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ARTÍCULO DE INVESTIGACIÓN

Revisión comparativa de las tecnologías de simulación de microgravedad y sus aplicaciones

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Recibido: 01/11/2025 • Revisado: 15/11/2025 • Aceptado: 30/11/2025

Resumen

Las tecnologías de simulación de microgravedad son fundamentales para comprender los efectos de la gravedad reducida en los procesos biológicos y físicos. Esta revisión compara diversos sistemas empleados para reproducir condiciones de microgravedad, entre ellos los clinostatos bidimensionales, las máquinas de posicionamiento aleatorio, los vuelos parabólicos, las torres de caída y otras tecnologías afines. Se analizan sus capacidades, sus aplicaciones en la investigación científica y los tipos de experimentos que permiten desarrollar. Asimismo, el estudio resalta investigaciones clave y examina las limitaciones propias de cada sistema, poniendo énfasis en factores como la duración de la exposición, los gradientes gravitacionales y la escalabilidad. En conjunto, este análisis ofrece una visión general de las tecnologías actualmente disponibles, abordando sus fortalezas, debilidades y su potencial futuro para el avance de la investigación en exploración espacial.

Palabras clave: Simulación de microgravedad, Plataformas de microgravedad terrestres, Ciencias de la vida espacial, Procesos biológicos y físicos, Exploración espacial.

Citar como:
De la Cruz-Calderón, N. F., Alvarez-Quichca, J. A., Duran-Cordova, A. J., Lope-Paredes, R. S., Salazar-Reyes, M., y Duran-Aquino, R. C. (2025). Comparative Review of Microgravity Simulation Technologies and their Applications. *Revista Científica de Astrobiología*, *2*(2), 56–107. `http://doi.org/10.69976/aspast.v2n2.4`

RESEARCH ARTICLE

Comparative Review of Microgravity Simulation Technologies and their Applications

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Recibido: 01/11/2025 • Revisado: 15/11/2025 • Aceptado: 30/11/2025

Abstract

Microgravity simulation technologies are essential for understanding the effects of reduced gravity on biological and physical processes. This review compares various systems used to replicate microgravity, including 2D clinostats, random positioning machines, parabolic flights, drop towers, and other technologies. It examines their capabilities, applications in scientific research, and the types of experiments they enable. The review also highlights key studies and explores the limitations of each system, focusing on factors like exposure duration, gravitational gradients, and scalability. This analysis provides an overview of current technologies, addressing their strengths, weaknesses, and future potential for advancing space exploration research.

Keywords: Microgravity simulation, Ground-based microgravity platforms, Space life sciences, Biological and physical processes, Space exploration

Cite as:
De la Cruz-Calderón, N. F., Alvarez-Quichca, J. A., Duran-Cordova, A. J., Lope-Paredes, R. S., Salazar-Reyes, M., y Duran-Aquino, R. C. (2025). Comparative Review of Microgravity Simulation Technologies and their Applications. *Revista Científica de Astrobiología*, *2*(2), 56–107. `http://doi.org/10.69976/aspast.v2n2.4`

1. Introduction

Low Earth orbit and space missions are inherently subject to microgravity, a state in which gravitational forces are significantly reduced to almost zero values (Melissa L. Gaskill, 2024; Vogt et al., 1995). Biological, chemical, and physical phenomena that behave fundamentally differently than they would under terrestrial gravity can be observed in this special environment. Understanding of these processes has greatly expanded, with a substantial impact on disciplines such as human physiology, pharmacology, biomedicine, and advanced materials engineering. To understand the complicated mechanisms underlying astronauts' bone and muscle atrophy and to optimize the formation of crystals of complex proteins, both of which have significant implications for rational medication design, microgravity research has proven essential (Ferranti et al., 2020; Oluwafemi & Neduncheran, 2022; ScienceDirect, 2017). However, since direct access to space is very expensive and scarce, it presents significant operational issues. Numerous terrestrial microgravity simulation methods have been developed because of this intrinsic obstacle (Herranz et al., 2013; Jarvis et al., 2022; Vashi et al., 2022). These instruments play a crucial role in democratizing access to this extremely specialized research by allowing scientists to examine the effects of lower gravity without depending on space flights (Nishimura, 2023; Palma-Jiménez et al., 2017; Zhang et al., 2022). It is important to note that although these simulations provide approximations, they do not accurately represent true microgravity; they often introduce residual gravitational gradients or have intrinsic temporal constraints that set them apart from the real space environment. Integrating and comparing these platforms is crucial and necessary due to the wide variety of simulation systems that are available, such as two- and three-dimensional clinostats (Rodríguez, 2020), Random Positioning Machines (RPMs) (Pino Alfonso et al., 2006), parabolic flights (Selig et al., 2010), drop towers (Kim et al., 2024), neutral buoyancy facilities (Han et al., 2010), gravity offload systems (L. Li et al., 2020), and newer methods like magnetic (Boudreaux et al., 2025) and acoustic levitation (Hammer et al., 2009). Selecting the best technology is a difficult and crucial choice for researchers because of the significant differences in their basic working principles, the accuracy of the simulation they offer, and the scale of the experiments they can support. The obvious lack of a thorough comparative guide poses a serious obstacle to making the most of the resources at hand and enhancing the effectiveness of the research (Herranz et al., 2013; Palma-Jiménez et al., 2017).

A deeper understanding of terrestrial microgravity simulators contributes to the development of more effective countermeasures against physiological deterioration during long-term space missions. These platforms also support improvements in drug testing protocols by replicating gravity-sensitive environments and facilitate advances in fields such as soft robotics and adaptive materials. By reducing reliance on orbital access, they enable research agendas that would otherwise remain out of reach for many institutions. Their operational principles, the capabilities of their physical facilities, the kinds of scientific investigations they support, and their most recent and pertinent applications in aerospace research will all be covered in detail in this work. It will also go over each method's inherent limitations and approximate related expenses. In addition to maximizing resource allocation and strategic decision-making in various academic and scientific contexts, this analysis principally seeks to serve as an informed and current guide that fosters significant improvements in both basic and applied knowledge.

2. Material and methods

This review presents an overview of ten commonly used methods for simulating microgravity conditions, both in terrestrial and space-related contexts. The selected techniques vary in complexity, cost, and applicability, depending on the biological, physical, or engineering focus of the experiment. For each method, its operating principle, main scientific applications, and relevant considerations for its experimental implementation are described.

2.1 Clinostats (2D and 3D)

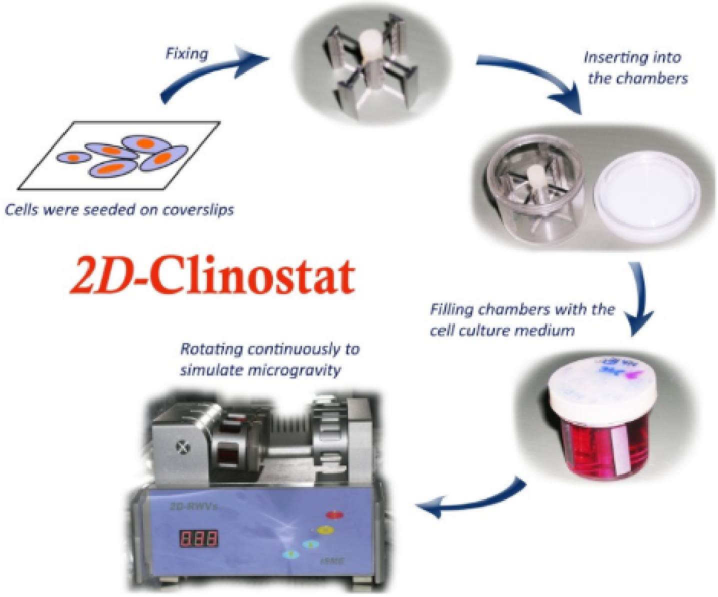
2.1.1 Description

Clinostats are electromechanical devices designed to simulate the effects of microgravity or altered gravity environments on biological systems in terrestrial environments. Their central objective lies in the continuous and controlled rotation of a biological sample around one or more axes. This rotation causes the gravitational force vector to act on the sample from multiple directions in succession. This, when averaged over time, eliminates the constant perception of a specific gravitational direction and prevents unidirectional settling of cells or particles (Nishimura, 2023; Wuest et al., 2015).

- **2D (Two-Dimensional) Clinostats:** These devices rotate the sample in a single plane (usually horizontal) at a constant angular velocity. The sample experiences a periodic variation in the sensed direction of gravity. If the rotational velocity is high enough for the sample to complete one cycle before significant settling occurs, the result is zero vector-averaged gravity in that two-dimensional plane. They are suitable for studying small organisms or cellular systems where the objective is to eliminate primary gravitropism (Nishimura, 2023).
- **3D (Three-Dimensional) Clinostats:** Unlike 2D models, these clinostats are designed to rotate the sample along multiple axes simultaneously to cancel out the gravity vector in all three dimensions. They aim to offer a more complete simulation of microgravity and create a truly isotropic environment. The most sophisticated implementation and the gold standard for this three-dimensional simulation is the Random Positioning Machine (RPM) (Clary et al., 2022; Nishimura, 2023; Shi et al., 2012), which is distinguished by its ability to perform precisely controlled, random rotation to optimize gravitational cancellation.

Figure 1

2D Clinostat



Note. Taken from Effects of Simulated Microgravity on Human Umbilical Vein Endothelial Cell Angiogenesis and Role of the PI3K-Akt-eNOS Signal Pathway, by Shi F, Wang Y-C, Zhao T-Z, Zhang S, Du T-Y, Yang C-B, et al. (2012), PLoS ONE 7(7).

2.1.2 Scientific Applications

Clinostats, both in their two- and three-dimensional forms, are key instruments in multiple areas of study. They facilitate the analysis of biology under modified gravity in terrestrial environments, which is essential for the development of space biology and other areas of knowledge, avoiding the high costs and access restrictions associated with experiments conducted in real space (Cao et al., 2023; Nishimura, 2023). Their most notable uses include:

- **Cell Biology:** Investigation of proliferation, differentiation, adhesion, migration, and the formation of three-dimensional structures (such as spheroids and organoids, especially with 3D clinostats/RPMs) in an environment where the directional gravitational signal has been minimized (Cao et al., 2023; Shi et al., 2012). This is crucial for understanding physiological changes in astronauts (e.g., bone and muscle atrophy, immune dysfunction) and for applications in regenerative medicine and tissue engineering.

- **Botany:** Study of growth, development (roots, stems), gravitropism, germination, photosynthesis, and gene expression in plants under simulated microgravity. This research is vital for the development of closed life support systems that would be necessary for future long-duration space missions (Cao et al., 2023; Nishimura, 2023).

- **Microbiology:** Analysis of microbial growth, biofilm formation, virulence, antibiotic resistance, and metabolism under microgravity conditions. This has direct implications for astronaut health and the integrity of space habitats (Clary et al., 2022).

2.1.3 Operational and Technical Parameters

The effectiveness of clinostats in microgravity simulation is intrinsically linked to the control and optimization of their physical parameters and technical capabilities. These range from 2D models, with a generally constant rotation speed, to systems that implement the 3D concept with multi-axial and random motions (Clary et al., 2022; Nishimura, 2023). Minimizing the rotation radius is crucial to reduce residual centrifugal forces, which are the main simulation artifact. Furthermore, load capacity varies between designs, and environmental control is critical for biological viability (Cao et al., 2023; Clary et al., 2022; Nishimura, 2023; Shi et al., 2012). The specific details of these parameters are presented in Table 1.

Table 1

Operational and Technical Parameters of Clinostats

Operational and Technical Parameters	Characteristics
Rotational Speed (ω)	**2D Clinostat:** Generally constant, typically between 0.5 and 4 RPM (revolutions per minute), or higher speeds if the settling velocity of the object being studied is high. The optimal speed is selected to ensure averaging of the gravitational vector before significant settling occurs. **3D Clinostat:** These involve rotations along multiple axes. The angular velocities of these axes (which can be expressed in RPM, although they usually vary continuously and randomly) are dynamic and controlled by software (Clary et al., 2022; Nishimura, 2023). Unlike the constant velocities of 2D clinostats, here the velocities are constantly and randomly varied along each axis to maximize the randomization of the gravitational vector and minimize the shear forces perceived by the sample.
Radius of Rotation (r)	A smaller radius is essential to minimize centrifugal forces generated by rotation, which are a simulation artifact. The sample should be positioned as close to the center of rotation as possible to ensure effective microgravity simulation (Nishimura, 2023).
Centrifugal Forces	They are the main artifact inherent in rotation. For a successful simulation of microgravity, these forces must be kept to a minimum, ideally below $10^{-2}g$ to $10^{-3}g$ in the sample region, to ensure that the observed effects are attributable to altered gravitational perception and not to mechanical forces (Nishimura, 2023).
Load Capacity	Varies significantly depending on the design and size of the clinostat. 2D models handle smaller volume samples (e.g., test tubes, small flasks). Systems that implement the 3D concept, such as RPMs, can accommodate a wider range of sizes, from small culture dishes to larger volume bioreactors, depending on their engineering and purpose (Shi et al., 2012).

