Human Postural Responses to Artificial Gravity Training

Alina Saveko (asaveko@gmail.com)
Russian Academy of Sciences

Milena Koloteva
Russian Academy of Sciences

Elena Tomilovskaya
Russian Academy of Sciences

Research Article

Keywords: Artificial gravity, Centrifuge, Life science, Countermeasure, Human space flight, Posture

Posted Date: July 7th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3128873/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

Short-radius centrifugation (SRC) is a promising and economically feasible countermeasure in space flight and applies to gravity therapy in terrestrial medicine. The potential occurrence of undesirable orthostatic and vestibular reactions limits the use of this method. One way to minimize these risks is the ability of a human to adapt to the effects of overload. It is known that artificial gravity training may improve orthostatic tolerance. New data demonstrated that cardio-postural interactions and muscle-pump baroreflex activation are present during short-arm centrifugation. Based on previous studies, we hypothesized that repeated SRC in the interval training mode with angular velocities from 22 to 28 rpm may also improve postural tolerance. Six healthy male volunteers were observed before and immediately after five consecutive SRC sessions. The rest between SRC was at least three days. The SRC mode was an interval and included five 300-second platforms with 1.27 g at the feet and four 300-second platforms with 2.06 g at the feet. We registered the main postural characteristics and ground reaction forces data when the participant kept the center of pressure at a given point in a standing position with biofeedback and without this. After the first SRC session, there was a significant posture decondition. The SRC training effect was already noticeable after the second SRC session and was stable until the end of the experiment. The results demonstrate the development of postural tolerance to artificial gravity exposure in this mode and expand the understanding of sensorimotor adaptation capabilities.

1. Introduction

Long before the first human flight in space, in the 18th century, the first mentions of the application of centrifugation for therapeutic purposes were found in the literature (Rosenblum 1963). At the end of the 19th century, Konstantin Tsiolkovsky – one of the fathers of the Russian space program – proposed using this method for creating centripetal accelerations that could provide an inertial load similar to the Earth's gravitational load – the so-called artificial gravity. Thus, particular interest in the effects of centrifugation appeared in the background of the evolution of aviation and space medicine (Kotovskaia and Will-Williams 2004). At the same time, studies of the therapeutic effects of centrifugation in patients did not stop. Thus, a unique research field was formed, where the experience of terrestrial and space medicine combine and complement each other (Isasi et al. 2022).

Particularly, short-radius centrifugation (SRC) is currently a promising and economically feasible method for both against the adverse effects of space flight (SF) (Clement 2015; Isasi et al. 2022; Seedhouse 2020) and for gravity therapy (GT) with beneficial effects on numerous conditions, such as immobility due to neuromuscular disorders, balance disorders, stroke, sports injuries, multiple sclerosis, ischemia of the lower extremities, peripheral and coronary artery disease, lymphedema, complex regional pain syndrome, secondary Raynaud's phenomenon, and systemic sclerosis (Kotovskaia and Will-Williams 2004; Isasi et al. 2022; Kourtidou-Papadeli 2021, 2022). Despite the rich history of research (Kotovskaia and Will-Williams 2004), now the lack of clear recommendations for the use of SRC (for example, load dose, duration, frequency) hampers the implementation of this method into the practice of SF (Isasi et al. 2022). A similar problem hinders the wider application of the therapeutic effects of SRC in terrestrial
medicine (Kourtidou-Papadeli 2021). To solve this problem, further accumulation of data on the influence of various SRC regimes on the human body is necessary.

The main difficulty of using centrifugation methods is the potential occurrence of undesirable orthostatic and vestibular reactions – syncope, cross-coupled illusion, and associated motion sickness. Moreover, tolerance to high G along the longitudinal body axis is degraded during SF (Clement et al. 2015; Kotovskaya 2010, 2015). In the problem of using SRC for prevention and treatment, an important aspect is not only the search for ways to increase positive effects but also the search for ways to minimize adverse reactions and health risks.

