accumulation of solution vapors in the cabin atmosphere.

For similar reasons, there are no space-based laundry capabilities. Moreover, traditional laundry detergents use surfactants, which would burden downstream wastewater processors with a substantial organic contaminant burden (NASA SBIR, 2016). For these reasons, dirty laundry is regularly exchanged for clean clothes from resupply ships, which remove the laundry for return to Earth or incineration in the atmosphere (Schlesinger, Broyan, Orndoff, 2014). A crew of 6 goes through over 400 kg. of clothing per year. To minimize the need for resupply, clothes may be worn for weeks to months at a time. As such, clothing has high levels of body oils, dander, particulate matter, salts, and odor-causing bacteria. These body-odor causing bacteria, the long-term stowage of garbage, the abundance of microbial life on surfaces, and the continuous attempts to combat surface colonization with disinfectant wipes combine to give the ISS a smell that is a combination of antiseptic, garbage, and body odor (Stockton, 2017). The high efficiency filters of the habitat systems work very well to minimize this smell through filtration, but in microgravity odors do not rise or descend as on Earth. Furthermore, filtration is not perfect and the rate of odor filtration is not matched by the rate of odor production. Moreover, despite the filters and the regular vacuuming performed by astronauts, dust remains airborne without gravity. It enters the eyes and nose, causing irritation and allergic reactions.

Microgravity precludes baths, showers, and terrestrial toilets. While astronauts can forgo showers, toileting needs must be accommodated. The current ISS toilet was approximately $19M to develop, costs millions in annual maintenance, and requires maintenance or repairs at least six times per year (Weislogel et al, 2022). As of 2022, a replacement toilet is being developed with a cost of $23M and a 10-year lifespan. In contrast, the average terrestrial toilet costs less than $500 to install, may require service once every 10 years, and has a nearly 50-year lifespan. However, the only way a terrestrial toilet would work in space would be in an acceleration field, such as in a centrifuge.

The lack of gravity causes other problems to wastewater reclamation. Wastewater from hygiene, urine, and condensed water vapor from crew perspiration and respiration is reclaimed to use as potable water. In addition to crew-generated wastewater, $CO_2$ and $H_2$ is used to produce water, which is then combined with the wastewater for processing. As of 2020, the ISS water recovery system has produced over 30,000 L of water since the start of its operation in November 2008 (Volpin et al, 2020). During this time, several microgravity-related problems with the water recovery system have become apparent. Some issues are a direct result of technology not functioning properly in microgravity, while other issues are a result of how microgravity alters the wastewater it must treat.

For instance, in the absence of gravity, the two-phase fluid dynamics of the water recovery system was altered (Volpin et al, 2020). In addition, without gravity to settle water-borne particulates, their detrimental effect on the water recovery systems performance increased. Aside from microgravity-related technical issues, there are a variety of microgravity-related changes to urine. The excess calcium in the urine as a result of microgravity-induced bone loss causes scaling on pipes or appliances used on the ISS.

The high calcium content in the urine caused calcium sulfate ($CaSO_4$) precipitates to form on the distillation assembly. In addition to the ISS machinery being impacted by such microgravity-driven changes in its human occupants, the microbial infestations that plague space stations have also caused problems. In 2010 the solenoid valve of a wastewater tank seized after it was clogged by a detached biomass that had been forming on the tank's wall (Muirhead, Carter, 2018; Volpin et al, 2020).

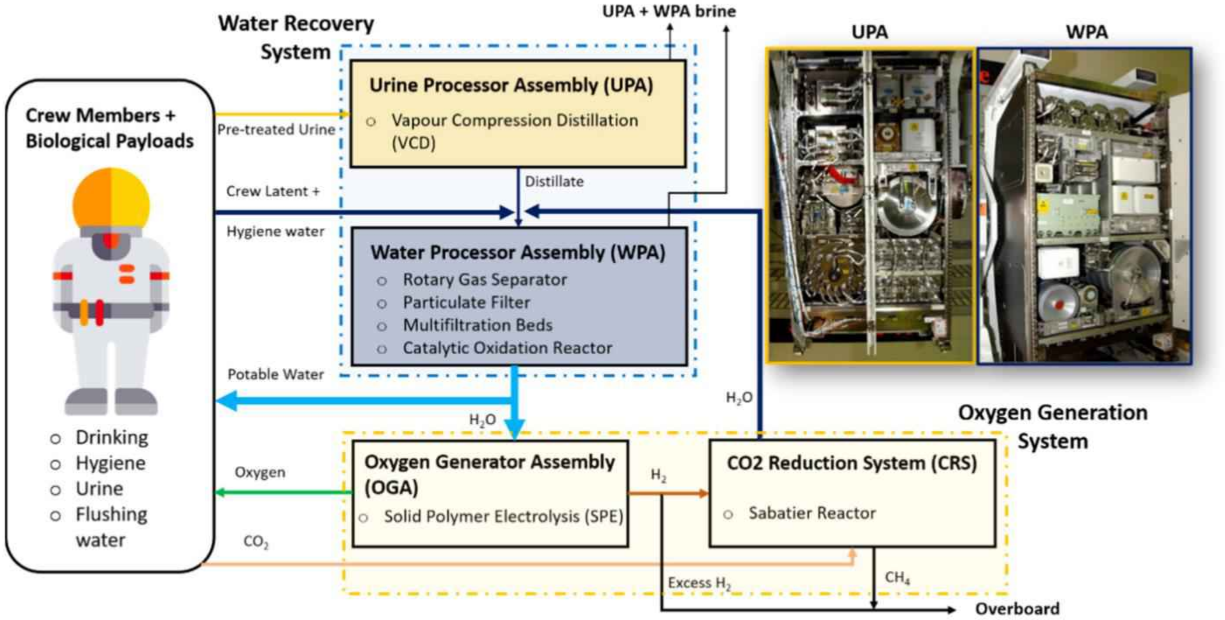

**Figure 12:** The water recovery system on the ISS.

## 6. REVIEW OF ARTIFICIAL GRAVITY LITERATURE

### 6.1 Introduction

Detailed calculations and various designs for artificial gravity space habitats were proposed decades before spaceflight ever became a reality. Artificial gravity generated by rotation was first proposed for spaceflight in 1883 by the Russian rocket scientist and founder of cosmonautics, Konstantin E. Tsiolkovsky (Clément, Bukley, Paloski, 2007). In the 1950s, there was no knowledge about what weightlessness could do to the body and the common assumption was that artificial gravity would be necessary. In the early 1960s, researchers explored the criteria for the "comfort zone" of several rotating habitats. In early May 1963, engineers at the NASA Manned Spacecraft Center in Houston—which became the Johnson Space Center after the death of Lyndon Johnson—examined 11 artificial-gravity Earth-orbital laboratory designs.

On September 14, 1966, artificial gravity was achieved in a crewed vehicle when the Gemini XI spacecraft was tethered to an Agena target vehicle with a 36-meter tether. Each pilot maneuvered their craft to keep the tether taut between them and to slowly rotate the tethered spacecraft, ultimately generating about 0.00015 g of artificial gravity (Seedhouse, 2013). The bulk of artificial gravity research, however, has occurred in centrifuges, rotating rooms, and rotating space station simulators (Bukley, Paloski, Clément, 2007). In the United States, this occurred at the Naval Aviation Medical Acceleration Laboratory, the Naval Aerospace Medical Research Laboratory, and the NASA Langley Research Center.

The "Space Race" diminished the urgency of designing spacecraft capable of providing artificial gravity with the rush to be first at each subsequent achievement. Bolstered by successful animal flights, flight capsules were developed instead of artificial gravity systems. As missions grew from minutes to days without life threatening events, space programs gained extensive experience with weightless flights. Thus, developing an artificial gravity platform was deprioritized. Artificial gravity was reconsidered for Skylab and other long duration missions (Clément, Bukley, Paloski, 2007) and experiments in rotating chairs were conducted aboard Skylab (Johnston, 1977).

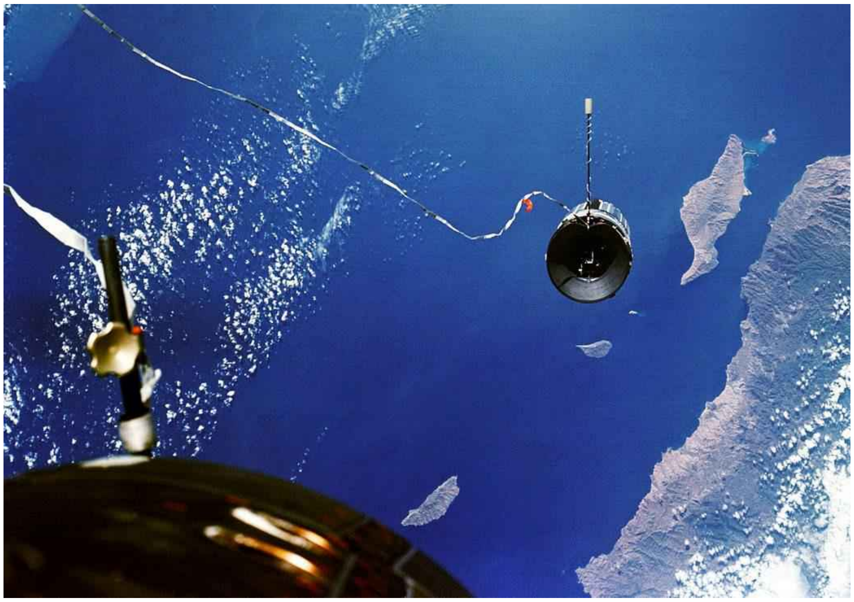

**Figure 13:** Gemini and Agena tethered together.

In the late 1960s as the Apollo Moon program neared an end, NASA commissioned industry studies investigating future space stations (Levine, 1982). Virtually every design indicated that artificial gravity would be essential. Yet Skylab demonstrated that microgravity was a unique feature for research that only a space station could offer. And even without artificial gravity, Skylab astronauts suffered no lasting adverse events, therefore artificial gravity was again deprioritized. The rotating space station simulator at NASA Langley was dismantled in the early 1970s (Diamandis, 1987).

There is a longstanding perception that construction and maintenance of a rotating vehicle is highly complex and extremely expensive. So, although artificial gravity would likely prove to be an effective *multisystem* countermeasure against the deleterious impact of microgravity, exercise, pharmaceuticals, and nutrition are perceived as much more cost effective and easier to implement. Funding was no longer allocated to investigate larger rotating habitats. As a result, much of the research involving rotating habitats is nearly 50 years old (Hall, 1997).

Artificial gravity interest has not waned. Small centrifuges have been taken aboard the Cosmos biosatellites, the Space Shuttles, and the ISS to provide environment-matched 1-G controls for animal studies in space (Clément, Bukley, Paloski, 2007). The international artificial gravity workshops (e.g., in 1999 and 2014) continued. During these workshops, artificial gravity was largely considered as a multisystem countermeasure for interplanetary missions and decreasingly proposed for ISS use. For instance, in cooperation with NASA, the Japanese space agency, then NASDA now JAXA, developed and partially constructed a Centrifuge Accommodation Module that contained a 1.25 meter radius multi-compartmental centrifuge that could accommodate rodents, fish, plants, insects, and cell cultures (Shayler, 2017; Thangavelu, Simurda, 2010). In addition to the centrifuge, the module would contain habitats and lab equipment. The centrifuge habitats were designed to be adjustable to different radii, permitting 2 simultaneous and different G levels, which generated up to 2 G at the perimeter. The module was intended to connect with the ISS in 2005 but was cancelled and what was constructed sits on display in a parking lot at Tsukuba, Japan's "Science City" (Shayler, 2017).

In addition to the cancelation of the Centrifuge Accommodation Module, a human centrifuge project was canceled. The Artificial GRavity with Ergometric Exercise (AGREE) project was designed in response to an International Life Science Research Announcement (Diaz, Trigg, Young, 2015). In 2009, the AGREE module was selected to fly on board the ISS. The objective of the AGREE project was to test the efficacy of artificial gravity generated by short-radius centrifugation as a countermeasure to human deconditioning on orbit. These studies were to have been the first of their kind. The AGREE centrifuge was intended to be combined with ergometric exercise. The AGREE module was to be constructed by ESA, launched by JAXA, and placed at the end of the Multi-Purpose Logistics Module. Unfortunately, a stress analysis showed that the induced vibrational loads would have structurally compromised the ISS nodes and the AGREE project was canceled in 2013 (Clément, Charles, Paloski, 2016).

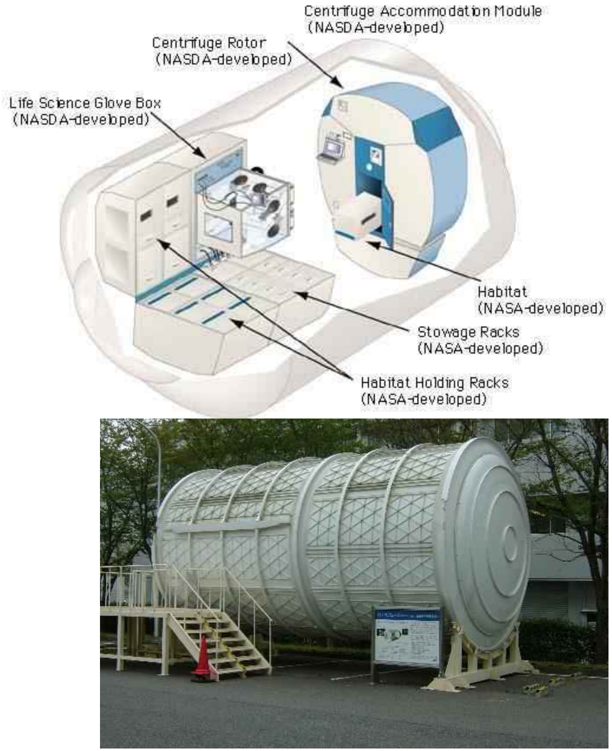

**Figure 14:** The Centrifuge Accommodation Module.

## 6.2 Artificial Gravity Research

In the United States, human artificial gravity research was largely conducted in three places (Clément, Bukley, 2007). One of those places was Pensacola Slow Rotation Room, which was in operation from 1960-1974. It was a multisided windowless room with a square post at its center that was 5 meters in diameter and 2.5 meters tall. Another location for artificial gravity research was the NASA Langley Rotating Space Station Simulator, which was a ceiling-less cylindrical room with a 12 m diameter and 1.8 m wall. Finally, there was the Rockwell Rotating Test Facility, which was a space station module mockup that measured 3 by 12 meters and could be rotated on a 22-meter arm. In the Soviet Union, artificial gravity research was conducted in the MVK-1 small rotating chamber and the larger 10-m radius Orbita centrifuge. In these rotating rooms, test subjects could be rotated at various rates for a few minutes to a few months. This allowed investigators to assess motor skills, neurovestibular adaptation, and other physiological effects.

Much of the research focused on the four major characteristics of a rotating habitat that cause artificial gravity to differ from Earth's gravity and what design parameters would facilitate the artificial gravity environment to be perceived as acceptable. These characteristics are:

1. The magnitude of artificial gravity required to be beneficial;
2. The tolerable gravity gradient;
3. The tolerable Coriolis forces; and
4. The tolerable cross-coupled angular accelerations (Bukley, Paloski, Clément, 2007).

Schematic drawing of the AGREE human centrifuge combined with a cycle ergometer in the Multi-Purpose Logistics Module of the International Space Station. A 30-rpm rotation generates 1 G at the feet of the crewmember, which would augment the benefits of the exercise activity.

**Figure 15:** The Artificial GRavity with Ergometric Exercise (AGREE) human centrifuge.

A brief review of the physics of rotating environments is presented towards appreciating the opportunities, benefits, and challenges to human health and operations in rotating habitats.