2.1.4 Operation

The operation of the clinostats, both in their 2D and 3D versions, is detailed through the following operational steps:

1. Preparation of the Biological Sample: The sample is prepared and introduced into a sterile culture container, compatible with the clinostat and biological needs.

2. Mounting on the Rotation System: The sample container is fixed to the rotational support. In 2D clinostats, rotation is ensured in one plane; in 3D clinostats, the sample is centered to optimize randomization and minimize centrifugal forces (Nishimura, 2023).

3. Setting and Activating Rotation: The rotation parameters are defined. For 2D, this is a constant speed; for 3D, software controls dynamic and random speeds and directions along multiple axes for three dimensional cancellation of the gravitational vector (Nishimura, 2023)..

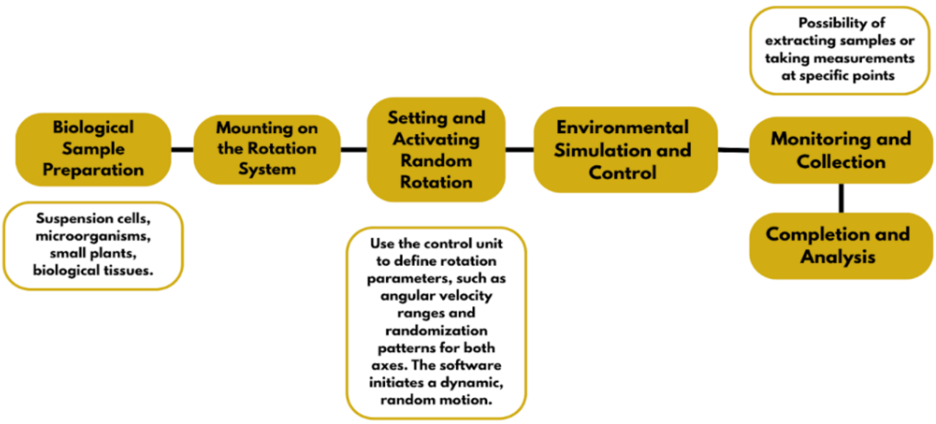
4. Altered Gravity Simulation and Environmental Control: The clinostat rotates, constantly changing the direction of gravity. In 2D, the variation is planar; in 3D, the vector is canceled out in three dimensions. Environmental control systems (temperature, CO_2, humidity, light) are activated to maintain optimal conditions.

5. Continuous Monitoring and Data Collection (Optional): Rotation is monitored and system stability is verified. Optionally, samples or intermediate data are collected to observe biological evolution.

6. Completion of the Experiment and Post-Simulation Analysis: At the end of the experiment, the clinostat is stopped and the samples are removed for morphological, biochemical, molecular, and physiological analysis (Nishimura, 2023). The results are compared with controls in normal Earth gravity (1 g).

Figure 2

2D/3D Clinostat Operating Diagram



2.2 Random Positioning Machine (RPM)

2.2.1 Description

The Random Positioning Machine (RPM) is considered the "gold standard.ªmong ground-based microgravity simulators. It is an advanced form of 3D clinostat designed to expose biological samples to a randomized, three-dimensionally averaged gravity vector, thereby creating an isotropic simulated microgravity environment (Krause et al., 2018; Yotov et al., 2022).

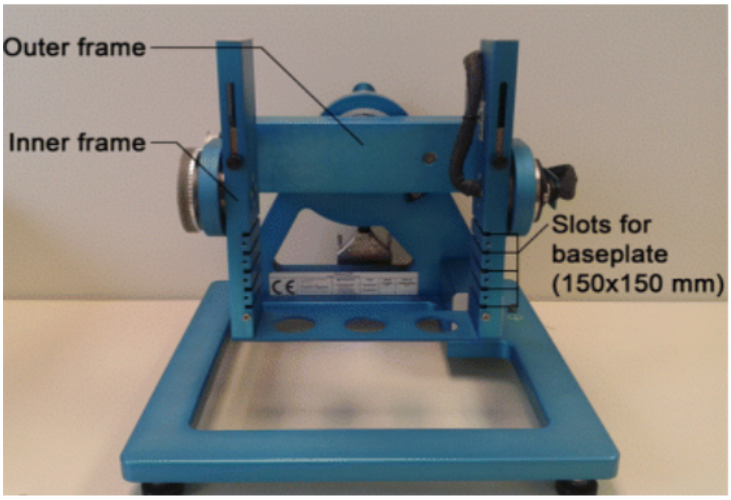
Unlike 2D clinostats or even other 3D clinostat concepts with more predictable motions, the RPM uses a system of two orthogonal rotating frames (gimbals), where the rotation speeds and directions of each axis are independently and randomly controlled by software (A. G. Borst & Van Loon, 2009; Melissa L. Gaskill, 2024).

This random, multidirectional motion ensures that the sample experiences the gravitational vector from an infinite number of orientations in short periods of time. This effectively prevents particle settling and gravitational polarization, resulting in a complete vector cancellation of the gravity perceived by the sample (A. G. Borst & Van Loon, 2009; Krause et al., 2018).

RPMs are particularly valued for their ability to generate a high-quality microgravity simulation environment, more faithfully replicating the weightless conditions experienced in space, with minimal residual forces (A. G. Borst & Van Loon, 2009; NASA Technology Transfer Program, 2021).

Figure 3

Random Positioning Machine



Note. Taken from *Analysis of Statoliths Displacement in Chara Rhizoids for Validating the Microgravity-Simulation Quality of Clinorotation Modes* (p.231), by Krause, L., Braun, M., Hauslage, J. et al., 2018, Microgravity-Science and Technology.

2.2.2 Scientific Applications

Random Positioning Machines (RPMs) are invaluable tools in biomedical and space research, offering three-dimensional microgravity simulation that enables more in-depth studies compared to 2D clinostats. Their applications include:

- **Biological studies:** These are used to investigate the effects of simulated microgravity on biological systems, such as cells, tissues, plants, and small animals (e.g., drosophila, fish, rodents) (G. Borst, 2007).

  - **3D Cell and Tissue Biology:** RPMs are essential for 3D cell culture, promoting the formation of spheroids, organoids, and complex tissues that better replicate in vivo physiological conditions (Krause et al., 2018; Yotov et al., 2022). This is crucial for cancer research, regenerative medicine, and tissue engineering, allowing the study of cell proliferation, differentiation, adhesion, and migration in the absence of directional gravitational signalling.
  - **Mechanotransduction Studies:** These allow for the investigation of how cells and tissues sense and respond to the absence of directional mechanical forces imposed by gravity, shedding light on the molecular mechanisms of muscle and bone atrophy, immune dysfunction, and cardiovascular changes observed in astronauts (Krause et al., 2018).
  - **Microbiology:** Investigation of the growth, virulence, biofilm formation, and antibiotic resistance of microorganisms under simulated microgravity conditions, with implications for crew health and the maintenance of space habitats (A. G. Borst & Van Loon, 2009).

- **Bioreactor Development and Pharmacology:** RPMs are used to test and optimize bioreactor designs that simulate weightless conditions, which is relevant for the production of tissues or pharmaceuticals in space. They are also used to study drug efficacy in an altered-gravity environment, which could influence the design of treatments for long-duration missions.

- **Hardware Development:** RPMs are also used in hardware testing to evaluate technology under altered gravity conditions (NASA Technology Transfer Program, 2021).

2.2.3 Operational and Technical Parameters

The effectiveness of RPMs in microgravity simulation depends largely on the optimization of their physical parameters and technical capabilities. Key aspects include dynamic and random rotation speed management, a minimized rotation radius to reduce residual centrifugal forces, and a versatile payload capacity (A. G. Borst & Van Loon, 2009; G. Borst, 2007; Krause et al., 2018; NASA Technology Transfer Program, 2021; Yotov et al., 2022) The specific details of these parameters are presented in Table 2.

Table 2

Operational and Technical Parameters of Random Positioning Machine

Operational and Technical Parameters	**Characteristics**
Rotational Speed (ω)	The RPMs operate with dynamic and random angular velocities on both axes (internal and external), controlled by software. These velocities vary continuously to ensure maximum randomization of the gravitational vector. Although they can reach speeds of up to 60 RPM or more, the objective is not a constant speed, but rather an unpredictable variation to effectively average gravity and minimize shear forces on the sample (Krause et al., 2018; Yotov et al., 2022).
Radius of Rotation (r)	It is crucial that the sample be positioned as close as possible to the geometric and rotational center of the gimbal system. A small rotation radius is vital to minimize the residual centrifugal forces generated, which are the main simulation artifact. In optimal designs, the sample radius is minimal (e.g., a few millimeters) (Krause et al., 2018).
Centrifugal Forces	As with clinostats, centrifugal forces are the primary artifact. In a well-designed RPM, these forces are minimized to very low levels, ideally below $10^{-2}g$ in the sample region (Krause et al., 2018).Active management of velocity randomness and the small sample radius contribute to reducing these forces so that the observed effects are attributable to the microgravity simulation.
Load Capacity	Modern RPMs can accommodate a wide range of samples, from small cell culture flasks, multiwell plates and test tubes, to larger volume bioreactors, depending on the specific equipment design (A. G. Borst & Van Loon, 2009; Krause et al., 2018; NASA Technology Transfer Program, 2021).

2.2.4 Operation

The operation of a Random Positioning Machine (RPM), as an advanced three-dimensional microgravity simulator, follows a systematic operating process:

1. **Biological Sample Preparation:** The sample is prepared and placed in a sterile culture vessel compatible with the RPM and biological requirements. The goal is to optimize cell quantity and density to prevent sedimentation before the start of random rotation.

2. **Mounting on the Rotation System:** The sample container is securely fixed in the center of the RPM gimbal system, ensuring that it is at the point of minimum centrifugal force and maximum randomization of gravitational orientation (Krause et al., 2018).

3. **Setting and Activating Random Rotation:** Specific rotation parameters are

defined through the RPM software. This includes angular velocity ranges and randomization patterns for both axes. The software initiates dynamic, random motion in multiple axes, crucial for three-dimensional gravitational vector cancellation (Krause et al., 2018).

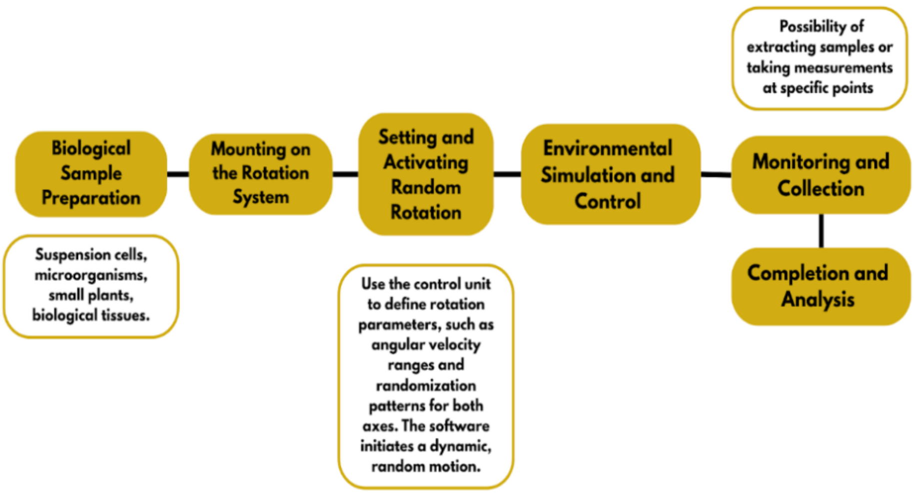
4. **Isotropic Microgravity Simulation and Environmental Control:** The RPM begins to rotate randomly, constantly changing the sample's orientation relative to Earth's gravity, which averages the gravitational vector to zero in all three dimensions. Simultaneously, integrated environmental control systems (temperature, CO_2, humidity, light) maintain optimal conditions for the sample (A. G. Borst & Van Loon, 2009).

5. **Continuous Monitoring and Data Collection (Optional):** The RPM is continuously monitored to ensure stability and randomness of motion, verifying the absence of vibrations or parasitic forces. Optionally, samples or intermediate data are collected at key points during the experiment to observe biological evolution (Krause et al., 2018).

6. **Experiment Termination and Post-Simulation Analysis:** At the end of the scheduled experiment, the RPM is brought to a controlled halt. Biological samples are carefully removed for processing and further analysis. Results are compared with those of controls grown in normal Earth gravity (1 g) to identify and quantify specific effects attributed to the isotropic microgravity simulation (Krause et al., 2018).

