Temple University

College of Engineering

Bioengineering

Problem Statement

Partial Gravity Bioreactor

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1. Overall Objective

Since the 1960s, space exploration has yielded intriguing discoveries that continue to unfold over time. Yuri Gagarin became the first human in space in 1961, paving the way for thousands of astronauts and cosmonauts to follow him as the years passed [1]. Various theories have been proposed based on space explorations, including the Croatian Barrel Theory, which explains how the solar system, stars, and other celestial bodies formed [2][3]. In 2002, research refuted the theory that gravity alone governs the universe, as it could not explain specific astronomical observations [4]. Sanders and McGaugh modified Newtonian gravity as an alternative to cosmic dark matter, known as Modified Newtonian Dynamics (MOND), correlating a relationship between the acceleration from Newtonian gravity and the observed acceleration at any radius in a galaxy [5][6].

Exploring space not only shows discoveries that are external to our planet, but it also uncovers truths that enhance and govern our lives. Advanced Combustion via Microgravity Experiments (ACME) investigates fuel efficiency and pollutant production in combustion under microgravity conditions on Earth [7]. One of their investigations, Flame Design, studied the quantity of soot produced under different flame conditions [7]. Such a discovery could lead to more efficient combustion, reducing pollution on Earth [7]. In the ongoing Moon exploration, researchers found that the Moon's gravity affects Earth's tides, plant growth, animal behavior, and agricultural practices [8]. Moreover, models have shown that the Earth-Moon coupled magnetospheres provide a buffer against the solar wind, allowing for a reduction in Earth's atmospheric loss to space [9]. The National Aeronautics and Space Administration (NASA) has been exploring Mars for over sixty years to decide whether it is or was a habitable world [10]. Since Mars is the most similar planet to Earth in the Solar System, understanding its surface and evolution is crucial for preparing for future human exploration [11]. With evidence suggesting that Mars was once full of water, warmer, and had a thicker atmosphere, it is highly likely that Mars could be a habitable environment [11].

Despite the profound findings, many questions remain unanswered. However, traveling outside the Earth's atmosphere to explore potential extraterrestrial life is a risky and expensive endeavor. Given our bodies' high dependence on gravity, any significant change in gravity would cause severe issues [12]. With that, it is highly unethical to send people into space without understanding the effects of partial gravity on the body, especially given the current state of technological advancements. In this paper, a proposed prototype of a device that cultures cells under the influence of partial gravity and microgravity is addressed, allowing for the correlation of certain cell behaviors with the gravitational difference.

2. Background

Understanding the effects of partial gravity on humans is less studied due to the high costs associated with conducting tests in a partial or microgravity environment. Between 1960 and 1973, the research experience and studies gained during the Apollo missions, which focused on lunar exploration, provided valuable information summarizing the different effects of partial gravity on the human musculoskeletal, cardiovascular, and respiratory systems, using either microgravity or Earth's gravity as control [13][14]. However, the Apollo missions cost $25.4 billion in 1969, equivalent to roughly $217 billion in 2024 [15]. In 2019, the health impact of a year-long mission in space was examined in molecular and psychological traits by comparing the DNA sequence of the twin brothers – Mark and Scott Kelly – with Mark Kelly staying on Earth, "the control," and Scott Kelly going to space [16][17]. The study revealed that extensive multisystem and gene expression changes occur in spaceflight [16].

Due to cost and ethical concerns, researchers aimed to simulate partial gravity on Earth, such as using a pulley-spring system to simulate partial gravity for rats [18]. However, one of the limitations of the apparatus was that the tail was suspended rather than the whole body, which would provide a weight shift in the rodent's body, thereby not providing a "true" simulation [18].

Aiming for the least unethical approach, cell culturing is the most favorable approach, with bioreactors being the most suitable device, as they provide controlled nutrients and biomimetic stimulus deliveries for cell growth [19]. NASA developed a unique bioreactor to address the challenge of treating injured astronauts in space, where medical resources are limited [20]. In microgravity, the bioreactor enables cells to grow in three-dimensional tissue structures that closely resemble natural development, facilitating advances in medicine both on Earth and in space [20]. The success of NASA's bioreactor shows how gravity influences biology. Microgravity fosters unique cell growth environments, while partial gravity (such as on the Moon and Mars) may present entirely different effects [21].

