

Thesis

Individualized Artificial Gravity Effects Across Seasons

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Declaration of Authorship

I hereby declare, under oath, that I have independently and without external assistance authored the present thesis, have not used sources other than those indicated, and have clearly marked any passages taken verbatim or in substance from the sources used.

Graz, am 18.06.2024

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Abstract in German

Zukünftige Weltraumfahrer*innen werden aufgrund der längeren Exposition in einer Umgebung mit geringer Schwerkraft mit physiologischen Herausforderungen konfrontiert sein. Die Auswirkungen der Exposition umfassen eine Dekonditionierung des Muskel-Skelettsystems und des Herz-Kreislauf-Systems, einschließlich orthostatischer Intoleranz. Diese wird bei der Rückkehr in eine Umgebung mit Schwerkraft zu einem Problem, da sie die Hirndurchblutung beeinträchtigt und zu einer Synkope führen kann, was die Leistungsfähigkeit der Besatzung und den Erfolg der Raumfahrtmissionen beeinträchtigt. Künstliche Schwerkraft ist eine potenzielle Gegenmaßnahme gegen Dekonditionierung und orthostatische Intoleranz im Weltraum, die durch zentripetale Beschleunigung in einer Kurzarm-Zentrifuge erzeugt wird. Während Studien positive Auswirkungen und Anpassungen der menschlichen Physiologie an die künstliche Schwerkraft gezeigt haben, wurde den jahreszeitlichen Schwankungen, die sich auf die künstliche Schwerkrafttoleranz auswirken, nur wenig Aufmerksamkeit geschenkt. Ziel dieser Studie ist es, die Unterschiede in der künstlichen Schwerkrafttoleranz zwischen verschiedenen Jahreszeiten und ihre möglichen Auswirkungen auf kardiovaskuläre Parameter zu analysieren. Wir stellten die Hypothese auf, dass die künstliche Schwerkrafttoleranz in kälteren Jahreszeiten aufgrund der bekannten Einflüsse saisonaler Veränderungen auf das Herz-Kreislauf-System höher ist. Um diese Hypothese zu testen, verglichen wir zwei künstliche Schwerkrafttoleranz-Studien, die jeweils nach zwei gleichwertigen Protokollen, aber zu unterschiedlichen Jahreszeiten durchgeführt wurden. Die künstlichen Schwerkrafttoleranz-Ergebnisse beider Studien wurden verglichen und es wurde eine Korrelation mit den Jahreszeiten hergestellt. Es wurde künstliche Schwerkraft von 0,6 G bis 1,7 G verwendet, wobei die künstliche Schwerkraft bei jedem Schritt um 0,1 G erhöht wurde. Jeder Schritt von 0,6 G bis 1,7 G war 3 Minuten lang, bis die Teilnehmer*innen präsynkopische Symptome verspürten. Die Zeit der künstlichen Schwerkrafttoleranz wurde anhand des Auftretens von präsynkopischen Symptomen bestimmt. Die künstliche Schwerkrafttoleranz war während der Wintersitzungen höher. Während des künstlichen Schwerkrafttoleranztests wurden signifikante Unterschiede in der Änderungsrate des Blutdrucks zwischen den Jahreszeiten beobachtet ($p < 0,05$). Die Veränderungsrate des Blutdrucks, während der künstlichen Schwerkrafttests war in den Sommersitzungen höher und in den Wintersitzungen konstanter. Es wurden jahreszeitliche Schwankungen in der künstlichen Schwerkrafttoleranz festgestellt, wobei im Winter eine höhere Toleranz und gleichmäßigere Blutdruckreaktionen beobachtet wurden. Diese Ergebnisse deuten darauf hin, dass

Umweltfaktoren, wie z. B. die Temperatur, die physiologischen Reaktionen des Menschen auf künstliche Schwerkraft beeinflussen können, was Auswirkungen auf die Planung künftiger Weltraummissionen hat. Unsere Ergebnisse zeigen, wie wichtig das Verständnis von künstlicher Schwerkrafttoleranzschwankungen für die Optimierung von Gesundheit und Leistung der Besatzung bei Weltraummissionen ist. Darüber hinaus können die gewonnenen Erkenntnisse zum Verständnis kardiovaskulärer Veränderungen beim Altern beitragen, was wiederum Auswirkungen auf klinische Probleme in der terrestrischen Medizin hat wie zum Beispiel Geriatrie.

Abstract

Future space explorers will encounter physiological challenges due to prolonged exposure to a microgravity environment. The exposure effects contain musculoskeletal system and cardiovascular deconditioning, including orthostatic intolerance (OI). This becomes a problem when returning to a gravity environment, which affects cerebral blood flow and can lead to syncope, affecting crew performance and the success of space missions. Artificial gravity (AG) is a potential countermeasure against spaceflight deconditioning and OI, generated by centripetal acceleration through a short-arm human centrifuge (SAHC). While studies have shown positive effects and adaptations of human physiology to AG, limited attention has been given to seasonal variations affecting artificial gravity tolerance (AGT). This study aims to analyse differences in AGT across different seasons and their potential impacts on cardiovascular parameters. We hypothesized that AGT would be greater during colder seasons due to known influences of seasonal changes on the cardiovascular system. To test this hypothesis, we compared two AGT studies, each following two equivalent protocols, but at different times of the year. The AGT results from both tests were compared, and a correlation was drawn with the seasons. AG from 0.6 G to 1.7 G was used, and AG was increased by 0.1 G at each step. Each step from 0.6 G to 1.7 G lasted for 3 minutes until the participant experienced pre-syncope symptoms. AGT time was determined based on the occurrence of presyncope symptoms. Artificial gravity tolerance was higher during winter sessions. Significant variations were observed in the rate of change of blood pressure (BP) across seasons during the AGT studies ($p < 0.05$). The rate of change of BP during AG runs was higher in summer sessions and more consistent in winter sessions. Seasonal variations in AGT were found, with higher tolerance and more consistent BP responses observed during winter. These findings suggest that environmental factors, such as temperature, may influence human physiological responses to AG, with implications for future space mission planning. Our results demonstrate the importance of understanding AGT variations for optimizing crew health and performance in space missions. Additionally, insights gained may contribute to the understanding of physiology and cardiovascular changes in aging, with implications for clinical problems in terrestrial medicine for example geriatrics.

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List of Abbreviations

AG:	Artificial gravity
AGT:	Artificial gravity tolerance
ANP:	Atrial natriuretic peptide
CVS:	Cardiovascular system
ECG:	Electrocardiogram
HDBR:	Head down bed rest
HR:	Heart rate
LBNP:	Lower body negative pressure
MAP:	Mean arterial pressure
OI:	Orthostatic intolerance
OTT:	Orthostatic tolerance
SAHC:	Short-arm human centrifuges
SBP:	Systolic blood pressure
TPR:	Total peripheral resistance

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1. Introduction

1.1. Gravity and its effects on the human body

Gravity is a fundamental force that exerts its influence on every aspect of the universe, including the complex mechanisms of the human body. Throughout evolution, humans have adapted to the presence of gravity, which has significantly shaped the morphology and physiological systems of humans (1). Regulatory mechanisms have evolved, to master the upright position and counteract the effects of gravity, regulating fluid distribution and maintaining continuous blood flow to the human brain, situated at the highest point in the body. The heart and the cardiovascular system (CVS) are able to provide a continuous blood supply, strong enough to compensate the force of gravity in the upright position. The body has developed both short-term and long-term mechanisms to counteract the downward flow of blood due to gravity. Activating the skeletal muscle pump through lower limb movement assists in pumping blood upward, while venous valves prevent backflow and plasma transudation (2). Additionally, increased abdominal pressure from the abdominal muscles and the diaphragm assists to move blood from the extremities to the chest, enhancing circulatory function (3, 4). The respiratory pump aids in increasing venous return by creating negative pressure during breathing and assisting blood movement towards the heart (5). The autonomic nervous system, including the baroreflex, plays a crucial role in securing adequate oxygenation of the brain (6).

Beyond the CVS and the nervous system, the morphology of our body including muscles and bones are designed to compensate the consequences of gravity (2). Gravity serves as a fundamental reference point for human performance (7, 8), influencing posture, movement, and cognitive function. To be active on Earth means to resist gravity, to move in the presence of gravity and to change one's posture ensures gravitational stress and stimulation on the body for different systems. Various gravity-sensing systems, including visual, proprioceptive, and cardiovascular mechanisms, are activated in response to gravitational shifts (9). The musculoskeletal system continues to function with the load placed on it, to support the weight of the body and provide postural stability (8). Even at rest, the body needs to resist gravity and maintain posture in comparison to microgravity. Gravity also plays a crucial role in cognitive function and mood regulation, serving as a reference for spatial orientation and the perception of time (10). Humans need gravity for navigation and interpretation of the environment, proprioception and vision are crucial for balance, maintaining the correct

posture of the human body, and moving it in its natural way (10-12). Even the smallest unit of our body, the cell, perceives gravity, as studies show (13).

Understanding the gravitational forces experienced by the human body is essential, particularly in the context of space exploration and artificial gravity research. While Earth's gravity provides a standard reference point (7), variations in gravitational forces on other celestial bodies, such as the Moon and Mars (14, 15), present unique challenges and opportunities for scientific exploration and physiological adaptation. Each celestial body possesses its own unique gravity environment, which is quantified in the international system of units (SI) as G. Earth's gravitational acceleration is approximately $9,81 \text{ m/s}^2$, defined as 1 G, whereas the gravity on the Moon and Mars is less than 1 G, known as hypogravity. While in space, gravity is nearly non-existent 0 G and is referred as microgravity (7). Figure 1 demonstrates the different gravitational environments along with their specific gravity level. Explorers spending extended periods in microgravity environments, such as aboard the International Space Station (ISS) or during voyages to the Moon or Mars, will face significant challenges to human physiology due to the prolonged exposure to microgravity and fluctuations in gravitational environments (15). Gravity, as suggested by Morey-Holten et al (2003) is needed for life (1) and its influence extends far beyond human physiology, governing the evolution and motion of the universe itself (16). As such, further research into the effects of gravity on human health and performance remains crucial for advancing mankind's understanding of both terrestrial and extraterrestrial environments.