Figure 4

Random Positioning Machine operating diagram



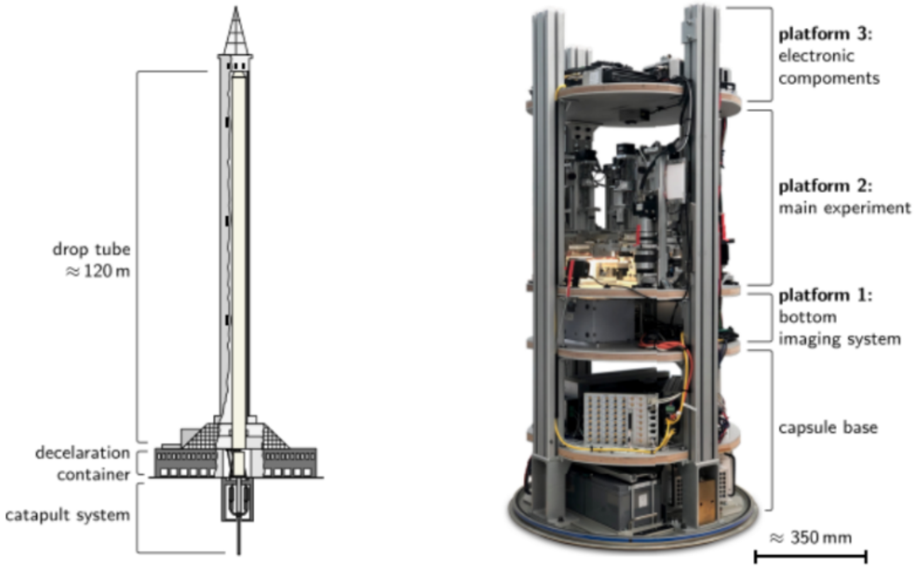
2.3 Drop Tower

2.3.1 Description

The Drop Tower (DP) method uses the condition of weightlessness by subjecting an object to free fall. In the same way, the falling tower is used as a sample in comparison with the experiments performed in space. After the free fall of the experimental capsule inside the evacuated tower, the equilibrium and the unidirectional perception of gravity are cancelled, creating weightlessness conditions analogous to microgravity. Experimentation with Drop Towers experience repeated drops that allow analysis of variables and parameters of time, velocity, distance, and perturbations or error variables. (Cui et al., 2022; D'Angelo et al., 2022).

Figure 5

Schematic of the ZARM Drop Tower



Note. Taken from *Spreading of droplets under various gravitational accelerations* (p.5), by Olfa D'Angelo, Felix Kuthe, Kasper van Nieuwland, Clint Ederveen Janssen, Thomas Voigtmann , Maziyar Jalaa, 2022, AIP publishing.

2.3.2 Scientific Applications

The Drop Towers reach a gravity of 10^{-6}, which makes it have a residual acceleration of 0,0000098 m/s^2. This gives a sample of how the experiment would react in a microgravity environment (D'Angelo et al., 2022). Their most notable uses include:

- **Cellular & Molecular Biology:** In biology, cell cultures or microorganisms are often used for experiments on membrane physiology and gravitation. Where multiple environmental parameters, such as temperature and pressure, are taken into account. This application is necessary to understand the processes of ultrafast physiological responses, such as the elimination of sedimentation effects, tests that are impossible on land.

- **Neurobiology and Behavior:** It is a free-fall experiment in the ZARM drop tower that studies the swimming of upside-down catfish to study sensorimotor disorders. Sensorimotor adaptation, which is responsible for manipulating visual error, in context, are well adapted to possible outcomes for astronauts after a space mission, as detailed in the article Rapid loss of postural control, mimicking vestibular disorders in astronauts"(D'Angelo et al., 2022; DeMaio, 2021).

- **Plant Physiology:** It is responsible for the thermal decomposition processes of solid fuels in a gaseous environment.

2.3.3 Operational and Technical Parameters

Drop towers reproduce microgravity through free fall in controlled environments. On the other hand, their performance is linked to key operational and technical parameters, such as: The exposure time (dependent on the height of the tower), the purity of the vacuum environment and the accuracy of the braking systems. These parameters determine not only the quality of the microgravity achieved, but also the experimental feasibility for specific payloads. Table 3 quantifies these critical operational parameters.

Table 3

Operational and Technical Parameters of Drop Tower

Parameters	Characteristics
Drop tower at ZARM	Total Height: 146 meters. Inner Vacuum Tube: 120 meters tall, fully decoupled from the outer structure. Drop Height (Drop Mode): 110 meters. Deceleration Container: Located at the bottom of the tower for safely stopping the dropped capsule (Cui et al., 2022; D'Angelo et al., 2022).
Drop Height (h) and Microgravity Time (t)	Effective duration of continuous microgravity. Determines the microgravity time ($t \approx \sqrt{2h/g}$). Typical range of vacuum drop: 0.6 s (small towers) to 4.74 s (146 m towers) (D'Angelo et al., 2022; González Perea, 2015).
Microgravity quality	Levels $\leq 10^{-6}$ g require: Extreme vacuum ($\sim 10^{-4}$ Pa), vibration isolation for unchanged levels, and precise centering of the capsule (optimally located) (D'Angelo et al., 2022; González Perea, 2015).
Launch/Braking Acceleration	Launching has a maximum acceleration while braking has a negative acceleration. Launch: 0–5 g (catapults). Braking: up to 50g (short spikes) (D'Angelo et al., 2022).
Braking Method	Pellet beds: With materials (polystyrene, etc.). Electromagnetic brakes: Controlled deceleration.

2.3.4 Operation

The operation of the drop towers is detailed through the following operational steps:

1. **Loading of the experiments:** All experimental modules are installed in the capsule (the main object to be analyzed), then sealing the capsule completely (it is necessary to check that it is completely closed) to withstand the high speed.

2. **Creating the vacuum environment:** Closing the chamber, closing the top and bottom gates to create the vacuum tube (tower) and vacuum pumping to reduce the pressure to $< 10^{-2}$ Pa to almost completely eliminate air pressure.

3. **Microgravity:** During the fall into the void, there are two methods of study:

    a) **Initial launch:** Have two options of "Free fall" with initial acceleration of 0 g and "Catapult" at 30–50 $\mathrm{m/s^2}$ (3–5 g).

    b) **Transition to free fall:** After the impulse, start the descent by gravity (Weightlessness phase: 4.0–4.74.).

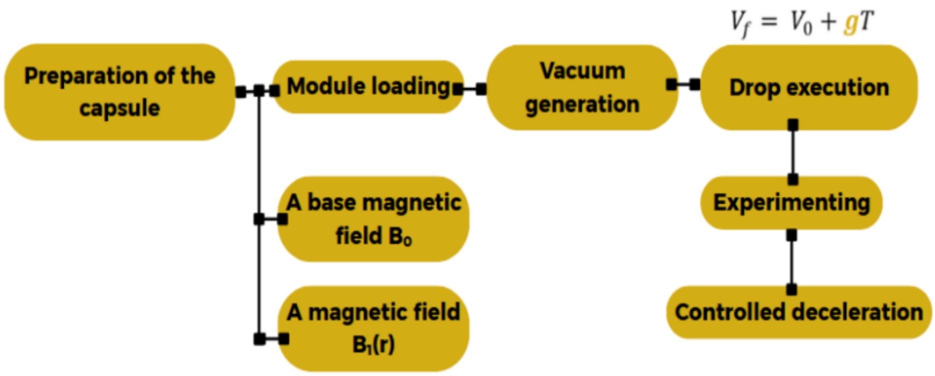
4. **Deceleration and recovery:** Controlled deceleration has two methods:

   a) "Pellet bed" (deceleration with expanded polystyrene)

   b) "magnetic brakes" (coils with electromagnetic fields opposite to the movement) (D'Angelo et al., 2022; DeMaio, 2021; González Perea, 2015; Takada et al., 2018).

Figure 6

Drop Tower operating diagram



2.4 Parabolic Flight

2.2.1 Description

During parabolic flight, the aircraft begins with a phase of horizontal flight with acceleration, gradually ascending until it reaches an inclination of 45°, while the crew experiences hypergravity, with forces between 1.5 and 1.8 g. Then, the engine power is reduced and the plane enters the parabolic ascent, where the total sum of the interactive forces on the plane creates the sensation of microgravity, which lasts for 21 to 22 seconds.

The plane then descends at an angle of -45°, at which point hypergravity returns. This cycle is repeated between 15 and 30 times, depending on the purpose of the flight. In total, crew members can experience between 5.25 and 11 minutes of weightlessness (AirZeroG, 2018a, 2018b).

Figure 7

Zero G Parabolic Flight ascent

Note. Taken from Zero-G Airbus A300 for parabolic flights [Photograph], by ESA, 2007, `https://www.esa.int/ESA_Multimedia/Images/2007/11/ZeroG_Airbus_A300_for_parabolic_flights`.

2.4.2 Scientific Applications

Parabolic flights are an essential means of simulating, testing, and practicing tools, methods, and protocols that serve as training for astronauts on long or similar missions, opening up the possibility of conducting research for companies, professionals, and students. Among its applications are:

- **Material research:** In parabolic flights, whose duration is suitable for controlled experiments, technical investigations are carried out on the *T*hermocapillary Effects in Phase Change Materials (TEPiM), aimed at improving heat transfer in materials used for thermal control in spacecraft (Berto et al., 2022; Ezquerro et al., 2020). Additionally, the characterization of these materials' parameters is studied for generalizations applicable to artificial habitats.
- **Fluids physics in fuels:** Experimental validations of simulations on the control of combustible fluids through high-frequency vibrations are conducted (ESA, 2016). These tests are useful for selecting and optimizing systems that reduce power losses during long-duration flights.
- **Innovation and development:** Parabolic flights allow the testing of tether-cable prototypes for artificial satellite orbits, taking advantage of the microgravity environment. They are also used to simulate Martian conditions, facilitating the study of meteorological phenomena relevant to robotic exploration and the sampling of Earth-analog environments.
- **Biotechnology and medicine:** These flights enable practical evaluations of basic, laparoscopic, robotic, and telesurgery procedures for crew medical support. They also contribute to the improvement of surgical skills under microgravity conditions (Prieto et al., 2021).

- **Gravitational biology:** Physiological and genetic changes, as well as health risks in humans and animals, are explored and tested, such as bone demineralization, muscle atrophy, cardiovascular deconditioning, and vestibular and sensory imbalances. A notable example is the 58 % increase in intraocular pressure during parabolic flight, which enables simulation of *Spaceflight Associated Neuro-ocular Syndrome* (SANS) (Furukawa et al., 2021; Ong et al., 2023), contributing to the development of protocols for its prevention and risk mitigation.

2.4.3 Operational and Technical Parameters

The effectiveness of the PF for microgravity simulation depends on external and internal physical parameters, which allow for the optimization of the level of gravity achieved. These elements include temperature, pressure conditions, and sound levels for experimental noise, as well as the angle that defines the gravitational magnitude achieved. The specific details of these parameters are presented in Table 4.

Table 4

Operational and Technical Parameters of Parabolic Flight

Parameters	Characteristics
Initial velocity (v_0)	The take-off speed for each campaign depends exclusively on the aircraft model used. However, the approximate range for the most used aircraft (A300/A310 Zero-G, Boeing 727, Falcon 20) is 800–810 km/h.
Take-off altitude (h)	Due to atmospheric pressure conditions and Earth's gravitational field intensity, the optimal altitude for campaigns is around 5,000 meters above sea level, considering fuel management, crew safety, and microgravity level.
Flight angle (α)	The flight angle relative to the horizontal determines the type of relative gravity experienced inside the cabin during each campaign. The angle ranges used for research are 38°, 42°, and 45°–47°, corresponding to Martian gravity (0.38g), lunar gravity (0.16g), and microgravity, respectively.
Sound level (dBA)	To ensure proper cabin conditioning and minimize noise interference in data recordings, it is recommended that the internal sound level remains between 70–75 dBA during weightless phases, and around 80 dBA during hypergravity phases.

2.4.4 Operation

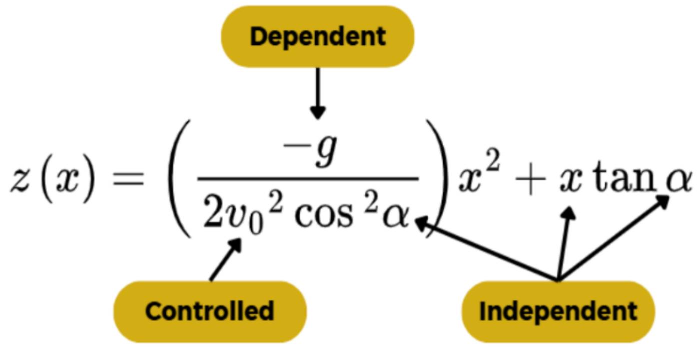
The operation of PF is complex and discontinuous, making it a sensitive method with relatively short-duration phases. It is carried out through a coordinated sequence of aerial maneuvers:

1. Safety protocols: The mission begins with a safety review, which includes aircraft inspection, calibration of onboard scientific equipment, and training of research personnel and crew. Experimental payloads are securely mounted to withstand both hypogravity and hypergravity phases and are conditioned according to the type of experiment.

2. Takeoff and ascent to target altitude: The aircraft takes off and climbs to the designated altitude, where atmospheric conditions and gravitational stability (of both the aircraft and the environment) are optimal to begin the control maneuvers.

Figure 8

Parabolic Flight Trajectory equation



3. Parabolic maneuvers: The aircraft follows a specified range of pitch angles, coordinated with the three main cabin control stations. During ascent, gravity increases to between 1.5 and 2 g (hypergravity), as the aircraft rises toward the apex of the parabola.