One of the promising ways to minimize the risks of using the SRC method is the ability of a human to adapt to the effects of overload. Besides developments in adapting humans to artificial gravity conditions are discussed for maintaining sensory-motor and structural integrity in missions involving transitions between different gravity environments. Recent studies using SRC and Human Centric Rotator Device with about 1 g at the subject’s center of mass and 2-2.5 g at feet suggest that any individual has the potential to tolerably vestibular acclimate to a given spin rate of operational importance (Bretl and Clark 2020, 2022). There is also evidence that artificial gravity training with a load from 1 g to 2.5 g at the feet for 35 min/day may improve orthostatic tolerance (Stenger et al. 2013).

Based on the above, and also taking into account the presence of cardio-postural interactions and muscle-pump baroreflex (Verma et al. 2017; Goswami et al. 2021) and their activation during short-arm centrifugation (Blaber et al. 2014), we hypothesized that repeated SRC may also improve postural tolerance.

The work aimed to study the postural characteristics after five consecutive SRC sessions with rest for at least three days between SRC in the interval training mode with angular velocities from 22 to 28 rpm and loads from 1.27 to 2.06 g at feet.

**2. Materials and methods**

**2.1 Subject**

Six healthy male volunteers took part in the study (37.8 ± 4.2 year, 180.7 ± 3.1 cm, 86.2 ± 5.1 kg). None of the participants had any neurological or musculoskeletal disorders. The sample size is small due to the specificity of such studies (Iwasaki et al. 2005; Iwase 2005; Stenger et al. 2011; Li et al. 2017; Reynolds and Shelhamer 2020). All subjects were admitted to participate in the experiment by a medical expert commission and signed a written Informed Consent to participate in the study following the provisions of the Helsinki Declaration of Human Rights. The research procedures were preliminarily reviewed and approved by the Commission on Biomedical Ethics of the Institute of Biomedical Problems of the Russian Academy of Sciences.

**2.2 Training protocol**
The research was carried out using the "Short-radius Centrifuge" stand (Fig. 1a) – part of a unique scientific installation "Medical and Technical complex for testing innovative technologies of space biomedicine in the interests of ensuring orbital and interplanetary flights, as well as the development of practical healthcare" – based on the Institute of Biomedical Problems of the Russian Academy of Sciences (Moscow, Russia).

Within the framework of this study, five SCR sessions were provided for each subject. The interval between SRC was at least three days and averaged 6.11 ± 2.17 days. The first SRC session was the first experience for all participants. All SRC sessions were the same and lasted 60 min. The rotation radius was 235 cm. The gravity gradient (ΔG) was 74.5%. The subject's head was at a distance of 60 cm from the axis of rotation.

The mode of overload exposure was an interval and consisted of several alternating episodes with a gradual increase and decrease in overload to the specified values. The starting speed set and braking at the end of each SRC session occurred at about 0.17 rpm/s. The SRC session included five 300-second platforms with angular velocities of 22 rpm and 0.32 g at the head, 0.58 g at the heart, and 1.27 g at the feet; as well as four 300-second platforms with angular velocities of 28 rpm and 0.53 g at the head, 0.95 g at heart, 2.06 g at feet. The velocity gradient of acceleration and deceleration between these platforms was 0.075 rpm/s (Fig. 1b).

The choice of the interval SRC mode is due to the better subjective tolerance of intermittent exposure — with a shorter exposure subjects note less discomfort caused by prolonged leg strain during overload. Moreover, in real SF, the comparative analysis of various modes of locomotor training showed higher preventive effectiveness of interval training compared to continuous workouts (Fomina et al. 2016).

### 2.3 Data acquisition

Entry Level Footscan system 0.5 m (RSscan International, Belgium) was used for the registration of postural characteristics and ground reaction forces (GRF) data before and immediately after each SRC session (Fig. 2a). The test included recording the pressure exerted by the feet on the sensors of the Entry Level Footscan system platform when the participant was asked to keep the center of pressure (COP) in a standing position for 20 seconds using biofeedback (image on the screen by Materialise Footscan 9 software; Fig. 2b). Then, on command, the participant closed his eyes and continued to stand for 20 seconds, trying to remain in the same position.