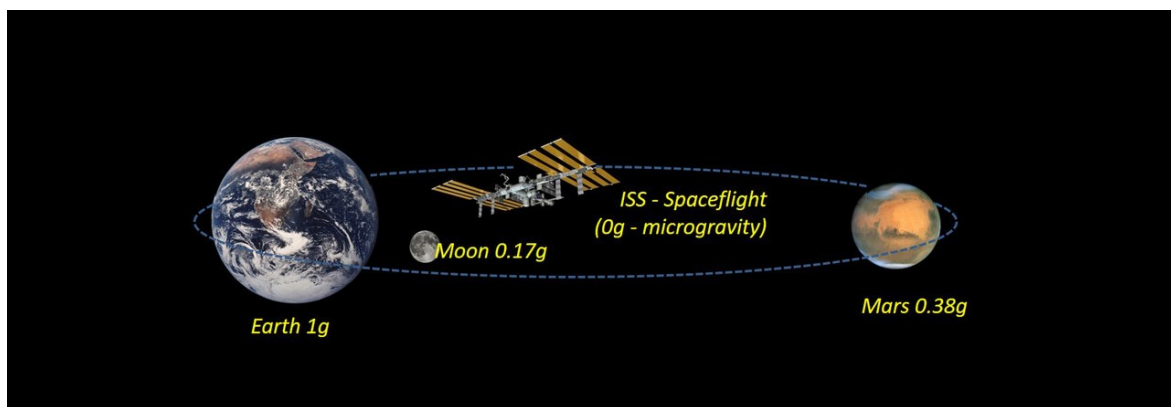


Figure 1: Different gravity environments.

The image illustrates gravitational levels on celestial bodies: Earth 1g, the ISS microgravity, Moon 0.17g, and Mars 0.38g (17).

1.2. Orthostasis

Referring to a body posture transition from a supine to an upright standing position, known as orthostasis, demonstrates the human body's evolutionary adaptation to gravity (18) and changes in posture, which constitutes a common stressor for the organism, particularly affecting the circulatory system and its regulatory mechanisms (19). In the supine position, where the heart and brain are on the same level, there is minimal hydrostatic pressure gradient (18). However, when changing posture from supine to standing upright, the body experiences the maximum influence of gravity, 600 – 900 ml of blood will pool in the vessels of the lower body coming from the central vessels (20). Leading to lower venous backflow and central venous pressure. As a cause, the right atrium receives less blood, resulting in decreased stroke volume, cardiac output, mean arterial pressure (MAP) and therefore less blood will arrive at the brain (19, 21). Figure 2 demonstrates the hemodynamic response of the body from supine to standing.

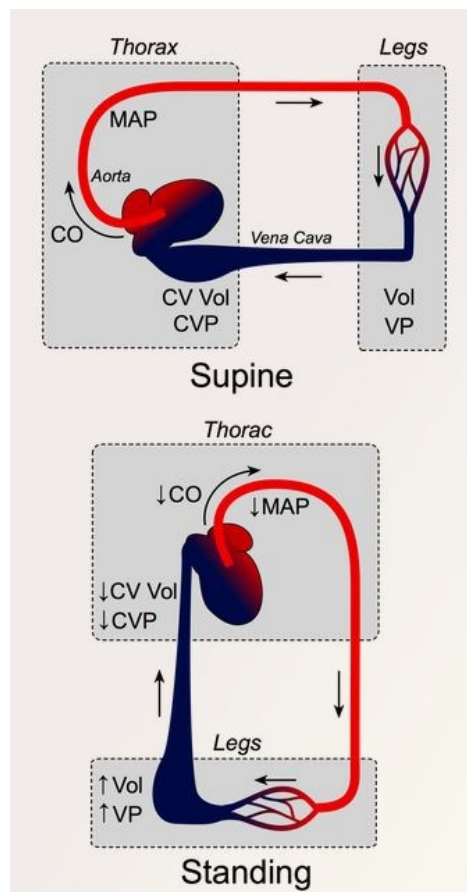


Figure 2: Hemodynamic response to postural changes.

The figure illustrates cardiovascular parameters, including CO cardiac output, MAP mean arterial pressure, CV Vol thoracic venous blood volume, CVP central venous pressure, Vol venous volume, VP venous pressure. In supine, Vol and VP are evenly distributed. While standing, blood shifts to the lower limbs, resulting in less CV Vol and CVP, consequently causing lower CO and MAP. (22)

The autonomic nervous system quickly responds to postural and MAP changes (19), activating several mechanisms to maintain hemodynamic stability and secure adequate cerebral perfusion (19). The baroreceptors, situated at the carotid sinus and aortic arch, detect changes in MAP and respond in a fraction of a second with a strong reflex. The Baroreflex involves a reduction in parasympathetic activity and an increase in sympathetic activity via the medullary cardiovascular centre, resulting in elevated heart rate and higher total peripheral resistance (TPR). Increased TPR via vasoconstriction, results in a higher MAP, while the elevated heart rate (HR) boosts cardiac output, contributing to the rise in MAP and thereby maintaining cerebral perfusion (19, 23). The ability how well the body react to these changes is called orthostatic tolerance (OTT) (2). Individuals experiencing low OTT due to an insufficient cardiovascular response may suffer from syncope, affecting astronauts with a decreased OTT after spaceflight as well as older persons with a lower OTT to upright posture in terrestrial medicine (2). It can be tested with the head-up tilt table testing (HUTT), the gold standard orthostatic tolerance test (21). Figure 3 illustrates the head-up tilt table. Cardiovascular measurements are obtained with the participant securely fastened to the table and then tilted, simulating changes in posture and capturing the hemodynamic response of the CVS.

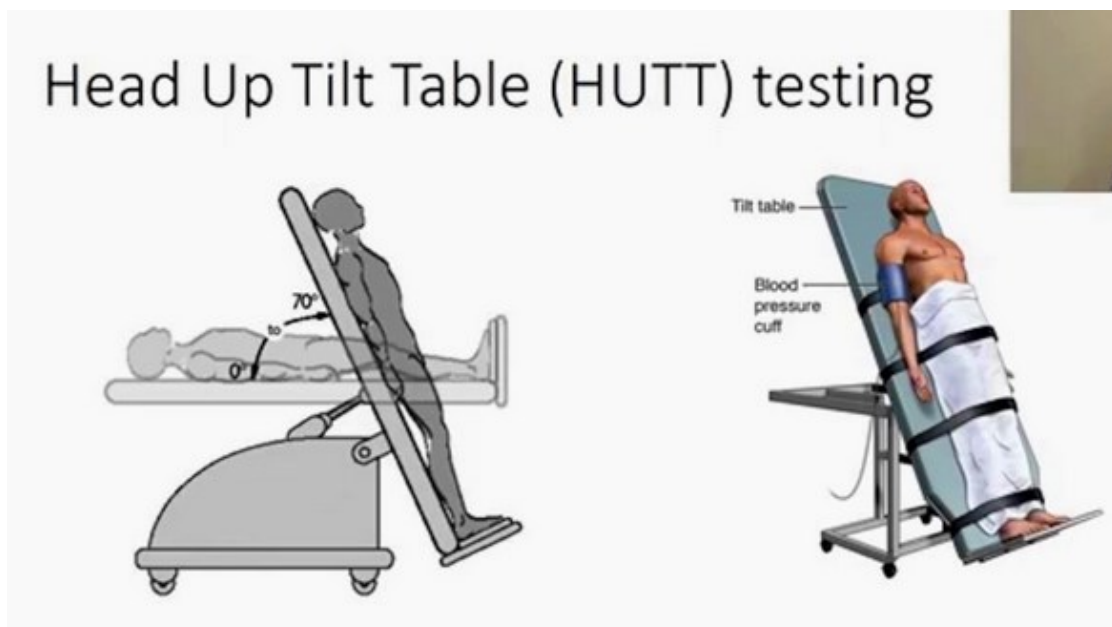


Figure 3: Head up tilt test.

Left side is illustrating the process of tilting a person from supine to an upright position at an angle of 70 degrees. On the right side, a person is shown strapped to the tilt table with a blood pressure cuff. (24)

Prolonged periods of standing exacerbate MAP fluctuations, predisposing individuals to syncope by imposing greater challenges on cardiovascular function through the heightened

hydrostatic pressure gradient. Blood pressure increases below the heart, while simultaneously decreasing above it, owing to the hydrostatic pressure gradient, which typically positions slightly below heart level. Given humans' substantial body mass and blood volume below heart level, exacerbates the effects (25). The higher transmural pressure by standing will push plasma from the vessel to the interstitial space resulting in less plasma volume and less venous backflow increasing the orthostatic challenge (19, 26). While parameters during walking closely resemble those observed in the supine position, underscoring the role of the skeletal muscle pump in mitigating orthostatic challenges. Human posture and gravity determine the fluid distribution, with average upright arterial pressures of about 70 mmHg in the head, 100 mmHg at heart level and 200 mmHg in the feet while standing (20). In the supine position, the arterial pressure is even at around 90 mmHg due to the low hydrostatic pressure gradient. Figure 4 illustrates the distribution of arterial and venous pressures in supine and standing. The intra- and extravascular hydrostatic pressure gradients are dependent on gravity, posture and the specific attribute of the vessel and determine the intravascular volume (25), impacting cardiac output. In summary, orthostasis represents a dynamic interplay between gravity, posture, and the cardiovascular system, highlighting the body's intricate mechanisms to maintain hemodynamic stability and cerebral perfusion in response to gravitational challenges.

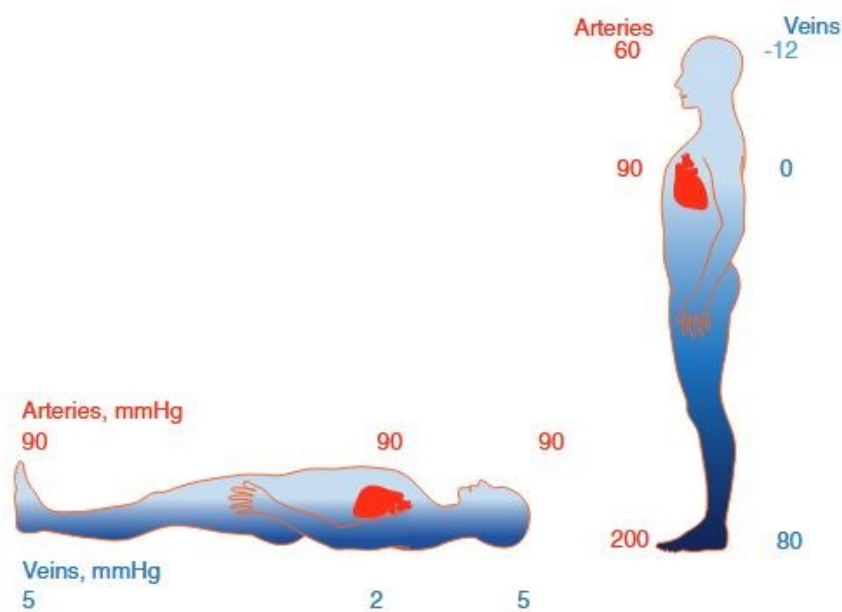


Figure 4: Arterial and venous pressure distribution in upright and supine.

