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The Partial Gravity of the Moon and Mars Appears Insufficient to Maintain Human Health

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Astronauts who spend many weeks or months in space in microgravity suffer serious health problems including muscle atrophy, cardiovascular deconditioning, bone calcium loss, impaired vision, and immune system changes. The debilitating effects of weightlessness were first demonstrated on the early Skylab, Salyut, and Mir missions, but it was then hoped that countermeasures including in-flight exercise and resistance training could reduce most of these problems. Similar effects are anticipated in the partial gravity of the Moon and Mars. Direct evidence of the long-term effects of partial gravity on humans is not yet available, but indirect evidence suggests that partial gravity exposure below 0.4 g will be insufficient to maintain musculoskeletal and cardiopulmonary conditioning over the long term. Some studies show a strong correlation between heart rate, oxygen consumption, net metabolic rate, and simulated gravity from 0 to 1 g. Exposure to moon and Mars gravities will probably cause less severe physiological deconditioning than microgravity, but the benefit of partial gravity seems likely to be roughly proportional to the level of gravity experienced. As in microgravity, exercise countermeasures seem useful but insufficient to preserve all physiological systems as they would be in Earth gravity.

I. Introduction

ASTRONAUTS who spend many weeks or months in space in zero g suffer serious health problems including muscle atrophy, cardiovascular deconditioning, bone calcium loss, impaired vision, and immune system change. Extensive exercise does not prevent these problems. The debilitating effects of long-term weightlessness were first demonstrated on the Skylab, Salyut, and Mir missions, but it was originally hoped that in-flight exercise could preserve a high level of conditioning.

A systematic review summarized "the different effects of partial gravity (0.1–0.4 g) on the human musculoskeletal, cardiovascular and respiratory systems." They found, "Partial gravity exposure below 0.4 g seems to be insufficient to maintain musculoskeletal and cardiopulmonary properties in the long-term." [1] Some of their reviewed studies showed a strong correlation between heart rate, oxygen consumption, net metabolic rate and simulated gravity levels from microgravity to Earth gravity.[1] The review concludes, "It can be anticipated that partial gravity environments as present on the Moon or on Mars are not sufficient to preserve all physiological systems to a 1 g standard if not addressed through adequate countermeasures."[1] Adequate countermeasures appear to be unavailable.

II. The Problems of Microgravity

Astronauts who stay in zero gravity for weeks or months undergo serious health problems. These include bone calcium loss and osteoporosis, muscle atrophy, cardiovascular deconditioning, body fluid shifts, impaired vision, loss of red and white blood cells and plasma, related damage to the immune system, and disturbance to the inner ear's sensing of orientation and movement.[1] [2] [3] [4] The most apparent effects on the bone, muscle, and cardiovascular system were seen on the Skylab missions in the 1970's and deeper investigation continued on Salyut, Mir and the International Space Station. Initially, it was hoped that that in-flight exercise could solve the problems of the bone, muscle, and cardiovascular system damage due to lack of gravity.[2] Unfortunately, "Extensive exercise does not prevent these (biomechanical and cardiopulmonary) problems."[1] "After a long-duration mission, it is not uncommon for crewmembers to be unable to lift their arms to remove the belt restraint. After flight lasting six months or more, they have to be physically removed from the vehicles on litters."[2]

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A. Bone Loss

Maintaining bone mass and strength requires the compressive loads and the high-force impulses provided by living and walking in Earth gravity. Without the forces they usually provide, "the major bones that support body weight begin to deteriorate, and a net loss of body calcium occurs, independent of the amount taken in with food or supplements."[2] Similar mass and strength losses occur during long bed rest, but these can be reduced by periods of walking.

In spaceflight, "Calcium is lost at a rate of about 1% per month, and the losses are reflected in the density and mass of weight-bearing bones. The rate of calcium loss is not reduced by vigorous exercise."[2] The lost calcium may produce kidney stones. The process of calcium loss has been observed to continue unabated for more than a year. In a multiyear microgravity mission, half the bone mass might be lost, increasing the risk of a bone fracture, especially during Earth reentry and recovery.

B. Muscle Atrophy

Maintaining back and leg muscle mass and strength requires that the muscles work against Earth's gravity to support body weight. In zero gravity, "Very significant losses of muscle strength, muscle volume, and total body weight are noted."[2] Muscle tissues break down and reorganize in weightlessness. Two weeks of zero gravity can atrophy muscle fibers by 30% so that the muscle generates less force and power. Muscles have two types of fibers, slow fibers that work constantly against gravity and fast fibers for rapid, quick forceful actions such as running and jumping. Since slow muscle fibers work against gravity, they are the most reduced in weightlessness.