During the first session of the experiment, the position of the feet on the platform (the distance between the heels and toes) was fixed and repeated for each experimental session. The monitor with visual feedback was in front of the eyes of the subject at a fixed distance of 55 cm from the bridge to the center of the screen. The test was performed in thin socks on an uncovered platform to ensure hygiene rules because the cover on the Footscan sensory platform can significantly reduce the accuracy of the recorded data (Xu et al. 2017).
Thus, three parameters were recorded with open and closed eyes separately: (1) the area of the ellipse of the COP displacement \( S = SDT(x) SDT(y) \pi \) – in mm², where \( x \) and \( y \) represents the COP displacement along the axis of the abscissa (frontal) and ordinate (sagittal); (2) the velocity of COP displacement in mm/s; (3) GRF values in N/m² – the average pressure value on all loaded sensors during 20 seconds of standing.

### 2.4 Statistical Analysis

No trends or significant differences were found between all sessions before SRC. We averaged data from 5 sessions held before SRC to indicate the baseline of values. Thus, there was no effect of sensorimotor learning to perform testing, and the duration of the breaks between SRC was sufficient to restore the studied parameters.

The data were analyzed using GraphPad Prism version 8 (GraphPad Software Inc., California, USA). We checked all data for normality using the Shapiro-Wilk normality test. We used the two-way RM ANOVA test (time point×visual feedback). The significance level was standard – \( p \leq 0.05 \). Besides, GraphPad Prism software detected a significant difference within the confidence interval of the Bonferroni correction. We presented all data as Mean ± SEM. When the population means are unknown, SEM help to make a reliable inference about how far the estimated value differs from the population mean. SEM shows both the SD value and the sample size and suits our situation better than the SD (Tang et al. 2019).

### 3. Results

It is worth noting that repeated rotations on SRC in this mode did not lead to the formation of pronounced vestibular disorders, or orthostatic instability. In addition, there were no significant deformations of the arches of the feet.

During visual feedback, the area of the ellipse of the COP displacement values were no statistically significant changes. A slight increase in this parameter compared to the baseline level was observed only after the first three SRC sessions – by 1.76 ± 1.50, 2.32 ± 1.58 and 1.86 ± 1.58 mm², respectively. Immediately after the elimination of visual feedback, the largest and most significant increase in the ellipse of the COP displacement compared to the initial values was observed only after the first SRC experience – by 5.68 ± 1.50 mm² (\( p = 0.005 \)). It is worth noting that before the start of the SRC session, there was no visible difference in this parameter between different conditions – between the data obtained with open and closed eyes. At the same time, rotation on SRC increased this difference after each experimental session (Fig. 3a).

After the first SRC session, the velocity of COP displacement significantly increased both with open and closed eyes – by 1.40 ± 0.52 (\( p = 0.05 \)) and 1.90 ± 0.51 mm/s (\( p = 0.006 \)), respectively. Interestingly, after the second SRC experience, this parameter remained significantly high compared to the baseline level only with open eyes – by 1.56 ± 0.53 mm/s (\( p = 0.04 \)). Starting from the third experimental session the
values of the velocity of COP displacement remained slightly high both with closed and open eyes – on average by 1.08 ± 0.61 mm/s (Fig. 3b).

In addition, after the first rotation, the GRF values significantly increased: with the eyes open – by 108.9 ± 28.72 N/m² (p = 0.005), and after closing the eyes – by 111.1 ± 28.73 N/m² (p = 0.004). After the second GRF session, this parameter was quickly restored – the GRF values were significantly lower than values obtained after the first session by 118.2 ± 30.26 (p = 0.004) and 117.6 ± 30.25 N/m² (p = 0.003) – with open and closed eyes, respectively. A significant decrease in the GRF values compared with the first session data was also observed after the third and fourth SRC sessions while visual feedback – by 90.49 ± 30.26 (p = 0.04) and 111.5 ± 36.78 N/m² (p = 0.04), respectively (Fig. 4).

4. Discussion

After the first SRC experience, we registered a significant decrease in postural stability indicators. This phenomenon led to the more active participation of the feet in the posture control – GRF reflexively increased as a result of an increase in the surface area of the feet used by the subjects to maintain equilibrium (demonstrated in Fig. 5). This reaction is expected, since the method of human centrifugation at similar overload (2 g), but with a longer (90 min) continuous exposure, was used to simulate the symptoms of space motion sickness (SMS). At the same time, 40 minutes of continuous exposure to 2 g was sufficient for a significant increase in EquiTest scores (Albery and Martin 1996).