### *6.2.1 Physics of Artificial Gravity & Rotating Environment (for full review, see (Bukley, Paloski, Clément, 2007)*

The artificial gravity discussed in this report is actually an inertial force in response to the centripetal acceleration caused by a rotating device. Centripetal forces are the actual forces required to change one's direction while centrifugal forces are the apparent forces that are felt as a result of inertia—the continual changes in direction make objects within a rotating frame behave and feel as though an outward force is acting upon them. Viewed from a non-rotating frame, the objects proceed as their inertia directs. This so-called centrifugal force is experienced every day on Earth for example, during fast turns in cars or the "Tilt-O-Whirl" amusement park ride.

**Centripetal acceleration** is a vector with a magnitude associated with a direction. The magnitude is the product of the tangential and angular velocity and is always directed towards the center of the rotating body.

The magnitude of the artificial gravity (i.e., the centrifugal force) is dependent upon how fast the object/space craft is spinning, or the angular velocity ($\omega$) in radians per second; the radius (r), or how far the object is from the center of rotation; and the mass (m) of the object. Thus, the **centripetal force** is $F = m\omega^2 r$, with positive defined towards the center of rotation. Since the **centrifugal force** is perceived as an equal and opposite reaction to the centripetal force, it is $F = -m\omega^2 r$, with negative defined outwards, away from the center of rotation. As these forces are dependent on radius, the perceived artificial gravity also varies with radius, resulting in a gravity gradient.

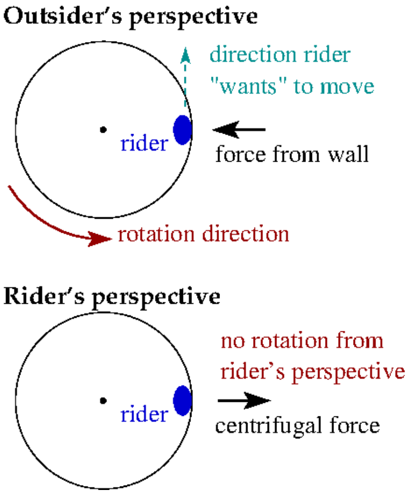

**Figure 16:** The difference between centripetal (actual) and centrifugal (apparent) acceleration.

Closer to the center of rotation, artificial gravity is less (smaller radius) and farther from the center, gravity is greater (bigger r). Therefore, an astronaut standing in such a field will experience less artificial gravity at her head and greater artificial gravity at her feet. For instance, 1 G at the feet and 0.98 G at the head is a "shallow" 2% gravity gradient, while 1 G at the feet and 0.8 G at the head is a "steep" 20% gravity gradient. The "steepness" of this gradient depends on the height of the object experiencing the gradient (e.g., mouse vs human) relative to the radius of the rotating habitat.

The **Coriolis acceleration**, the result of linear movement, is another feature of rotational environments to be considered and it plays a significant role in the onset of motion sickness. Like centrifugal forces, Coriolis forces are apparent forces. They do not cause motion but are a result of a rotating environment Coriolis acceleration is equal to two times the cross product of angular velocity $\omega$ and the linear velocity $v$ ($2\omega v$) of the moving object—whether the object is a person, a fluid, a ball, or a body part. The direction of Coriolis acceleration is perpendicular to the plane in accordance with the right-hand-rule of vector calculations. The force is proportional to the linear velocity of the movement in the rotating frame and the sine of the angle between the direction of movement and the axis of rotation. The Coriolis force is independent of the radius; it is the same at all distances from the center of rotation. Its effect can be described by considering velocity. Each rung on the ladder in Figure 18 has the same angular velocity ($\omega$), but different tangential linear velocities ($v_T = \omega r$), which vary with radius. Moving an object towards lower tangential linear velocities causes that object to match that lower velocity, thus decelerating the object’s speed. Likewise, moving towards higher linear velocities causes the object to match the higher velocity, thus accelerating the object. Outside of the rotating environment, the tangential linear velocity can be observed. Within the rotating environment, objects do not perceive their tangential linear velocity. Therefore, the acceleration and deceleration are perceived as a lateral force in the direction of the tangential linear velocity.

**Table 5: Characteristics of the Coriolis Force or Acceleration**

| | |
|---|---|
| **A.** | When the velocity $v$ is zero, the Coriolis acceleration is zero. |
| **B.** | When $v$ is parallel to the rotation axis, the Coriolis acceleration is zero. |
| **C.** | When $v$ is directed radially inward towards the axis of rotation, the resulting Coriolis acceleration is aligned with the direction of rotation (parallel to the tangential velocity). |
| **D.** | When $v$ is directed radially outward away from the axis of rotation, the resulting Coriolis acceleration is opposed to the direction of rotation (parallel to the tangential velocity). |
| **E.** | If $v$ is aligned with the direction of rotation (parallel to the tangential velocity), the Coriolis acceleration acts radially outward from the axis of rotation |
| **F.** | If $v$ is opposed to the direction the rotation (parallel to the tangential velocity), the Coriolis acceleration acts radially inward toward the axis of rotation |

### *6.2.2 Humans and Living Organisms in Artificial Gravity*

As discussed, rotation produces centripetal acceleration ($a = \omega^2 r$) that is exploited in the rotating spacecraft designs to produce artificial gravity. As such, desired artificial gravity levels can be achieved by increasing the angular velocity ($\omega$) or the radius ($r$) of the habitat. In this sense, artificial gravity can be a tradeoff between the complexity and the cost of the habitat—the cost generally increases with radius, while the physiological and psychological impacts may increase with angular velocity. For instance, an astronaut jogging in the direction of a station’s rotation increases her speed in that direction and by adding to her tangential linear velocity, she is also adding to her rotational velocity and hence centripetal and in turn centrifugal acceleration; in short, she feels heavier. If she runs fast enough in the opposite direction, she may be able to cancel out the artificial gravity altogether, leaving her weightless. These effects may cause partial gravity to be sufficient if it turns out that a 30-minute jog can increase the artificial gravity to 1 G and thus provide sufficient gravitational stimulation.

#### *6.2.2.1 The magnitude of artificial gravity required to be beneficial.*

In the latter half of the 1970s, the Soviet biosatellites Kosmos 782 (19 day flight) and Kosmos 936 (18 day flight) sent facilities into orbit in which ants, plants, rats, turtles, as well as cell and tissue cultures were centrifuged at 1 G, alongside a 0-G control group (Adamovich et al, 1980; Gurovsky et al, 1980; Shipov, Kotovskaya, Galle, 1981). After return to Earth, examination of both groups showed that while the expected changes occurred in the 0-G control group, the “artificial-gravity groups showed no evidence of typical adverse effects of microgravity.” While these studies suggest the efficacy of artificial gravity at combatting microgravity-induced alterations, there is no data on whether partial gravity would suffice (Clément, 2017).

Long duration centrifuge studies on Earth conducted by Russian investigators suggest that 0.3 G is the minimum effective artificial gravity needed as a human countermeasure, with 0.5 G recommended to increase feelings of well-being and enhance normal performance. Studies of perception on orbit have shown that humans can detect artificial gravity at levels of 0.5 G, but cannot detect levels 0.22 G or below (Bukley, Lawrence, Clément, 2007).

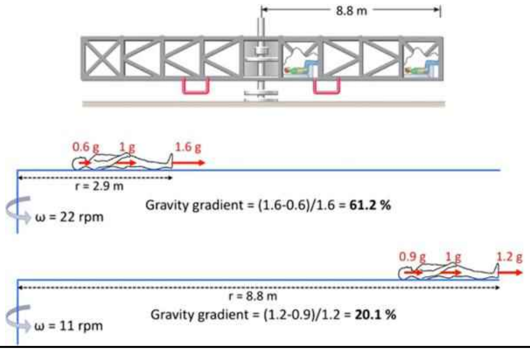

**Figure 17:** The gravity gradient and its dependency on radius and subject height.

### *6.2.2.2 The tolerable gravity gradient.*

Because centripetal acceleration varies linearly with radius, artificial gravity also varies linearly: it is zero at the center of rotation where the radius is zero, and at its maximum at the outer radius of the craft. Moving towards or away from the center of rotation would result in a person's weight becoming heavier or lighter. Objects would become heavier when setting them down and lighter when lifting them. In addition, the gravity at a person's head would be less than at that individual's feet (Figure 17). As discussed, this variation is the gravity gradient. For instance, in a rotating habitat with a 100-meter radius, the gravity gradient would vary linearly from 0% at the center to 100% at the rim. Therefore, for an astronaut who is 2 m tall, at her feet she would feel 100% of the artificial gravity, while at her head only 98%. This corresponds to a gravity gradient of 2%. For a rotating habitat with a 10-meter radius, the gravity gradient varies by 10% per meter, inducing a 20% gravity gradient in that same astronaut, which may be perceived as a bent posture even when standing upright.

### *6.2.2.3 The tolerable Coriolis forces.*

In Figure 18, Coriolis forces are induced when ascending or descending the ladder; on Earth, Coriolis forces are induced when ascending or descending latitudes. Because Earth has such a large radius, large distances must be traversed before there is a significant difference between angular velocities at one latitude and the next. Thus, the Coriolis effect is only perceived by objects on Earth traversing large distances at high velocities. On Earth, the Coriolis accelerations due to the Earth's rotation are clearly noted to affect atmosphere and hence weather patterns but are relatively small and imperceptible to humans. For instance, a person running at 5 miles per hour in New York would be subject to a Coriolis force of ~0.0035 lbs. However, in a rotating environment where the rotation itself produces significant acceleration, the Coriolis acceleration is large.

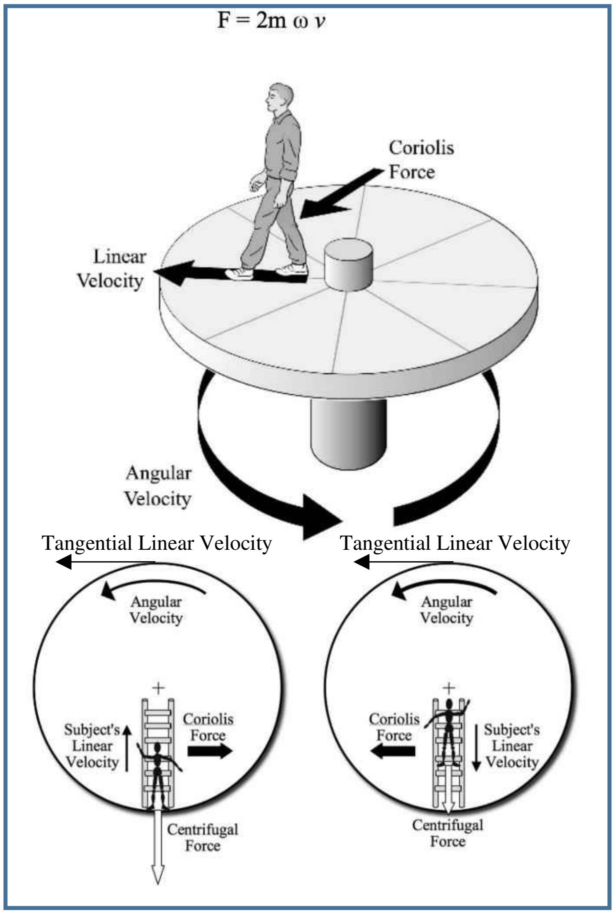

**Figure 18:** Coriolis forces are apparent forces that are a result of a rotational environment. Attempts to walk radially outward on a spinning platform are met with a tangential force pushing sideways. Coriolis and centrifugal forces exerted on an individual climbing a ladder up (left) or down (right) in a rotating environment. The Coriolis force has the same amplitude in both conditions, but its direction is reversed.

Because the Coriolis acceleration acts perpendicularly to the direction of motion, unless moving parallel to the axis of rotation, a person's vestibular system will detect these Coriolis accelerations and without corroborating visual cues that person may experience motion sickness. In addition to the explanation in section 6.2.1 in which Coriolis forces were described using velocities, the Coriolis phenomenon can also be understood in terms of angular momentum. A person walking towards the center of a spinning platform or the astronaut climbing a ladder will be reducing their rotational radius. When the radius of a spinning object is reduced without constraining that object, angular momentum is conserved and this reduction of radius occurs with a corresponding increase in angular velocity—in the same way that a tether ball increases its speed as it winds around a pole. In a system in which the object is constrained from increasing its angular velocity, such as an astronaut on a ladder, that ladder is rotating at a constant rotational velocity and thus slowing the increased velocity that conservation of momentum would otherwise impart to the astronaut. The vestibular system will sense this slowed velocity. This is perceived as a lateral force and will affect poured fluids, limb motion, and locomotion.

Such Coriolis forces will affect the hand-eye coordination controlled by the central nervous system. Incidentally, microgravity also affects the hand-eye coordination system because the central nervous system has to adjust to a weightless arm. Adaptation of the hand-eye coordination system reportedly happens relatively quickly in microgravity, depending on the complexity of the task (Bock, 1998); however, this may not be the case for a rotating environment. With microgravity, there is a single new variable that the central nervous system must adjust for—suddenly weightless arms. In a rotating habitat, the Coriolis forces will depend on whether the astronaut is moving or not, which direction the astronaut is facing, which direction the astronaut's arm is moving, the speed that the astronaut's arm is moving, etc. The new variable is not constant. A suggestion to assist with this type of adaptation is to have visual aids for rotating habitat occupants that indicate the orientation of the axis of rotation. Additionally, individuals in rotating environments can slow their movements; when the speed of the arm is low and the distance it must traverse is small, Coriolis forces will not significantly cause deviations to the arm trajectory.

#### *6.2.2.4 The tolerable cross-coupled angular accelerations*.

While Coriolis forces are induced by *linear* motion that is not parallel to the direction of rotation, Coriolis cross-coupled angular accelerations are induced by *angular* motion about an axis that is not parallel to the axis of rotation. These rotations induce gyroscopic forces, which act on the semicircular canals of the vestibular system. When subjects on spinning platforms rotate just their heads or their whole bodies out of the plane of the rotation, they experience unusual stimulation of the semicircular canals. The brain interprets the unusual stimulation as the body or environment moving in a manner that can be very disorienting. For the same reasons that they do not induce significant Coriolis forces, nodding or turning the head on Earth does not produce the Coriolis cross-coupled angular accelerations because the Earth's radius is so large. To induce noticeable Coriolis forces and Coriolis cross-coupled angular accelerations on Earth, researchers use rotating chairs and have subjects, with their eyes closed, move their heads in and out of the plan of rotation to investigate motion sickness. The stimulation induces symptoms that vary in both intensity and duration corresponding to the individual's tolerance threshold to such vestibular stimuli.

