Review on the Effects of Hypergravity on Workload and Fine Motor Skills in Humans

Judith Bütefür[1,*], Julia Habenicht[1,*] and Elsa Andrea Kirchner[1,2][a]
[1]*Institute of Medical Technology Systems, University of Duisburg-Essen, Duisburg, Germany*
[2]*Robotics Innovation Center, German Research Center for Artificial Intelligence (DFKI GmbH), Bremen, Germany*

Keywords: Hypergravity, EEG, ECG, EMG, Fine Motor Movements, Simulated Hypergravity.

Abstract: As the human body has adapted all functions and movements to Earth gravity it has to adapt its functions and movements when gravitational forces increase. Astronauts are for example exposed to increased gravity, i.e., hypergravity, during rocket launches. To prevent security incidents on the missions, it is important to achieve the best possible cognitive and motor performance from the outset, which requires a better understanding of cognition and behavior under hypergravity. The aim of this paper is to provide an overview of studies investigating the electroencephalogram (EEG), the electrocardiogram (ECG), muscle activity (EMG) and aiming accuracies in hypergravity as these biosignals are known to capture human cognitive performance and motor performance in order to make a statement about the effect of hypergravity on the human body. The literature review shows that all investigated parameters change under hypergravity. This fact highlights the need for further analysis of how these changes affect the human body in relation to motor performance. It also shows the need for novel and flexible training methods that allow astronauts to acclimatize to the new gravity conditions without limiting the duration of training, such as when training takes place during a parabolic flight or using a centrifuge. We propose the use of an active upper body exoskeleton as a new and flexile training method.

1 INTRODUCTION

If more G-forces act on the body than under Earth conditions (1.0g), this is referred to as hypergravity (Frett, Petrat, van Loon, Hemmersbach, & Anken, 2016). Increased gravitational forces (G-forces) occur, for example, when flying fighter jets, driving racing cars or under special helicopter maneuvers (Reid & Lightfood, 2019; McMahon & Newman, 2016; Honkanen, Oksa, Mäntysaari, Kyröläinen, & Avela, 2017). Astronauts are as well exposed to increased G-forces during rocket launches (Badalì, Wollseiffen, & Schneider, 2023). The human body has adapted its functions and movements to Earth gravity (Man, Graham, Squires-Donelly, & Laslett, 2022). If the body is exposed to hypergravity, it must adapt to the new condition. This normally takes some time and repetition of the same task (Clark, Newman, Merfeld, & Young, 2014). Astronauts have to achieve the best possible cognitive and motor performance from the beginning of their mission, otherwise mistakes can occur that end fatally due to the safety-critical conditions. This paper deals with the current state of the art in research on the effects of hypergravity on the human body and in particular on cognition, cardiovascular activity, muscle activity and fine motor skills. Some of the most relevant biosignals to measure the effect of hypergravity on the human body are the following: the electroencephalogram (EEG), the electrocardiogram (ECG) and muscle activity (EMG). These biosignals were chosen as they are known to reflect cognitive performance (Bütefür, Trampler, & Kirchner, 2024; Debie, et al., 2021) and motor performance (Habenicht & Kirchner, Preliminary Results on the Evaluation of Different Feedback Methods for the Operation of a Muscle-Controlled Serious Game, 2024; Aoyama & Kohno, 2020) of humans. Another

---

[a] https://orcid.org/0000-0002-5370-7443
* These authors contributed equally to this work and share first authorship

Bütefür, J., Habenicht, J. and Kirchner, E. A.
Review on the Effects of Hypergravity on Workload and Fine Motor Skills in Humans.
DOI: 10.5220/0013266400003911

In *Proceedings of the 18th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2025) - Volume 1*, pages 996-1001
ISBN: 978-989-758-731-3; ISSN: 2184-4305

parameter to analyze the motor performance is the investigation of the performance of fine motor movements. This paper will also discuss why it is important to experience the effects of hypergravity on the human body and to practice movements under these conditions before launching space missions. Currently it is only possible to create hypergravity on Earth by for example centrifuges suitable for humans, in underwater scenarios or during a parabolic flight. Especially underwater training and parabolic flights are costly and for parabolic flights the time in which hypergravity is experienced is very limited. Therefore, a new training method which faces these problems is needed and one will be proposed in this work.