The SRC mode used in this study did not cause the SMS symptoms: significant changes in postural characteristics were recorded only immediately after the first verticalization of the subjects and were practically invisible without the measuring instruments. Acknowledged the cause of motion sickness during centrifugation is the influence of cross-coupled “Coriolis” accelerations (Kotovskaia 2004; Cheung et al. 2007; Elias et al. 2008; Clement 2015; Clement et al. 2015). In the work of Lewkowicz R., the G-baseline level at 1.41 g and motion cueing (0.05 g/s) gave minimal motion sickness (Lewkowicz 2019). In our study, the acceleration/deceleration rate was about 0.01 g/s, and during the SRC session, the average load was about 1.5 g. Moreover, the speed rotation, acceleration, and deceleration used in this study were sufficient for the gradual vestibular adaptation and the avoiding the development of motion sickness symptoms (Cheung et al. 2007; Bretl et al. 2019). Taking into account the results obtained and the results of the study of squat exercise while centrifugation with a similar radius (2 m) and even a higher rotation speed (30 rpm; Duda and Jarchow, 2012) – the mode used in this study may apply with squat exercise without developing significant motion sickness symptoms. It is worth noting that women need fewer gravity loads (Masatli et al. 2018).

An important result of this study is the confirmed training effect of the selected SRC mode because significant negative postural reactions, which were recorded by the devices, disappeared already during the third rotation (Figs. 3 and 4). This phenomenon may be associated with neurovestibular (Bruni 2004) and sensorimotor adaptation (Bloomberg et al. 2015). A relatively significant decrease in motion sickness during the transition from 30 to 23 rpm was observed earlier with the 3rd SRC experience (Elias and
Jarchow, 2008). At the same time, a significant contribution of cardiovascular adaptation to this training effect cannot be excluded (Blaber et al. 2014). A daily 5-day intermittent centrifugation protocol from 1.0 to 2.5 G at 1.9 m human-powered centrifuge (HPC) at the NASA Ames Research Center caused an increase in orthostatic load tolerance. At the same time, these results suggest that AG training improved tolerance through training of local mechanisms in the peripheral vascular or extrinsic control of peripheral vascular resistance rather than through changes in the autonomous control of heart rate (Stenger 2005).

Thus, the obtained results demonstrate an increase in tolerance to the chronic effects of artificial gravity not only of the mechanisms of the cardiovascular system regulation but also of the postural control system. These data are useful for reducing adverse postural reactions to centrifugation in space and terrestrial medicine.

5. Conclusion

Thus, the obtained results demonstrate an increase in tolerance to the chronic effects of artificial gravity not only of the mechanisms of the cardiovascular system regulation but also of the postural control system. These data are useful for reducing adverse postural reactions to centrifugation in space and terrestrial medicine.

Declarations

The authors declare that they have no conflict of financial or non-financial interests that are directly or indirectly related to the work submitted for publication. Each of the authors has read and concurs with the content in the final manuscript. All authors have made substantial contributions to all of the following: the conception and design of the study, acquisition of data, analysis and interpretation of data, drafting and final approval the article.

Ethical Approval

The research procedures were preliminarily reviewed and approved by the Commission on Biomedical Ethics of the Institute of Biomedical Problems of the Russian Academy of Sciences (protocol # 595 of September 6, 2021).

Consent to participate and consent to publish

All subjects gave their informed consent participate in the study following the provisions of the Helsinki Declaration of Human Rights and for publication of identifying information/images in an online open-access publication.

Competing interests

The authors declare that they have no conflict of financial or non-financial interests that are directly or indirectly related to the work submitted for publication.
Authors' contributions

M.K. and E.T. designed the research; A.S. and M.K. conducted the research; A.S., M.K. and E.T. analyzed the data; A.S., E.T. drafted the manuscript. A.S., M.K. and E.T. interpreted the data and have read and approved the final submitted manuscript. A.S. had primary responsibility for the final content.