### *6.2.3 Pensacola Slow Rotating Room Investigations*

Rotating room experiments have been conducted since the late 50s and early 60s and have exposed human subjects to rotation rates up to 20 revolutions per minute or for durations up to 4 weeks (Clément, Bukley, Paloski, 2007; Graybiel, 1970; Graybiel et al, 1965; Guedry, 1965b; Guedry, Kennedy, Harris, 1964; Kennedy, Graybiel, 1962; Reason, Graybiel, 1969). Most of the U.S. rotating room experiments were conducted at the Pensacola Slow Rotation room. Experiments there demonstrated that by avoiding head movements out of the plane of rotation averted inducing disorienting stimuli. Most importantly, investigators demonstrated that an individuals' predisposed susceptibility to motion sickness in addition

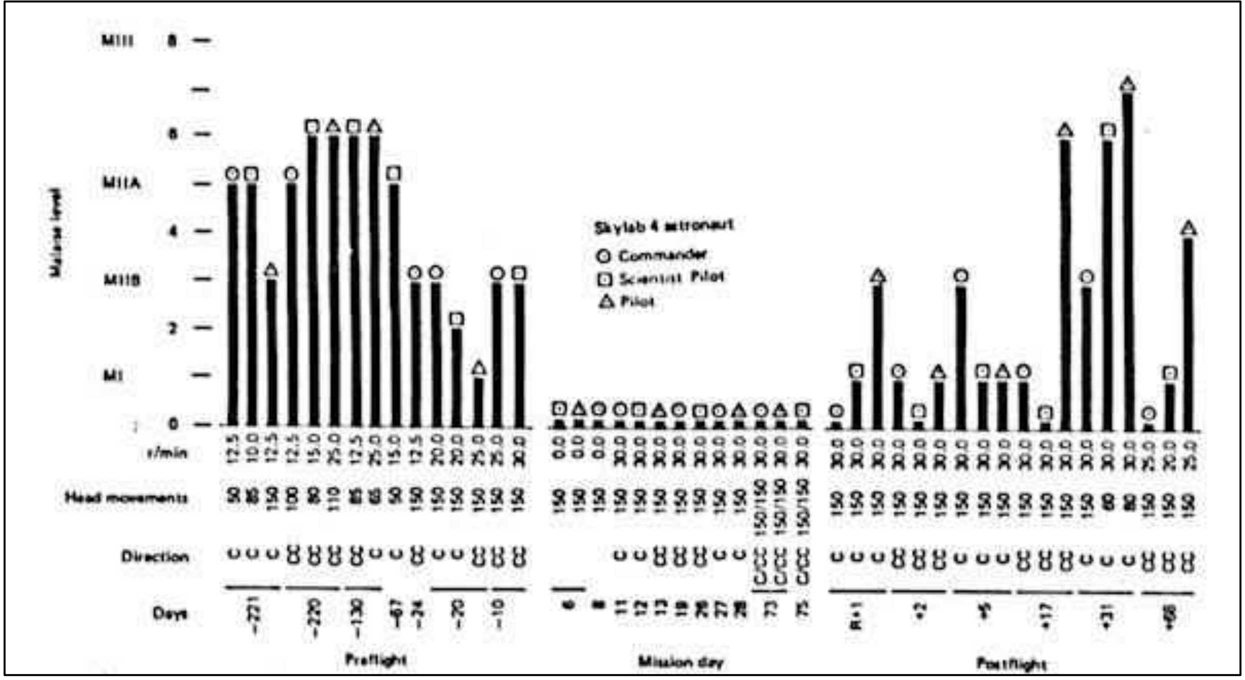

**Figure 19:** Motion sickness symptomatology of Skylab 4 astronauts quantitatively expressed in terms of malaise level as evoked by the test parameters (rotational velocity, number of head movements, and direction of rotation) used before, during, and after the Skylab 4 mission.

to the angular velocity of the room were determining factors for which subjects suffered symptoms. All subjects could easily adapt to 1 revolution per minute, while only certain subjects could adapt and function in a room rotating at 10 revolutions per minute. This ability to adapt varied widely from person to person and could take as long as 2 weeks, all while suffering through symptoms of motion sickness until fully adapted. Several experiments explored how to accelerate adaptation while reducing symptoms.

Researchers investigated whether incrementally increasing rotational speeds could shorten time to adapt to rotating environments (Graybiel, 1970; Reason, Graybiel, 1969). The study's authors concluded that it may be possible to shorten the adaptation time from 25 to 2 days by incrementally increasing the rotation rate in conjunction with controlled head movements.[6]

During the course of the experiments, investigators noted that subjects seemed to develop some "generalized immunity" to varied disorienting stimuli with more exposure. Researchers postulated that given the similarity between Space Adaptation Syndrome and Coriolis sickness, an astronaut adapted to

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[6] One series of investigations used incremental increases in angular velocity from 1 – 10 revolutions per minute. Multiple increment schedules were attempted. None could avert motion sickness with the exception of a 9-step increase over a period of 25 days. A second set of investigations combined the stepwise approach with deliberate head and body movements. With each increase of 1 revolution per minute, three subjects were to complete 1,000 head movements while the rotation of the room was increased to 10 revolutions per minute over the course of 2 days. Two of the subjects adapted readily. The third was extremely susceptible to motion sickness and experienced drowsiness at 2 revolutions per minute, nausea at 5 revolutions per minute, then refused to make further head motions at higher revolutions per minute. Though the authors concluded that incremental increases and prescribed head motion might reduce adaptation time from 25 to 2 days, these conclusions were based on 2 of 3 subjects. In addition, they evaluated subjects who were suspended such that they could walk on the walls. These subjects were compared to subjects who remained vertical and there was no difference in adaptation. Further, "horizontal" subjects could adapt to vertical conditions and vice versa.

Space Adaptation Syndrome could more readily tolerate rotating environments. Therefore, they reasoned space habitats with both artificial gravity and weightlessness would not require readaptation when transitioning between the two. Studies from Skylab missions offer some preliminary evidence to support their hypothesis (Evans et al, 1977; Graybiel, Miller, Homick, 1977; Johnston, 1977).[7]

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[7] The investigators noted similarities between "Coriolis sickness" and Space Adaptation Syndrome and the subsequent adaptation to each and posited hypotheses that would explain both. Their hypothesis was that the adaptation observed was either due to neurovestibular/sensorimotor learning or fatigue. In the former, the new sensory inputs from the rotating environment updates the sensorimotor systems' internal model of expected relationships. The latter assumes that the systems involved in motion sickness undergo fatigue whereby the sensitivity and threshold of the vomit and autonomic brain centers are adjusted. The investigators surmised that the former explanation would mean subjects would be desensitized to the specific environment they experienced while the latter explanation would render some immunity to novel disorienting stimuli. In support of the fatigue hypothesis, when subjects were trained at length in rotating chairs, they showed diminished sensitivity to novel disorienting stimuli. The investigators termed this "generalized immunity" and posited that a person who had adapted to the disorienting environment of space would have an acquired immunity to a rotating habitat, provided they entered the rotating habitat after their Space Adaptation Syndrome had fully run its course. Thus, habitats with both artificial gravity and weightlessness would not require readaptation when transitioning between them.

In Skylab 2, 3, and 4, astronauts were on orbit for 28, 59, and 84 days, respectively. A series of studies, the "M131" experiments conducted aboard the Skylab missions were investigations conducted to assess the susceptibility of astronauts in microgravity to motion sickness caused by cross-coupled Coriolis accelerations. Subjects were tested preflight, during the mission after day 5 (after adaptation to space), and postflight as soon as day 1 after return. Astronauts were placed in rotating chairs at rates of 12-30 revolutions per minute. While spinning, they conducted 150 rhythmic head movements and were monitored for symptoms of motion sickness. All astronauts tested while on orbit exhibited an immunity to motion sickness, even those who had been symptomatic during preflight testing. In addition, Skylab 3 and 4 astronauts, who spent a longer time in space than Skylab 2 astronauts, exhibited some level of postflight immunity that lasted 2 days for Skylab 3 astronauts and 5 days for Skylab 4 astronauts. The investigators further posited that this immunity is also contextual. For instance, subjects who had mild motion sickness in a rotating room had increased motion sickness when the rotation stopped. Or astronauts returning to Earth experience dizziness and motion sickness, which would not be expected with a generalized immunity theory. Thus, the investigators posited that the context of the rotating environment and the context of the zero-gravity environment are also cues that get incorporated into the generalized immunity response. The cue of being on Earth overrides the immunity and astronauts are disoriented because the unusual inputs they are continuing to receive are not expected in the Earth environment.

Another experiment examined the hand-eye coordination of subjects in rotating rooms. The investigators found that if subjects remained standing in a fixed orientation, after a period of adaptation they could throw darts consistently (Graybiel, Clark, Zarriello, 1960). Similarly, individuals in a centrifuge rotating at 12.2 rotations per minute with their head and body fixed could accurately depress buttons located 51 centimeters away. However, neither study allowed the subjects to change their orientation and then reassess their hand eye coordination.

**Figure 20:** NASA Langley rotating space station simulator.

### *6.2.4 NASA Langley Rotating Space Station Simulator Investigations*

The NASA Langley Rotating Space Station simulator was a platform shaped like a cylindrical room. It was 12 meters in diameter with a 1.8-meter wall surrounding all sides. It was equipped with servomechanized boom that could suspend subjects and allow them to walk on the walls. In 1971, research was conducted to assess the effects of rotation on walking abilities (Graybiel, 1970; Graybiel, Clark, Zarriello, 1960; Graybiel et al, 1965; Graybiel, Knepton, 1972; Guedry, 1965a, 1965b; Guedry, Kennedy, Harris, 1964; Kennedy, Graybiel, 1962). The simulator was rotated at speeds varying between 3–10.5 revolutions per minute, which corresponded to artificial gravity at levels from 0.05–0.75 G at the subject’s feet. Subjects reported that walking in the direction of rotation was most comfortable at artificial gravity levels between 0.167–0.3 G. The subjects reported sensations of leg and body heaviness when artificial gravity was above 0.3 G, which was unsettling at levels greater than 0.5 G. At 0.5 G, the lowest artificial gravity level investigated, subjects could walk in the direction of rotation, but not against it.

### *6.2.5 North American Rockwell Rotational Test Facility Investigations*

In order to better assess the appropriate artificial gravity parameters for space stations they were designing in response to NASA’s request for proposals, North American Rockwell built a rotational test facility (Diamandis, 1987). The facility had a crew module located at a mean radius of 22 meters from the center of rotation and was capable of rotating the crew module at 3, 4 and 5 revolutions per minute. Rotational forces would cause the module to swing outwards, placing the walking surface perpendicular to the total (Earth + artificial) gravity vector. Within the 3 by 12-meter crew module were a bathroom with a toilet, shower, and sink; 4 bunks; a kitchen/recreation area, and a psychomotor test area. The facility also had a movable enclosure that could be positioned at radii of 6, 12, 18, or 21 meters. Subjects were supported by sling systems that permitted walking on walls as in the Langley experiments. The room contained weighted boxes that subjects could manipulate and investigators could assess their performance.

The facility was also instrumented with equipment capable of monitoring electrocardiogram, electroencephalogram, and blood pressure changes. Subjects underwent psychomotor tests to evaluate fine motor control and dexterity; tests to assess changes in short term memory; and examinations to assess alterations in vision. The goal of the assessments was to capture the full range of effects that long-duration rotation exerted on physiological and psychological function. After an extensive physical and psychologic evaluation, including susceptibility to motion sickness, 4 subjects who exhibited low susceptibility to motion sickness were selected to participate in a 7-day experiment. These selected subjects were rotated at 4 revolutions per minute for the full 7 days.

When analyzing the results of the psychomotor tests, investigators noted a large variability between subjects, with 2 subjects' performance unaffected by rotation and the other 2 subjects' psychomotor test scores dropped significantly from pretest values (Diamandis, 1987). In addition, investigators could not distinguish between adaptation and learning as performance returned to pre-test levels within 2 days and continued to improve for all subjects over the duration of the experiment. Investigators also noted that in all subjects their psychomotor performance was faster at the hub and slowed as a function of increasing radius/G levels.

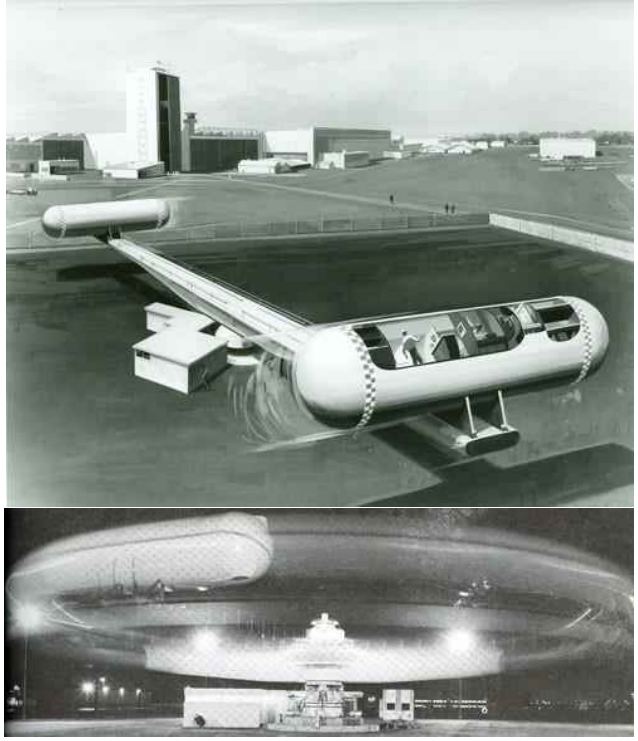

**Figure 21:** North American Rockwell rotational test facility. Artist's rendition (top), Facility in action (bottom).

As in the NASA Langley Rotating Space Station Simulator, subjects reported that walking in the direction of spin was easier (Diamandis, 1987). Subjects reported an easier ability to start and stop walking as well as an increased overall body control when walking in the direction of spin, even at artificial gravity levels as low as 0.1 G. When at a radius of 12 meters and a rotation of 4 revolutions per minute, subjects experienced 0.2 G. At this gravity level, subjects reported that walking in either direction was comfortable. At a radius of 21 meters and a spin of 5 revolutions per minute, delivering 0.6 G, subjects described walking as feeling very "Earth-like" with respect to balance and work. Subjects also reported that the most comfortable condition was the 18-meter position while rotating at 4 revolutions per minute for a 0.3 G artificial gravity force. Subjects reported that the most uncomfortable and unstable position was at the 6-meter position, regardless of revolution per minute.

Subjects used an elevator or a ladder to travel radially between the crew module and the hub. They could travel from one end through the hub to the other end. Subjects did not find any level of moving radially caused particularly stressful vestibular responses. Though they preferred the elevator, they found the ladder acceptable. When psychomotor tests were repeated after rotation stopped at the conclusion of the experiment, it took 2–4 hours for subjects to consistently perform at their pretest baselines. Symptoms of ataxia persisted for at least an additional 24 hours, but there were no severe symptoms reported by any of the subjects.

### *6.2.6 Overall Conclusions from Artificial Gravity Human Research*

The overall conclusions from researchers at the three rotating facilities have been summarized as follows (Joosten, 2007):

1. "…ground-based results can be extrapolated to the spaceflight environment only when the artificial gravity in that environment is equivalent to 1 g" (Diamandis, 1997).

2. "…at a speed of 4 rpm, some individuals will be naturally immune to motion sickness while others will have motion sickness but will adapt after a few days and suffer little decline in performance" (Shipov, 1997)

3. "When rotation ranges from 3 to 6 rev/min … the initiation of rotation will elicit changes in postural equilibrium as well as symptoms of motion sickness, the extents of which are a function of the magnitude of the angular velocity. Nevertheless, adaptation can be achieved under these conditions in 6 to 8 days, and the remainder of the stay in the rotating environment is characterized by normal health and performance" (Diamandis, 1997).

While the rotational room investigations offer some insight into the ability of humans to adapt to a rotating environment, these studies are performed on Earth where the overwhelming acceleration subjects experience is that of Earth's gravity. For instance, when at a radius of 22 meters and a rotation of 4 rotations per minute, the vector sum of the resultant centripetal acceleration (0.4 G) and gravitational acceleration (1 G) totals to 1.08 G. In microgravity, the only acceleration would be 0.4 G. These results cannot inform whether such acceleration will prevent physiologic deconditioning. These results did, however, demonstrate the ability of subjects to overcome motion sickness and perform with high proficiency. Anticipated problems with eating, sleeping, or other activities were not noted.

### 6.3 Artificial Gravity "Comfort Charts" and Design Criteria

The effort to understand and design for artificial gravity human habitats leads to attempts to simplify design criteria by optimizing and visualizing the intersection of various design and engineering parameters. Data used to establish these comfort zone visualizations, or "Comfort Charts" included the results of the aforementioned rotation room studies as well as mathematical predictions. One of the earliest was the 1962 Hill and Schnitzer comfort chart, which was widely circulated (Hall, 2006; Hill, Schnitzer, 1962). Over the years multiple authors have crafted comfort charts that used different formats and at times failed to properly account for statistical variation among subjects, which is particularly important in life sciences research.