Partial gravity bioreactors, although not extensively studied, have been investigated previously. Research dating back to the 1900s has examined the effects of clinostats, or rotating wall vessels, on biologics [22].

To understand the concepts that encompass partial gravity apparatuses, it is essential to differentiate between zero gravity, gravity, microgravity, and partial gravity. Zero gravity (0g) refers to the lack of gravitational force on an object due to its infinitely far distance from another gravitational object or the net sum of all forces acting on the object equaling zero [23]. Gravity is an abstract phenomenon that can be quantified, but the fundamental cause remains unknown [24]. The gravitational constant (G) is not a force or acceleration but is utilized as a scaling factor for Newton's Law of gravitation, shown in Eq. 1 [24].

$$F = \frac{G m_1 m_2}{r^2} \qquad \text{(Eq.1)}$$

The impacts of gravity on an object can be either displacement or deformation [25]. Microgravity refers to a condition where the net gravitational force acting on an object is minimal, typically within the range of 10^{-4} to 10^{-6}g [26]. They are still affected by the forces of gravity but are in continuous free fall [26]. Partial gravity refers to the gravitational force that is reduced but not eliminated compared to the force of gravity on Earth, ranging from 0.1g to 0.4g, such as that on the Moon (0.16g) and Mars (0.38g) [17]. On Earth, partial gravity can be simulated through centrifugation, parabolic flight, or modified rotation devices that produce acceleration lower than 1g [27]. Understanding the varying gravitational conditions is essential for space exploration and medical applications.

Prior bioreactors were developed as ground-based to approximate aspects of weightlessness or reduced gravity that a biological organism experiences in space. Many early partial gravity bioreactors tested their impact by using plant species, which can constantly grow against the gravitational forces found on Earth [28]. Early renditions included clinostats, which continuously rotate a sample so that the gravitational vector is effectively averaged to near zero [22]. This rendition of a partial gravity bioreactor cannot fully replicate "true" freefall since cells still experience mechanical stimulation and gradients that differ from the actual microgravity environment [22]. Later, rotating wall vessel (RWV) bioreactors were introduced as a specialized form of clinostats [22]. RWVs are fluid-filled cylinders containing cells that create a low-shear, controlled environment, allowing for cellular differentiation in three-dimensional space [29]. By rotating at a terminal velocity, RWVs ensure proper nutrient delivery to the tissue culture, thereby promoting healthy tissue and cell growth [29].

3. Needs Statement

The progress of human exploration to space, the Moon, and Mars is not considered safe due to the limited understanding of how partial gravity affects human cells, nor has it been fully addressed due to cost limitations and the inability to simulate partial gravity on Earth accurately. Building a partial gravity cell culturing prototype would enable the study of the relationship between cell properties and different gravitational environments, therefore allowing for human exploration without health complications.

4. Implications of Project Success

In case of the prototype's success, both life in space and on land would be enhanced. Understanding how different gravitational environments influence cells would provide more informed conclusions for human explorations. With such findings, solutions would be developed to ensure the safety of humans beyond Earth. Having humans travel to space, including Mars and the Moon, increases the information we have about outer space and helps answer questions about extraterrestrial life. It could potentially unlock new planets or locations in space where humans can start a new life.

The prototype's success is based on the United Nations Sustainable Development Goals (UNSDG) [30]. A Sustainable Development Goal (SDG) addressed is Life on Land (Goal #15), focusing on ensuring the safety of nature on our planet [31]. The prototype would primarily concentrate on combating desertification by collecting soil from other planets or studying the Moon's role in enhancing agricultural methods. Another SDG addressed is Industry, Innovation, and Infrastructure (Goal #9), which focuses on promoting sustainable industrialization and fostering innovation [32]. With the ability to travel outside Earth, there would be increased innovations, whether by drugs or technologies, to allow humans to compensate for the gravitational difference. This would not only be required for a limited time, but there would also be a constant need to produce new vital drugs and technologies to sustain human life. For SDGs #12 and #13, the success of the prototype would promote sustainable strategies for space and Earth by demonstrating how biology adapts to reduced gravity and sustains life in space [33][34]. Finally, SDG #3, which refers to "good health and wellbeing," the prototype's success could benefit health and biology in space travel conditions by demonstrating the gravitational effects on cellular development [35]. If the potential of life outside Earth is true, such a prototype would address all the goals stated above.

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