4. Microgravity phase execution: At the top of the parabola, the aircraft follows a ballistic trajectory with reduced engine power. Objects and personnel onboard experience microgravity conditions for 20 to 25 seconds, allowing for the performance of gravity-sensitive experiments.

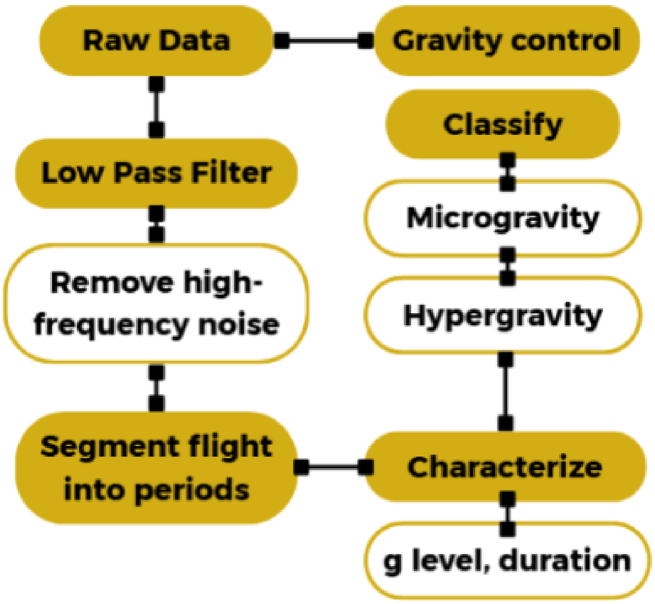
5. Descent and stabilization: As the aircraft exits the parabola, it descends at a similar angle, generating another phase of hypergravity. It then momentarily stabilizes in horizontal flight before initiating a new parabola.

6. Repetition: A typical flight includes 30 to 40 parabolas. This repetition allows for the collection of multiple comparable data sets under controlled gravitational conditions.

7. Post-flight analysis and sample retrieval: Once all maneuvers are completed, the aircraft returns to base. Scientific equipment and study objects are removed. The collected data are then analyzed to identify the specific effects and consequences of microgravity exposure.

Figure 9

Operation of Parabolic Flight



2.5 Neutral Buoyancy

2.5.1 Description

Neutral buoyancy is one of the best ways to simulate microgravity. This simulation method allows you to test out the technology under these physical conditions. But its real strength is how it helps train crews, since it's a great place for them to get used to this kind of environment, both physically, mentally, and kinaesthetically, under microgravity. NASA has the largest laboratory of this type, called the Neutral Buoyancy Lab (NBL) at NASA's Johnson Space Center in Houston, which is specifically used for mission planning, procedure development, hardware verification, astronaut training, and refinement of time-critical operations necessary to ensure mission success during spacewalks (Jairala et al., 2012; John Charles, 2016).

2.5.2 Scientific Applications

Neutral buoyancy is one of the most widely used methods in the preparation and training of crews for space missions, as well as in testing equipment for such missions. The following studies provide some specifications on these applications.

- **Extravehicular Activity (EVA):** Research shows that extravehicular activities (EVA) allow for the maintenance of spacecraft on a mission or space station; however, these activities require physical strength on the part of the individuals who perform them. Training using Neutral Buoyancy allows subjects exposed to this system to strengthen their physical abilities through continuous training in an environment like that experienced in the aforementioned areas, a space mission or space station (J. Li et al., 2017), which increases the chances of success and improves productivity (John, 2021; Macaluso et al., 2016).
- **Spacewalk Training:** Since the first space mission to the Moon, spacewalks have attracted special attention due to the challenge they represent for the space sector.

Precision and ease of movement are indicators of the success of space missions. NASA developed the Neutral Buoyancy Laboratory after testing this method of immersion in water in more limited spaces and observing its effectiveness for this type of training. Missions following the initial underwater training demonstrated the contribution of this methodology in the space sector (NASA, 2019).

- **Space suit test:** Neutral buoyancy has been shown through various studies to be an efficient testing method, given the multiple facets of evaluation for space suits, as it assesses the resistance of the materials used to pressure and humidity; the comfort it can provide to the individual; and the range of movement it allows, among other factors. These evaluations allow the design team to more accurately identify the strengths and weaknesses of the model so that the designs are less vulnerable to failure in the missions or activities for which they are used (Jacobs et al., 2009).

Figure 10

The Neutral Buoyancy Laboratory facilities

Note. Taken from *Neutral Buoyancy Laboratory* [Photograph], by Johnson Space Center, https://www.nasa.gov/johnson/neutral-buoyancy-laboratory/

2.5.3 Operational and Technical Parameters

The installed capacity of the neutral buoyancy laboratory allows for a variety of specialized simulation activities. All or most of these physical facilities, with their corresponding descriptions, are shown in Table 5.

Table 5

Operational and Technical Parameters of Neutral Buoyancy Laboratory

Parameters	Characteristics
The Pool	**Dimensions:** 202 feet (61.5 m) long, 102 feet (31.1 m) wide, and 40 feet (12.2 m) deep. **Volume:** 6.2 million gallons of chlorinated fresh water. **Temperature:** Maintained between 84°–86° F (28.9°–30° C).
Site Support	Includes outdoor space for training activities and designated areas (covered and uncovered) for hardware storage. Features a hyperbaric chamber, a hypobaric altitude chamber, medical treatment rooms, and locker facilities.
Diver Support	Provides operations support, reconfiguration, camera operations, and safety diving. Equipped with SCUBA and surface-supplied systems (nitrox/air). Includes an ISO Level 8 Clean Room for specialized maintenance and repair.
Logistics and Mockup Facility (LMF)	A series of workshops staffed by highly skilled personnel. Services include mockup fabrication, machine shop, welding, sewing, woodworking, and multi-disciplinary engineering for equipment maintenance.

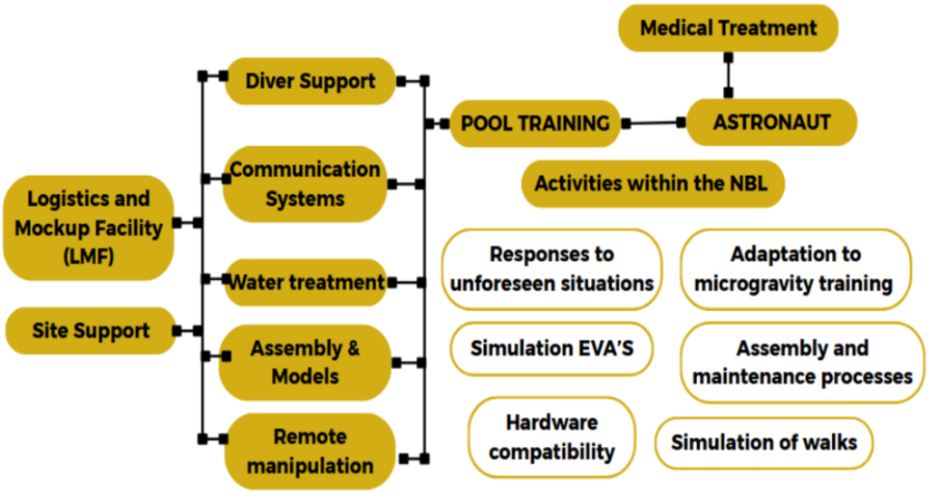
2.4.4 Operation

For the development of research or simulation, the following key points must be taken into account in order to improve the experience:

1. Capabilities and activities: Check in advance what type of studies this laboratory allows you to carry out, whether it is suitable or adapts to your research or training requirements.
2. Activity to be simulated: Ensure that the environment has the appropriate architectural design, which in the NBL varies depending on the scenario to be set up.
3. Installation: Locate additional materials and equipment, and perform a preliminary medical examination of the test subject(s) and accompanying team.
4. Development: The communication team will act as mediators to maintain contact with the test team and all other support systems in the event of any changes or needs, as well as to facilitate the collection of data or other necessary information.

Figure 11

Operation of Neutral Buoyancy Laboratory



2.6 Gravity Offload System

2.6.1 Description

The Gravity Offload System (GOS) is a passive setup that simulates microgravity conditions by counterbalancing a test article's weight using a trolley and counterweight mechanism, allowing realistic ground-based deployment testing (Tanimoto et al., 2007). A representative system based on this approach is The Active Response Gravity Offload System (ARGOS). It is a state-of-the-art platform developed by NASA to simulate microgravity and partial gravity conditions for testing and training purposes. It offers significant technical and operational advantages over previous systems(Tanimoto et al., 2007).

Figure 12

Active Response Gravity Offload System (ARGOS) at JSC

Note. Taken from *Reduced Gravity Testing of Robots (and Humans) Using the Active Response Gravity Offload System*, by Paul Valle, 2017, ntrs.nasa.gov/api/citations/20170008856/downloads/20170008856.pdf

2.5.2 Scientific Applications

Gravity Offload Systems (GOS) are essential tools for simulating reduced gravity conditions, such as those found on the Moon or Mars, this in terrestrial laboratories [54]. By counterbalancing the weight of a test object through mechanical or electromechanical means, GOS enable realistic, long-duration experiments without the limitations of parabolic flight or orbital platforms. Their versatility makes them valuable across multiple scientific and engineering domains, including:

- **Astronaut Training:** GOS allow astronauts to train under simulated partial gravity, supporting extravehicular activity (EVA) practice and spacesuit mobility assessments. This is critical for mission preparedness, ensuring that crew members can perform essential tasks in non-Earth environments.
- **Robotics and Mobility Systems Testing:** These systems facilitate the evaluation of planetary rovers, robotic arms, and mobility aids under simulated lunar or Martian gravity. Engineers can assess performance, stability, and motion control algorithms in conditions that mimic the intended operational environment.
- **Human Physiology Research:** By unloading body weight partially or entirely, GOS support studies on musculoskeletal adaptation, postural control, locomotion in low gravity and rehabilitation studies. Allowing the study of human physiology in a safe and controlled environment (Harvey, 2020)..

2.6.3 Operational and Technical Parameters

The effectiveness of Gravity Offload Systems (GOS) depends on the precision and range of their mechanical and control characteristics. The specific details of these in ARGOS and more parameters are presented in Table 6.

Table 6

Operational and Technical Parameters of Active Response Gravity Offload System

Operational and Technical Parameters	**Characteristics**
Type of installation	Indoor steel gantry structure (bridge crane design).
Working dimensions	Approximately 11 m (L) × 5.5 m (W) × 5.8 m (H) (36 × 18 × 19 ft) (Krause et al., 2018).
Main structure	Fixed steel frame with motorized bridge and trolley.
Degrees of freedom	Motion in three axes (X, Y, Z) plus rotation via gimbal system (Krause et al., 2018; Larry K. Dunganl et al., 2015)
Testing environment	Flat laboratory floor, open space for walking, running or jumping (Larry K. Dunganl et al., 2015).
Load Capacity	Supports humans (in or out of suits), robots, tools, up to 340 kg (Larry K. Dunganl et al., 2015).
Control technology	Force sensors, electric motors, real-time PD + PID control loops (Larry K. Dunganl et al., 2015).

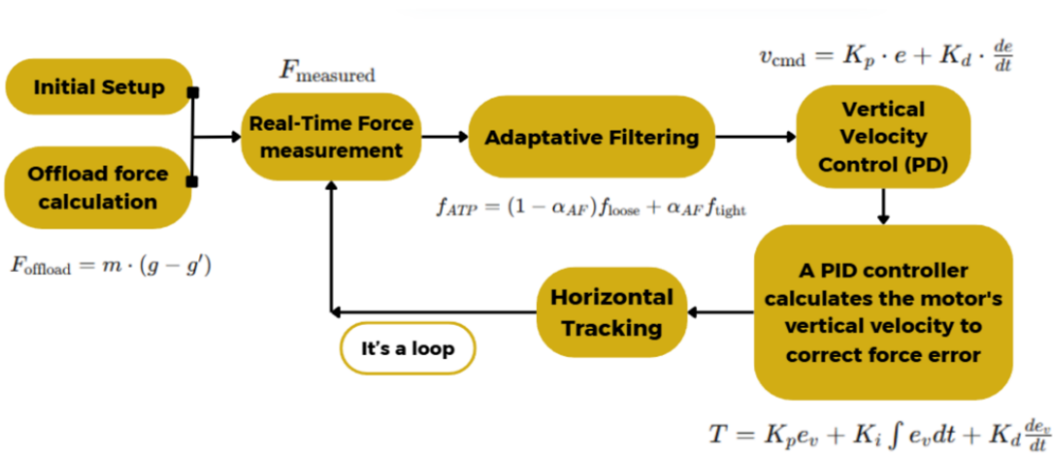
2.6.4 Operation

The operation of the Active Response Gravity Offload System (ARGOS), as a microgravity simulator, is detailed through the following operational steps:

1. Initial Setup: The subject (human, suit, or robot) is connected to a harness or gimbal suspended from the system.
2. Offload Force Calculation: The desired gravity level is set (e.g., Moon or Mars gravity).
3. Real-Time Force Measurement: A load cell measures the actual vertical force on the subject.
4. Adaptive Filtering: A dynamic filter blends two signals (tight and loose) to produce a stable control output.
5. Vertical Velocity Control (PD): A PD controller calculates the motor's vertical velocity to correct force error.
6. Motor Torque Control (PID): A PID controller applies the required motor torque to follow the target velocity.
7. Horizontal Tracking (X–Y): Cable angle sensors detect user movement; the trolley adjusts to stay aligned overhead.
8. Continuous Feedback: The system continuously monitors and adjusts to maintain consistent simulated gravity.