Based on the research conclusions from the three facilities reviewed above, many subsequent studies assumed a maximal rotational rate of 4 revolutions per minute, which impacts spacecraft design— at that rate, to achieve an artificial gravity of 1 G, a radius of 56 meters is necessary. Others have assumed a maximum of 6 revolutions per minute, thus requiring a radius of 25 meters. These criteria were incorporated into multiple "comfort charts" based on research with individuals in spinning rooms. Yet, such studies assume that astronauts cannot adapt to higher rotational rates, which is untrue—adaptation to higher rates were shown by the M131 investigations aboard Skylab and in the Pensacola rotating rooms. Subjects were able to eventually adapt to a rotational rate of 10 revolutions per minute with no intervention, and with a stepwise intervention they were able to adapt comfortably and with no symptoms. The M131 astronaut subjects adapted to rates higher than this without difficulty. Ground subjects undergoing rotation are actually experiencing a vector sum of accelerations. If rather than assuming ground-based levels of comfort, rotating habitat design set a gravity gradient to an uppermost value of 20%, then the minimum radius for the habitat would be 7.5 meters with an 8 revolution per minute rotation to achieve 1 G.

Various investigators developed different versions of a comfort chart based on their own experimental research or mathematical models. Figure 22 is a composite of these multiple comfort charts into a single representative Comfort Chart.

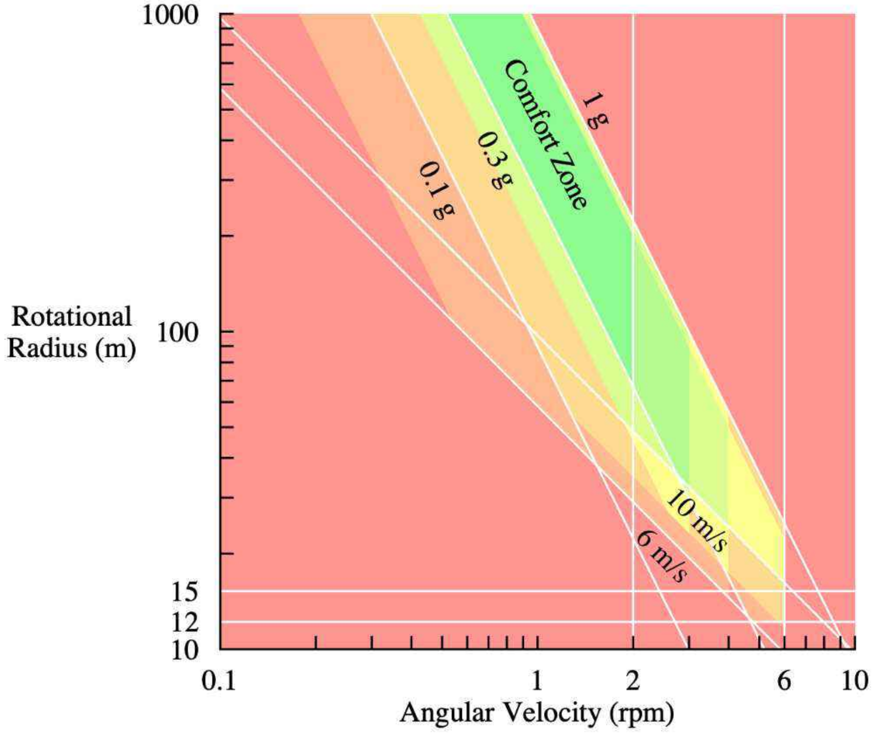

**Figure 22:** The green zone depicts conditions that all agree were comfortable, requiring little adaptation. The red zone depicts conditions that all agree are not comfortable, even after a period of adaptation. The intermediate zones ranging through shades of yellow and orange depict areas of disagreement. Moving through these zones, away from the green and toward the red, demands greater adaptability of the inhabitants to the peculiar conditions of life in constant rotation.

### *6.3.1 Artificial Gravity Designs (20th Century)*

The 11 artificial-gravity Earth-orbital laboratory designs examined in 1963 by the NASA Manned Spacecraft Center were based on repurposing Apollo Command, Service, and Mission Modules (NASA Manned Spacecraft Center, 1963; Portree). Their designs assumed a maximum rotation of 4 revolutions per minute. At 4 revolutions per minute at a distance of 40 feet from the center of rotation, astronauts would feel an acceleration that varied by 15% from head to toe. The maximum acceleration at the feet was set at 1 G and the minimum at the head specified to be no lower than 0.2 G (roughly lunar gravity). Their studies focused on the maximum amount that astronaut movement parallel to spin axis would perturb the laboratory's spin (e.g., precession or "wobble") as well as keeping the acceleration variation under 15%. For all eleven designs, the precession angle is indicated by the design number (e.g., D1—D11), as shown in Figure 23.

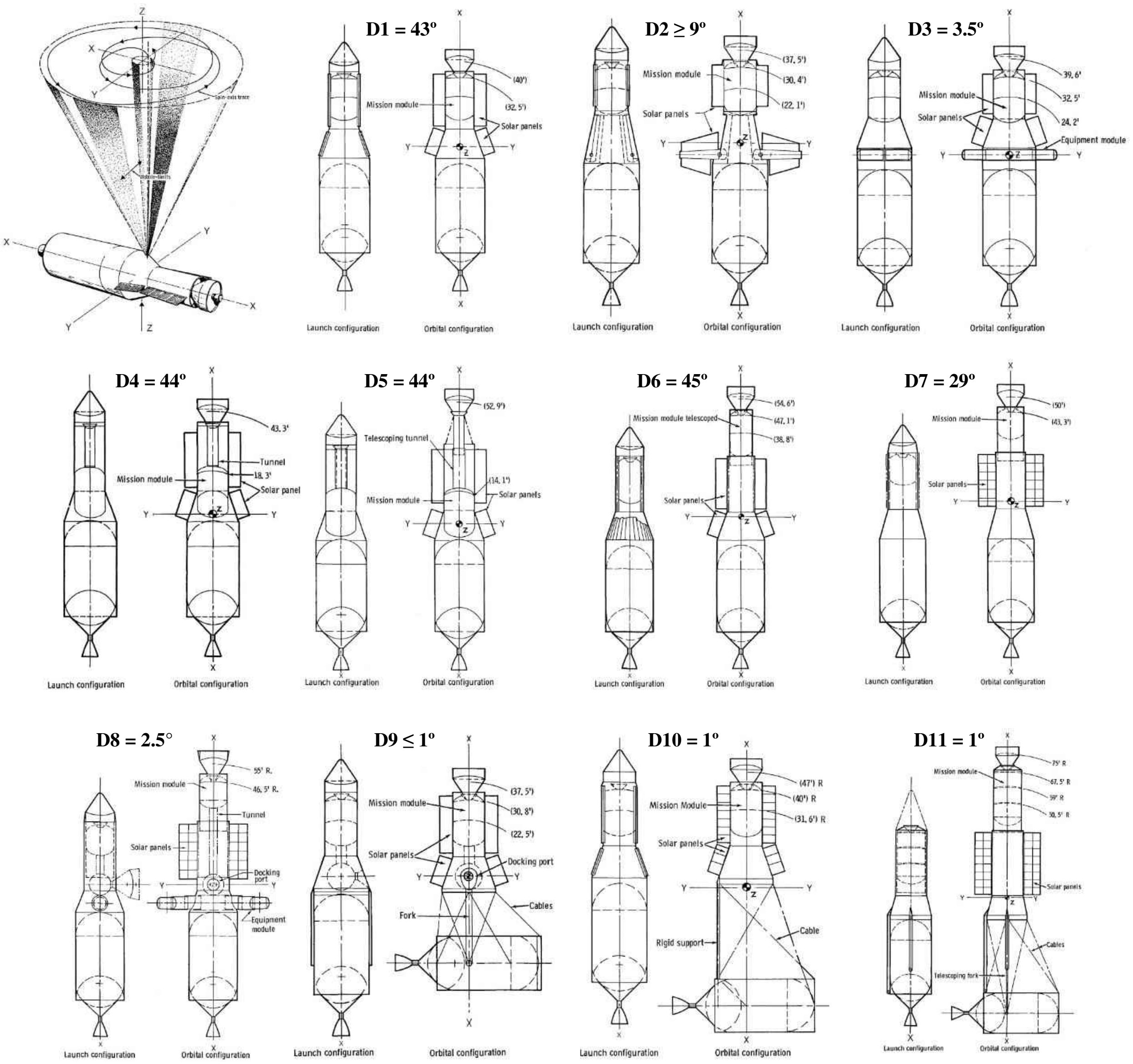

**Figure 23:** 1963 NASA designs for artificial gravity Earth orbital laboratory using repurposed Apollo Command, Service and Mission Modules.

Following these designs, in 1966 the Manned Spacecraft Center developed three classes of space station designs with artificial gravity, designated “I,” “Y,” and “O” (Bukley, Paloski, Clément, 2007; Faget, Olling, 1968)

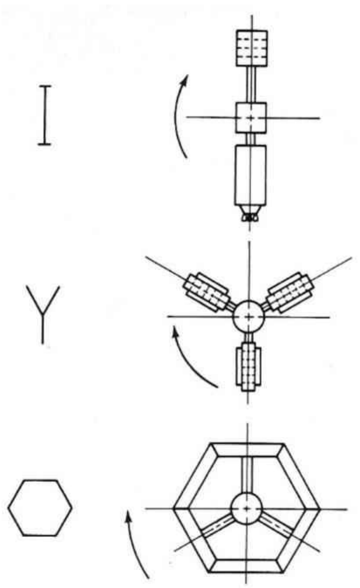

**Figure 24:** The I, Y, and O space station designs.

Many of the I designs consisted of a habitat module and a spent Saturn V second stage rocket, which were designed to connect to a central 0-G hub with telescoping arms (NASA Manned Spacecraft Center, 1966). The spent rocket would provide the counterweight for rotation. If the station were rotating at 4 revolutions per minute, this would provide artificial gravity in the lower deck of the station at roughly equivalent to 0.5 G. This preliminary station would be the proof of concept for a larger “one million pound” station that would measure 187 meters and house 50 astronauts (Gilruth, 1969). The center of rotation of the station was designed to be 73 meters to the outermost part of the habitat module. A 3.5 revolution per minute rotation would provide 1 G. The central hub would rotate in an equal and opposite direction, providing a platform for 0-G investigations. Based on preliminary ground-based studies in rotating rooms, the belief was that short-radius systems with higher rotational velocities would cause crews to suffer disorientation and motion sickness and result in collateral disorienting effects, such as dropped items falling in a curve rather than in a straight line.

The Y station was informally referred to as “Project Olympus,” and was intended to house 24 astronauts (Compton, Benson, Dickson, 2011; Portree, 2013). It would supply different levels of gravity at different distances from the central hub. The hub’s centrifuge would also permit varying gravity for a variety of experiments. One Y station design featured elliptical arms that measured 14.7 meters in diameter and 18.6 meters long. Within each arm contained with three decks each that were 2.4 meters high and 4.5 meters in diameter internally. A centrally located tube through the decks permitted movement between them. In this design, the artificial gravity would vary by deck, therefore sleeping quarters were in the maximum 0.2 G floor at the outer edges of the station’s arms. A 10% scale model (320 kg) of this station was built to evaluate deployment mechanics.

The O station was first proposed as a self-deploying rotating hexagon in June 1960 in a design study with North American Aviation before they merged with Rockwell Manufacturing Company (Fries, 1986, 1988; Heppenheimer, 1999). The design specified that the station would provide 0.2 G of artificial gravity. The 6 segments of the hexagon were comprised of modules measuring 23 meters long and 3 meters in diameter. This hexagonal rim was then connected to a central hub by 1.5-meter diameter, 14.6-meter-long spokes. The hub itself was designed to be 3.9 meters in diameter and was 5.2 meters tall. The station was intended to carry 21 astronauts, with 7 of them rotating continuously in three 8-hour shifts. There were other various proposed station designs, for instance, circular rather than hexagonal rims were to be constructed using inflatable components.

Of the 3 station designs, the I station was preferred due to payload size and weight constraints that arose when plans shifted from deploying the station aboard a Saturn V rocket to new requirements that the station fit within a Space Shuttle payload bay (Heppenheimer, 1999). Therefore, more I stations were conceived.

Though having performed its own studies, NASA released a call for proposals to industry on 19 April 1969 to investigate a 12-man Space Station and a reusable Space Shuttle to transport the crew back and forth (Compton, Benson, Dickson, 2011; Lewis, 2010). The 12-man Space Station was intended to be the first step towards a 100-man Earth-orbital Space Base (Tiesenhausen, 1970). The intent was to launch the 12-man Space Station on a Saturn V rocket in 1975. Once in orbit, the station would operate for 10 years. The companies Grumman, McDonnell Douglas Astronautics Company, and North American Rockwell submitted proposals. The latter two companies were awarded contracts on July 22, 1969, with work formally beginning in September 1969 (Heberlig, 1972). Each company's team included over 30 subcontractors. NASA's Manned Spacecraft Center in Houston managed North American Rockwell's work, while Marshall Space Flight Center in Huntsville, Alabama, managed McDonnell Douglas Astronautics Company's work.

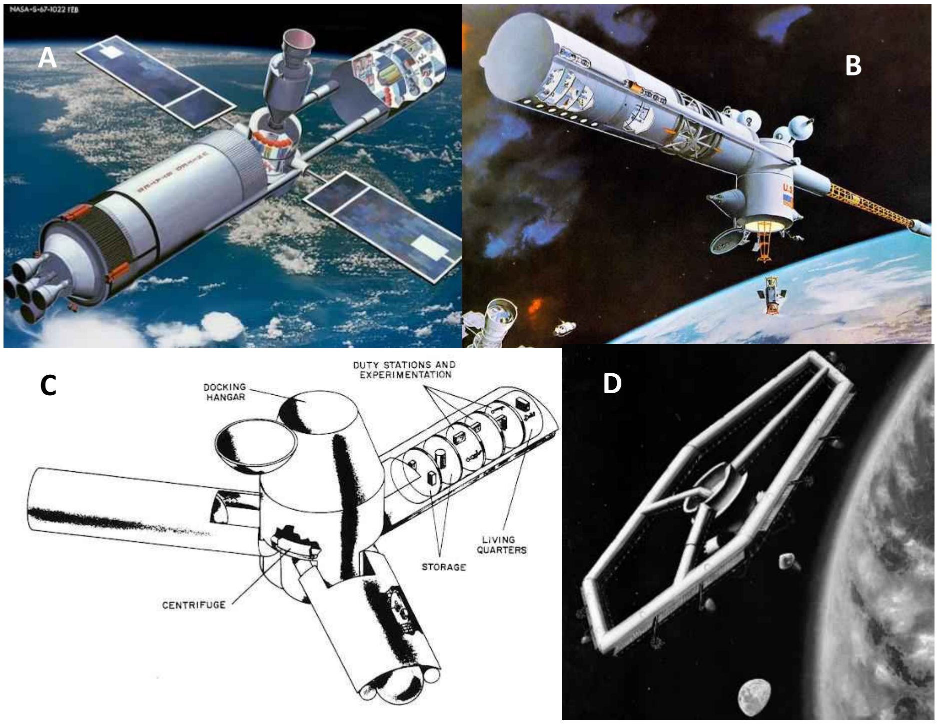

**Figure 25:** **A**: Manned Spacecraft Center Space Station design with artificial gravity. Top right of image shows habitat module and bottom left shows a repurposed Saturn V second stage rocket. **B**: "One-million-pound station." Both A and B are examples of I-type designs. **C**: "Project Olympus" station was a Y type design intended to serve 24 astronauts. **D.** This "O" design was a hexagonal self-inflating station.

The design criteria were as follows: "Space Base will provide artificial G and 0 G environments in separate volumes simultaneously. For example, the principal living quarters, command and control stations, and some laboratory space may be located in the rotating arm for the effectiveness, comfort, and convenience of the crew…. Acceleration levels in the main operating and habitability volumes will be between 0.3 and 0.7 times gravity. The nominal rotational rate will be 4 rpm" (Green, Peacock, Holm, 1971).