2 METHOD

The search for studies took place online. The websites PubMed and google scholar were used to find studies related to hypergravity and the effects on the human body. The keywords hypergravity, muscle activity, EMG, fine motor skills, aiming accuracy, EEG, workload and ECG were used. Only studies in which the test subjects were humans were included. Studies that conducted their experiments with animals as well as cell studies under hypergravity condition were excluded.

3 RESULTS

In the following the results of the literature research for the biosignals EEG, ECG and EMG in hypergravity are presented as well as for studies investigating aiming accuracy in hypergravity.

3.1 EEG in Hypergravity

Marusic et al. (2014) reviewed brain activities in hypergravity, particularly the effects of changing gravity on the EEG. They reported a study from Schneider et al. (2008) which shows a significant decrease of the alpha-2 power for 1.8g on a parabolic flight in comparison to 1.0g pre-flight. They also show that changes in EEG are mainly in the frontal and occipital regions of the brain due to degraded neuronal functions as a protective mechanism of the body due to decreasing oxygen levels in the brain. (Schneider, et al., 2008)

A decrease of theta rhythms during hypergravity was observed by Wiedemann et al. (2011) and may be explained with higher arousal during this condition. In a study by Schneider et al. (2009) an increase of alpha-1 and beta-2 power during 3.0g was shown in the right frontal lobe. The authors assume that these changes are induced by a summation of physical and mental stress which occur in hypergravity. (Schneider, Guardiera, Abel, Carnahan, & Strüder, 2009)

The study of Baladì et al. (2023) analyzed the electrocortical activity and the neurocognitive performance during hypergravity. Therefore, the participants had to perform a dual task during the micro- and hypergravity phases of a parabolic flight, i.e., during 0g and 1.8g. The primary task was an oddball, and the secondary task was a mental arithmetic task. Results show a significantly later P300 with a higher amplitude for the dual task in hypergravity with its maximum at Pz electrode. The P300 for the simple oddball was highest at Oz electrode. The P300 showed an increase in peak latency and a higher amplitude in hypergravity as for the dual task. (Badali, Wollseiffen, & Schneider, 2023)

3.2 ECG in Hypergravity

In a study of Kourtidou-Papadeli et al. (2021) 28 healthy participants had to do cycling movements on an ergometer with low intensity on a short arm human centrifuge (SAHC). To define the individual intensity the heart rate (HR) was allowed to be between 40-59% of the individual maximum HR. Gravity levels between 0.5g and 2.0g were tested. To analyze the effect of hypergravity the ECG data from each gravity phase above 1.0g were compared to ECG data in a standing position. Each condition was performed for 5min and the last 60s were used for analysis. Results show a statistically significant main effect for heart rate variability (HRV). Performing Bonferroni post-hoc procedure pairwise comparisons between standing position and 1.2g as well as for standing position and 1.5g shows a statistically significant difference for gravity levels above 1.0g. No statistically significant difference for pairwise comparisons in HRV was found for 1.7g and 2.0g in comparison to standing position. A significant increase of the HR was shown for 2.0g in comparison to standing position. (Kourtidou-Papadeli, et al., 2021).

Masatli et al. (2018) analyzed gender related differences of changes in HR during hypergravity on a SAHC. To this end, the same acceleration/ deceleration pattern, i.e., 1.0g / 2.0g / 1.0g, was used for all participants. Each participant performed two rounds of the acceleration/deceleration pattern. Results show a significant increase of HR for both, men and women. (Masatli, et al., 2018)

3.3 EMG in Hypergravity

In a study of Honkanen et al. (2017) the difference in EMG activation of the neck and shoulder muscles between experienced and unexperienced pilots during controlled hypergravity exposure in a centrifuge was analyzed. Results show a significantly higher muscle activity of pilots without experience. (Honkanen, Oksa, Mäntysaari, Kyröläinen, & Avela, 2017) An increase in muscle activity in muscles, responsible for stabilization of the body during hypergravity was also found in the results of a study investigating spinal stiffness on a parabolic flight (Swanenburg, Langenfeld, Easthope, & Meier, 2020). Kunavar et al. (2021) analyzed the muscle activity of the upper limb muscles performing aiming movements during hypergravity as well as on a parabolic flight. Results also show an increase in muscle activity of the measured muscles. (Kunavar, et al., 2021) The investigation of simulated hypergravity with help of a weighted vest worn during daily activities shows a slight increase of muscle mass in comparison to the baseline test. (Rantalainen, Ruotsalainen, & Virmavirta, 2012)