Funding

The study was supported by the Ministry of Science and Higher Education of the Russian Federation under agreement № 075-15-2022-298 from 18 April 2022 about the grant in the form of subsidy from the federal budget to provide government support for the creation and development of a world-class research center, the “Pavlov Center for Integrative Physiology to Medicine, High-tech Healthcare and Stress Tolerance Technologies”.

Availability of data and materials

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

References


https://doi.org/10.3389/fnsys.2015.00092
13. Fomina, E.V., Lysova, N.Y., Chernova, M.V. et al.: Comparative analysis of preventive efficacy of
https://doi.org/10.1134/S0362119716050078
16. Iwasaki, K., Shiozawa, T., Kamiya, A. et al.: Hypergravity exercise against bed rest induced changes in
17. Iwase, S.: Effectiveness of centrifuge-induced artificial gravity with ergometric exercise as a
https://doi.org/10.1016/j.actaastro.2005.03.013
18. Kotovskaia, A.R., Will-Williams, I.F.: The short-arm centrifuge: history and possible uses in
19. Kotovskaya, A.R.: Symptoms of negative effects cumulation in humans and animals under the
action of g-loads of varying direction in context of aviation and space flights. Aviakosm. Ekolog.
(2010). https://doi.org/10.1134/S0362119710070078
https://doi.org/10.3389/fneur.2021.746832
https://doi.org/10.3389/fphys.2021.644661
23. Lewkowicz, R.: A centrifuge-based flight simulator: Optimization of a baseline acceleration profile
https://doi.org/10.1016/j.actaastro.2019.07.007
24. Li, X., Yang, C., Zhu, Y. et al.: Moderate exercise based on artificial gravity preserves orthostatic
https://doi.org/10.33549/physiolres.933493

https://doi.org/10.3389/fphys.2018.01028

26. Reynolds, R.J., Shelhamer, M.: Introductory Chapter: Research Methods for the Next 60 Years of
Space Exploration. In Reynolds, R.J. (eds.) Beyond LEO – Human Health Issues for Deep Space

27. Rosenblum, D.E.: Some materials for the history of studying the effects of accelerations on the body.
In: Parin, V.V. (eds.) Aerospace medicine, pp. 100–101. Moscow (1963)


2005-1

https://doi.org/10.1016/j.actaastro.2006.08.008

University of Kentucky, United States (2005)

32. Tang, L., Zhang, H., Zhang, B.: A note on error bars as a graphical representation of the variability of
data in biomedical research: choosing between standard deviation and standard error of the mean.


34. Xu, C., Wen, X.X., Huang, L.Y. et al.: Normal foot loading parameters and repeatability of the Footscan

Figures
Figure 1

a – "Short-radius Centrifuge" stand at the Institute of Biomedical Problems of the Russian Academy of Sciences. b – Scheme of SRC mode: 1 - 130 s acceleration up to 22 rpm; 2 - 300 s 22 rpm, head - 0.32 g, heart - 0.58 g, legs - 1.27G; 3 - 80 s acceleration up to 28 rpm; 4 - 300 s 28 rpm, head - 0.53 g, heart - 0.95 g, legs - 2.06 g; 5 - 80 s deceleration up to 22 rpm; 6 - 130 s deceleration to 0 rpm.
Figure 2

a – The sensory platform of Entry Level Footscan system 0.5 m. b – The image by Materialise Footscan 9 software the subject saw when performing the test on the screen.
Dynamics of the area of the ellipse of the COP displacement (a) and the velocity of COP displacement (b) and while maintaining a vertical posture with visual feedback (columns without fill) and immediately after its elimination (grey columns) before SRC exposure (Baseline) and after each of five consecutive SRC sessions (SRC1-5). * - a significant difference from the initial data.
Figure 4

Dynamics of GRF values while maintaining a vertical posture with visual feedback (columns without fill) and immediately after its elimination (grey columns) before SRC exposure (Baseline) and after each of five consecutive SRC sessions (SRC1-5). * - a significant difference from the initial data. # - significant difference compared to values obtained after the 1st SRC session.
Example of visualization of the received data of one subject using Materialise Footscan 9 software before SRC exposure (Baseline; on the left) and the 1st SRC session (on the right).