The McDonnell Douglas proposed station was 9.2 meters in diameter and 34 meters long (Messerschmid, Bertrand, 2013). It was designed to have two main modules: an artificial gravity module and a core module. The antigravity module was designed to be conical and had two decks. The core module was cylindrical and had four decks. Each module was designed with living and research areas with independent life support systems. Once on orbit, a telescoping component would separate the two modules by several meters. The station would then achieve artificial gravity through small thrusters in an artificial-gravity module that set the station spinning at a rate of 4 revolutions per minute about its center of mass. Deck 1 of the core module was 19.2 meters from the station's center of the mass and would provide 0.35 G. The Deck 6 living area was 39.3 meters from the center of mass and would provide 0.7 G. The rotation providing the artificial gravity could be stopped and restarted up to 4 times.

In order to better assess the appropriate artificial gravity parameters, North American Rockwell used their rotational test facility to guide their station designs. The North American Rockwell 12-man design did not include artificial gravity in order to accommodate solar panels. The crew compartment, however, was designed to be modular, and when scaled up to the 100-man nuclear powered station, would be repurposed and attached to arms that would rotate around the station.

Concurrently to examining space stations, NASA also explored interplanetary spacecraft. In 1962 NASA funded three contractors to examine piloted flyby and orbiter expeditions to Mars and Venus. Aeronutronic focused on flybys; Lockheed explored both flybys and orbiters; and General Dynamics focused on orbiters (Genta, 2017; Ordway, Sharpe, Wakeford, 1994). These studies were part of the Early Manned Planetary-Interplanetary Roundtrip Expeditions (EMPIRE) program at NASA Marshall Spaceflight Center (Ordway, Sharpe, Wakeford, 1994). All three contractors designed heavy spacecraft structures for generating artificial gravity.

NASA Marshall's in-house piloted Mars spacecraft design was a 150-meter long, diamond-shaped, flat ship. A nuclear reactor that supplied power would also serve as a counterweight to provide artificial gravity. The separation needed to keep the crew a safe distance would serve as the spin radius, and the ship would rotate 1.3 times per minute to produce acceleration equal to 0.1 G.

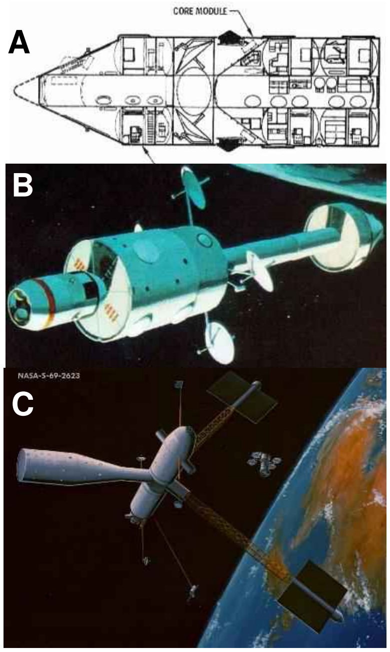

**Figure 26:** **A**: Cutaway of McDonnell Douglas Astronautics Company's 12-man space station in launch configuration. Black triangular features are twin isotope/brayton nuclear power units. **B**: McDonnell Douglas's station with artificial-gravity module (right) extended. **C**: McDonnell Douglass's 100-man space station.

Aeronutronic's design consisted of a ship's core containing the command center; spent second-stage hydrogen propellant tanks to help shield the ship's core against radiation and meteoroids; and two cylindrical crew compartments. To engage artificial gravity, the crew compartments would deploy from the core on booms; then the entire ship would rotate.

The Lockheed design consisted of an Apollo Command and Service Module, a habitation module, and a lightweight flyby spacecraft stacked on one another. These would be launched together, then while in space they would separate. At this point, the flyby spacecraft would automatically unfold two long booms from either side of a hub. Then the Command and Service module would dock at the end of one boom to act as the counterweight for a cylindrical habitation module located at the end of the other boom. Both the command and service module and the habitation module would experience artificial gravity.

The General Dynamics design had multiple ship configurations for each propulsion stage; after each major maneuver, the rocket stage would be cast off. In essence, Maneuvers 1-4 had stages M-1 through M-4. A spine module 23 meters long and 3 meters in diameter was attached to the M-4 stage and the crew module, both to separate the astronauts from the nuclear engines to reduce radiation exposure to the crew and to elongate the spin radius. The artificial gravity parameters were arbitrarily set to be 0.25 G at 5 rotations per minute, which was decided to be the upper limit for the crew to be comfortable. However, as stages M-1 through M-3 were

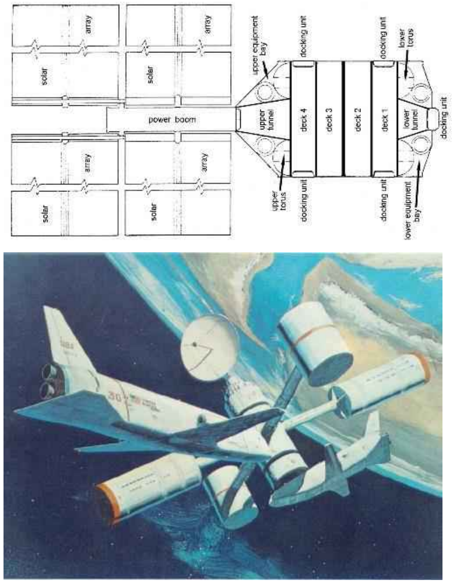

**Figure 27:** North American Rockwell's 12-man design (top) and 100-man design (bottom).

discarded the spin radius progressively decreased, increasing the rotation rate necessary to maintain 0.25 G. They proposed docking with an accompanying service module after the loss of M-3 to prevent the rotation rate from increasing to levels considered too high.

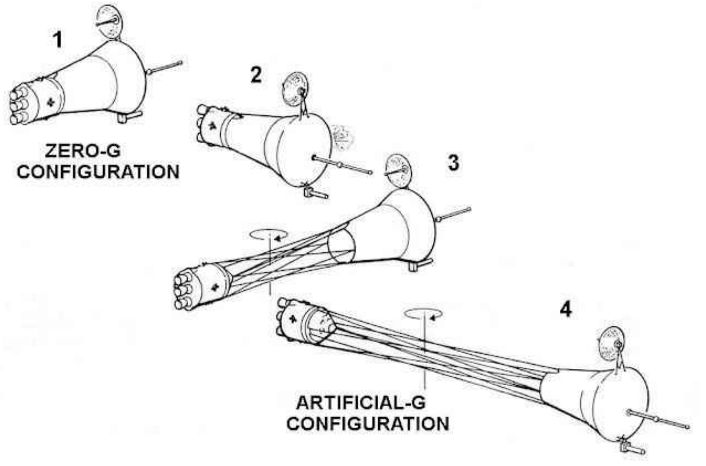

**Figure 28:** The North American Aviation Mars flyby design.

Following the contractor investigations, in 1963 multiple NASA centers began investigating the possibility of adapting Apollo spacecraft and Saturn rockets for crewed Mars and Venus flybys (Bell, 1967; Crocco, 1956; North American Aviation, 1965; Portree, 2014; Yarymovych, 1983). NASA's Ames Research Center contracted with the TRW Space Technology Laboratory to explore a non-nuclear design. To provide artificial gravity, the TRW study proposed to spin the main spacecraft via a 150-meter-long tether linking it to the expended booster stage. TRW had NASA Langley use computer modeling to confirm the long-term rotational stability of their design. The NASA Manned Spacecraft center contracted with North American Aviation. The North American Aviation Mars flyby proposal offered artificial gravity as an option that could be deployed or decided against while in flight. To engage the artificial gravity, crew would put the spacecraft in a spin and separate the housing encasing the spacecraft. Then they would slowly feed out connecting cables and the concept relied upon the rotational acceleration to cause the housing to move away from the main spacecraft, until the cables reached their maximum extension of 48.1 meters. Four rotations per minute would provide 0.4 G, which is roughly equivalent to gravity on Mars.

After EMPIRE, during the Unfavorable Manned Planetary-Interplanetary Roundtrip Expeditions (UMPIRE), Marshall Future Projects Office team began an in-house study to investigate repurposing Apollo hardware for Mars exploration (Portree, 2001). Their study deemed that artificial gravity systems that rotated the entire craft were too complex and heavy. Instead, their design included a spherical habitat containing a radiation shelter and a small centrifuge to provide artificial gravity.

In 1971, the Planetary Missions Requirement Group (PMRG), which included representatives from several NASA centers, oversaw the last Mars mission design until the 1980s (Rapp, 2007, 2016; Shayler, Salmon, Shayler, 2005). The Manned Spacecraft Center's design would comprise three modules and six chemical propulsion stages. The Mars spacecraft would be assembled in space and contain a 20 meter long Electrical Power System module and a Mission Module with 4 decks weighing approximately 55 tons. The spacecraft was designed to be in an I configuration to simplify transport into orbit using Shuttles. To achieve artificial gravity, the spacecraft would be rotated at 2 revolutions per minute to produce 1/6 G, which is approximately 1 Lunar G.

In 1989, the Space Exploration Initiative (SEI) called for NASA to write a report describing their plans to construct a space station, revisit the Moon, then travel towards Mars (Johnson-Freese, 2004; Zubrin, 2011). They had 90 days to complete the study. One of the plans put forth a visit to Mars' moon Phobos, followed by travel to Mars itself (Stuart, McElrath, Petropoulos, 2015; Zubrin, Baker, Gwynne, 1991). The design had a large aerobrake shaped like a disk for entry into the atmosphere and two cylindrical habitats that would have relied upon future space station technology. The habitat modules would be extended from the aerobrake with the tethers, then the two would be rotated to achieve artificial gravity. Shortly afterwards, Lawrence Livermore National Laboratory proposed an alternative to The 90-Day Study, called The Great Exploration (Roy, 1998).

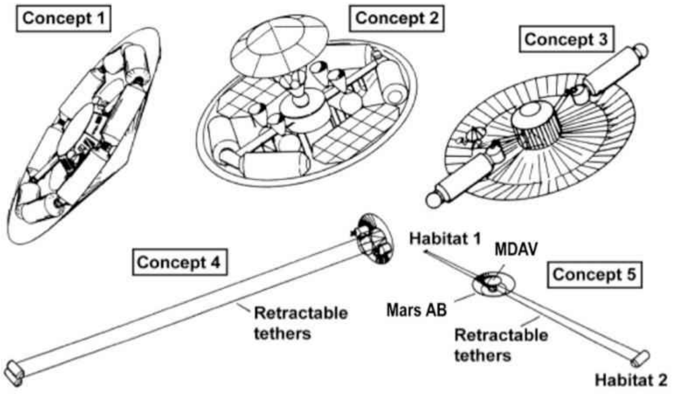

**Figure 29:** Martin Marietta's Mars Direct aerobraking and artificial gravity tether designs.

The Great Exploration focused on space stations, which would be launched into orbit in a folded configuration. An Earth Station, a Gas Station, and an Apollo Command Module would be stacked and once in orbit, would deploy and inflate automatically. Seven 15-meter-long cylindrical modules stacked longitudinally comprised the Earth Station. The Earth Station would achieve artificial gravity by undergoing 4 revolutions per minute. Because the decks would be arranged perpendicularly to the long axis of the cylinders, artificial gravity would vary from Lunar to Martian gravity at decks progressively further from the center of rotation.

On April 20, 1990, Martin Marietta presented their research aimed at developing Space Exploration Initiative concepts. Their plan, entitled "Mars Direct" did not involve assembly in space but rather proposed a direct route to Mars by exploiting *in situ* resource utilization and combining concepts from the 1950s-1960s, including using a tether to supply artificial gravity (Zubrin, Baker, Gwynne, 1991). A disk-shaped crewed spacecraft 8.4 meters in diameter and approximately 5 meters tall would contain two floors (Figure 29). The top floor would house the crew while the bottom carried cargo and equipment. The upper stage of a rocket would launch the spacecraft towards Mars and detach, but the stage and the spacecraft would remain attached by a 1,500-meter tether. Artificial gravity equivalent to Mars gravity would be achieved by rotating the tethered stage and spacecraft at 1 revolution per minute.

In 1999, NASA Glenn Research Center proposed a Mars vehicle named *von Braun* that used nuclear propulsion and power, eliminating the need for solar panels (Donahue, 1999). This permitted rotation of the vehicle about its center of mass and perpendicular to its trajectory. On the way to Mars, the ship would be rotated at 4 revolutions per minute to provide artificial gravity equivalent to gravity on Mars (0.38 G). During the return to Earth, the rotation rate would be increased to 6 revolutions per minute to provide closer to Earth gravity (0.79 G). By increasing the rotation rate to 6.8 revolutions per minute, full Earth gravity could be achieved. Many of the concepts in the Glenn Research Center's design were borrowed from the Mars Direct concept. In fact, from 1992 onwards, many of NASA's Mars plans have originated from the Mars Direct concept (Dolan et al, 2020).

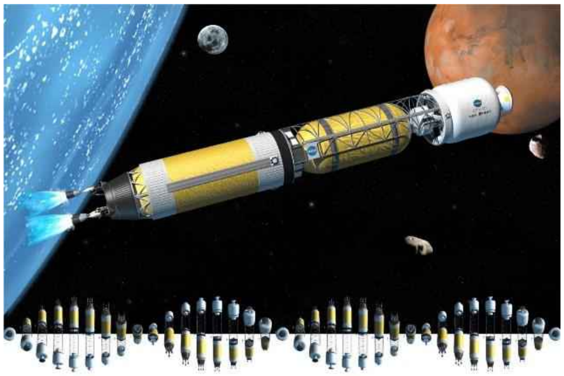

**Figure 30:** NASA Glenn Research Center *von Braun* design.

### *6.3.2 Artificial Gravity Designs (21st Century)*

In 2006, researchers proposed 0.2 - 0.5 G levels of artificial gravity using the control systems of the Space Shuttle (Bukley, Lawrence, Clément, 2007; Bukley, Paloski, Clément, 2007). One method required rotating the shuttle about an eccentric roll axis similar to the baseline orbital trajectory of the vehicle at a constant angular velocity. The eccentric roll maneuver would induce artificial gravity towards the bottom of the vehicle. The other method involved rotating the shuttle in pitch about its center of gravity. The pitch maneuver would induce artificial gravity towards the nose of the shuttle.

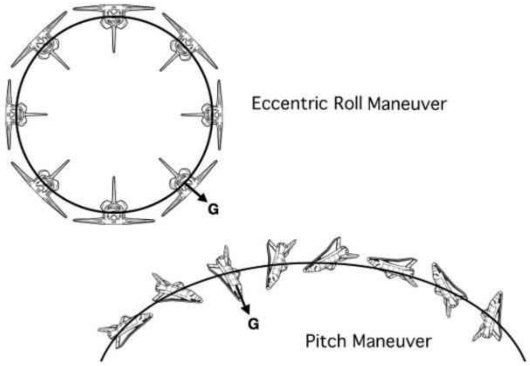

**Figure 31:** Artificial gravity system with the Space Shuttle using its control systems.

Following a feasibility analysis of the eccentric roll maneuver it was determined that the maneuver was beyond the capabilities of the Space Shuttle orbital control system. The pitch maneuver, however, was possible and the Space Shuttle actually performed it during the return-to-flight missions STS-114 and STS-121 prior to docking with the ISS (Bukley, Paloski, Clément, 2007). This maneuver permitted the ISS crew to photograph the Shuttle's heat shield. However, the rotation rate during the pitch maneuver was 0.125 revolutions per minute, which generated artificial gravity of 0.0003 G, significantly too low for human perception.