Figure 13

Operation of the Active Response Gravity Discharge System



2.7 Suborbital Spaceflight Systems

2.7.1 Description

Suborbital Spaceflight Systems are advanced platforms that provide access to real microgravity conditions by launching vehicles along parabolic trajectories beyond the edge of space without entering orbit (Ferl et al., 2023). These systems offer 3-4 minutes of true weightlessness, making them valuable for scientific experiments, space technology testing, and astronaut training (Ferl et al., 2023; Schroeder et al., 2021; Smith & Buckey, 2022).

Figure 14

Suborbital spacecraft. Blue Origin's 'New Shepard'

Note. Taken from *Anaesthetists and aerospace medicine in a new era of human spaceflight* (p.2), by T. G. Smith and J. C. Buckey Jr, 2022, Anaesthesia 2022, 77.

2.7.2 Scientific Applications

Suborbital Spaceflight Systems provide brief access to real microgravity and rapid gravity transitions in a controlled, crewed environment. Their unique flight profile enables real-time experimentation, making them ideal for studying fast biological and physiological responses. Key scientific applications include:

- **Study of rapid genetic responses in plants:** Analysis of how microgravity affects gene expression in Arabidopsis thaliana at different phases of the flight. Kennedy Fixation Tubes (KFTs) were manually activated by an astronaut during ascent, microgravity, and re-entry, revealing phase-specific molecular changes not detectable in automated or orbital experiments (Ferl et al., 2023)..
- **Study of acute physiological effects in humans:** Evaluation of how the body responds to extreme gravitational changes ($+6\,Gz$, 0 g) within minutes. Observations include fluid shifts toward the head, mild hypoxia, respiratory difficulty, and cardiovascular stress, with implications for medical screening and risk management in future crewed flights (Kluge et al., 2013).
- **Validation of hardware for crew-operated in-flight experiments:** Successful testing of portable experimental devices (KFTs) handled directly by astronauts during flight. This demonstrates the feasibility of conducting real-time biological experiments in suborbital missions, expanding scientific capabilities beyond automated payloads (Ferl et al., 2023).

2.7.3 Operational and Technical Parameters

The operational and research value of Suborbital Spaceflight Systems relies heavily on their specific operational and technical parameters throughout flight. Characteristics such as peak G-loads, microgravity duration, and gravity transition dynamics define the onboard environment for both crew and experiments. The details of these and related parameters are presented in Table 7.

Table 7

Operational and Technical Parameters of Suborbital Spaceflight System

Operational and Technical Parameters	Characteristics
Flight Altitude (h)	The maximum altitude defines whether the flight qualifies as spaceflight and influences both the gravity level onboard and the duration of microgravity.
Microgravity Duration (Δt_{0g})	Suborbital trajectories provide 3–4 minutes of effective microgravity below $10^{-2}\,g$, allowing real-time observation of early biological and physical responses.
G-Load Profile ($Gz_{\text{máx}}$)	During ascent and especially re-entry, gravitational forces can reach up to $+6\,Gz$. These loads are brief but intense and require prior medical screening.
Cabin Pressure (P)	The spacecraft maintains a pressurized cabin throughout the flight to ensure human and biological safety. Adequate level of pressure helps avoid hypoxia while accommodating a wide range of passengers and experimental materials.
Load Capacity	Suborbital vehicles have constrained volume and mass limits due to their design and safety regulations. While the payload mass is limited, the environment supports complex biological and molecular research over short timeframes.

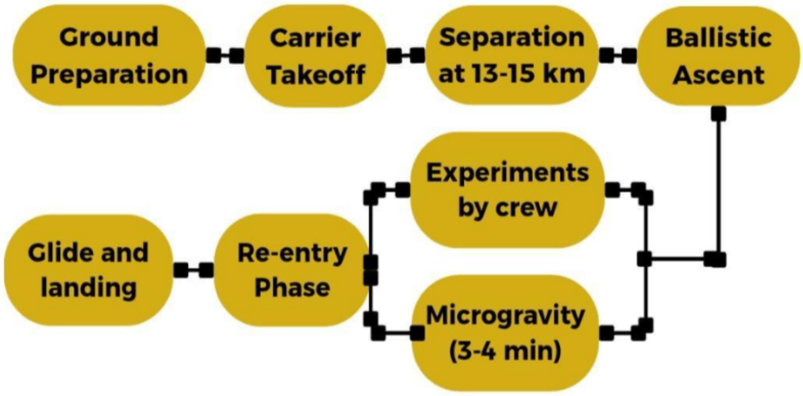
2.7.4 Operation

The operation of the Active Response Gravity Offload System (ARGOS), as a microgravity simulator, is detailed through the following operational steps:

1. **Ground preparation:** The spacecraft is attached to the mothership. Crew and scientific payloads (e.g., KFTs) are secured and pre-flight checks are completed.
2. **Carrier takeoff and ascent:** The system takes off horizontally. Conditions remain at 1g inside the cabin.
3. **Separation and rocket ignition:** At 13–15 km altitude, the spacecraft separates and fires its rocket for around 60 seconds, producing up to +6 Gz.
4. **Ballistic ascent and microgravity:** The vehicle coasts to around 85 km altitude. Microgravity lasts 3–4 minutes. Experiments can be performed during this phase.
5. **Re-entry:** The spacecraft descends, experiencing strong G-forces again. Feathered configuration stabilizes descent.
6. **Glide and landing:** The vehicle glides unpowered and lands on a runway like a plane.
7. **Post-flight:** Crew and samples are recovered. Scientific data is analyzed on Earth.

Figure 15

Operation of a Suborbital Spaceflight System



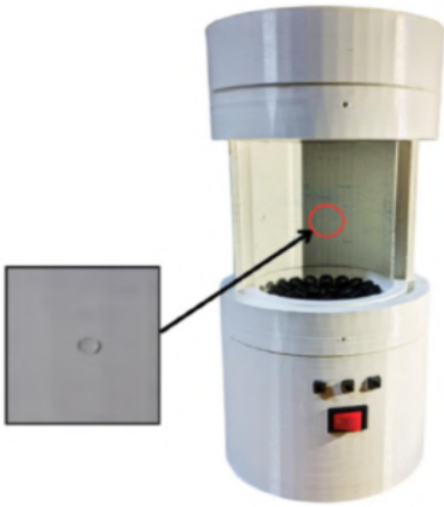
2.8 Acoustic Levitation

2.8.1 Description

Acoustic levitation consists of suspending particles or liquids without physical contact, due to the balance between acoustic pressure counteracting Earth's gravitational pull, as the upward force generated by the acoustic field must balance the downward gravitational force (weight) acting on it. This balance is crucial for maintaining stable levitation within the acoustic chamber, allowing the perceived gravity to be manipulated to conditions such as microgravity (Duran Aquino et al., 2024; Tracy V. Wilson, 2023).

Figure 16

Acoustic Levitation System



Note. Taken from *Can Acoustic Levitation Simulate Microgravity in Fluids?* (p.6), by Rivaldo Carlos Duran Aquinoa, Karen Esteincin Cuba Vargas, Samir Stefano Suarez Rios, JohnnyRomero Milián, Avid Roman-Gonzalez, 2024, 75th International Astronautical Congress (IAC).

2.8.2 Scientific Applications

Acoustic levitation systems are an essential method for inducing reduced microgravity environments, making them an ideal tool for biological and chemical experiments or micro-scale testing. Among their most notable applications are:

- **Biotechnology and pharmaceutical development:** Feasibility analysis of cell culture technologies and acoustic particle manipulation for long-duration space missions via levitation in induced microgravity. Includes biological safety assessments of embryonic (e.g., zebrafish) and germline development under simulated weightlessness, with critical implications for sterile pharmaceutical research (Dumy et al., 2020).
- **Fluid manipulation and crystallization dynamics:** Study of evaporation and crystallization in saturated saline solution droplets (NaCl, KCl, NH_4Cl) under microgravity and reduced pressure. Utilizing acoustic manipulation to observe *in situ* dynamics and the Marangoni effect under extreme conditions, informing research in astrochemistry and sustainable resource management (L. Li et al., 2020).
- **Manufacturing and acoustic innovation:** Characterization of mechanical stresses in structures manipulated by vibration, such as acoustically coupled granular rafts, to obtain force-displacement curves and optimize torsion resistance elements (Hadidi et al., 2025). Includes the development of substrate-free additive manufacturing (3D printing) using acoustic polymer manipulation to reduce supply dependence during space missions (Brown et al., 2024).
- **Advanced material research and thermomechanics:** Experimentation on material casting and the characterization of thermomechanical properties under extreme conditions. Focuses on the deep undercooling of liquids below freezing points and the processing of glass and ceramics at ultra-high temperatures to discover novel material phases (Raffel et al., 2024).

2.8.3 Operational and Technical Parameters

The effectiveness of the acoustic levitation system for microgravity simulation depends on external and internal physical parameters, which allow the desired level of microgravity to be established. These parameters include the pressure and density of the medium, the simulator model used, the simulation position within the generated field, and the characteristics of the object under study. The specific details of these parameters are presented in Table 8.

Table 8

Operational and Technical Parameters of Acoustic Levitation

Operational and Technical Parameters	**Characteristics**
Operating frequency (f)	It defines the rest of the parameters and is used to determine the sample to be investigated. Generally, the frequency in small acoustic-gravitational simulation oscillators is between 16.7 and 40 kHz.
Wavelength (λ)	It is established by the simulator model, which consists of a cylinder (upper part) and a concave reflector (lower part) at the ends, to adapt to the resonance mode. Generally, the wavelength is usually 20 mm.
Gor'kov potential (U)	Potential drop between resonance phases. Its distribution allows us to determine the positions where Earth's gravity is counteracted, where the object of study can be located.
Acoustic pressure (p)	Pressure generated by the transducers (ends), which must balance the weight of the object under study. It is estimated using the Gor'kov potential. In traditional simulators, it usually varies between 297 and 540 Pa.
Density of the test object (ρ)	Its magnitude defines the appropriate parameters for the stability of the experiment; the denser it is, the greater the acoustic potential drop must be.
Particle radius (r)	As part of the characteristics of the object under study, its radius must be less than the minimum wavelength for the Gor'kov potential.
Node position (x_n)	Modifiable depending on the relative phase of the transducers. These are the points of greatest gravitational stability, and their width or centrality will depend on the experiment.

2.7.4 Operation

The acoustic levitation system is delicate, complex, and continuous, making it sensitive to vibrations and external conditions. It is carried out through a sequence of procedures and calibrations:

1. **Characterization of the object of study:** The type of experiment to be performed is determined, as well as the parameters of the object, and the simulation values for generating the potential field are adjusted accordingly. Ideally, it should be spherical (like liquids in suspension), with a radius smaller than the working wavelength (~ 20 mm) and low density. The object must be clean, dry, and free of electrostatic charge to avoid unwanted movements or repulsions.

2. **Alignment of the transducer:** The simulator is assembled by aligning the transducer and the concave reflector to adjust the resonance and the desired wavelength

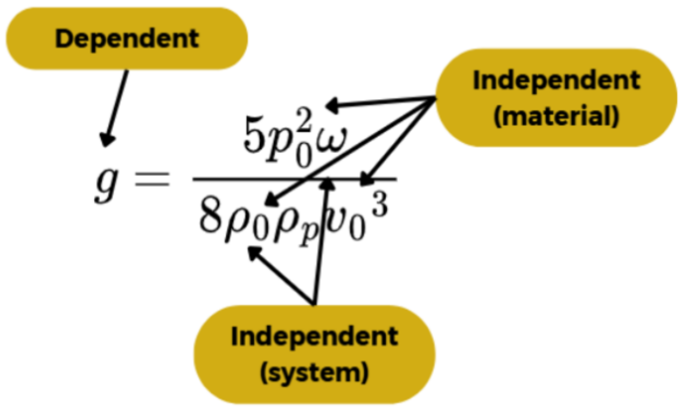
(estimated according to the characteristics of the Gorkov potential). Mechanical stability is ensured to avoid misalignments during operation.

3. **Signal configuration and phase control:** The operating frequency is set using the wave generator or microcontroller. The phase difference for standing waves is calibrated from the transducers. The dual-channel configuration allows real-time phase manipulation, enabling systematic noise to be subtracted.

4. **Activation of the acoustic field:** The potential field is established by powering the transducers. Basic tests are performed for the previously calculated empirical identification of pressure nodes, and the ideal acoustic pressure is verified.