Arterial (indicated by values in red) and venous (indicated in blue) pressure distribution in upright and supine positions in mmHg. (20)

1.3. Orthostatic intolerance

Phenotypically, orthostatic intolerance following spaceflight may present as orthostatic tachycardia, orthostatic hypotension, fatigue, or neurally mediated syncope. Multifactorial reasons contribute to orthostatic intolerance, including changes in cardiovascular regulation, like decreased peripheral vascular resistance, less sympathetic activity and changes in baroreflex function (19)(26). Blaber et al (2011) further mention alterations in cerebral blood flow, as a contributing factor (27). Conditions such as space travel, aging, and certain diseases may also exacerbate OI, attributed to factors including baroreceptor hyposensitivity and muscle loss resulting from immobilization (26). OI occurs when there is decreased venous return leading to inadequate brain perfusion after a shift in posture to standing. About 30% of space explorers face OI while on short space flights, augmenting to 80% after longer flights, as shown in Figure 5 (2).



Figure 5: Italian astronaut returning back to Earth.

Italian astronaut Samantha Cristoforetti from the European Space Agency (ESA), returning back to Earth and is assisted out of the space vehicle, probably experiencing post-spaceflight deconditioning. (28)

1.4. Blood pressure regulation

Blood pressure, defined as the hydrostatic pressure stretching the walls of the CVS, serves as the physical force for blood circulation and is primarily generated by the work of the heart. The MAP decreases gradually from the aorta leaving the heart to the arterioles, with back-flow occurring against gravity with very little pressure (19).

The regulation of blood pressure involves a complex interplay between the cardiovascular system, neuroendocrine system, renal system and local endothelial factors. This coordination aims to maintain homeostasis, adapt to internal and external changes (29) and ensure metabolic supply to all tissues of the body. The blood pressure is largely influenced by cardiac work and peripheral resistance (23). The equation for MAP is defined as:

$$MAP = (SV \times HR) \times CO \times TPR$$

Where Stroke volume (SV) and heart rate (HR) determine the cardiac output (CO), which along with the total peripheral resistance (TPR) define the mean arterial pressure (MAP). Should one-factor decrease, compensatory adjustments in the others are necessary to keep a stable MAP and secure perfusion. TPR, regulated by local endothelial autocrine mechanisms, modulates vasoconstriction and vasodilation, affecting BP. Vasoconstriction increases blood pressure through endothelin and endothelin 1. Vasodilation reduces it through e.g. NO (29). Arterioles and the small vessels exert the most significant influence on TPR, precipitating the greatest decline in blood pressure. In contrast, larger vessels exhibit lesser resistance to blood flow (19, 29).

These regulations of the CVS and maintenance of homeostasis are carried out by the autonomic nervous system centred in the medulla oblongata (30), comprising the sympathetic nervous system and the parasympathetic system. Short-term regulation of blood pressure primarily involves neuronal mechanisms, such as responses to changes in posture and rapid movements, necessitating swift reactions. Rapid response baroreceptors, located in the aortic arch and carotid sinus play a pivotal role, in controlling MAP to ensure constant blood flow. Upon detecting a sudden decrease in MAP, efferent sympathetic and parasympathetic pathways influence the CVS, including the heart and vessels, leading to vasoconstriction of the

vessels and augmented cardiac output, which will result in a normalized MAP level. Conversely, if the receptors measure elevated MAP then normal, the parasympathetic nervous system reduces the sympathetic activity influencing CO and dilates the vessels, resulting in normalizing the MAP (31). The baroreflex and its mechanism are explained in Figure 6.

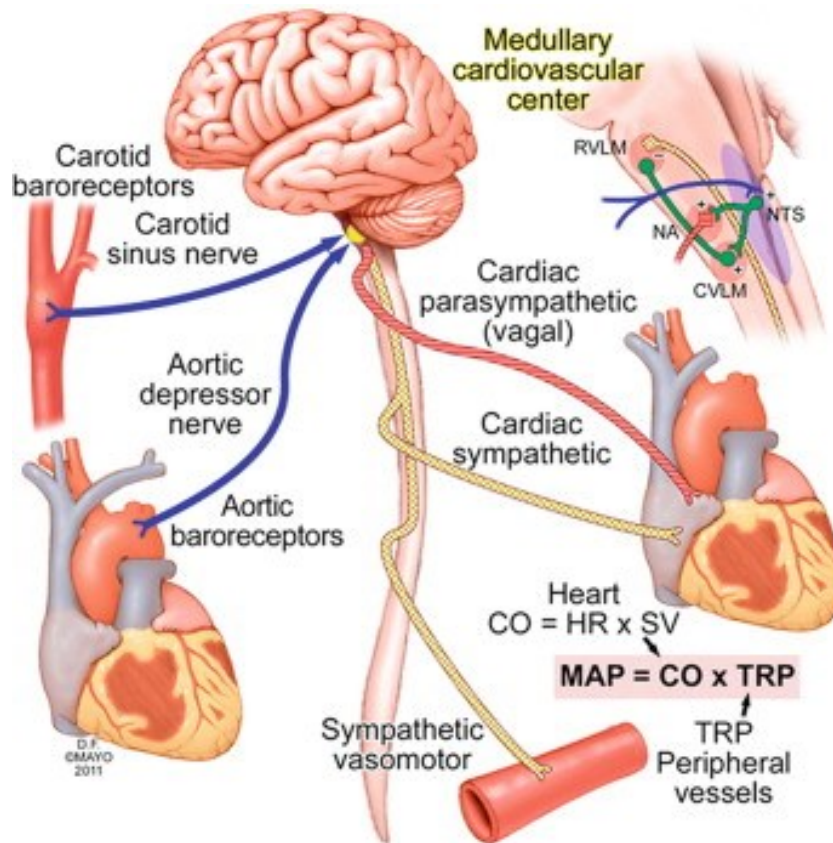


Figure 6: MAP regulations.

Mechanisms to regulate and sense the MAP by the autonomic nervous system. In summary, neural sensors detect MAP changes, which are transmitted via afferent pathways for central processing. Efferent parasympathetic and sympathetic pathways then regulate MAP by adjusting CO and TRP. (32)

Long-term blood pressure control is mostly regulated by the renal-endocrine systems, controlling the body fluids and the resulting blood volume. Governed by humoral factors, hormones and the sympathetic system to increase and decrease body fluid, thus influencing cardiac output and MAP (33). The kidney regulates plasma volume through the excretion of water and NaCl, if there is more blood volume, more blood arrives in the right heart and the cardiac output increases, causing the blood pressure to rise and vice versa (19). The main hormones are the Renin-Angiotensin-Aldosterone-System (RAAS) responding to changes in blood volume and pressure. Renin is activated by lower pressure in the kidneys, reduced NaCl concentrations and decreased intravascular volume. Low blood volume and BP lowers

the activations of the atrial receptors and baroreceptors, which in turn increase the activity of the sympathetic renal circulation nerves and thus increase Renin release. Renin stimulates the conversion of angiotensinogen to angiotensin I, which is further converted to angiotensin II, a potent vasoconstrictor that increases blood pressure. Aldosterone secretion promotes sodium and water reabsorption in the renal tubules, increasing blood volume and BP (19). Conversely, increased blood pressure triggers mechanisms to decrease blood volume and pressure, such as increased diuresis mediated by hormones like atrial natriuretic peptide (ANP) and brain natriuretic peptide (BNP), they are the antagonist of Angiotensin II (19). Figure 7 illustrates the key organs and hormones responsible for long-term control of BP. Understanding how blood pressure responds to changes in gravitational environments and across seasons is important, especially in the context of AG as a countermeasure to investigate the intricate relationship between different gravitational levels, cardiovascular dynamics and specifically in our study the changes across seasons.

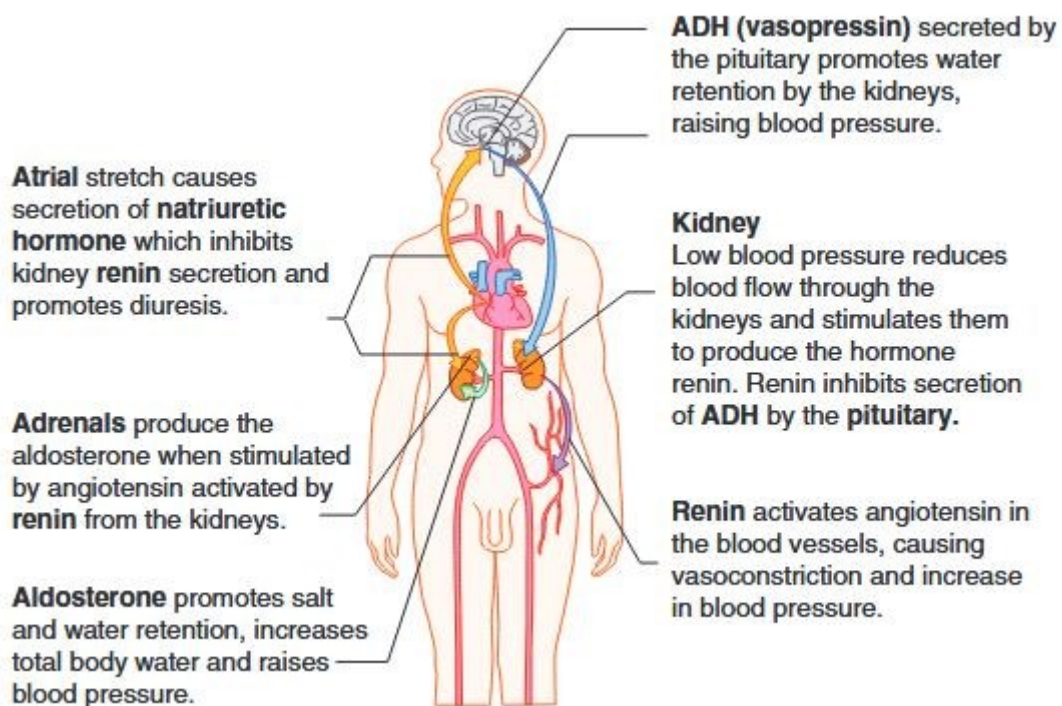


Figure 7: Long-term regulation of blood pressure.