3.4 Aiming Movements in Hypergravity

Chen et al. analyzed the pointing arm shift under gravity condition changes during a parabolic flight. Results show an upwards shifting in movements during hypergravity. (Chen, et al., 1999) The same effect was found by Bock, Arnold and Cheung (1996) who investigated aiming movements in the phase of hypergravity on a parabolic flight. A downwards shift in "paper and pencil" aiming movements in the phase of hypergravity on a parabolic flight was found in a study of Ross (1991). In a study of Kunavar et al. (2021) aiming movements on a parabolic flight were investigated as well. A decrease in aiming accuracy during hypergravity was found (Kunavar, et al., 2021). Artiles, Schor and Clement (2018) investigated the influence of gravity on cognitive and sensorimotor processes by letting subjects point to randomly appearing dots during the hypergravity, microgravity and Earth gravity phases of parabolic flights. No significant differences were found between pointing accuracies and gravity conditions. (Artiles, Schor, & Clément, 2018)

Clark et al. (2014) conducted a study on a SAHC where participants had to control an airplane cabin with help of a joystick in 1.0g, 1.5g or 2.0g in randomized order. All participants were pilots. Results show a significantly higher root mean square error (RMS) for 2.0g in comparison to 1.0g. The difference between 1.5g and 1.0g was not significant. They also show that the performance of the task improves with longer duration in a given hypergravity condition. The participants also reported a higher subjective workload during hypergravity phases which underlines the findings of a lower performance during these phases. (Clark, Newman, Merfeld, & Young, 2014)

4 DISCUSSION

The main objective of this paper was to summarize the state of the art of different modalities to analyze the effect of hypergravity on the human body as well as the performance of fine motor movements.

There is not much literature investigating the effects of hypergravity on the EEG. In summary the given literature shows that hypergravity does influence the EEG, especially for alpha-2 (Schneider, et al., 2008), alpha-1 and beta-2 power (Schneider, Guardiera, Abel, Carnahan, & Strüder, 2009) in the frequency domain. Both studies were done with eyes closed, which is not a suitable condition for astronauts during a rocket launch. Therefore, it is necessary to analyze the effect of hypergravity on the EEG during a more application-orientated scenario. In future, it could be possible to detect the workload level during hypergravity phases by using EEG, which makes the rocket launch safer, because a higher workload level leads to a higher risk of making mistakes (Morris & Leung, 2006).

The study of Badalì et al. (2023) shows significant effects in the analysis of the time domain for hypergravity (1.8g) in comparison to Earth gravity (1.0g). They showed that the P300 was significantly higher and later for a primary oddball task for 1.8g in comparison to 1.0g. For the dual task, they showed a significantly higher and later amplitude as well and also a shift to the occipital brain region (i.e., Oz electrode) for 1.8g in comparison to 1.0g. Changes in the P300 amplitude could also be related to the different workload conditions during a parabolic flight caused by changing gravity levels. However, Pergher et al. (2018) showed a significantly higher P300 amplitude for lower workload conditions in comparison to higher workload conditions. These results contradict each other, because for hypergravity in comparison to Earth gravity higher workload would be expected. This needs to be investigated further, as training the astronauts could also influence the workload and the P300 amplitude could also change as a result.

The reviewed studies investigating ECG show a significant increase of either HR or HRV during hypergravity. The study of Kourtidou-Papadeli et al. (2021) only shows an increase of HRV for 1.2g and 1.5g compared to standing position. However, Masatli et al. (2018) shows a significant increase in HR for 2.0g in comparison to 1.0g. Both studies do not compare participants who are trained under hypergravity conditions to untrained participants. The differences between trained and untrained subjects should be investigated since training before space missions would be possible for astronauts and could have an impact on the HR and HRV. Investigating the influence of training to the HR and HRV, could also bring an advantage if the workload of the astronauts should be monitored, as the HR and HRV changes with changing workload conditions as well (for an overview see introduction of (Bütefür, Trampler, & Kirchner, 2024)).