Figure 17

Acoustic levitation gravitatory behaviour equation



5. **Positioning and control of the object under study:** The object to be evaluated is introduced into the minimum potential points (depression node) of the field, using non-conductive clamps. Adjustments can be made to the phase or frequency to precisely control the height or move the object between nodes.

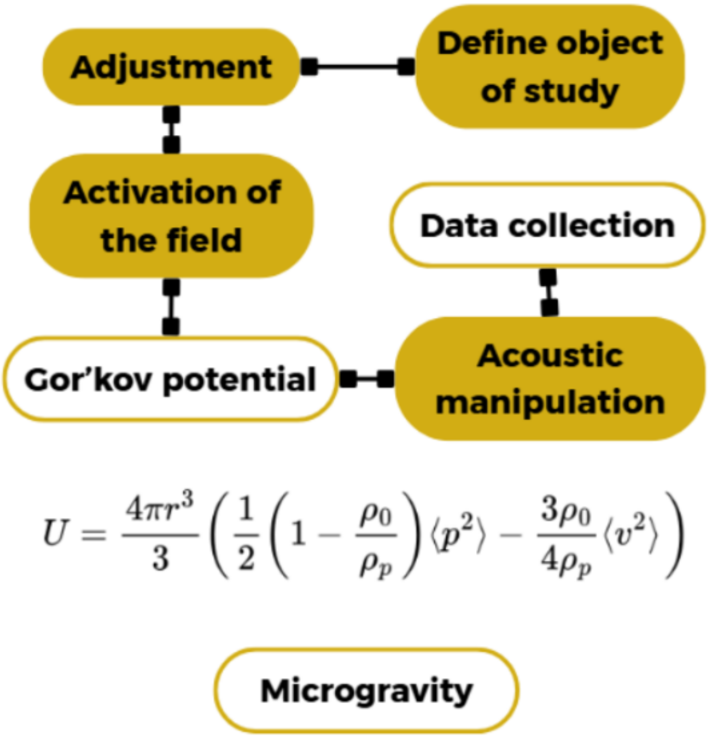
6. **Experimental manipulation and observation:** External factors such as temperature, air currents, or vibrations are minimized while data on the various parameters of the object under study are recorded.

7. **Removal of the object under study:** The field is gradually deactivated at the end of the test. The object is carefully returned to avoid systematic variations due to shocks or falls. The data is compared with the terrestrial standard.

8. **Post-experimental review of the system:** All electronic components are turned off and disconnected. The physical condition of the transducers and circuits is checked for possible wear or displacement.

Figure 18

Operation of Acoustic Levitation



2.9 Magnetic Levitation

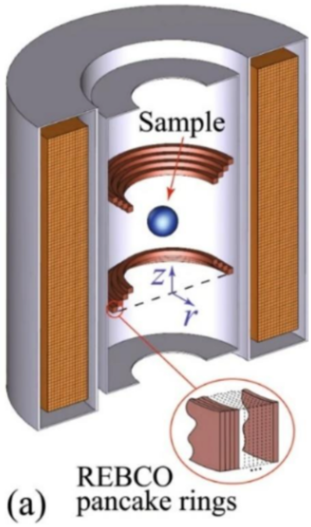
2.9.1 Description

Magnetic levitation is a technology that allows objects to be suspended and moved without any contact, through the interaction of magnetic fields that generate repulsive or attractive forces. It uses magnets and superconducting materials that repel magnetic fields, allowing objects to be suspended stably.

This technology is fundamental in applications such as scientific medical research, in which microscopic individuals are generally studied to provide alternative solutions to various diseases or, in the case of space, analysing the behaviour of different cells in microgravity to prevent damage in future missions. Other applications include improving energy and sustainable transport, contributing to the creation of more efficient systems with less wear and tear (Hammer et al., 2009; Liang et al., 2024).

Figure 19

Magnetic Levitation System



Note. Taken from *A magnetic levitation based low-gravity simulator with an unprecedented large functional volume* (p.4), by Hamid Sanavandi and Wei Guo, 2021, *npj Microgravity*.

2.9.2 Scientific Applications

Magnetic levitation offers a wide range of scientific applications in controlled environments, allowing terrestrial microgravity to be simulated to study physical and chemical phenomena and biological development without gravitational influence. Among its most notable applications are:

- **Microgravity simulation and physicochemical study:** Implementation of experiments that normally require space-based environments to observe physical and chemical behaviors that do not occur under standard Earth gravity. This setup enables the analysis of fluid dynamics and reaction kinetics in induced weightlessness (Wang et al., 2021; Xuesong et al., 2025).
- **Biological research and biotechnology:** Observation of organismal and cellular development without gravitational influence. This research is essential for advancements in tissue engineering, biotechnology, and understanding the long-term effects of microgravity on human biology and cellular health (Knigge et al., 2025).
- **Superconductor research and high-precision engineering:** Development of sensors, contactless motors, and high-precision devices. By utilizing magnetic levitation in superconductors, friction is eliminated, which enables significantly more efficient performance and extends the operational life of components by preventing mechanical wear and tear (Wang et al., 2020).

2.9.3 Operational and Technical Parameters

To conduct a magnetic levitation experiment, different physical designs in size and shape can be used. However, Table 9 shows a common and accessible design for small experiments.

Table 9

Operational and Technical Parameters of Magnetic Levitation

Operational and Technical Parameters	Characteristics
Design	Maxwell coil in a gradient field. Diameter $D = 8\,\text{cm}$ in the presence of an applied uniform field B_0.
Contour	Black dots denote the boundary of the entrapment region, and the solid black outline shows the low-force region (i.e., acceleration $< 0{,}01g$).
Origin of coordinates	It is in the center of the lower current loop.
Potential energy	Specific calculated $E(r)$ of a small sample of water placed in the magnetic field for $I = 112{,}6\,\text{kA}$ and $B_0 = 24\,\text{T}$.

2.9.4 Operation

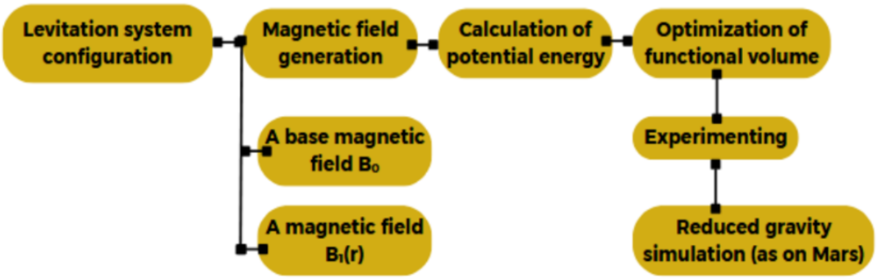
To carry out a magnetic levitation experiment, the following steps must be taken into account. However, these steps may be increased or decreased, or even merged, depending on the specific experiment or research being conducted.

1. **Levitation system configuration:** A magnetic levitation design is implemented using a superconducting magnet and a Maxwell coil with a gradient magnetic field. The system is assembled with a Maxwell coil, which is placed inside the superconducting magnet.
2. **Magnetic field generation:** The magnetic field is produced in two phases:
   - A base magnetic field B_0 is produced by the superconducting magnet, which is fairly uniform.
   - A magnetic field $B_1(r)$ is generated by the Maxwell coil, which has a constant gradient. This configuration produces a non-uniform magnetic field that allows objects to levitate.
3. **Calculation of potential energy:** The potential energy of an object in a magnetic field is calculated using a formula that depends on the magnetic susceptibility of the material and the density of the object. The levitation position in space is determined, where the magnetic force compensates for gravity, creating microgravity conditions.
4. **Optimization of functional volume:** The functional volume $V_{1\%}$ is calculated, which is the volume in which the acceleration is less than 1 % of Earth's gravity. The goal is to increase this volume to allow larger objects to levitate. The system is optimized by adjusting the current applied to the Maxwell coil and the intensity of the magnetic field.
5. **Experimenting:** Once the parameters have been optimized, the object (e.g., a water sample) is placed in the center of the magnetic field where levitation occurs. The object is suspended in space without physical contact, simulating microgravity conditions.

6. **Reduced gravity simulation (as on Mars):** In addition to simulating Earth's microgravity, the system can also be adjusted to simulate reduced gravity conditions, such as those on Mars (approximately 38% of Earth's gravity), expanding the simulator's applications.

Figure 20

Operation of Magnetic Levitation



2.10 Head Down-Tilt Bed Rest (HDTBR)

2.10.1 Description

The "head-down bed rest" (HDTBR) is a method of studying the physical changes that occur in people who travel to space. It consists of lying in bed with the head tilted downward at -6°, usually for days, weeks or months. And it is often used to study the consequences of spaceflight, from various methods of inducing them into a state of cerebral weightlessness (by having fluids directed at the head) (Schmitt et al., 2000).

Figure 21

The Head Down-Tilt Bed Rest (HDTBR)

Note. Taken from *One Small Step . . . Without Ever Leaving Bed* [Photograph], by Monica Edwards, 2019, https://www.nasa.gov/humans-in-space/one-small-step-without-ever-leaving-bed/

2.10.2 Scientific Applications

Currently, multiple experiments have been performed on the Head Down-Tilt Bed Rest (HDTBR), providing critical data on physiological adaptation to simulated microgravity:

- **Cardiovascular deconditioning:** Analysis of alterations in heart parameters, blood flow, and muscle stiffness. These changes occur due to simulated microgravity and are primarily driven by the prolonged inactivity of the body (Rabineau et al., 2022).
- **Muscle atrophy and functional decline:** Investigation of the loss of muscle mass generated by prolonged bodily rest. Research indicates a logarithmic loss in mass and function resulting from the constant disuse of specific muscle groups (Marusic et al., 2021).
- **Bone loss and mineral balance:** Studies during experimental bed rest indicate a negative bone mineral balance. It has been observed that the calcium isotopic composition of urine becomes lighter compared to pre-rest levels, correlating with reduced bone densitometric measurements (Heuser et al., 2019).
- **Sensorimotor and neurological adaptation:** Analysis of brain adaptation to sensory disturbances, including spatial disorientation and vestibular system imbalances. These findings are fundamental for developing rehabilitation strategies for post-spatial exploration recovery (Edwards, 2019; Heuser et al., 2019; Platts et al., 2009; Tays et al., 2023).

2.10.3 Operational and Technical Parameters

The Head Down-Tilt Bed Rest (HDTBR) method is more part of the neural responses during fluid direction change. Thus, the following table of operational and technical parameters specifies specific things like the conditions that the environment needs in order to have a better sensation of microgravity.

Table 10

Operational and Technical Parameters of Head Down-Tilt Bed Rest

Parameters	**Characteristics**
Angle of inclination	$-6°$ (head downward). Stretcher that can cover little more than the person's body and with the head towards the side of the inclination (Schmitt et al., 2000).
Environmental Conditions	**Temperature:** 20–25°C (controlled). **Humidity:** 35–55%. **Lighting:** Day/night cycles (Edwards, 2019; Rabineau et al., 2022).

2.10.4 Operation

The operation of the Head Down-Tilt Bed Rest (HDTB) is based on the following steps:

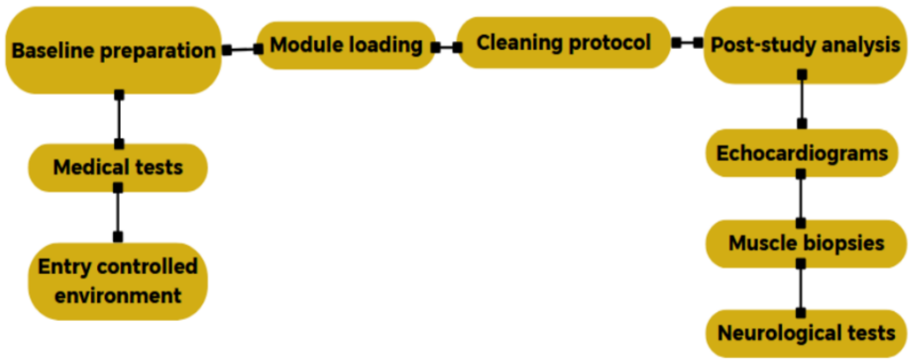
1. **Baseline preparation:** It starts by selecting volunteers (in good health), not older adults or children. To ensure the health of the participants, complete medical tests are conducted, including blood and urine analysis, bone density tests, among others. Admission is granted to a room temperature environment equipped with an adjustable horizontal bed.

2. **Cleanliness and duration of the experiment:** Maintain cleanliness in the space and of the participant to ensure good health without influencing the results. Daily controls are implemented to keep all physiological data accessible and monitored throughout the duration of the simulation.

3. **Data collection and post-experiment tests:** After the time in the inclined bed, it is time to analyse the changes; for this purpose, echocardiograms are necessary as a test of orthostatic tolerance, muscle biopsies to see the density of their muscles and neurological tests (to see balance, coordination and vision) (Brauns, 2022; Edwards, 2019; Marusic et al., 2021; Platts et al., 2009; Tays et al., 2023).