Muscles are adaptable tissues and using an exercise bike or running on a treadmill reduces muscle atrophy. However, aerobic spaceflight exercises are designed to condition the cardiovascular system, not condition muscles. "Yet despite rigorous exercise, astronauts return to Earth shockingly weaker than when they left. Exercise alone has not prevented muscle wasting during spaceflight."[2]

C. Cardiovascular Deconditioning

On Earth, the cardiovascular regulating system must work against gravity to maintain adequate blood pressure. In space, the lack of gravity causes many changes that reduce cardiovascular fitness. The first change noted after launch is the shift of blood and other fluids from the lower to the upper body. The face swells and the legs shrink. There is a rapid loss of body fluid and blood plasma. The increased concentration of red blood cells leads to a reduction in their number. White blood cells, which help the immune system destroy pathogens, are also reduced in microgravity Weightlessness causes increased heart rate, irregular heart rhythm, briefer pulse duration, and decreased heart chamber volume. These factors explain a reduced ability to work and exercise.[2]

Deconditioning of the cardiovascular regulating system occurs in microgravity but is usually a problem only on return to Earth. When a person stands in 1 g, about ¾ liter of blood in the thorax is instantly moved downward. The cardiovascular system acts to preserve blood pressure, especially blood flow to the brain, and so prevent fainting due to orthostatic hypotension. Returning astronauts can feel lightheaded and standing can lead to fainting, sometimes long after landing.[2]

D. Sensory and Motor Deconditioning

Sensory-motor deconditioning occurs in zero gravity because of the loss of signals to the vestibular motion sensing organs of the inner ear and to the internal body sensors of motion and position. These systems aid spatial orientation and the control of posture, movement, and hand-eye coordination. The sensory-motor systems must adapt to zero gravity after launch and to Earth normal gravity after reentry. Because the only stimulus to the vestibular system in weightlessness is linear acceleration due to movement, the sensory-motor systems are disturbed, and new sensory-motor strategies must be learned. Furthermore, information from the vestibular system influences heart rate, blood pressure, immune responses, and circadian rhythms. Initial space motion sickness is common and spatial disorientation often occurs throughout a mission. Most returned astronauts experience postural imbalance, uncoordinated locomotion, and vertigo and nausea similar to space motion sickness for months.[2]

Bed rest studies are useful in understanding bone loss, muscle atrophy, and cardiovascular deconditioning but are not useful in understanding sensory-motor deconditioning because Earth gravity is still a reference for orientation. Although they do not appear as effective as once hoped, exercise and artificial gravity are plausible countermeasures to bone loss, muscle atrophy, and cardiovascular deconditioning, but they seem unsuited to prevent sensory-motor deconditioning. A short radius centrifuge "may well have negative side effects for the neurovestibular system, such as spatial disorientation, miscoordination, and nausea."[2]

E. Regulatory Physiology Disruption

"The physiology of humans is composed of a totally integrated set of complex subsystems that maintain critical physiological parameters (e.g., temperature, fluid balance, biological rhythms, and electrolyte levels) at relative stable levels, a function called homeostasis. Operational observations and spaceflight experiments have demonstrated changes in these physiological parameters and processes. For example, changes in electrolyte balance, blood cell mass, hormone synthesis, and hormone action have been observed during spaceflight."[2]

The effects of weightlessness on the cardiovascular system include loss of blood volume, red blood cells, and white blood cells. Spaceflight also suppresses the cell-mediated immune system, reducing the ability to fight infection. The responses of the endocrine and immune systems to weightlessness are unclear, but pharmacological, dietary, and chemical countermeasures may be found.[2]

III. Countermeasures for Microgravity

Countermeasures are therapeutic methods used in space and are intended to mitigate the damage of microgravity and help maintain astronaut physical fitness. The best-known counter measure, exercise, has potential benefits for the musculoskeletal, cardiovascular, and possibly immune systems. Healthy nutrition and specific pharmaceutical treatments have been suggested. Artificial gravity has been proposed using either small radius centrifuges or fully rotating spacecraft.[2]

A. The Ineffectiveness of the Usual Countermeasures

"However, despite intensive in-flight schedule, the effectiveness of the current exercises for maintaining bone, muscle, and aerobic fitness has not been demonstrated. Furthermore, they have inconsistent effect on sensory-motor adaptive changes and postflight orthostatic hypotension." And, "although improvements in exercise protocols, changes in diet, or pharmaceutical treatments of individual systems may be of value, they are unlikely to adequately eliminate the full range of physiological deconditioning induced by weightlessness."[2] "In-space countermeasures can mitigate the damage of microgravity but are not sufficient to prevent serious debility/damage." [4] The Russian view is similar, "that the in-flight countermeasures on their long missions were insufficient to prevent postflight physiological symptoms such as orthostatic intolerance and musculoskeletal deterioration."[4]