All previously introduced studies investigating fine motor movements under hypergravity condition, except for one, found a decrease in the performance of fine motor movements under hypergravity condition compared to the same movements under Earth gravity condition. As astronauts constantly have to work with their hands, it is important to prepare them for movements in hypergravity, such as those that occur when launching a rocket. Results of the study of Clark et al. (2014) show an improvement of the performance of fine motor movements under hypergravity condition after a short while compared to the first movements under hypergravity condition. This suggests that it is possible to adapt the movements to this condition. To make this adaptation as fast as possible, practicing fine motor movements under hypergravity condition before launching the space mission would be useful. Practicing fine motor movements is not a one-day process. The previous studies used parabolic flights or SAHC to create hypergravity to let subjects perform fine motor movements. For practicing fine motor movements in hypergravity the time of this condition on a parabolic flight lasts approximately 20 seconds per parabola. Although there are 62 phases of hypergravity on one parabolic flight, the time for practice is quite short. Besides this, parabolic flights are expensive as well. When using a centrifuge, hypergravity can be introduced for a longer period of time. As the centrifuge is moving all the time, subjects can suffer from motion sickness which can have a negative impact on the performance of fine motor movements. Another negative aspect about the centrifuge is that the gravitational forces acting on the human body are not the same at all points of the centrifuge. The g forces are higher on the outside than on the inside at the pivot point. These methods are very useful for research aspects but not for practicing fine motor movements.

Results of studies which investigated EMG activity under hypergravity condition show an increase in muscle activity compared to Earth gravity. The used weight vest of Rantalainen et al. (2012) for simulating hypergravity induced just a slight increase of muscle activity compared to Earth gravity. A reason could be that the vest was not individually adapted to the subjects' weight or that the weight of the vest did not affect all measured muscles. As muscle activity can be an indicator for motor learning under Earth gravity, it might also be an indicator for motor learning in hypergravity (Aoyama & Kohno, 2020). This aspect has not been investigated yet. Methods such as parabolic flights and centrifuges are useful for research to get to know the short-term behavior of muscle activity under this condition. The analysis of the state of the art shows that a novel training method for hypergravity would be useful in terms of cost and risk minimization to train under changing gravity conditions. This is also supported by the fact that parabolic flights and the use of centrifuges as the best alternative are expensive and associated with a risk of motion sickness. The time of hypergravity during these experiments is also limited. All these issues could be solved with a novel training method where no time limitations are caused by the training method itself. With this background, we want to test whether an active upper body exoskeleton (Kirchner, et al., 2016) with several contact points to the upper limbs of the human body can be used to generate hypergravity condition and therefore, train astronauts before being exposed to hypergravity in a safety-critical environment for the first time. The Recupera REHA exoskeleton built at DFKI-RIC can be used for this purpose. It has 7 active degrees of freedom per arm, so that all movement phases of the arms can be influenced by the exoskeleton. Tests with a stroke patient show that it is possible to compensate for the Earth gravity acting on the patient's arm with the exoskeleton. Instead of compensating for G-forces acting on the human arm, the exoskeleton can also be used to generate hypergravity, i.e., to amplify G-forces. The contact points with the upper limbs make it possible to perform free movements. Compared to recent training opportunities the training time is not limited as on parabolic flights and there is no hazard of motion sickness which can occur while using a centrifuge. (Habenicht, Tabie, Will, & Kirchner, 2022) The exoskeleton could also be used to analyse the effect of introducing external force on the upper limbs separately from all effects of natural hypergravity, which also includes acceleration that has a strong effect on the cardiovascular system by its own. Introducing forces by active exoskeletons could be used to analyze whether the effects seen in HR and HRV are caused by the increased force or by the acceleration acting on the cardiovascular system. This would make it possible to differentiate between the effects of force exposure and force exposure including circulatory stress (e.g., blood displacement due to acceleration in SAHC). On the other hand, this could also be a limitation since it could also be helpful to train the cardiovascular system and all other organs to be in hypergravity, which is not possible by using an active upper body exoskeleton.

5 CONCLUSIONS

In this paper we analyzed the current state on research investigating the effects of hypergravity on the human body and in particular on cognition, cardiovascular activity, muscle activity and fine motor skills analyzing cognitive (EEG, ECG) and motor performance (EMG, aiming accuracy). Our survey shows that all parameters are changing under hypergravity conditions. It is important to further investigate how and, above all, why the aforementioned parameters change in hypergravity, as there are currently only a few studies on this. In our future work, we want to test an active exoskeleton for the upper limbs to simulate hypergravity as a novel training method for astronauts to prepare them for the different gravity conditions already during training on Earth. Such intensive training could reduce the workload under real hypergravity and the adaptation time to it, which could make working in safety-critical environments safer from the start.