Long-term regulation of blood pressure by the renal-endocrine system. Interplay of hormones and organs to control body fluid. (20)

1.5. Humans in Space and the effects of different gravity environments

The moment space explorers will depart from Earth's surface, the human body will be put into extreme conditions. To leave the Earth, the rockets will speed at 28.000 km/h to achieve orbital velocity. Most missions towards the International Space Station (ISS) will be reached between 3 hours and 3 days depending on the location and vehicle used, after 100km they will reach the Karman line, which is the international border of space (34). The space environment presents inhospitable conditions for humans, absence of air to breathe, intense vacuum, extreme temperatures and high levels of radiation. However the most dominant effect for the human body is the absence of gravity and its impactful physiological adaptations. Gravity as a fundamental stimulus is lost, for maintaining homeostasis across various different systems (9). Space travellers experience severe physical forces while leaving Earth, enduring acceleration forces up to 4,5 g, depending on the vehicle, just to enter free fall within a split second and silence when the engines switch off. The body directly takes a new neutral position in weightlessness shown in Figure 8. Astronauts will work, sleep and spend their time in this new postural position affecting the body's size, form, and functional capacities (34). Postural muscles, also known as antigravity muscles, undergo atrophy as a consequence of the absence of gravitational forces and to maintain upright posture (35, 36).

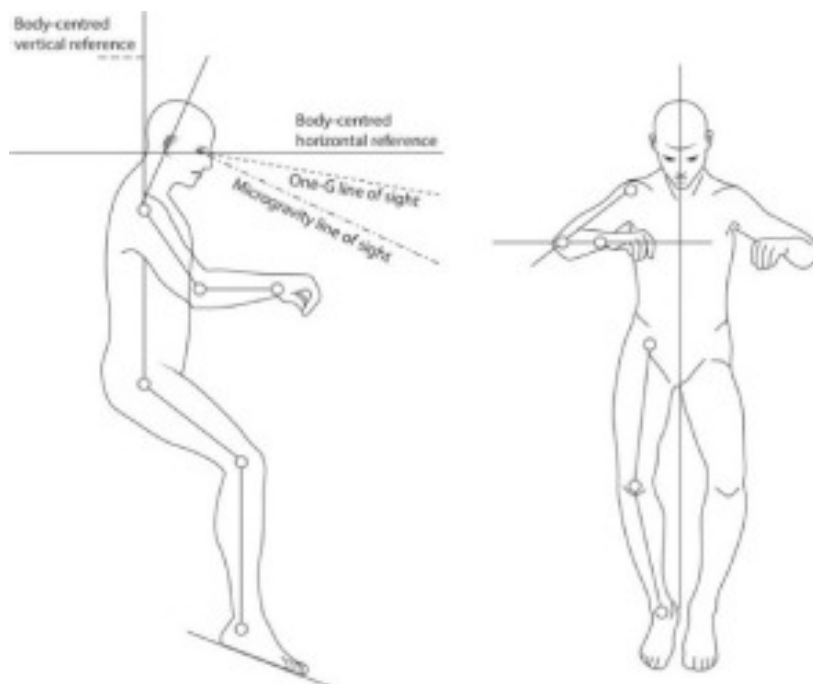


Figure 8: Neutral body posture in microgravity. (34)

The sudden shift to microgravity induces immediate effects to the crew, blood starts pooling into the chest and head, called fluid shift. The hydrostatic gradient is lost (18) and about 2000 ml of blood will move from the legs towards the upper body. Blood pressure in the head and feet will be the same in contrast to Earth. An increase in intrathoracic pressure amplifies the effect and explorers will experience facial puffiness and so-called chicken legs (37). Space adaptation syndrome or space motion sickness including emesis, headache and fatigue may occur within the first minutes related to the neuro-vestibular system (34). Long-term effects of spaceflight include autonomic nervous system dysregulation, less immunity to infections, disrupted sleep patterns, circadian rhythm disturbances, the removal of stimuli and gravitational information, musculoskeletal changes and a reduction in sensory system performance will take weeks or months (2, 9). Figure 9 illustrates the adaptations and time to microgravity.

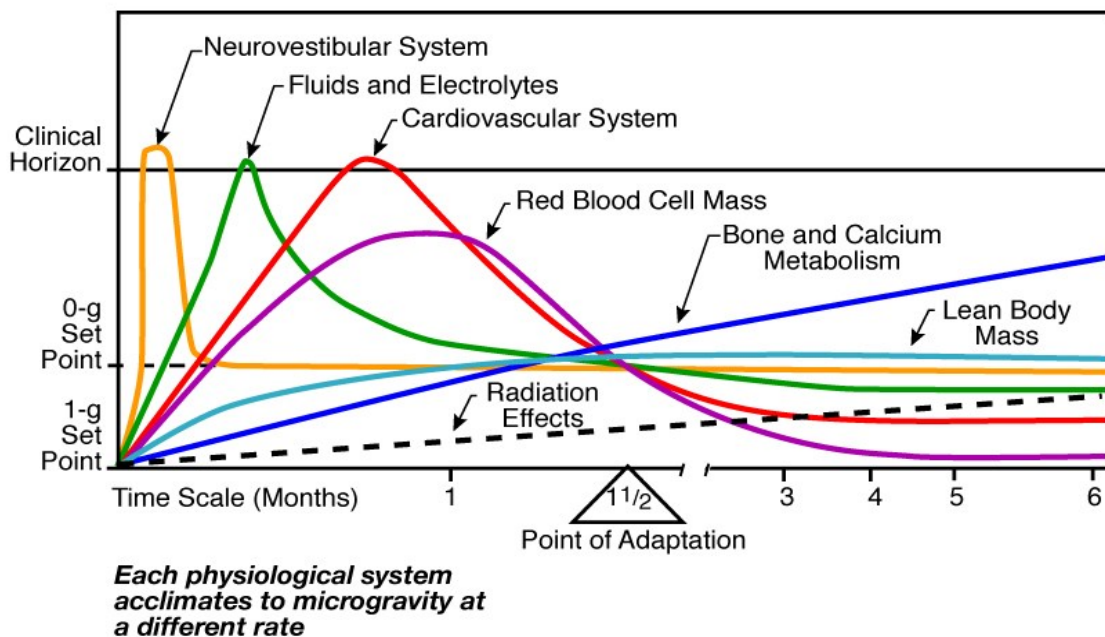


Figure 9: Adaptations and time to microgravity.

Illustrating the adaptation of various physiological systems and parameters over time in months. Each graph originates at a baseline of 1 G, representing normal Earth gravity, with a set point of 0 G, symbolizing microgravity, with the pivotal point of adaptation at 1,5 months. Additionally, clinical effects are shown at the clinical horizon line. Provided by Prof. Goswami

However, the most significant of these changes occur within the CVS and its regulation. The increased volume in the upper body activates various compensatory neuroendocrine and hemodynamic mechanisms. The baroreflex is activated, lowering sympathetic activity and decreasing norepinephrine release (38). Cardiac work and TPR decrease through peripheral vasodilation, to react to the new conditions. A constant low BP and low vascular resistance lead to wall atrophy and less venous compliance (2, 39). Increased volume in the heart inhibits the sympathetic system. Simultaneously triggered baroreceptors suppress the RAAS system, while the release of atrial natriuretic peptide (ANP) is increased (37). An augmentation in diuresis and sodium excretion reduces plasma and blood volume. The reduced volume lowers the central venous pressure (CVP) and less blood reaches the heart, resulting in less ventricular filling and less cardiac output. Summed up, this leads to heart atrophy, dysfunction (40) and cardiovascular deconditioning. The autonomic control functions to regulate the BP are affected and have a decreased activity, due to absent postural changes and even arterial pressure in all body parts. These adaptive changes combined with the mentioned other factors lead to a system adapted to microgravity shown in Figure 10. These are not problematic in microgravity, but pose a challenge when explorers enter a gravity environment like Mars, Moon or return to Earth. The autonomic control mechanisms, the CVS and local vessel modulations, affecting TPR, are not strong enough anymore to maintain perfusion against gravity. Blood will rush into the legs and along with less blood volume, cerebral perfusion may not be secured. Heart atrophy and changes in heart rate response are a result of less workload for the heart (2, 40). Venous backflow and vascular responsiveness are decreased in standing, resulting in post-spaceflight OI and possible syncope. These conditions will impact the health of future crews and their success on missions (38).

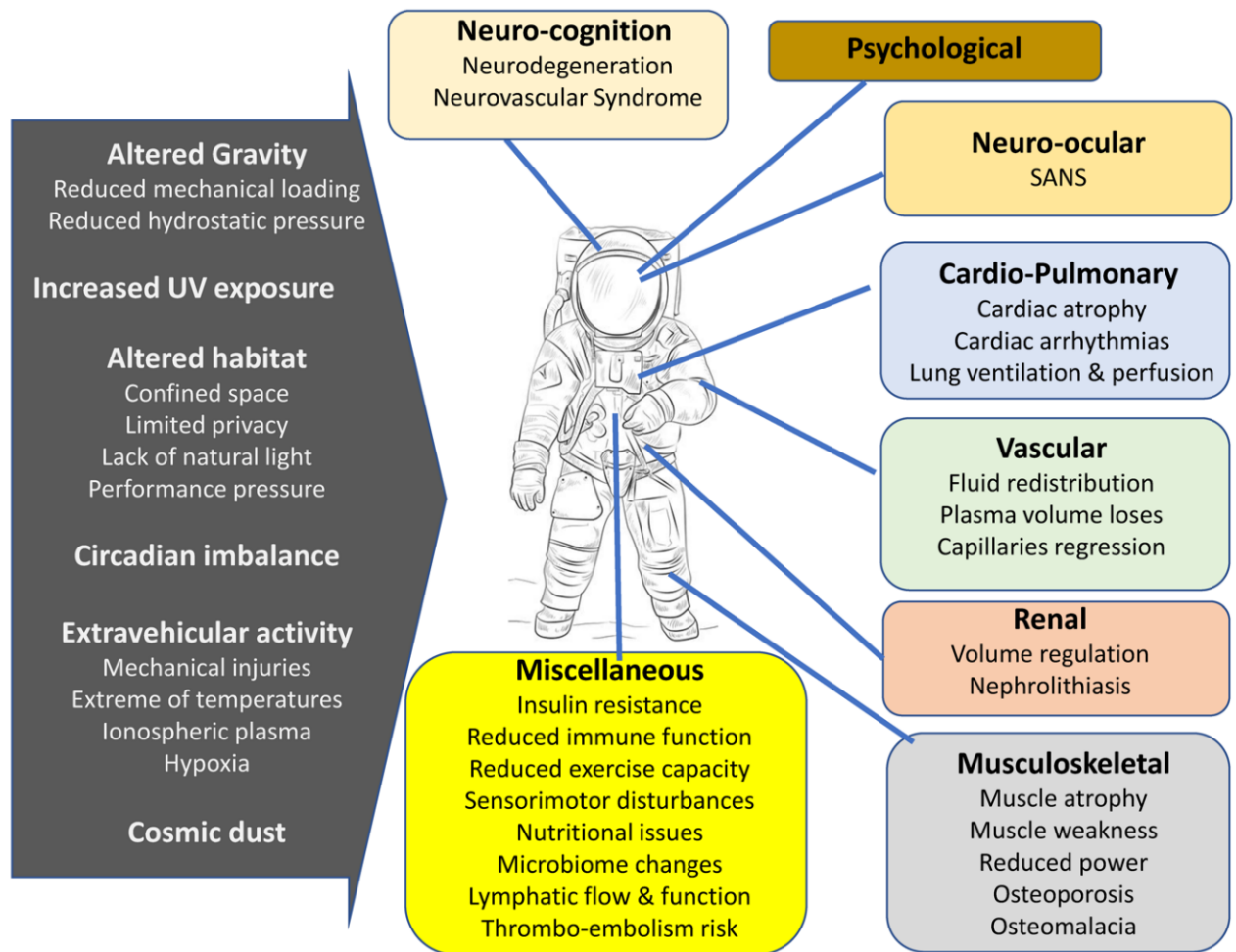


Figure 10: Effects and hazards of spaceflight on different systems in the body (41).