Different types of exercise are required to build bone, strengthen muscles, and improve cardiovascular fitness. Exercise cannot directly deal with sensory and motor deconditioning and regulatory system disfunction. The most certain countermeasure is producing an environment with gravity close to Earth's, using artificial gravity.[2]

1. *Artificial gravity*

All the identified problems of microgravity might be solved using artificial gravity throughout the mission. Two approaches have been suggested for spaceflight, a small on-board centrifuge and a large rotating spacecraft. Early theorists before the space age usually suggested a large rotating spacecraft producing 1 g artificial gravity. Such spacecraft would be very large and massive. The much less expensive alternative that has been studied is a small spinning centrifuge where astronauts can lie with their head near the center and feet pressing against the outer rim for an hour or two each day.

2. *Short Radius Centrifuges*

Short radius centrifuges have been proposed for use in spacecraft and on the surface of the moon and Mars. However short radius centrifuges can produce the Coriolis effect, creating problems for the neurovestibular system, such as spatial disorientation, loss of coordination, and nausea.[2] Often a maximum rotation rate of 4 rpm is set to limit the Coriolis effect perceived in a rotating system. If someone in a rotating cylinder moves closer to the axis of rotation, they will feel a force pushing them in the direction of spin. The force acts on the inner ear and can produce disorientation and motion sickness.[5] Increasing the force of artificial gravity produced by rotation requires increasing either the radius of rotation or the rotation rate. A maximum spin rate of 4 rotations per minute (rpm) and 1 g determines a minimum habitat radius of 56 meters. Short radius centrifuges would require much higher spin rates to achieve 1 g, leading to attempts to mitigate the Coriolis effect. "Preliminary results suggest that in a few days, individuals can increase the spin rate at which the (Coriolis) illusion is imperceptible (e.g. 10 RPM)."[6] "Increasing the spin rate to 10 rpm, however, requires specialized habituation techniques, including programmed head movements over a two-week period."[4] For 10 rpm, rotation producing 1 g can be achieved with a radius of 8.9 meters and a diameter of 17.8 meters, still much too large for a feasible spacecraft but possible in a planetary base. A 2-meter radius human centrifuge must rotate at above 60 rpm to produce an artificial gravity level of 1 g or greater."[2]

It has been suggested that crew members on a planetary surface could spend 3 or 4 hours standing in a 1 g centrifuge "may help to partially mitigate some of the health impacts of living in reduced gravity."[7] Crew turning their heads in this environment will experience a significant Coriolis effect.[7] "Head movements and resultant Coriolis forces on the rotating platform may limit the usefulness of economical short centrifuges for other than brief periods of intermittent stimulation."[4]

3. Large Radius Rotating Spacecraft

"Artificial gravity human spacecraft have not been built largely because of their much greater mass and launch cost. Other reasons are that zero gravity is tolerable for short periods, that zero gravity counter measures such as exercise have some effect, and that zero gravity is interesting for scientific and engineering research."[1]

As noted above, a maximum spin rate of 4 rotations per minute (rpm) to limit the Coriolis effect and a 1 g artificial gravity requirement determine a minimum habitat radius of 56 meters. The Coriolis effect is likely to produce motion sickness unless the rotation rate is as low as 1 rpm. A large rotating space station with diameter of one kilometer and rotating at 1 rpm would produce a centripetal acceleration of 1 g and avoid the Coriolis effect.[4]

4. Rotating Habitats on Planetary Bases

A rotating artificial gravity habitat has been suggested for the moon. In addition to preventing the problems of partial gravity, it would provide "a living environment which is compatible with our current social, physical, and psychological needs."[8]

An interesting idea for creating 1g on Mars is a large rotating underground wheel. "(T)he outer wall of the wheel (the floor where people walk) must be tilted to give an effective 1g gravity on a person standing inside the wheel. The centrifugal force caused by the gravity wheel rotation causes an outward force on a person that is horizontal to the Mars surface. But the Mars native gravitational force pulls vertically downward on a person. So a person standing in the gravity wheel has both forces acting on him or her simultaneously." The wheel diameter and rotational speed are adjusted to provide 1g, and the floor is perpendicular to the 1g force.[9]

Human physical activities can be much better understood, planned, and conducted in 1 g. Work, exercise, and sports at low spin rates can proceed as on Earth. Perceptions of difference, strangeness, and disorientation would be reduced by the inclusion of familiar objects and activities.