In the early 2000s, NASA commissioned designs that investigated artificial gravity (Borowski, McCurdy, Packard, 2014). In 2007, engineers from Johnson Space Center proposed an I type spacecraft that was 125 meters in length. This design had a nuclear reactor on one end and a crew compartment on the other. In designing the structure, engineers assumed that 1 G was necessary because there was no evidence supporting or disproving the efficacy of partial gravity. It was designed to rotate at 4 revolutions per

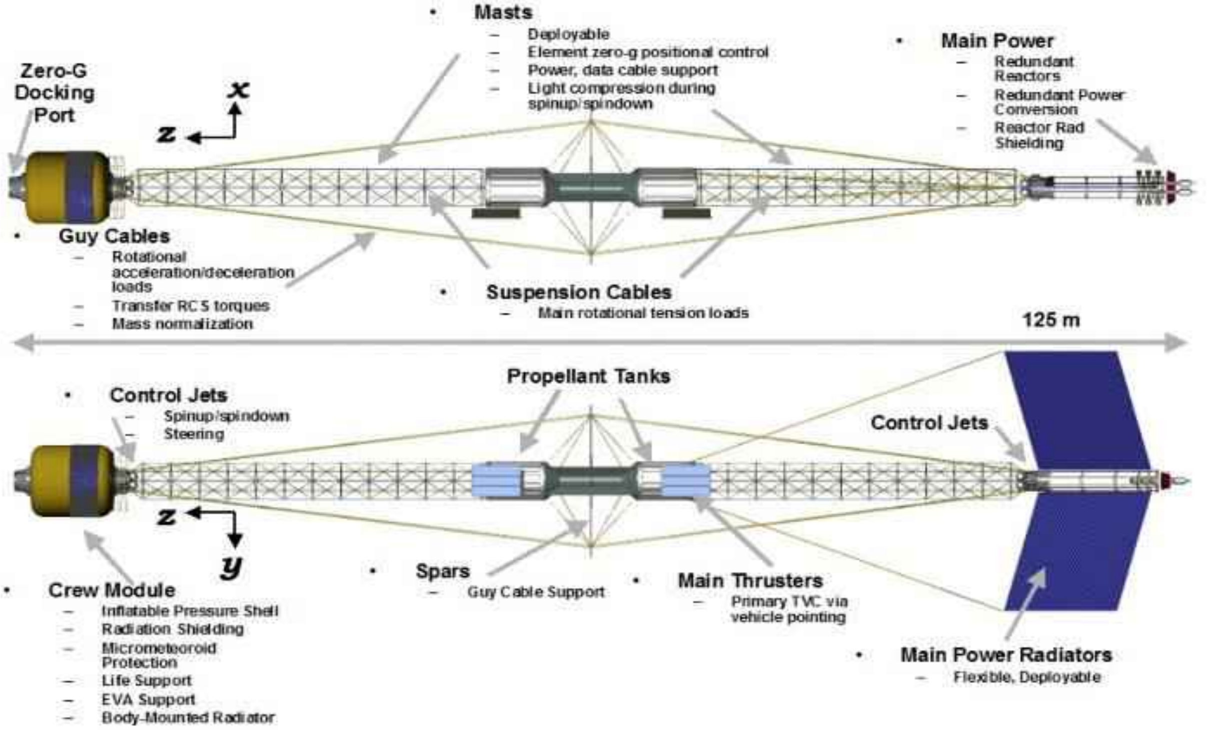

**Figure 32:** Johnson Space Center artificial gravity spacecraft.

minute. The propulsion of the spacecraft would act perpendicularly to the ship's longitudinal axis and along the axis of its spin to transport astronauts to Mars and back.

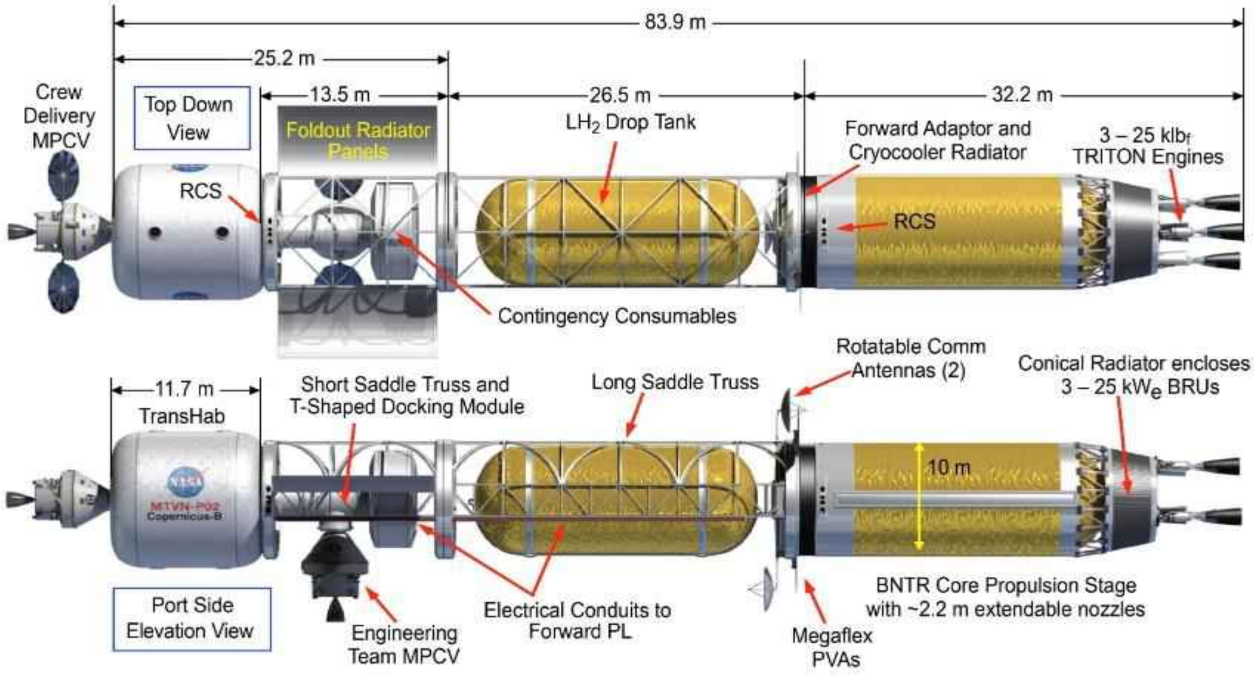

**Figure 33:** NASA Glenn Research Center's *Copernicus-B* design

From 2007 to 2008, NASA conducted an inter-center, multi-directorate investigation to better describe the necessary requirements and concepts for a human mission to Mars (Ja'Mar, 2019). Called the Mars Design Reference Architecture (DRA) 5.0 study, it was essentially an update to the earlier Design Reference Mission (DRM) 4.0 study conducted in 1999 that resulted in the *von Braun*. Because artificial gravity vehicles were ruled out of the Design Reference Architecture 5.0 study, the *Copernicus* spacecraft design proposed was a 0 G design (Borowski, McCurdy, Packard, 2014). After the Design Reference Architecture 5.0 study was complete, NASA Glenn Research Center developed the *Copernicus-B* spacecraft, because crew fitness after approximately 2.5 years in space was unlikely. The *Copernicus-B* spacecraft was designed with an overall length of 83.9 meters, a rotation radius of 35.8 meters, and a 1 G rotation rate of 5.2 revolutions per minute. The mission design had the spacecraft rotating at 5.2 revolutions per minute (1 G) to maintain maximum crew fitness, then 30 days before their arrival at Mars that rotation rate would be reduced to 3.1 revolutions per minute to provide 0.38 G, which is equivalent to Martian gravity. Crew would be readapted to 1 G on the return from Mars to Earth, where the rotation rate would be increased by 0.124 G per month until the final month of the mission when artificial gravity would again be 1 G.

In 2011, engineers from NASA Johnson Space Center developed the concept spacecraft called the Non-Atmospheric Universal Transport Intended for Lengthy United States eXploration (*Nautilus-X*) (Holderman, 2011). The *Nautilus-X* was designed with a 6.5 by 14-meter main corridor that was stationary and a rotating habitable torus with expandable, inflatable structures that would be

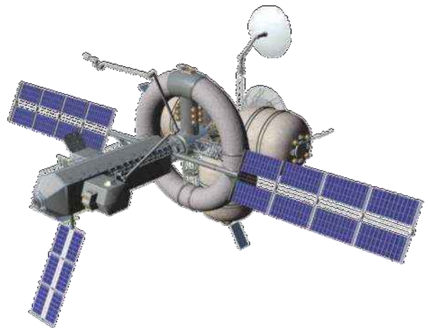

**Figure 34:** NASA Johnson Space Center's Nautilus-X.

reinforced by rigid structures. The design was modular, with the goal that it could easily be reconfigured to accommodate multiple types of mission specific modules.

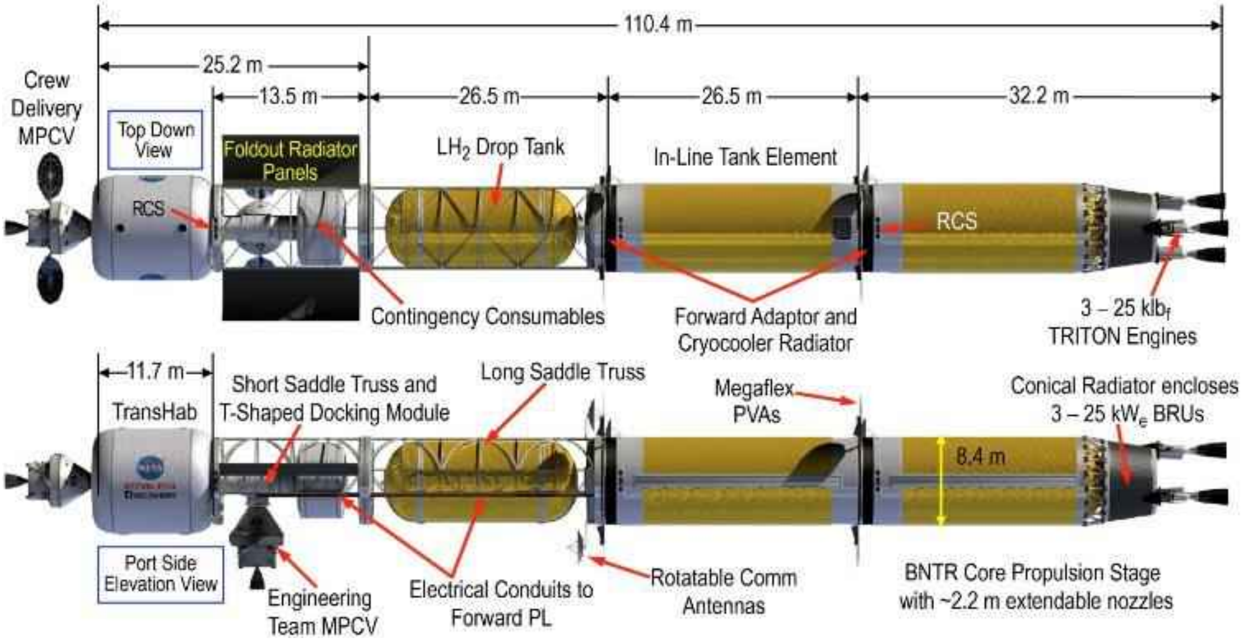

**Figure 35:** The Discovery spacecraft design

In 2016, an elongated version of the *Copernicus-B* called *Discovery* was designed with a length of 110.4 meters a larger rotation radius of ~46.7 meters (Borowski, McCurdy, Packard, 2014). It would follow the same vehicle spin-up / spin-down out to Mars and back to Earth as that proposed for the *Copernicus-B*. During the first 150 days of transit to Mars, the *Discovery* would rotate at 4.38 revolutions per minute to generate 1 G at the crew compartment in the crew compartment (the TransHab). In the last 30 days, the *Discovery* would rotate at a rate of 2.7 revolutions per minute to generate 0.38 G at the TransHab. During the return trip to Earth, because the *Discovery* would have ejected mass from rocket stages, landers, and propellant while in Mars orbit, its center of mass would have shifted backwards to 38 meters. With this new rotation radius, the required spin rate needed to generate 0.38 G for the return trip would be 3 revolutions per minute. After the first 30 days, as with the Copernicus-B the artificial gravity would be gradually increased by 0.124 G per month over the next 4 months until the spacecraft is 30 days from Earth. At this point, 4.84 revolutions per minute would achieve 1 G for the crew.

A final design with a twin habitat configuration, named the *A. C. Clarke*, was designed to rotate about its longitudinal axis while following a trajectory perpendicular to that axis (Borowski, McCurdy, Packard, 2014). The *A.C. Clarke* was designed with an overall length of 89.4 meters and a rotation radius intended to be 17 meters from the center of the operations hub to the floor of each habitat module. To achieve Mars gravity (0.38 G), it would be rotated at a spin rate of 4.5 revolutions per minute, while lunar gravity (0.167 G) would require 3 revolutions per minute, and Earth gravity (1 G) would require 7.25 revolutions per minute. Although the 7.25 revolution per minute rotation rate is higher than the 4-6 revolution per minute limit recommended by some authors, it is well below the 10 revolution per minute rotation rate test subjects were exposed to during the Pensacola studies. Nevertheless, the rotation rate can be reduced by increasing the rotation radius via extending the length of the *A.C. Clarke's* star truss, thereby lengthening the transfer tunnels. The *A. C. Clarke* would follow the same transitions from Earth to Mars to Earth levels of artificial gravity as would the *Copernicus-B* and *Discovery*.

Finally, in 2020 engineers from NASA Marshall Space Flight Center developed a concept for a “common design” for Deep Space Transport (DST; Figure 37) (Marquez, Smitherman, 2020). The spacecraft was designed to reduce costs of a mission to Mars by building multipurpose elements into it. The common design could be adapted to 2 different layout configurations. The first was a 0-G spacecraft in which its habitats are stacked. The second was an artificial gravity spacecraft that would rotate the stacked habitats perpendicular to the spacecraft’s axis, extend the habitats on booms, then rotate the entire spacecraft to provide artificial gravity. In both configurations, the habitat could also be used as a habitat on Mars.

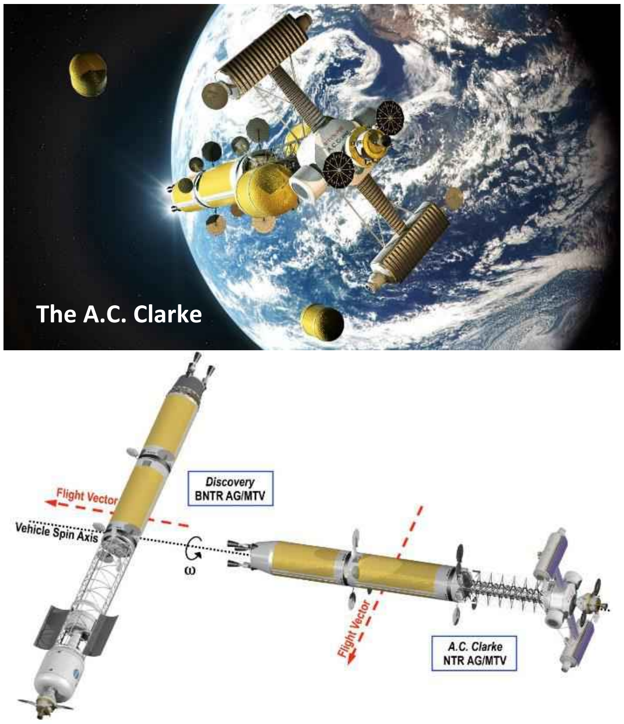

**Figure 36:** Top: The A.C. Clarke spacecraft design. Bottom: The Discovery and A.C. Clark showing rotation and flight direction.

To date, none of the designs proposed have been built. There are engineering, propulsion, vibration, human factors, and spacecraft docking complexities involved with rotating the entire vehicle or station. Though rotating one component of a vehicle while keeping the remainder of it stationary averts some of these complexities, there are additional moving parts required, which adds complexity in another area. Therefore, the short-radius centrifuge is being further investigated both for cost and reduction in (actual and perceived) complexity. There are additional complexities to using centrifuges, such as a high gravity gradient imparted to the subject, high vibration imparted to the supporting station—both of which necessitate costly vibration isolation systems, which contributed to the cancellation of both centrifuges intended for the ISS (Clément, Charles, Paloski, 2016).