1.6. Countermeasures

The long-term exposure to microgravity presents a significant challenge for space medicine. Physiological adaptations have significant consequences, particularly for muscles, bones, and the CVS, including orthostatic intolerance (OI) and impaired autonomic control of blood pressure (42). To mitigate these adaptations, especially during extended missions like a potential journey to Mars, where astronauts will experience varying gravity levels, effective countermeasures must be taken (15). The objective is to ensure, that the crew not only remains healthy but also be able to fulfil their mission productively (7), without experiencing syncope due to OI during transit phases, which can have far-reaching consequences for the health of the crew and the success of the mission (15). It remains unclear whether the gravitational force of 0.38 g on Mars is sufficient to prevent health adaptations, or if additional countermeasures are necessary. Developing and optimizing suitable countermeasures is crucial to ensure the progress of future missions. A recent systematic review conducted by the ESA was undertaken by Syed Shozab Ahmed et al (2024), evaluating the effectiveness of various countermeasures, including centrifugation and LBNP (14). Without resolving these issues, long-term missions, such as those to Mars, will not be possible (15). Various countermeasures have been developed over the years to target specific physiological systems.



Figure 11: Resistive exercise in space.

The Advanced Resistance Exercise Device by NASA is an all-in-one gym developed to provide a constant force through the entire movement, to prevent bone and muscle loss.(43)

These include daily high-intensity physical training, including resistive exercise, shown in Figure 11, which has proven to be particularly effective for the musculoskeletal system (2, 7). Additionally, treadmill training with bungee cords and high-intensity aerobic exercises are crucial to improve aerobic capacity and cardiovascular function. Presently, physical exercises are applied as a principal countermeasure on the ISS, but studies have proven, that these countermeasures may not be entirely sufficient (14, 44). A combination of countermeasures must be utilized, mentioning nutrition as an important factor, as adequate food intake and vitamin D supplementation are essential for the musculoskeletal system (2, 7).

Another utilized and researched countermeasure is skin surface cooling, which has demonstrated efficiency in preserving orthostatic tolerance in head-down bed rested studies (45). By activating the sympathetic nervous system, decreasing the accumulation of blood in the cutaneous vessels and increasing arterial blood pressure, proving skin surface cooling is a valuable intervention (14). This highlights the strong correlation between temperature and its effects on the CVS. Heat stress can impact blood pressure regulation (46) and OTT (47). Therefore, skin surface cooling is used to cool down astronauts during re-entry in their space suits (45), preventing the risk of cardiovascular events and ensuring the health and success of the mission. As skin surface cooling showed efficacy (14), further research is required.

Lower Body Negative Pressure (LBNP) shown in Figure 12, serves as both a research tool and a training method to prevent upward fluid shift in microgravity (14, 48). Syed Shozab Ahmed et al (2024) evaluated that LBNP has been shown to sustain orthostatic tolerance, as well as LBNP simulates some of the gravitational stress, experienced by the cardiovascular system on Earth, which is absent in microgravity (14).



Figure 12: LBNP in Graz.

The figure illustrates a participant undergoing Lower Body Negative Pressure (LBNP) testing, a procedure used to simulate the physiological effects of changes in gravitational forces. LBNP helps to study cardiovascular function and fluid shifts, aiding in the development of countermeasures for spaceflight and orthostatic intolerance. (49)

However, existing measures alone may be insufficient to adequately address all physiological systems, especially BP regulation (15). Prolonged stays in microgravity pose challenges to blood pressure regulation, necessitating simulations of earth-like movements and conditions to avoid syncope and stimulate the cardiovascular system. These simulations generate stimuli, similar to those experienced when standing upright and moving under gravity, which can only be achieved through artificial gravity (AG) in a microgravity environment (15). Passive countermeasures could have a substantial outcome of protecting crew health and optimising performance by mitigating spaceflight deconditioning on missions, where exercise alone may prove insufficient (14).

Artificial Gravity

AG emerges as a possible alternative to prevent spaceflight deconditioning caused by microgravity (15). Several studies have shown that AG is an effective countermeasure for multiple physiological systems (2, 38). It has been demonstrated to enhance OTT and blood pressure regulation (50) while simulating Earth-like cardiovascular responses (38). AG can be generated by centrifugal acceleration, either continuously through the rotation of the whole space vehicle, as seen in examples like the Voyager-class space station, which has a diameter of 200m and a gravity of 1/3 g or the H3 Human Hypergravity Habitat project, a ground-based facility (Figure 13).

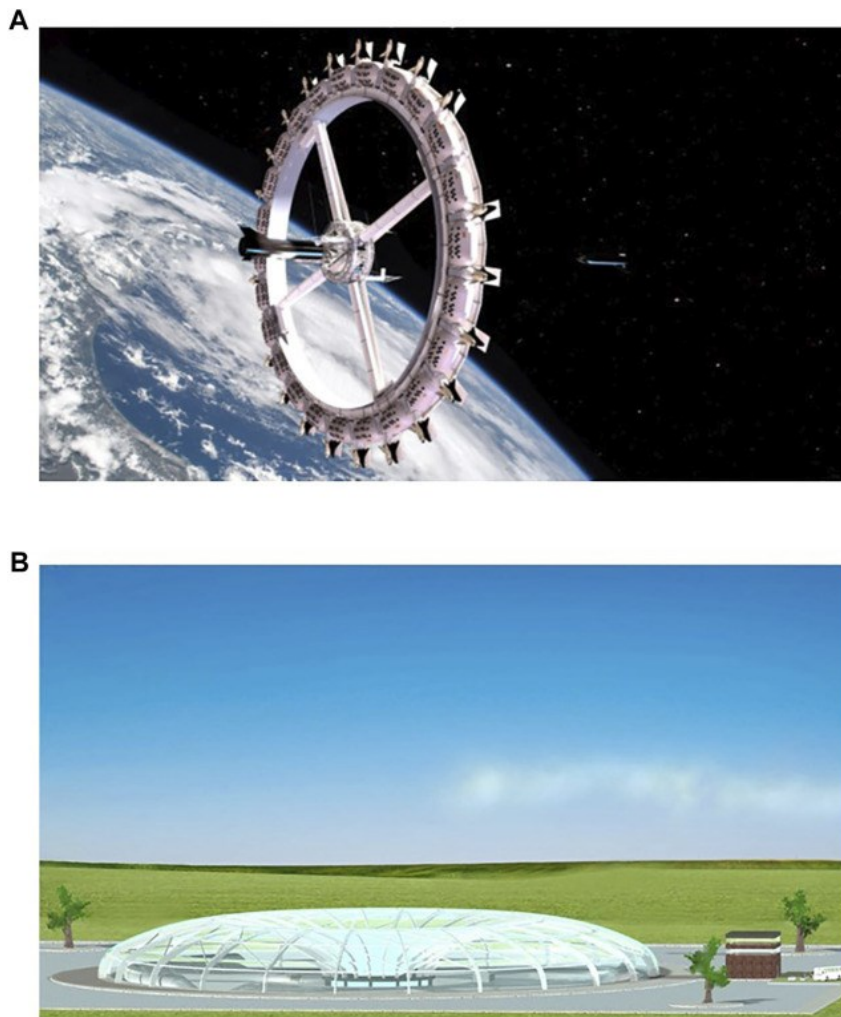


Figure 13: A Voyager class space station. B H3 Human Hypergravity Habitat. (51)

Yet, a rotating vehicle poses significant financial and engineering challenges. Therefore, a centrifuge with a short radius is more feasible for providing and researching artificial gravity (AG) as soon as possible. It is unclear whether humans require gravity continuously or if intermittent AG produced by an SAHC is sufficient (15).

Short arm human centrifuge (SAHC)



Figure 14: MEDES SAHC

as part of ESA with me as a participant, connected to monitoring and measurements. (my own picture)

SAHC is a realistic countermeasure for long-duration missions. It has the potential to counteract the dangerous effects of spaceflight deconditioning, such as bone and muscle deterioration and cardiovascular deconditioning. SAHC strengthens postural muscles, exposes the skeleton to pressure, stimulates the cardiovascular system, and activates the vestibular organ (15). The individual lies with their head towards the centre of the centrifuge and their feet outwards, creating a centrifugal force along their longitudinal axis as shown in Figure 14. The SAHC can create artificial hypergravity with different g-loads (42), that influence hydrostatic pressure in the body. This pushes blood into the legs, activating the cardiovascular system and forcing it to work against the load. It is crucial to individualise AG stimulation, as each person's AGT is different. Further studies utilizing centrifuges in weightlessness are crucial, as previous research has been conducted solely on Earth (38). It is also essential to combine AG with other countermeasures such as exercise, diet, and medication to optimize crew health. Further research is necessary, also regarding the parallels of spaceflight deconditioning and deconditioning effects of bedded elderly persons, who spend most of their time lying down. These countermeasures might contribute to enhancing the physiological function of older persons (2).

1.7. Seasonal changes to the cardiovascular system

The impact of seasonal variations on human physiology is substantial, as changes in the environment throughout the year affect various aspects of life on Earth, including most living organisms and humans (52). Among the influential factors in our study, temperature emerges as particularly significant, although other variables also play a role in shaping human physiology. As seasons transition, alterations in daylight duration (53) impact human behaviour and mood, consequently influencing brain function (52). Additionally, seasonal variations affect physiological functions such as metabolism and dietary habits, further contributing to fluctuations in human physiology.