Figure 22

Head Down-Tilt Bed Rest operation



3. Results

Based on the data characterizing each microgravity simulation method, a comparative parameterization is performed to evaluate its effectiveness in terms of resources, experimental duration, scientific accuracy, and operating costs. The integrated figures and tables show the distribution of methods according to their continuous microgravity duration and level of scientific fidelity, their popularity in scientific literature and in use for each technique, as well as international partnerships and commitment to the development of weightless research. This representation makes it easier to identify the advantages, limitations, and areas of application of each technique according to its accessibility, technical requirements, and experimental value.

3.1 Technical Characteristics and Metrics of the Methods

For a general, yet specific and timely overview, the data, parameters, and metrics for each method are grouped together. Table 11 lists these elements so that they can be compared in terms of versatility, ease of use, reliability, and relevance. Our goal is to compare which of these methods is most functional in terms of performance, emphasizing the balance between durability, g-fidelity, and cost. For future research, hybrid approaches could fill the gaps in terms of scalability and quality. These are issues that we will highlight in the conclusions.

In terms of simulation duration, the ISS stands out by offering the longest continuous exposure to microgravity, with the lowest microgravity levels, below $10^{-5}g$, but at a high cost and with significant logistical complexity. For this reason, it will be used as a standard to highlight equally efficient but more accessible options for training and research.

In terms of simulation level, suborbital flights provide a similar range to that of the ISS, but with discontinuous tests lasting 5 to 10 minutes. In addition, they are costly and logistically laborious, making this method ideal for short-duration experiments, prioritizing the level of microgravity over duration and cost. Similarly, parabolic flights have a lower level of microgravity, but are more accessible in terms of cost and personnel requirements, with campaigns aimed at university student research. However, it is a discontinuous simulation method, lasting between 20 and 25 seconds per campaign. On the other hand, drop towers offer the best level of microgravity, but are less accessible in terms of cost, with simpler logistics but limitations in terms of usage time, as the duration is only 5 to 10 seconds, thus excluding research into long-term phenomena.

Laboratory systems, on the other hand, guarantee continuous testing, making them suitable and ideal for studies in biotechnology or gravitational biology that require hours or days of exposure, although they have the limitation of their physical capacity, being restricted to samples of reduced size and mass, as well as presenting residual accelerations of greater magnitude. The clinostat and RPM have more affordable unit prices for the general public, but they introduce radial centrifugal forces and velocity gradients in the fluid that can skew biological and/or physical results. While levitation techniques (acoustic and magnetic) partially reduce these noises in the results, as their control is more precise and accurate, they require more rigorous technical complexity to control the field produced, as well as possible repercussions on samples that are more sensitive to these environments than to microgravity itself.

Finally, physiological analogue systems (HDTBR, GOS, and NBL) accurately simulate changes in body fluids, muscle atrophy, and pressure distribution, offering prolonged periods of simulation in controlled environments, although they do not replicate weightlessness. These platforms are ideal for astronaut training and preparation, as well as for studies with larger and heavier samples, and for research in human physiology. However, their logistics are more complicated than those of laboratories, becoming more functional and complex to ensure the efficiency of the effects. This requires higher budgets, depending on whether it is for a space agency or academic research.

Table 11

Technical specifications of microgravity simulation method

Simulation	Level (g)	Period	Cost	Repeat.	Mass	Infra.	Inter.	Type	Limitations
True μg									
Drop Tower	$10^{-2\cdots-6}$	5–10 s	\$5,800	Limited	< 160 kg	Static	TC	Disc.	Minimal vibrations during fall
Parabolic Flight	$10^{-2\cdots-3}$	20–25 s	\$5,298.91	Limited	Human	Comp.	Human	Disc.	High vibration and residual acc.
Suborbital Flight	$10^{-4\cdots-5}$	5–20 min	\$8,040.90	Limited	< 360 kg	Comp.	TC	Disc.	Vibrations during launch
Sim. effects									
Clinostat	Sim. effects	hours–days	\$206.49	Frequent	< 1 g (5 mL)	Movable	Human	Cont.	Residual centrifugal forces
RPM	Sim. effects	hours–days	–	Limited	< 1.5 kg	Movable	Human	Cont.	Constant mechanical movement
Acoustic Lev.	$10^{-4\cdots-5}$	min–days	\$28.48	Limited	≈ 0.05–0.1 μL	Movable	Human	Cont.	Intense sound waves
Magnetic Lev.	$10^{-4\cdots-5}$	min–days	\$92.27	Limited	≈ 10–100 μL	Movable	Human	Cont.	Intense magnetic fields
NBL	$10^{-1\cdots-2}$	5–10 hours	\$265.2	Frequent	Human	Static	Human	Cont.	Water resistance and laminar flow
GOS	$10^{-1\cdots-2}$	0.5–8 hours	–	Limited	Human	Movable	Human	Cont.	High sensitivity to human movement
HDTBR	Sim. effects	days–months	–	Frequent	Human	Movable	Human	Cont.	Side effects due to posture

Note. "Simulate effectsrefers to systems designed only to replicate the physiological and psychological outcomes of microgravity, without reproducing its physical conditions. "Discontinuousïndicates that the experiment consists of separate test sessions with a reduced simulation time per trial, while Çontinuous"means a single, extended session is used for the experiment. Regarding infrastructure, "Static"means no movement of the system is required, "Movableïndicates the setup is transportable, and Çomposedrefers to a full or partial combination of static and movable elements. Finally, "Humanïmplies direct human intervention, whereas "TC"(telecommunication) involves remote operation without physical human presence.

3.2 Quantitative Evaluation of Simulation Fidelity vs. Duration

Microgravity simulation methods can be classified into two broad categories: those that generate real microgravity through free fall or suborbital trajectories (Drop Tower, Parabolic Flight, Suborbital Flight, and, at one extreme, the ISS) and those that only emulate its effects through rotations, suspensions, or counterbalancing of gravitational force, which can be divided into laboratory systems (clinostats, RPM, and levitators) and analog systems (NBL, GOS and HDTBR).

Figure 23

Logarithmic distribution of the efficiency parameters of each quantifiable simulation

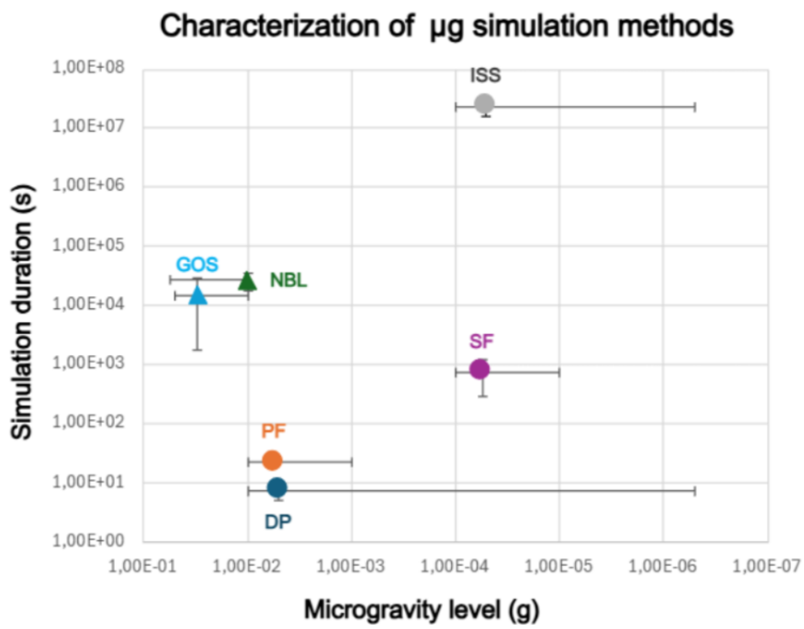


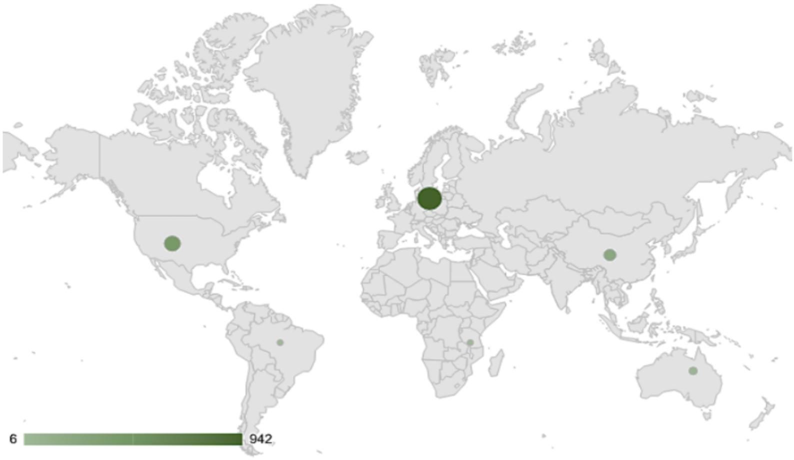
Fig. 23 specifically compiles the relationship between efficiency and effectiveness, with the minimum and maximum duration of each simulation technique, as well as the accuracy range of the microgravity level achieved by each one according to the experiments performed or their usage parameters. It shows that free-fall platforms offer the highest scientific accuracy but provide the shortest exposure times to microgravity. In contrast, analog and laboratory-based systems offer longer durations but with less fidelity to actual space conditions. This classification highlights the relationship between scientific accuracy and experiment duration, clearly showing how each technique ranks in terms of its similarity to actual space environments and its usefulness for conducting experiments in microgravity conditions. It is important to supplement this information, for a practical assessment of usability, with the costs and parameters in Table 11.

3.3. Geographic Distribution of Scientific Production

Fig. 24 shows a world map with the regional distribution of the number of scientific publications on microgravity simulation methods produced between 2000 and 2025. It uses a color scale that varies in intensity according to the number of publications per region, allowing for a comparative visualization of scientific productivity in this field at the global level.

Figure 24

Distribution of Research Publications by Region



Note. Compilation of papers on microgravity simulation methods by region, from 2000 to 2025.

The geographical distribution of scientific publications (papers) on the subject of microgravity simulations shows a considerable regional imbalance. Europe leads with 942 articles, representing 56.9 % of the world total, more than half, driving institutional and infrastructure investment in the sector. For its part, the United States produced 427 publications (25.8 %), showing strong investment in science and technology, in addition to its strong track record in the area. Asia published 218 articles (13.2 %), although this includes a large and diverse group of countries with varying levels of research capacity.

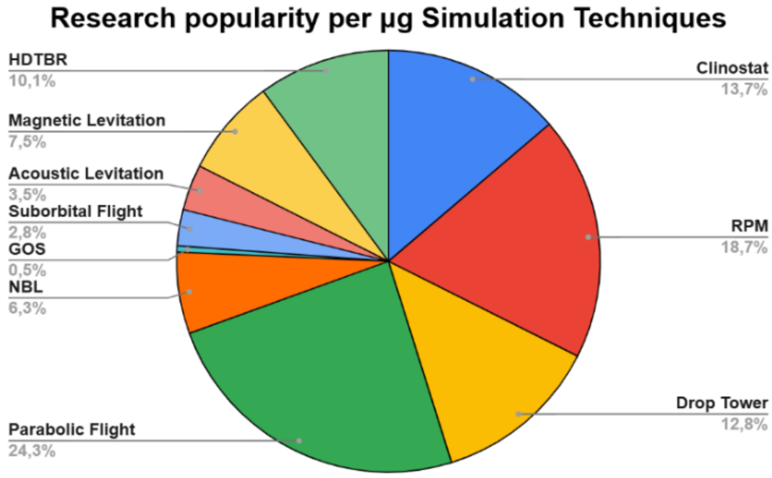
On the other hand, South America, Africa, and Oceania have contrasting statistics, with only 0.8 % (14 articles), 0.4 % (6 articles), and 3.0 % (49 articles), respectively. These figures highlight a disparity in technological progress, access to infrastructure, and funding for microgravity research, suggesting potential obstacles to the democratization of scientific development in space sciences. This difference underscores the need for more open international collaboration with mechanisms to promote science.

3.4 Distribution of Scientific Literature by Methods

Fig. 25 shows the percentage distribution of scientific publications according to the microgravity simulation method used. Each segment of the graph represents a specific technique. This visualization allows us to compare the relative popularity of the different methods based on their frequency of use in scientific research related to microgravity conditions.

Figure 25

Research Publications According to Microgravity Simulation Method



Parabolic flights (24.3 %) and RPM (18.7 %) represent the most prevalent methods. In terms of accessibility, especially for high school and university students, the Clinostat and RPM become an economical, ergonomic, and timely alternative concerning the needs of microgravity surface effects verification, thus explaining their popularity.