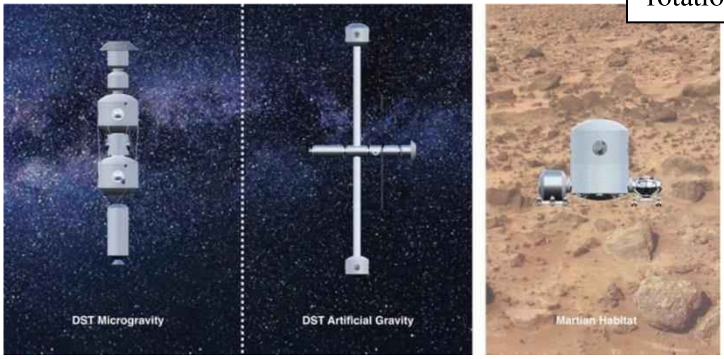

**Figure 37:** NASA Marshall Space Flight Center Common Design for Deep Space Transport

## 7. BENEFITS AND CHALLENGES OF VARIABLE AND PARTIAL G HABITATS

To date, there is no definitive answer as to the benefits of artificial gravity on human health and functioning in space. And although there are no current existing operational countermeasures that have been fully effective in preventing deconditioning during long-duration spaceflight, the vast majority of knowledge on human physiology and performance during spaceflight is in microgravity. While suggestive, conjecture on the impact of artificial gravity in space is based off of very little *direct* human evidence. Centrifugation to approximate artificial gravity in ground-based studies results in a vector sum of the centrifugal and gravitational forces. These summed force vectors confound direct interpretation/ application to a rotating habitat in space. Further, while bed rest studies have shown some level of benefit provided by centrifugation for certain physiological systems, it does not benefit all physiological systems

(Akima et al, 2005; Stenger et al, 2012; C.-B. Yang et al, 2011). Furthermore, bed rest does not fully mimic spaceflight. Finally, centrifugation while in bed rest may not directly translate to centrifugation while in microgravity because, as described above, the gravity vectors are different on Earth than would be experienced in space. Similarly, ground-based studies have suggested that exercise in an artificial gravity field is necessary to prevent microgravity-induced deconditioning (Akima et al, 2005), but their predictive value cannot be relied upon.

NASA, in cooperation with many international partners, is currently planning various mission scenarios to cis-lunar space, the Moon, near Earth asteroids, Mars, and the Martian moons. In 2014, a 2-day international artificial gravity workshop was held at NASA Ames Research center. The conference was attended by "… knowledgeable space physiologists, crew surgeons, astronauts, vehicle designers, and mission planners" (Paloski et al, 2014). The goal was to assess the need for artificial gravity in vehicles that would travel to these destinations. The workshop also proposed research questions that need answers in order to fully assess the value of artificial gravity. Proposed experiments included short-radius human centrifuges that would be used on the ground, while long term (30-180 days) rodent research on the ISS would explore the efficacy of 1 G artificial gravity at preventing typical physiological changes. In addition, research proposed included investigations aimed to answer whether intermittent artificial gravity in a short radius centrifuge may provide benefit. The 2014 artificial gravity workshop proposed either intermittent artificial gravity or continuous artificial gravity. Intermittent artificial gravity could be achieved by either spinning part of the spacecraft or using a short radius centrifuge, while continuous artificial gravity would be achieved by spinning the entire spacecraft.

In their final report, the National Commission on Space recommended the construction and launch of an orbiting Variable-G Research Facility to better understand the gravity requirements and tolerances of the human body. In NASA's many reports throughout the years, there are many concepts to draw from when designing an orbiting habitat, including inflatable habitats. Each design is an opportunity to build upon or cannibalize.

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Research on animals in rotating habitats in space provide insight to guide human studies. In 2017, investigators with JAXA reported the impact of artificial gravity (1 G) and microgravity on mice using newly developed mouse habitat cage units (Shiba et al, 2017). These units were installed aboard the International Space Station in the Centrifuge-equipped Biological Experiment Facility. Although centrifuge experiments had been conducted aboard the ISS since 2008 with aquatic organisms, cultured cells, plants and worms, because the centrifuge was so small (0.15-meter radius) no vertebrate studies had been performed until the development of these habitat cage units. In this facility, Earth's gravity (1 G), Martian gravity (0.38 G), and lunar gravity (0.16 G) can all be approximated by the rotating the centrifuge at 77, 48, and 31 revolutions per minute, respectively.

Twelve male mice were housed either in artificial gravity or microgravity for 35 days; while a concurrent ground control experiment with identical housing conditions was also conducted (Shiba et al, 2017). Upon examination, microgravity-exposed mice showed significant decreases in bone mineral density of the femur as well as dramatic declines in the weight of the soleus/gastrocnemius muscle complex (Okada et al, 2021; Tominari et al, 2019). In contrast, mice maintained in artificial gravity retained the same bone density and muscle weight as mice in the ground control experiment.

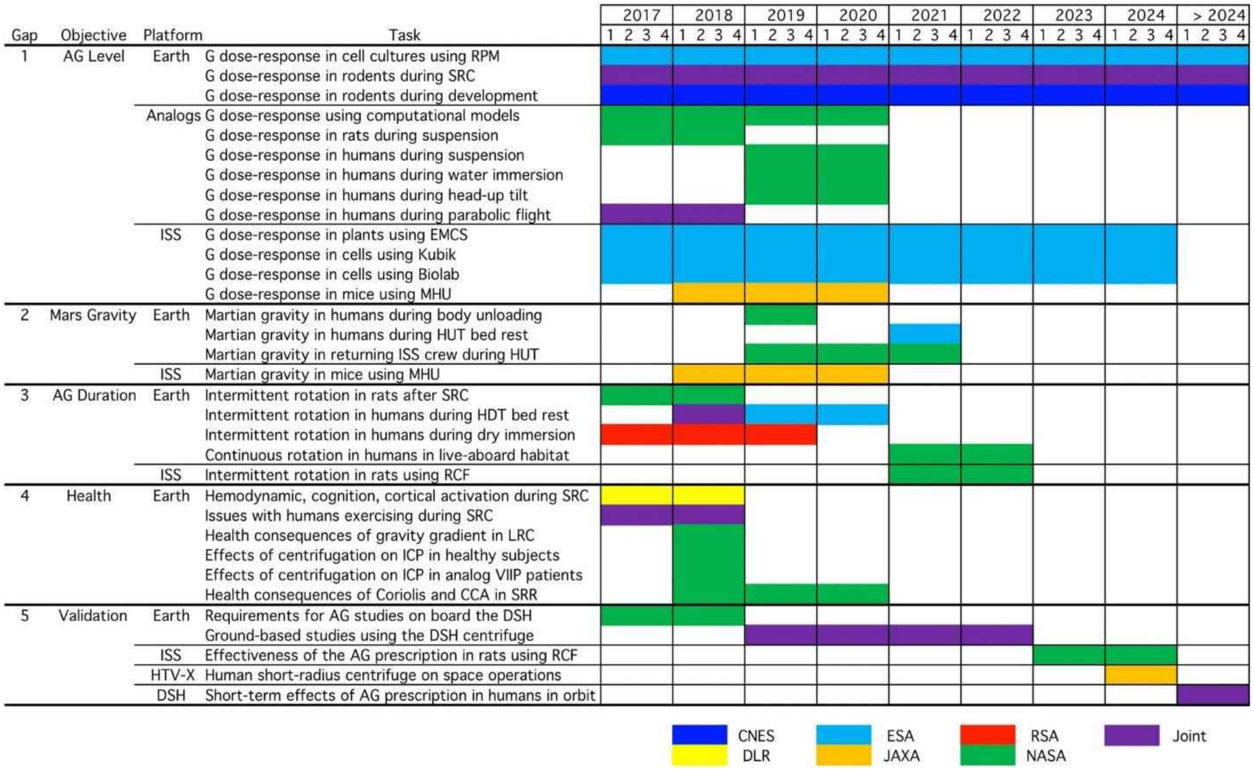
These data strongly support the benefit of artificial gravity. The reports are also the first of their kind reporting evidence that artificial gravity can prevent decreases in bone density and muscle mass. Nevertheless, it is important to note that these data were conducted in mice, housed in very small habitats. There were no tasks they were required to complete. While there was video observation, there was no ability to assess mouse performance on orbit. Assessments of vestibular function were conducted following return to Earth. Mice were given a mid-air righting reflex test and evaluated for their ability to walk on a rotating rod to assess their vestibular function and coordinated movement. One of the mice in the artificial gravity group failed to assume an upright position. Because mice cannot vomit, which is a clear indicator of nausea that can readily be monitored through video, it is not known whether their artificial gravity experience was without discomfort. If discomfort was present, it did not rise to the level to alter mouse behavior; however, there is no way from this study to know whether the artificial gravity would alter mouse performance in specific tasks. In this study, artificial gravity provided effective countermeasures for bone and muscle loss in mice, but there is no direct evidence that it would accomplish the same in humans nor is there a means to predict its impact on a decline in human performance.

Gaps in knowledge and research include whether full Earth's gravity (1 G) is required to prevent deconditioning, or if partial gravity with exercise would suffice. Investigators built a partial weight suspension system using a two-point harness to support an adjustable amount of mice body weight without disrupting their quadrupedal locomotion (Ellman et al, 2013). Then, studies were conducted that exposed skeletally mature female mice to partial weight bearing at 20%, 40%, 70%, or 100% of body weight for 21 days. The results showed proportional declines in bone mass to partial gravity. The investigators found that total body and hind limb bone mineral density, calf muscle mass, trabecular bone volume of the distal femur, and cortical area of the femur mid shaft were all linearly related to the degree of unloading. Since unloading studies only partially recapitulate the microgravity environment, these studies could be repeated in microgravity with variable centrifuges. Four gravity conditions could be evaluated: Earth, lunar, Mars, and microgravity. In addition, exercise wheels could be provided to or withheld from rodents to assess the contribution of exercise in mitigating musculoskeletal losses. Such studies would be the first step in establishing the need for a partial gravity habitat for humans.

In addition to unknowns about the benefits of partial gravity, the duration of full gravity needed to ameliorate musculoskeletal deconditioning has not been established. It is unknown whether intermittent acceleration in a short radius centrifuge would be sufficient, nor is it known whether continuous artificial gravity is necessary. Because astronauts must be able to function independently on any future Mars mission, a variable or partial gravity habitat may enable their ability to do so. Both the intermittent short radius and continuous long radius scenarios should be examined, and a variable or partial gravity habitat would provide this crucial research.

To better understand the landscape of artificial gravity knowledge, NASA hosted a workshop in February 2016 in Galveston, Texas, and invited artificial gravity scientists as well as representatives from the National Center for Space Studies (CNES; French: Centre National d'Études Spatiales), the European Space Agency (ESA), the German Aerospace Center (DLR; German: Deutsches zentrum für Luft-und Raumfahrt), the Japan Aerospace eXploration Agency (JAXA), as well as from multiple NASA centers to develop an artificial gravity roadmap (Figure 38) (Clément, 2017). The goal of the roadmap was to highlight the existing research that has laid the foundation for artificial gravity and to also identify the necessary research that has yet to be performed—the gaps. The goal of identifying such research is to better describe the design constraints and requirements of an artificial gravity system as well as the potential benefits to and drawbacks for the humans using any such system. There has been very limited human research with artificial gravity, but recurring interest from space partners. Successful countermeasures diminish the perceived need for artificial gravity, but with the increased incidence of Spaceflight-Associated Neuro-Ocular Syndrome (SANS), interest in artificial gravity was rekindled.

## The International Artificial Gravity Roadmap



| Gap | Objective | Platform | Task | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | > 2024 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 | 1 2 3 4 |
| 1 | AG Level | Earth | G dose-response in cell cultures using RPM | ESA | ESA | ESA | ESA | ESA | ESA | ESA | ESA | ESA |
| | | | G dose-response in rodents during SRC | Joint | Joint | Joint | Joint | Joint | Joint | Joint | Joint | Joint |
| | | | G dose-response in rodents during development | CNES | CNES | CNES | CNES | CNES | CNES | CNES | CNES | CNES |
| | | Analogs | G dose-response using computational models | NASA | NASA | NASA | NASA | | | | | |
| | | | G dose-response in rats during suspension | NASA | NASA | | | | | | | |
| | | | G dose-response in humans during suspension | | | NASA | NASA | | | | | |
| | | | G dose-response in humans during water immersion | | | NASA | NASA | | | | | |
| | | | G dose-response in humans during head-up tilt | | | NASA | NASA | | | | | |
| | | | G dose-response in humans during parabolic flight | Joint | Joint | | | | | | | |
| | | ISS | G dose-response in plants using EMCS | ESA | ESA | ESA | ESA | ESA | ESA | ESA | ESA | |
| | | | G dose-response in cells using Kubik | ESA | ESA | ESA | ESA | ESA | ESA | ESA | ESA | |
| | | | G dose-response in cells using Biolab | ESA | ESA | ESA | ESA | ESA | ESA | ESA | ESA | |
| | | | G dose-response in mice using MHU | | JAXA | JAXA | JAXA | | | | | |
| 2 | Mars Gravity | Earth | Martian gravity in humans during body unloading | | | NASA | | | | | | |
| | | | Martian gravity in humans during HUT bed rest | | | | | ESA | | | | |
| | | | Martian gravity in returning ISS crew during HUT | | | NASA | NASA | NASA | | | | |
| | | ISS | Martian gravity in mice using MHU | | JAXA | JAXA | JAXA | | | | | |
| 3 | AG Duration | Earth | Intermittent rotation in rats after SRC | NASA | NASA | | | | | | | |
| | | | Intermittent rotation in humans during HDT bed rest | | Joint | ESA | ESA | | | | | |
| | | | Intermittent rotation in humans during dry immersion | RSA | RSA | RSA | | | | | | |
| | | | Continuous rotation in humans in live-aboard habitat | | | | | NASA | NASA | | | |
| | | ISS | Intermittent rotation in rats using RCF | | | | | NASA | NASA | | | |
| 4 | Health | Earth | Hemodynamic, cognition, cortical activation during SRC | DLR | DLR | | | | | | | |
| | | | Issues with humans exercising during SRC | Joint | Joint | | | | | | | |
| | | | Health consequences of gravity gradient in LRC | | NASA | | | | | | | |
| | | | Effects of centrifugation on ICP in healthy subjects | | NASA | | | | | | | |
| | | | Effects of centrifugation on ICP in analog VIIP patients | | NASA | | | | | | | |
| | | | Health consequences of Coriolis and CCA in SRR | | NASA | NASA | NASA | | | | | |
| 5 | Validation | Earth | Requirements for AG studies on board the DSH | NASA | NASA | | | | | | | |
| | | | Ground-based studies using the DSH centrifuge | | | Joint | Joint | Joint | Joint | | | |
| | | ISS | Effectiveness of the AG prescription in rats using RCF | | | | | | | NASA | NASA | |
| | | HTV-X | Human short-radius centrifuge on space operations | | | | | | | | JAXA | |
| | | DSH | Short-term effects of AG prescription in humans in orbit | | | | | | | | | Joint |

**Figure 38:** Blank areas indicate a lack of necessary research. The roadmap lists the research activities (tasks) that address each of the five identified knowledge gaps, specifically, the effect of : 1) artificial gravity levels; 2) Mars gravity, 3) artificial gravity duration, 4) health during short radius centrifugation; and 5) validation of artificial gravity. Research projects are ground-based (Earth, Analogs) or space-based (ISS, DSH, HTV-X). Projects are planned on board the ISS up to 2024 and other vehicles/habitats thereafter. AG artificial gravity, CCA cross-coupled angular accelerations, EMCS European Multi Cultivation System, HUT head up tilt, HDT head down tilt, ICP intracranial pressure, LRC large radius centrifuge, MHU Mouse Habitat Unit, RCF Rodent Centrifuge Facility, SRC short-radius centrifuge, SRR slow rotating room, RPM random positioning machine, VIIP visual Impairment due to Intracranial Pressure (since renamed Spaceflight-Associated Neuro-Ocular Syndrome (SANS)). (Clément, 2017)

Regardless of the gaps in knowledge concerning the benefit of artificial gravity as a countermeasure, there are intuitively obvious benefits to artificial gravity, including establishing a well-defined vertical and horizontal reference frame. If artificial gravity does prove to be an effective countermeasure, crew compliance with lengthy and tedious 0-G exercise protocols would become unnecessary. Floating particulates, trash, and other items would eventually settle to a floor or wall rather than floating about the habitat area. This settling of dust, dander, etc., reduces the potential risk of inhaling microbial, allergenic, or toxic particles. In addition, rather than the million-dollar toilets with high service schedules, conventional, reliable toilets can be used. Moreover, eating can proceed more normally, as well as sleeping, bathing, and grooming practices. Finally, in the event of an emergency, complex medical procedures, such as surgery could be performed more easily (e.g., blood does not fall away but domes at the incision site, obscuring the field; bubbles from IVs do not float up but remain within solution) and with less risk (e.g., suspended particulates do not settle but would drift into the surgical field).