Blood pressure, as one of our key parameters, has been extensively investigated in relation to seasonal changes (53-57). Research by Hayashi et al. (2007) has indicated that blood pressure levels fluctuate across seasons, with weather conditions and resultant temperatures identified as primary contributing factors (57). Lower temperatures have been consistently associated with higher systolic blood pressure levels (57), underlining our hypothesis that AGT varies across seasons, as the other parameters do as well.

Seasonal changes have a significant impact on the cardiovascular system (CVS) and orthostatic tolerance, emphasising the significant impact of environmental factors, particularly temperature, on human physiological responses. Studies have shown that seasonal factors influence the CVS (58), with Trozic et al (2020) confirming differences in haemodynamic parameters and heart rate across seasons (59). As well as indicating that blood pressure is higher in winter compared to summer, particularly mean arterial pressure (MAP) and diastolic value (59).

Temperature also affects the autonomic nervous system (60), with increased temperature leading to increased peripheral vasodilation due to reduced sympathetic activity and decreased peripheral resistance. Heat causes an accumulation of blood in the cutaneous vessels, which alters blood distribution, with more blood in the periphery and less centrally, causing lower venous backflow (60, 61). Moreover, a relationship exists between heightened venous compliance, leading to diminished venous return in the upright body posture, and the ambient temperature (62). In contrast, winter shows increased sympathetic activity. Previous studies found a faster heart rate when standing in winter (60, 63).

Hormonal activity also changes in different seasons (64). In winter, increased catecholamine levels and aldosterone levels can be observed, which have a positive influence on blood volume and blood pressure (64, 65). Vasopressin is reduced in winter, as is endothelin, in contrast to NO, which peaks in summer and is responsible for vasodilation (64, 65). Orthostatic tolerance is affected by reduced venous return and less blood supply to the head, with the effects exacerbated by hypovolaemia and sweating through salt and fluid loss (58). The drop in blood pressure during orthostasis is more pronounced in summer than in winter (60), influenced by thermoregulatory responses and cardiovascular shifts leading to a drop in systemic vascular resistance (66).

Bradley suggests that astronaut training temperature and ambient temperature influence changes in cardiovascular function and response (67). Stress from elevated temperatures reduces central volume and thus decreases venous return, which affects stroke volume (63). Variations in blood pressure and orthostatic tolerance across different seasons can be attributed to a combination of factors such as sympathetic tone, hormonal activity and vascular resistance. Increased temperature affects blood volume and blood distribution, which leads with the other mentioned factors to reduced cardiac output thus impacting cerebral blood flow during orthostatic stress. (63) Seasonal factors and influences are illustrated in Figure 15.

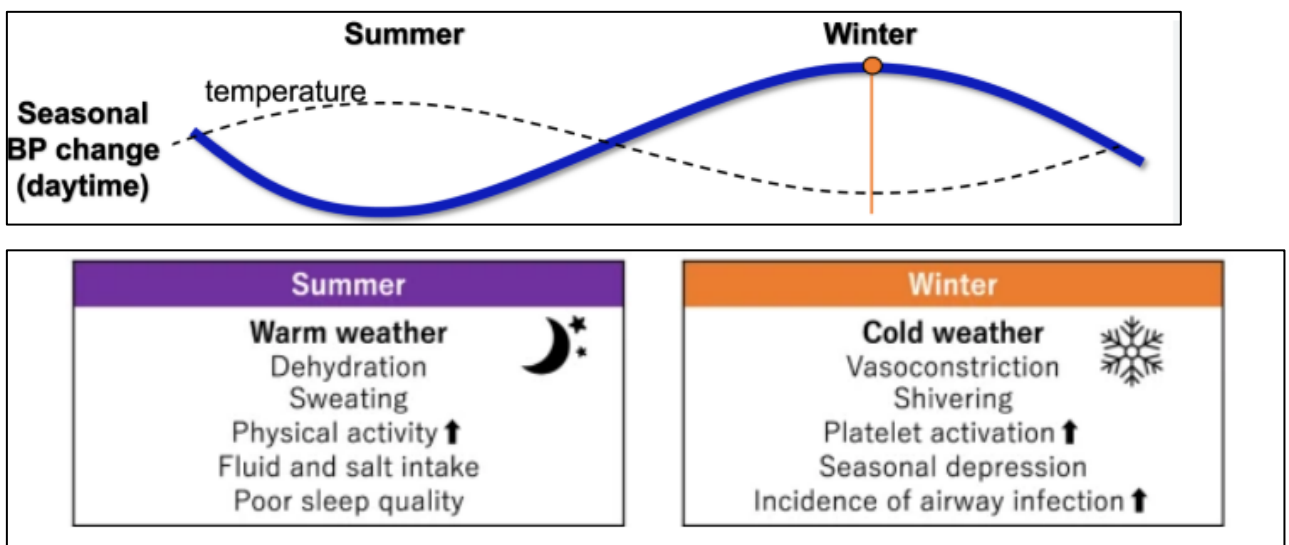


Figure 15: Seasonal blood pressure variations.

Highlighting the various seasonal factors and influences contributing to these changes of BP (68)

2. Aims and Objectives

The main aim of this study is to analyse differences in artificial gravity tolerance across different seasons and assess the effects of environmental factors, such as temperature, on individual artificial gravity tolerance. A further aim is to investigate the effects on cardiovascular parameters associated with these seasonal variations. The results of this study are of great importance, as they contribute to the improvement of countermeasures in space medicine and address the problem of post-spaceflight OI to enhance crew health and performance.

Two participants took part in two AGT tests, each following two equivalent protocols, but at different times of the year. The AGT results from both tests were compared and a correlation was drawn with the seasons. We hypothesized that AG tolerance would be greater during colder seasons due to known influences of seasonal changes on the cardiovascular system. In particular, parameters such as blood pressure and heart rate were analysed to determine how these factors change across different seasons and their potential impact on individual AGT. The first step requires analysing the differences in AGT across various seasons and drawing a connection between seasonal changes and AGT. Subsequently, evaluating the seasonal influences on the CVS parameters is essential to understand the extent of these parameter changes and their implications for AGT. Previous studies have demonstrated that seasonal changes affect blood pressure, orthostatic tolerance and cardiovascular function (59, 67). Understanding the environmental conditions under which the CVS optimally performs in relation to AGT is crucial to further research and utilise these conditions.

The results of this study contribute to a deeper understanding and optimisation of one of the major challenges in space medicine. They aid in perfecting AG as a countermeasure and improve the space environment for explorers. Moreover, they assist in planning AG training on space missions and make countermeasures against spaceflight deconditioning more effective for humans. As the negative effects of microgravity pose a major risk for future missions, it is important to minimise these effects through optimal countermeasures in space medicine. The findings of this research are also of great importance for terrestrial medicine, as there is a substantial correlation between space medicine and geriatric medicine.

3. Methodology

The studies were conducted at MEDES in Toulouse, France.

The participants were provided with detailed information about the study's objectives and procedures, as well as potential risks, and gave their written consent. The participants' written consent forms are kept at MEDES. The study was approved by Toulouse Ethics Committee, in accordance with the ethical principles of the Declaration of Helsinki.

3.1. Participants

Inclusion and exclusion criteria:

The prior selection criteria included an age range of 20 to 45 years, a height range of 160 to 188 cm, and a BMI range of 20 to 26. Recruitment for the study was carried out by MEDES Toulouse in France.

The study participants were identified as having a healthy lifestyle, being physically active, non-smokers, and normotensive. Prior to their participation in the study, all participants underwent a medical screening procedure. This included clinical chemistry analyses, such as glucose, creatinine, urea, uric acid, liver enzymes, total cholesterol, as well as high-density lipoprotein (HDL) and low-density lipoprotein (LDL) levels. Additionally, the participants underwent haematological examinations (blood counter), a urine analysis (glucose, protein, urobilinogen), a resting electrocardiogram (ECG), and an exercise test, to evaluate their endurance capacity. To further evaluate the health and fitness of the participants, a standing test was conducted to assess orthostatic tolerance, along with a comprehensive medical history. Before testing, each participant was familiarized with all aspects of the study, including the equipment and the personnel involved.

3.2. Protocol

Measurement day:

Prior to the experiments, participants were required to fast for at least 2 hours and abstain from consuming caffeinated or alcoholic beverages for at least 12 hours. The experiments were conducted at MEDES Toulouse between 8 am and 2:30 pm. The room temperature and humidity levels were maintained at 23°C and 55%, respectively, throughout the experiment.

The room lights were dimmed during testing. The 2 studies were conducted in different seasons. The cold season was defined from November to April and the warm season from May to October. Figure 16 illustrates the average low and high temperatures in Toulouse for each month.

On the day of the intervention, the participants were positioned supine with their heads towards the centre of the centrifuge, on one of the two-bed nacelles of the (SAHC), where their instrumentation and monitoring took place. The participants were instructed to breathe normally and avoid leg movements. The AG exposure began with a baseline level of 0 G for ten minutes (centrifuge not running, but measurements already running), followed by ten minutes of 0.6 G acceleration (measured at heart level). The acceleration was increased by 0.1 G every three minutes. This process continued until the participant experienced pre-syncope symptoms. Following this period, the AGT time was calculated. The participant was then returned to the baseline (0 G) level for ten minutes. The protocol is shown in Figure 17. Artificial gravity tolerance time, including time in min and gravitational acceleration in Gz.

The AG presyncope run is conducted to determine the participants' AGT, assessed by AGT-time determined based on the occurrence of presyncope symptoms and the determination of the presyncopal G level using the SAHC.

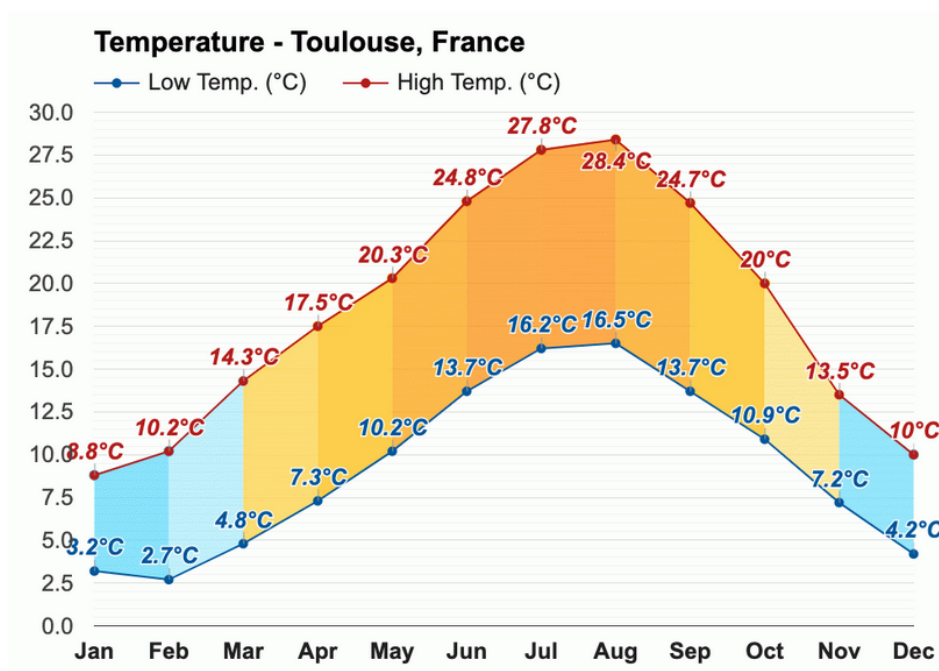


Figure 16: Average low and high temperatures in Toulouse France (69).