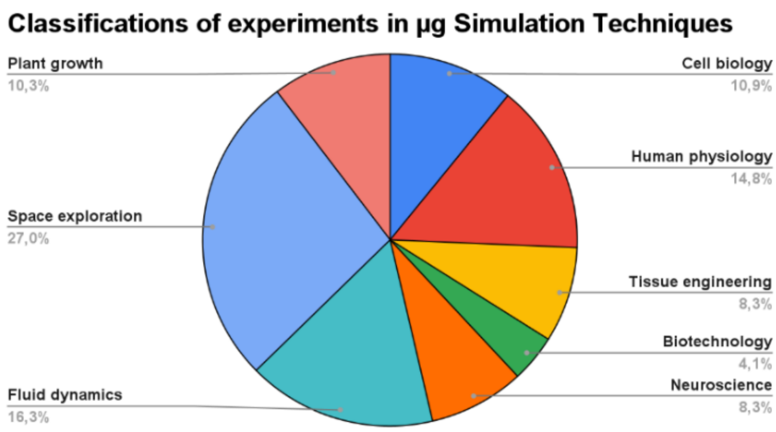
On the other hand, the low popularity of GOS (0.5 %) reflects its limitations of accessibility, complex infrastructure, and low microgravity level ($< 10^{-2}g$). Suborbital Flights have the highest level of microgravity and longer duration, but with high costs and infrastructure at bureaucratic request, making the experiments performed scarcely accessible to private research.

3.5 Distribution of Scientific Literature by Experiments

Fig. 26 shows the thematic distribution of publications on microgravity research, which are related to the popularity, accessibility, and level-duration of each method.

Figure 26

Research Publications According to Type of Experiment



Based on the distribution, each region and the associated topics are evaluated in order to identify their relationship with accessibility, technical level, and quality of the methods used. Likewise, the most commonly used simulation techniques in each case are determined:

- **Space exploration and mission protocol validation:** Representing 27% of experiments, this versatile field encompasses both microscopic and macroscopic methodologies. It serves as a critical platform for astronaut training, hardware testing, and soil behavior sampling, allowing for the verification of life support systems and mission protocols in weightless conditions prior to actual deployment.
- **Fluid dynamics and phase phenomena:** Accounting for 13.3% of research, this area utilizes diverse samples ranging from fuels to water droplets. The absence of sedimentation in microgravity enables the isolated observation of conductivity, convection, and mixing phenomena—effects that are typically masked by stratification and buoyancy-driven flotation on Earth.
- **Human physiology and cellular biology:** Comprising 25.7% of the research volume, this biomedical field focuses on fluid redistribution and cardiovascular adaptation. While laboratory analogs like Clinostats and Random Positioning Machines (RPM) do not recreate true microgravity, they provide the continuous exposure (hours to days) necessary to observe evolutionary changes in tissues and cell lines.
- **Plant growth and tissue engineering for life support:** Representing 18.6% of studies, these areas address food management and biomaterial development. Laboratory and free-fall systems are employed to study morphogenesis under weightlessness, although experimental scale remains influenced by the high reliability standards of the International Space Station (ISS).
- **Neuroscience and biotechnological constraints:** Accounting for 12.4% of research, these studies face methodological gaps due to the discontinuity of parabolic flights and the limitations of terrestrial analogs. Research into brain physiology, protein synthesis, and compound production is currently restricted by the availability of suborbital flights and the operational reliability of rotary systems.

3.6 Accessibility to Scientific Production and Research

Table 12 is the institutional table, which emphasizes a laboratory's accessibility to each method, such as infrastructure distribution, cost barriers, collaboration models, and the number of scientific publications, which determine the feasibility of replicating research in microgravity.

Table 12
Research Publications According to Type of Experiment

Simulation	Publications	Activity	International collaborations
Clinostat	706	1980s–present	University-level research.
RPM	946	2000s–present	Joint research projects (e.g., France, Germany, US, Japan) using shared protocols.
Drop Tower	1244	1990s–present	ZARM (Center for Applied Space Technology and Microgravity), Bremen, Germany.
Parabolic Flight	2071	1950s–present	ESA (European Space Agency), CNES (France), DLR (Germany), NASA (USA).
NBL	551	1960s–present	Major facilities (NASA NBL, ESA L-ROBE, China). Focus on astronaut training (ISS/Artemis).
GOS	29	2000s–present	ESA (Moon/Mars Laboratory at EAC, Germany), NASA (ARGOS).
Suborbital Flight	137	1960s–present	Blue Origin (New Shepard), Virgin Galactic (VSS Unity).
Acoustic Lev.	247	2010s–present	University-level research.
Magnetic Lev.	542	2010s–present	University-level research.
HDTBR	522	1970s–present	ESA, NASA, DLR, CNES, CSA (Canada), JAXA (Japan).

Note. "University-level research" refers to methods that do not require large partnerships for their maintenance or operation but are simple replicas that can be patented or replicated by university students and high school students.

Although Parabolic Flight and Drop Tower have a great impact, their accessibility is limited, which increases the use of technologies such as laboratory systems, which are versatile enough to be replicated in universities and schools, thereby increasing research through them. In addition, other alternatives are emerging that are more endorsed by institutions such as space agencies and private companies, such as NBL and HDTBR, solely for the training of their personnel. Therefore, we recognize that global access to high-fidelity microgravity platforms is part of global disparity; we hope that in the future there will be equity in the production and replication of these platforms to accelerate science-driven research.

True Microgravity methods (Drop Tower, Parabolic Flight, Suborbital Flight) offer high fidelity ($10^{-4} - 10^{-2}$ g) but are infeasible for emerging countries due to prohibitive costs ($5,800–$8,040/experiment), static infrastructure and limited time (seconds–minutes).

In contrast, effects simulation methods (RPM, magnetic/acoustic levitation) provide functional microgravity ($10^{-4} - 10^{-1}$ g) at 200x lower costs (\$28–\$92), with continuous operation (hours–days) and mobile infrastructure. For Peru, prioritizing these techniques —validated by 789 combined publications (Fig. FIRST CIRCLE)— optimizes scarce resources, allows iterative experimentation (high repeatability) and facilitates global academic alliances. This democratizes spatial research, avoiding North–South technology gaps through scalable solutions.

4. Analysis of the Applications of Microgravity

Microgravity simulation technologies have proven essential for mission readiness, human physiology research, and technological development in space-like conditions. Their implementation ranges from highly controlled ground-based platforms to suborbital flights and orbital laboratories. Each technology offers specific advantages depending on the type of study, required duration, and experimental sensitivity, making them versatile tools across disciplines.

For astronaut training and hardware testing, parabolic flights (Selig et al., 2010), the Neutral Buoyancy Lab (NBL), and Gravity Offload Systems (GOS) (L. Li et al., 2020) are among the most widely used. Parabolic flights provide repeated short periods of microgravity, typically 21 to 22 seconds per parabola, which are suitable for testing posture control, movement, and equipment performance in space-like conditions (AirZeroG, 2018a, 2018b). For that, they are recommended for postgraduate researchers and professionals working in biomechanical or physiological studies, particularly when funding and aerospace collaboration are available. The NBL is specifically designed for astronaut training, hardware verification, and mission planning under simulated weightlessness using neutral buoyancy techniques (Jairala et al., 2012). While effective for astronaut training, this facility is best suited for agencies or university programs working directly with space missions. The Gravity Offload System (GOS), by contrast, uses a passive trolley and counterweight mechanism to simulate microgravity by offloading a subject's weight, enabling realistic deployment and mobility tests on Earth (Tanimoto et al., 2007). While some simplified GOS setups can be adapted for university research, full-scale systems like ARGOS are typically reserved for use by advanced laboratories or space agencies.

In scientific and medical research, technologies offering prolonged or small-scale simulation of microgravity are prominent. Clinostats (Rodríguez, 2020) and Random Positioning Machines (RPMs) (Pino Alfonso et al., 2006) allow long-term observation of cellular processes such as proliferation, cytoskeletal reorganization, and gene expression under near-zero gravity (Cao et al., 2023; Shi et al., 2012). Because of their low cost and accessibility, they are highly recommended for beginner-level researchers, including high school and early undergraduate students exploring space biology. On the other hand, technologies such as magnetic (Boudreaux et al., 2025) and acoustic levitation (Hammer et al., 2009) have enabled experiments in biotechnology (Dumy et al., 2020) and superconductor research (Wang et al., 2020) under simulated microgravity conditions. Therefore, these methods require specialized knowledge and are best applied by advanced students or research groups with strong physics or engineering backgrounds.

From a physiological standpoint, Head-Down Tilt Bed Rest (HDTBR) is a widely adopted model used by NASA and ESA to simulate the long-term effects of microgravity on the human body (Schmitt et al., 2000). Its implementation requires medical oversight, which suggests its use be limited to graduate-level researchers or medical institutions conducting controlled studies on cardiovascular deconditioning (Rabineau et al., 2022), muscle loss, and countermeasures (Marusic et al., 2021). For real microgravity exposure over short durations, Suborbital Spaceflight Systems provide a unique opportunity. These flights are used to validate hardware (Ferl et al., 2023), study of acute physiological effects in humans (Kluge et al., 2013), and rapid genetic responses in plants (Ferl et al., 2023) within 3 to 4 minutes of actual weightlessness (Smith & Buckey, 2022). However, due to high launch costs and technical demands, this approach is generally limited to large institutions, space agencies, or commercial entities with specialized objectives. Finally, the International Space Station (ISS) remains the gold standard for long-duration microgravity research, supporting advances in tissue regeneration, space pharmacology, human health, and robotic systems (Melissa L. Gaskill, 2024). Access to the ISS is restricted to highly specialized missions and large-scale collaborations, making it the domain of governmental space agencies and multinational research programs.

5. General Limitations of Microgravity Simulators

Despite advances in microgravity simulation technologies, significant limitations remain that affect the validity and applicability of the results obtained. For a meaningful comparison between simulation platforms, these limitations require thorough evaluation.

One of the most pressing challenges lies in the discrepancy between simulated environments and the actual conditions aboard the ISS compared to ground-based technologies (Melissa L. Gaskill, 2024). While devices like drop towers can achieve microgravity levels close to 10^{-6} g (D'Angelo et al., 2022), their extremely short durations make them unsuitable for studying biological or physicochemical processes that require extended observation periods. On the other hand, more accessible devices such as clinostats and RPMs offer prolonged exposure to simulated microgravity, but volume limitations may restrict the types of experiments that can be performed (Nishimura, 2023). Although magnetic and acoustic levitation techniques can achieve favorable microgravity levels, they inherently introduce strong magnetic fields or sound waves (Tracy V. Wilson, 2023) that may interfere with sensitive samples, particularly in biological research; furthermore, they possess volume and size limitations (Liang et al., 2024), which restrict their general applicability.

Among large-scale simulators like parabolic flights, the Neutral Buoyancy Lab (NBL), and Gravity Offload Systems (GOS), another set of limitations arises. Parabolic flights are known for their short periods of microgravity, lasting only a few minutes (AirZeroG, 2018a, 2018b). The NBL, although excellent for astronaut training, fails to reproduce the physiological effects of weightlessness due to the properties of water. Meanwhile, GOS, a dynamic vertical body-weight support system, provides more precise gravitational simulation over longer periods; however, the mechanical stiffness and small oscillations introduced by its suspension mechanism can interfere with natural movement patterns, especially in locomotion and neuromuscular research.

Horizontal body-weight support systems like HDTBR (Head-Down Tilt Bed Rest) are widely used for long-duration studies. Still, they bring secondary effects associated with forced body posture, such as abnormal fluid redistribution and cardiovascular changes. While useful in simulating deconditioning effects, they do not accurately replicate real microgravity environments. Ultimately, Suborbital Spaceflight Systems provide actual microgravity conditions (10^{-4} to 10^{-5} g) for 3–4 minutes. However, their high costs, limited flight opportunities, and strong launch-phase vibrations significantly restrict their use to very specific and time-constrained experiments.

Finally, there are still problems with standardization between platforms and unequal access to advanced technologies, which makes it difficult to compare results between laboratories and institutions globally. These limitations demonstrate that, although useful, ground-based simulators still require validation in real space environments.

6. Conclusions

The study sought to provide a detailed analysis of each of the methods presented, identifying the benefits of each, as well as their contribution to the scientific field and their importance in the areas in which they are most useful.

The 10 microgravity simulation methods studied show various strengths and limitations, with some similarities and differences between them. The study sought to identify an ideal or suitable method among them all that meets optimal characteristics in areas such as simulation time, simulation fidelity, cost, ease of use, and influence on research areas, among others. This set of characteristics ensures easy reproduction and implementation for all scientific fields. This exhaustive analysis has shown us that it is not possible to establish an ideal method and that even the fusion of these methods, which is left to future research, can generate amazing results that allow the aforementioned characteristics to be met.

The methods mentioned in the results show high potential in terms of fidelity, but time, cost, and ease of use are often limiting factors. Others also have medium levels of fidelity, with longer times and lower costs, but are limited by the capacity of their samples and the ability to move or manipulate them when exposed to this environment. Others, while not having high levels of microgravity simulation as such, are ideal for simulating the effects of this environment, allowing for sample mobility and large sample size, but are limited by their costs and the extensive complexity of their simulation environments.

Therefore, the use of a specific simulation method will be related to the nature, characteristics, and requirements of each research project, which means gaining in some aspects due to the benefits and potentialities and investing in other limiting aspects. However, this trade-off can be reduced and even eliminated with the development of methods that merge the aforementioned methods due to the similarities in their characteristics, development environments, and others.

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