Aside from these benefits, there may also be drawbacks. One considerable drawback to artificial gravity may be that astronauts will lose a degree of freedom. In particular, they will lose the 3rd dimension and will no longer be able to easily access, work, or lounge on the ceiling as is possible in microgravity. A strong caution regarding "normal" performance of activities—"like on Earth"—is that the Coriolis effect, particularly for rotating habitats with shorter radii, can introduce significant "weirdness" to movement and tasks. This distortion or weirdness must be considered in engineering, architecture, and human factors design, as well as in mission design, procedures, and training.

The challenges of variable gravity habitats also include the fuel required to rotate the habitat and to cause it to stop, the potential precession of the rotation caused by human locomotion, determining the optimal orientation of the habitat, the optimal ranges for the radius and rotation rate, the acceptable range of Coriolis forces and cross-coupled angular accelerations, the challenges of spacecraft docking with the habitat, and the vibration of the rotating habitat imparted to other structures, etc.

# 8. OPPORTUNITIES AND CONSIDERATIONS FOR DESIGNING A ROTATING ARTIFICIAL GRAVITY HABITAT

New materials and methods for assembling space habitats are rapidly evolving as new operators and functions for Low Earth Orbit and cis-lunar space are engaged. Such innovations and capabilities provide a fertile backdrop for the expeditious development of artificial gravity facilities for use in space.

## 8.1 Highlights and Design Directions from the Review of the Literature.

### *8.1.1 Artificial Ground Based Studies*

The impact of gravity on Earth-bound operations do not compare with any impact on operations by artificial gravity generated by a rotating space habitat. First and foremost, the gravity of Earth is not due rotation, but rather is the result of the Earth's mass. (If it were due to rotation, we would all be spinning off the surface). And second, the effect of moving in the Earth's rotational frame of reference is not large enough for humans to notice.

This leads to acknowledgment that Earth-based ground studies on artificial gravity provide data points that are instructive but must not be interpreted as fully representative of what the experience will actually be in space. Most critically, everyone involved must recognize that the first instance of designing, building, and occupying an artificial gravity habitat in space will be experimental. Therefore, the habitat's equipment, procedures, and schedules must have observation, testing, and measurement built into the protocols, mission design, and every inhabitant's schedules. The flexibility built into schedules and operations is essential to adapt to "new learnings." Ideally, the ability to "rearrange" some physical aspects of the habitat would be desirable as well as an ability to perform real time testing, modification, and correction of crew equipment, tools, and operations as experience and insight develops. Taking advantage of any built-in flexibility should be clearly discussed, documented, and agreed upon by crew, engineers, schedulers, designers, and flight surgeons prior to any actions or changes being made.

### *8.1.2. Regarding Design Parameters*

As human space presence has evolved and progressed, not only has the direction in space exploration changed, but also the people going to space has changed—gender, ethnicity, race, size variability, ages (18-90) and physiological/health status.

Since the vast majority of space studies have been performed on healthy, subjects with normal physiology, without cardiac or chronic illness, and frequently Caucasian males, the application of Earth-bound studies must consider not only the need to modify protocols and equipment to accommodate a rotating space habitat, but also to accommodate the wider variability of the spacefarer's physiology—from professionally trained crews to space tourists.

It is our assessment that the most appropriate operational approach for LEO rotating habitats is one that provides the best experience and creates the least strain on physiology, psychosocial wellbeing, and movement/operations for the widest range of humans—at minimum, encompassing 1 standard deviation from the norm in both directions.

### *8.1.3 Design Factors*

Rotating structures located in Low Earth Orbit or interplanetary space that generate artificial gravity from a range of 0.2 to 1 G offer potentially game-changing habitats for human space exploration—research, discovery, manufacturing, and a range of industries. However, successfully exploiting this potential is highly dependent on thoughtful engineering, architecture, and human factors (ergonomics and aesthetics) focused on optimizing the function of professional crews and guests.

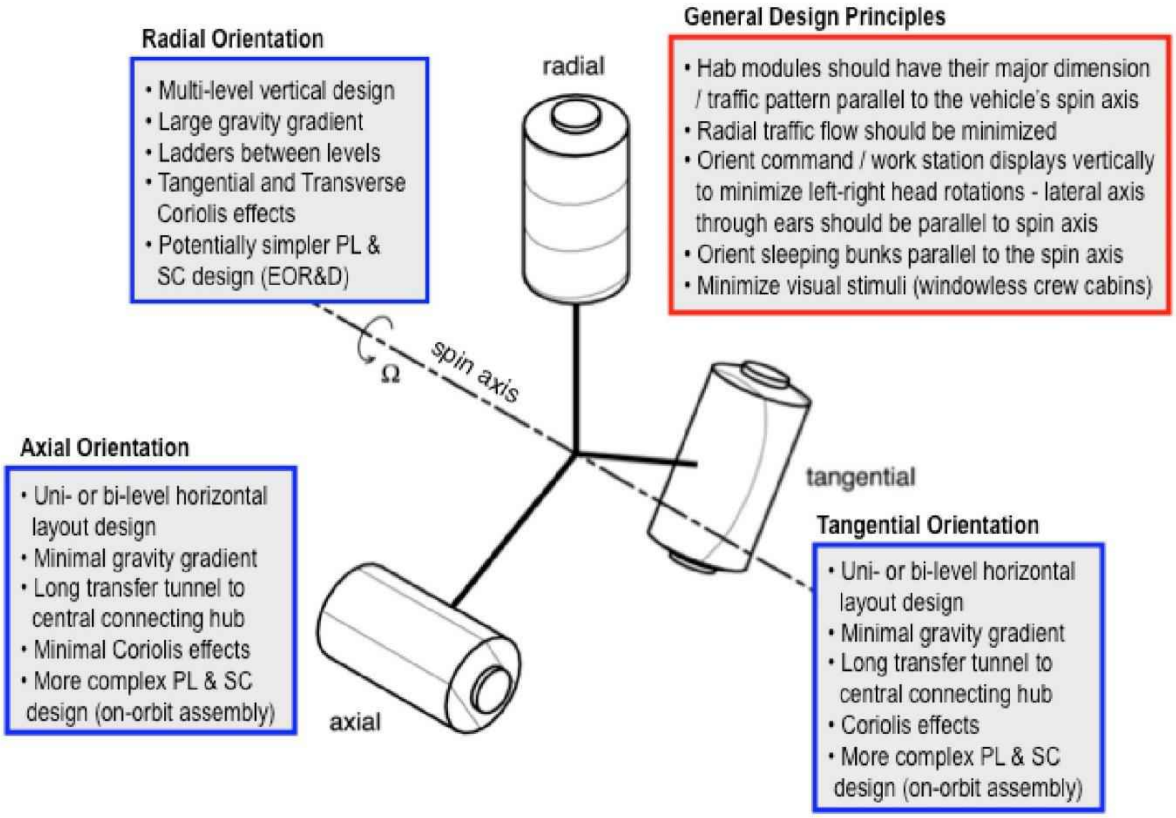


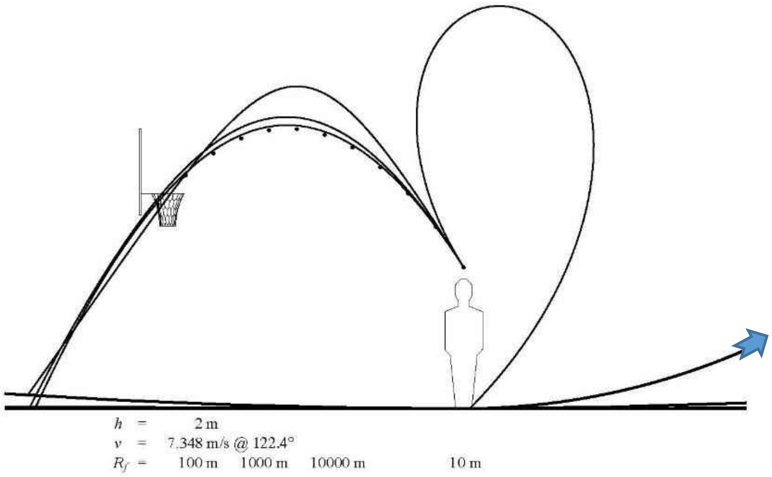
**Figure 39:** Options for habitat module orientation and associated human factors (PL = payload; SC = spacecraft).

1. Factors critical to achieve a successful design recognize that human operations in artificial gravity inside a rotating structure must be approached with the same rigor and meticulousness as is applied

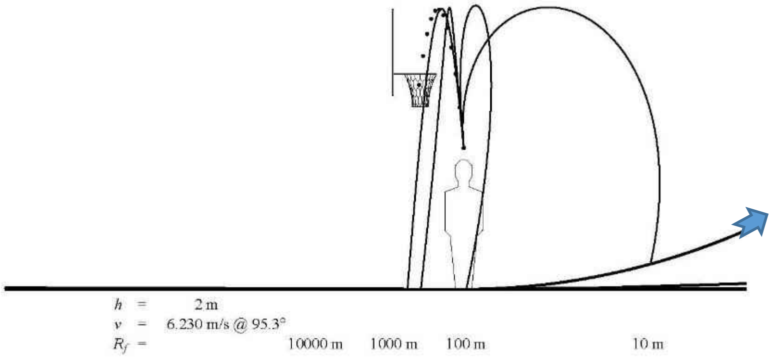
to the engineering, launch, assembly, and maintenance of structures in this dynamic environment.

2. In designing artificial gravity environments, it seems obvious that reducing the radius and rotation rate reduces costs of mass and energy. Yet these very same "savings" have the potential to increase costs of operating in a "distorted gravitational environment" (Hall, 2006), for instance, if the aforementioned disorientation causes every task to take longer to complete.

3. Standardizing a set of tests, such as a ball drop from a certain height, or a timed leap, can be helpful in comparing the potential distortion in different gravitational environments in a generic way. Below is an example using identical shots of a basketball in 1-g rotating environments of different radii. Note that due to Coriolis effects that in some cases the ball travels retrograde to the direction it was thrown. Imagine the implications of this for surgery. For instance, surgery requires precise hand movements. Hand-eye coordination is disrupted by weightlessness alone. Considering this, the potential for disruption by Coriolis forces is great since Coriolis forces will change with the position of the surgeons and the speed that they are moving their arms.



**a. Shooting from the free-throw line.**



**b. Shooting from close under the net.**

**Figure 40**: Basketball in artificial gravity. The dots represent a successful shot on Earth gravity. The curves represent identical shots in 1-G rotating environments with radii of 10 m, 100 m, 1000 m, and 10,000 m. The blue arrows indicate the direction of rotation.

4. Though rotation may generate gravity-like forces, other aspects of the experience and sensory cues—visual, tactile, proprioception, and auditory—may vary wildly from what is acceptable or expected on Earth. Designs of the habitats, operations, behavioral, and haptic components must facilitate crew member acclimatization and successful functioning from the unique frame of reference of the specific rotational environment in which they are living and across their various states of adaptation.

5. Visual cues include making the direction of habitat rotation clear from any vantage point, as well as including subtle (or not so subtle) up and down direction clues. Such visible cuing connects the visual senses with the vestibular system, which may mitigate Coriolis effects. Color patterns associated with certain directions is a possible example.

6. Habitat designs that demand multiple levels/floors for activities, must have movement from one level to another planned with Coriolis effects in mind. Examples of such planning would be orienting a ladder such that Coriolis forces would push them into the ladder rather than off of it.

7. Hall (2006) suggests that wide floors (with respect to the rotational radius) should be cylindrical arcs, thereby orienting the centrifugal acceleration always perpendicular to the floor's surface. This helps avoid slopes created by changing gravity gradients that would occur over a rotating flat surface.

8. When cylindrical habitat volumes are used, they should be aligned in a grid with the axis of rotation and tangential velocity well-marked. Additionally, partitions in the space should be similarly aligned to axial and tangential velocity grids.

9. The varying levels of artificial gravity must be clearly defined prior to the design process and re-interrogated throughout the design, engineering, and early prototype manufacturing. For example, if the primary reason for rotation is the health of the crew, it may be that 0.3 to 0.5 G is sufficient in and of itself. If insufficient, it may be that exercising in certain directions in the rotational framework could be sufficient as countermeasures for key physiological concerns. The need for manual operations in microgravity would drive another set of criteria, depending on the duration and volume required. Establishing functions and priorities for the station and artificial gravity components in as much detail as possible, while incorporating points of flexibility, will create the greatest chances to optimize designs for both health and operations. This may be obvious, but it cannot be overstated.

10. Artificial gravity from 0.3 to 0.5 G was found to be comfortable for subjects in rotating rooms on Earth. Though for all the reasons enumerated previously, translation to a rotating habitat in space could reduce the requirements for rotational velocity and/or the radius of the structure.

11. Tantalizing insight that could influence the design of a variable gravity space structure is that the transition of moving between rotating and microgravity environments may not require separate, independent adaptation periods. This observation is derived from the Pensacola Slowly Rotating Room studies, with some support from Skylab M131 data, and would facilitate the operation of habitats with both microgravity working environments and artificial gravity environments, namely because once adapted to one or the other—weightlessness or rotational artificial gravity—inhabitants could move from one to the other without suffering ill effects.

### 8.2 Directions for Future Studies and Initiatives

Incremental development of artificial gravity facilities in Low Earth Orbit and cis-lunar space is clearly a sound approach. However, developers should be cautious and not assume that incremental necessarily means starting with short-radius habitats then slowly evolving over time to longer radius structures. The lessons learned in the "distorted" environment attendant to short-radius rotating habitats—from the engineering, facilities, and schedule management, as well as the physical and psychosocial well-being—may not be applicable or indicative of the potential successful operation of artificial gravity structures of bigger sizes.

Artificial variable gravity in orbiting facilities could provide a range of manufacturing, research, and service opportunities that could benefit life on Earth. Though beyond the scope of this report, the capabilities of variable gravity facilities in space can be invaluable to an impressive range of medical, physiological, and life sciences. Manufacturing products in which control of the deposition or separation processes may gain more precision by varying gravity—for example building nanomaterials or separating large molecules.

Studies examining cognitive, reflex, and emotional changes should be made a priority. Again, with a wider range of individuals in a habitat, the more potential there is for conflict, emotional extremes, misunderstandings, and sociocultural friction.

Convene a transdisciplinary group of experts from a wide range of fields—e.g., engineers, designers, behaviorists, artists, athletes, health professionals, architects, investors, chemists, ecologists—who may or may not have had experience in space exploration for initial and intermittent discussion of the facilities. Adroitly facilitated, such a group can be invaluable to fully exploring the strengths, weaknesses, and gaps in an idea, plan, or process.

As the capacity to put more people and more items in Earth orbit increases, it is incumbent upon all involved, spacefarers, spacecraft builders, investors, launch service providers, and service procurers for Low Earth Orbit and cis-lunar space to commit to maintaining space as a sustainable resource. Incorporating the 1987 United Nations Brundtland Commission definition of sustainability we must use space in such a way that it "meet(s) the needs of the present without compromising the ability of future generations to meet their own needs" (UN Special Working Session, 1987).

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