Centrifuge Protocol

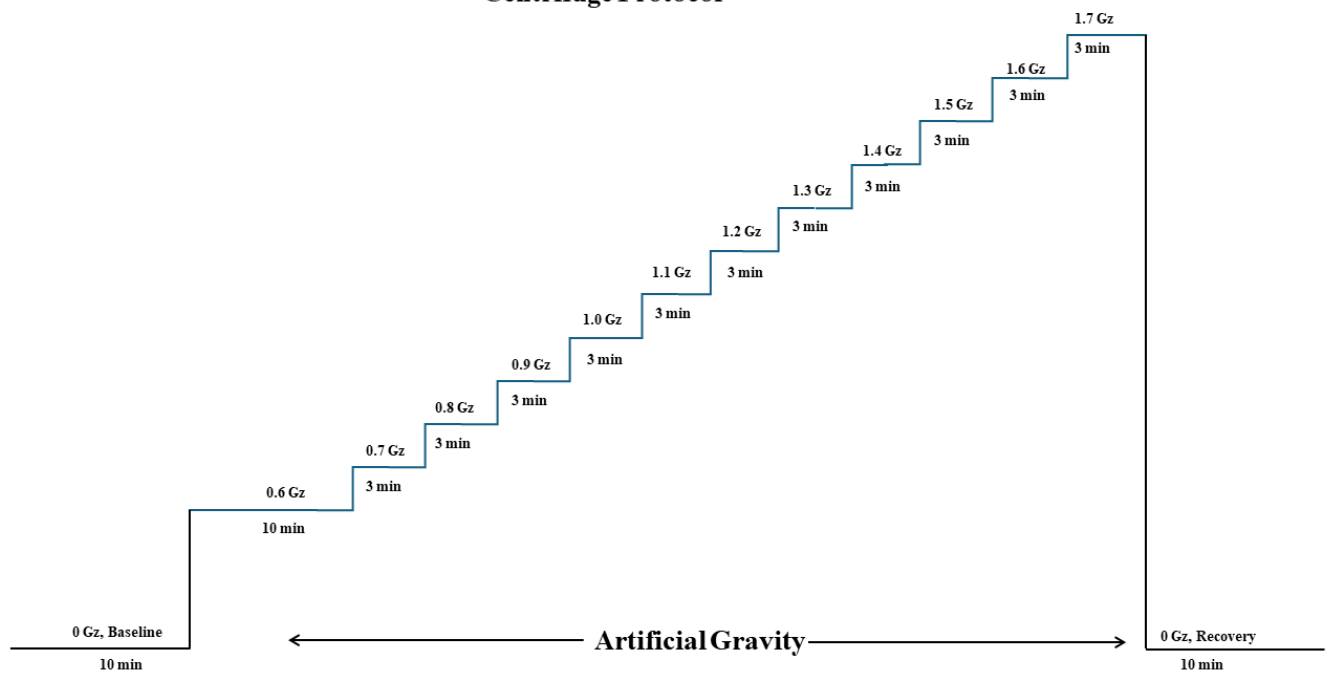


Figure 17: Centrifuge protocol.

Termination criteria/presyncope symptoms:

During the AG tolerance to presyncope test, several physiological signs and criteria have been established to protect the health and safety of the participants. These include a sudden drop in blood pressure, defined as blood pressure of >25 mmHg/min, a diastolic blood pressure of >15 mmHg/min, or a sudden drop-in heart rate, defined as >15 bpm. The run was stopped if participants experienced pre-syncopal symptoms such as nausea, cold, clammy skin, excessive sweating, or pale skin. The run could also be stopped at any time by the participant.

Physiological measurements/monitoring:

Throughout the entire experiment, participants were instrumented to obtain continuous beat-by-beat heart rate (HR) using a 3-lead electrocardiogram (Biopac Systems, Goleta, CA, USA) and continuous beat-by-beat arterial finger blood pressure (BP) was measured using a Finometer device (Finapres Medical Systems (FMS), Amsterdam, The Netherlands). The finger cuff was placed around the third finger of the left hand. The left hand was fixed by a sling at the level of the fourth intercostal space, assumed to be at the level of the heart. Finometer measurements were validated using absolute arterial blood pressure

measurements obtained by an automated sphygmomanometer (Intellivue MMS X2, Philips, Best, The Netherlands). Measurements and monitoring are shown in Figures 14 and 18.



Figure 18: Measurements and monitoring.

(my own picture)

3.3. Statistical Analysis

The data were stored on a laptop with password protection to ensure data security and privacy. Data analysis was performed using OriginPro Lab 2023 to compare the differences in blood pressure and heart rate responses between the summer and winter seasons. To check for normality, the Kolmogorov-Smirnov test was performed on the data. The data included blood pressure and heart rate, and the Student's t-test was used to measure the statistical differences ($p < 0.05$).

4. Results

In this study, 2 male participants were compared.

Artificial gravity tolerance was higher during winter sessions in both participants. Significant variations were observed in the rate of change of blood pressure (BP) across seasons during the AG tolerance test ($p < 0.05$). The rate of change of BP during AG runs was higher in summer sessions and more consistent in winter sessions.

Artificial gravity tolerance time

Figure 19 summarizes the AGT time for the 2 different testings in minutes of the 2 participants in winter and summer. The AGT improved in both participants in winter from 36 min to 41 for participant 1 and 36 min to 37 min for participant 2.

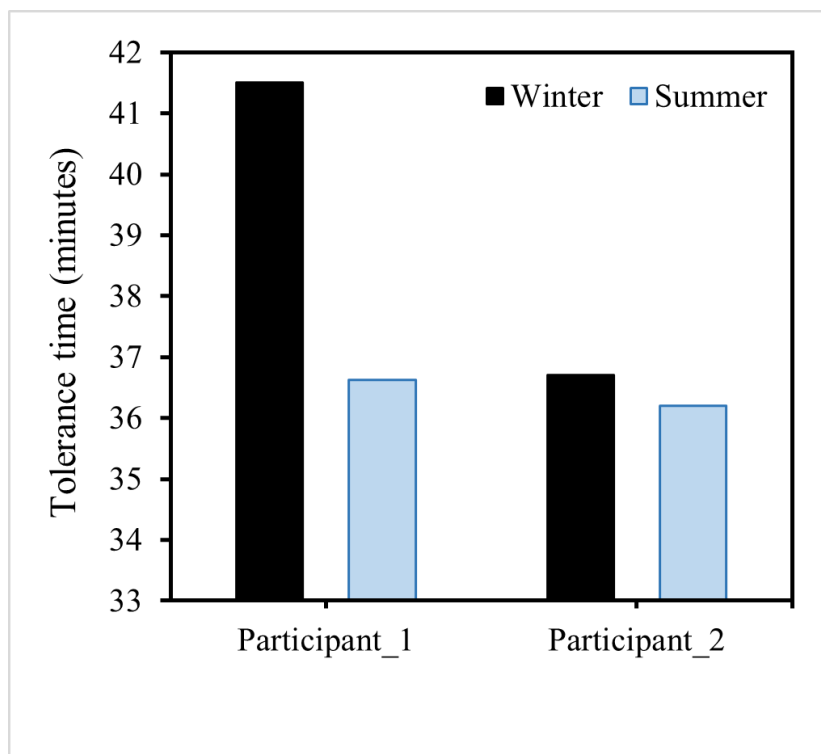


Figure 19: Tolerance time in (min) Participant 1 and 2

illustrating higher tolerance time for both participants in winter then in summer.

Cardiovascular Effects

Figure 20 presents a graph of the typical temporal progression alongside heart rate in bpm, as the participant approaches their threshold in artificial gravity tolerance while experiencing presyncopal symptoms, evident as a drop in heart rate. Specifically, the graph illustrates participant 1, who increases his AGT between winter and summer, as shown by the grey (summer) and black (winter) dotted lines.

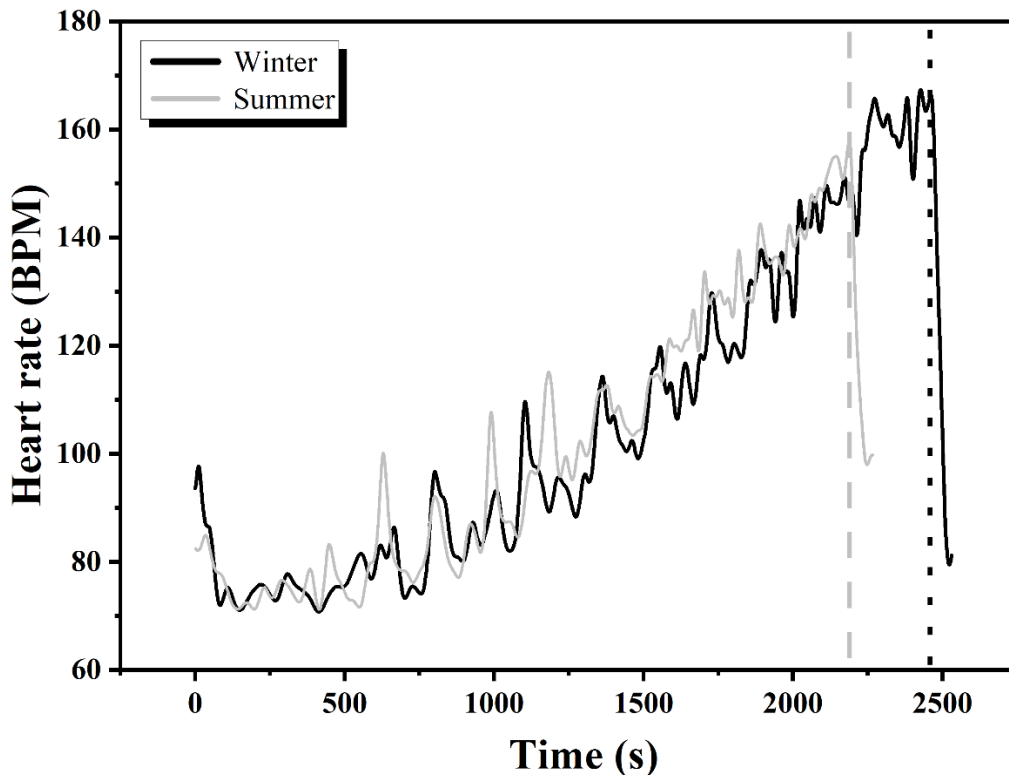


Figure 20: Heart rate in (BPM) and Time in (s) for Participant 1.