IV. The Effects of Moon and Mars Partial Gravity

While the long-term effects of microgravity on humans in have been studied since the 1970's, humans have had only two weeks of exposure to lunar gravity and none to Mars gravity. It seems reasonable that partial gravity will have some benefit, but how much and at what gravity levels is uncertain. Some microgravity effects such as bone loss seem likely to improve as gravity increases, while others such as a sense of up and down seem to appear at a certain level of gravity. Improvements with gravity may be nonlinear and gravity thresholds may occur at different levels of gravity. Is there some gravitational acceleration less than Earth's that can maintain normal functioning? The physiological responses to long term exposure to moon and Mars gravity are unclear because of the lack of direct data, but Earth experiments can replicate some of the effects of partial gravity.

Richter, Braunstein, Winnard, Nasser, and Weber, investigated "Human biomechanical and cardiopulmonary responses to partial gravity - A systematic review." The review "summarizes the different effects of partial gravity (0.1–0.4 g) on the human musculoskeletal, cardiovascular and respiratory" systems using lunar data and experiments. Partial gravity experiments attempt to simulate reduced gravity and its impact on human physiology.[1] Different studies used vertical body weight support, tilted body weight support, parabolic flights, lower body positive pressure, and centrifugation. Partial gravity reduces the work necessary to move the human body which has the long-term detrimental effects of bone loss, cardiovascular deconditioning, and biomechanical changes.[1]

A. Bone Loss

As noted above, in microgravity bone calcium is lost at a rate of about 1% per month.[2] A model was used to predict bone mineral density change in partial gravity. It predicted a weekly loss of 0.39% for bone mineral density in lunar gravity and a weekly loss of 0.22% in Martian gravity. These rates are similar to or higher than the calcium loss rates in microgravity. It was apparently assumed that bone mineral density loss is not prevented or even reduced by partial gravity environment. Whether the bone density loss is a constant amount or is proportional to the remaining mineral content, bone strength will be seriously reduced in two or three years of lunar or Mars gravity.[1]

B. Cardiovascular Deconditioning

Exposure to partial gravity causes an immediate decrease in cardiopulmonary parameters including heart rate, oxygen consumption, and metabolic rate. Studies found a strong correlation between heart rate, oxygen consumption, and metabolic rate and simulated gravity levels in the range between 0 and 1 g. These cardiopulmonary parameters had either large decreasing trends or significant reductions with lower gravity. Moon and Mars gravity will probably cause significant cardiovascular deconditioning, but probably less than in microgravity.[1]

C. Biomechanical Changes

Biomechanical studies found that ground reaction force, mechanical work, stride frequency, stance phase duration, and preferred walk-to-run transition speed in partial gravity are reduced compared to 1 g. This is because partial gravity reduces body weight and the external forces acting on the human body, so the external mechanical work needed to move the body over height and distance is less. The internal work necessary to move the arms and legs is also reduced. The reduction in total mechanical work in partial gravity causes extremely large effects including a reduced load on the cardiopulmonary system. Heart rate and oxygen consumption are correlated with work performance which explains why these parameters decrease in partial gravity.[1]

D. Partial Gravity Summary

The partial gravity study found extremely large long-term effects that were poorly understood. The reduced mechanical forces caused by walking and running in Moon and Mars gravity are probably not sufficient to maintain terrestrial mineral density and muscle mass in the long-term. The different human physiological systems react differently at any particular gravity level which makes it unlikely that any particular gravity threshold can maintain all systems equally. Exercise and other counter measures provide some limited benefit in microgravity but are unable to preserve all physiological systems to a 1 g standard. Countermeasures will probably have a similar limited effect in partial gravity. “Partial gravity exposure below 0.4 g seems to be insufficient to maintain musculoskeletal and cardiopulmonary properties in the long-term.”[1]

V. Conclusion

Humans suffer severe debility if they spend long periods in microgravity. The usual countermeasures are ineffective. Long term residence in space seems to require artificial Earth gravity provided by rotating spacecraft. A survey concluded that, “The moon and Mars do not provide sufficient gravity to support satisfactory human physiological conditioning.”[1] The physiologic reactions to partial gravity appear to prevent permanent habitability of the moon and Mars, unless the residents inhabit a large rotating centrifuge. It would be helpful to study the long term effects of partial gravity on animals by using a centrifuge on the International Space Station.

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