The 4 following tables present the measurements and monitoring. Artificial gravity is shown, as blood pressure and the heart rate. Each table represents one measurement day, participants 1 and 2 in summer and winter.

Heart Rate

Participant 2 shows a significant variation ($p < 0.001$) between summer and winter, whereas participant 1 did not ($p = 0.49$).

Blood Pressure

Participant 2 shows a significant variation ($p < 0.001$) between summer and winter, whereas participant 1 did not ($p = 0.05$).

Table 1: Participant 1 in summer.

Participant 1 in Summer			
Time Frame	Artificial gravity	BP	HR
Start	0.6	136.189	80.82747
End	0.6	126.7024	79.82777
Start	0.7	156.8114	80.77108
End	0.7	160.318	84.74893
Start	0.8	155.1807	91.34009
End	0.8	146.475	81.34768
Start	0.9	162.4037	83.59374
End	0.9	133.9088	101.9802
Start	1	155.721	91.15534
End	1	141.649	98.12837
Start	1.1	140.1024	103.2031
End	1.1	127.9833	109.4247
Start	1.2	141.9021	111.22
End	1.2	128.2641	124.4023
Start	1.3	146.666	112.1648
End	1.3	134.6416	124.7003
Start	1.4	133.787	135.0004
End	1.4	117.1087	140.7155
Start	1.5	136.5494	138.8094
End	1.5	129.0894	152.2605
Start	AG STOP	120.639	147.7928
End	AG STOP	133.4754	104.639

Table 2: Participant 1 in winter.

Participant 1 in Winter			
Time Frame	Artificial gravity	BP	HR
Start	0.6	129.0914	98.17835
End	0.6	128.1674	74.1109
Start	0.7	137.7685	78.54247
End	0.7	153.8895	70.53741
Start	0.8	143.9271	86.72413
End	0.8	132.0523	80.88523
Start	0.9	133.0086	89.06947
End	0.9	138.6089	103.2765
Start	1	137.1608	100.4465
End	1	118.8606	104.3569
Start	1.1	139.8105	83.01501
End	1.1	131.6348	108.5617
Start	1.2	143.5307	97.16407
End	1.2	142.5287	98.03191
Start	1.3	132.9784	120.1565
End	1.3	122.6019	131.4723
Start	1.4	137.431	132.0677
End	1.4	124.0775	138.8557
Start	1.5	124.704	141.5258
End	1.5	152.4745	128.3145
Start	1.6	129.9104	144.3633
End	1.6	128.2324	160.7764
Start	1.7	151.0789	143.591
End	1.7	118.3004	122.492
Start	AG STOP	120.3628	111.5747
End	AG STOP	135.1088	76.89108

Table 3: Participant 2 in summer

Participant 2 in Summer			
Time Frame	Artificial gravity	BP	HR
Start	0.6	156.2351	58.91619
End	0.6	150.924	63.78431
Start	0.7	148.8818	66.96847
End	0.7	155.7779	60.63984
Start	0.8	154.1887	64.21444
End	0.8	159.3379	67.29947
Start	0.9	154.7768	72.80928
End	0.9	154.4477	69.20002
Start	1	154.6076	70.77862
End	1	154.4372	82.15932
Start	1.1	150.6278	85.6483
End	1.1	161.1797	80.94831
Start	1.2	153.2452	91.72834
End	1.2	148.7287	92.29123
Start	1.3	156.104	97.04858
End	1.3	151.0084	103.7988
Start	1.4	155.2975	103.9522
End	1.4	157.7504	102.6126
Start	1.5	134.9718	115.2794
End	1.5	118.7342	68.91693
Start	AG STOP	113.5552	66.12778
End	AG STOP	139.3851	49.74853

Table 4: Participant 2 in winter

Participant 2 in Winter			
Time Frame	Artificial gravity	BP	HR
Start	0.6	128.4093	60.45403
End	0.6	140.8933	63.34984
Start	0.7	134.9522	67.61285
End	0.7	110.1605	66.77793
Start	0.8	131.0561	70.55592
End	0.8	133.8045	71.25276
Start	0.9	113.715	75.78895
End	0.9	124.2535	77.86566
Start	1	118.4731	82.81501
End	1	108.9877	86.79456
Start	1.1	100.213	85.33281
End	1.1	81.10611	101.0015
Start	1.2	90.45318	109.5179
End	1.2	65.3444	113.1301
Start	1.3	79.25988	122.8817
End	1.3	54.42618	110.1421
Start	1.4	49.72669	113.9703
End	1.4	43.60321	111.8048
Start	1.5	47.06491	113.3322
End	1.5	50.49957	121.2806
Start	AG STOP	42.9845	124.7459
End	AG STOP	34.55404	120.1125

5. Discussion

In this pilot study, we aimed to investigate the influence of different seasons on artificial gravity tolerance and hemodynamic responses. Specifically, we examined whether artificial gravity tolerance varies when studies are carried out during warm and cold seasons. Two male participants were compared, each undergoing the same protocol during two separate studies conducted in different seasons. We compared their artificial gravity tolerance time and the rate of change of blood pressure, determining artificial gravity tolerance time based on the occurrence of presyncope symptoms. Our hypothesis was confirmed, as we observed significant differences in artificial gravity tolerance time across seasons, with artificial gravity tolerance time being higher in winter for both participants. This demonstrates the importance of understanding artificial tolerance variations for optimizing crew health and performance in space missions since artificial gravity will be a key countermeasure for prolonged spaceflight missions (15). It's the first pilot study, that takes seasonal effects into account in artificial gravity tolerance to develop better countermeasures and spaceflight conditions.

Participant 1 showed an increase of 5 minutes compared to his artificial gravity tolerance time in the summer, participant 2 showed a significant increase as well. We can assume, that seasonal influences and environmental factors such as temperature, have an impact on the cardiovascular system, which has been observed in previous studies such as Segal et al (2015) (70) and Hoffmann et al (2022) (67). Focusing on artificial gravity tolerance, our results suggest a strong correlation between seasonal influence and artificial gravity tolerance. Multiple factors may contribute to higher artificial gravity tolerance in the winter, including the interplay of hypothalamic thermoregulatory responses (43, 45, 46), the autonomic nervous system (38), and hormonal activity (41, 42). Higher sympathetic activity, catecholamine levels and increased vasoconstriction have been reported in winter (39, 41, 42), while lower catecholamine levels and vasodilation are seen in in summer months. Seasonal differences in hormonal activity, including aldosterone, vasopressin, and NO (41, 42), also play a role. Additionally, factors such as hypovolemia through fluid and electrolyte loss by sweating, contribute to lower MAP from reduced venous return (35).

We also observed higher heart rates in response to higher gravity levels in the winter for both participants, indicating that seasonal influences may lead to increased orthostatic tolerance.

Additionally, one of our presyncope signs was a drop in heart rate, with both participants showing an increased time during winter and the higher heart rate was maintained longer and reached a higher maximum. These results are consistent with Hoffmann et al (2022) findings, suggesting similar differences in heart rate due to seasonal influences in a head-down tilt bed rest study, involving participants reclining at an angle of 6° with their head positioned lower than their feet for 60 days in bed rest, to simulate the effects of microgravity on the body (67).

Furthermore, our study demonstrated that the rate of change of blood pressure during artificial gravity runs was higher in summer sessions and more consistent in winter sessions. Assuming that a more consistent rate of change of blood pressure has an impact on artificial gravity tolerance, these findings suggest a strong correlation between seasonal influences and artificial gravity tolerance, as shown in Figure 19. In our study, we did not observe higher resting blood pressure in winter or lower blood pressure in summer, but we can show a significant variation between summer and winter in Participant 2. However, Trozic et al (2020) reported higher resting DBP and MAP in winter, while lower SBP and generally lower BP were observed in summer (59). Similar results were obtained with the Hoffmann et al (2022) study which observed similar differences in summer and winter with lower SBP and DBP trends in summer (67).

Environmental temperature could potentially be crucial in long-term space missions since it affects human health and also task performance (71). As Stahn et al (2017) discussed, that small increases in core body temperature can impair physical and cognitive performance (71). Additionally, as spaceflight deconditioning is associated with orthostatic intolerance (2, 39, 42, 50) and possibly syncope, syncope and temperature are strongly correlated (37), more research is needed to understand the impact of temperature and seasons on orthostatic tolerance in astronauts. Insights gained from our study may have implications for terrestrial medicine, particularly in preventing syncope, which occurs more frequently in the summer (48). Overall, the findings from this study will not only contribute to space exploration but also benefit terrestrial medicine and geriatrics, especially as older persons are more likely to develop orthostatic intolerance and experience deconditioning effects similar to spaceflight as Goswami et al (2017) outline (2).

Limitations

In our study, we only investigated male participants. Further investigation with female participants is needed to explore gender-specific cardiovascular and autonomic regulations to optimize spaceflight challenges for both male and female astronauts, as previous studies have shown that cardiovascular responses are strongly influenced by gender (27, 49).

The limited sample size of our pilot study necessitates an increase in sample size, however, this pilot study is very important as we are able to show AG differences across seasons.

The challenge of the study lies in narrowing down the potential influencing factors of artificial tolerance. While room temperature remains constant in both protocols, the outside temperature could have varied significantly from day to day, even in the same season and was not measured in this study.

Finally, in our study, we only assessed AG tolerance and hemodynamic parameters. Future studies should study the impact of seasons on hormones, plasma volume losses, which provide insights into fluid shifts, and other variables that can influence artificial gravity tolerance.

Conclusion and Future Directions

Participants in our pilot study experienced higher artificial gravity tolerance in colder seasons. Our results highlight the importance of understanding how external factors, such as environmental temperature, affect artificial gravity tolerance and the cardiovascular system with implications for future space mission planning. The determination of artificial gravity tolerance was based on the occurrence of presyncope symptoms, indicating that several mechanisms work together to maintain constant cerebral perfusion while the gravitational load is enforced on the physiological system. Further research is needed to understand how external factors and gender affect artificial gravity tolerance, autonomic regulations and the cardiovascular system across seasons.

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