ACKNOWLEDGEMENTS

The work is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) under the grant number FKZ 50RP2340A in the project VASKuM.

REFERENCES

Aoyama, T., & Kohno, Y. (2020, July 20). Temporal and quantitative variability in muscle electrical activity decreases as dexterous hand motor skills are learned. *PlosOne*.

Artiles, A. D., Schor, D., & Clément, G. (2018). Effects of inverted vision on hand-pointing performance in altered gravity during parabolic flight. *IEEE Xplore.* USA.

Badalì, C., Wollseiffen, P., & Schneider, S. (2023, September). Under pressure-the influence of hypergravity on electrocortical activity and neurocognitive performance. *xp Brain Res.*

Bock, O., Arnold, K., & Cheung, B. (1996, February). Performance of a simple aiming task in hypergravity: I. overall accuracy. *Aviat Space Environ Med.*

Bütefür, J., Trampler, M., & Kirchner, E. (2024). Evaluation of Gel and Dry Electrodes for EEG Measurement to Compare Their Suitabiloty for Multimodal Worklaod Detection in Humans. *Proceedings of the 17th International JOint Conference on Biomedical Engineering Systems and Techologies - Volume 1, ISBN 978-989-758-688-0*, pp. 747-754.

Bütefür, J., Trampler, M., & Kirchner, E. (2024, Decemeber). Technical Test of a Dry Electrode Headset for EEG Measurement in Microgravity. In M. Guarino, *Biomedical Engineering Systems and Technologies. BIOSTEC 2024. Communications in Computer and Information Science.* Springer (to be published).

Chen, Y., Mori, S., Koga, K., Ohta, Y., Wada, Y., & Tanaka, M. (1999, June). Shift in arm-pointing movements during gravity changes produced by aircraft parabolic flight. *Biol Sci Space*.

Clark, T., Newman, M., Merfeld, D., & Young, L. (2014). Pilot control and stabilization of a rate-controlled vehicle in hyper-gravity. *IEEE Xplore*.

Debie, E., Rojas, R., Fidock, J., Barlow, M., Kasmarik, K., Anavatti, S., . . . Abbass, H. (2021). Multimodal Fusion for Objective Assessment of Cognitive Workload: A Review. *IEEE Transactions on Cybernetics, No. 51, Vol. 3*, pp. 1542 - 1555.

Frett, T., Petrat, G., van Loon, J. J., Hemmersbach, R., & Anken, R. (2016, June). Hypergravity Facilities in the ESA Ground-Based Facility Program – Current Research Activities and Future Tasks. *Spinger Nature*.

Habenicht, J., & Kirchner, E. A. (2024). Preliminary Results on the Evaluation of Different Feedback Methods for the Operation of a Muscle-Controlled Serious Game. *17th International Conference on Bio-inspired Systems and Signal Processing.* Rom.

Habenicht, J., Tabie, M., Will, N., & Kirchner, E. A. (2022). Survey on studies investigating the effect of simulated microgravity on the musculoskeletal system. *International Anstronautical Congress.* Paris.

Honkanen, T., Oksa, J., Mäntysaari, M., Kyröläinen, H., & Avela, J. (2017, February). Neck and Shoulder Muscle Activation Among Experienced and Inexperienced Pilots in +Gz Exposure. *Aerosp Med Hum Perform.*

Kirchner, E., Will, N., Simnofske, M., Benitez, L., Bongardt, B., Krell, M. M., . . . Kirchner, F. (2016). Recupera-Reha: Exoskeleton Technology with Integrated Biosignal Analysis for Sensorimotor Rehabilitation. . *Conference: 2. Transdisziplinäre Konferenz "Technische Unterstützungssysteme, die die*

Menschen wirklich wollen". Transdisziplinäre Konferenz "Technische Unterstützungssysteme, die die Menschen wirklich wollen". Hamburg.

Kourtidou-Papadeli, C., Frantzidis, C., Gilou, S., Plomariti, C., Nday, C., Karnaras, D., . . . Vernikos, J. (2021). Gravity Threshold and Dose Response Relationships: Health Benefits Using a Short Arm Human Centrifuge. *Front. Physiol. 12*, pp. 644661, doi: 10.3389/fphys.2021.644661.

Kunavar, T., Jamšek, M. B., Blohm, G., Nozaki, D., Papaxanthis, C., White, O., & Babič, J. (2021, October 21). Effects of Local Gravity Compensation on Motor Control During Altered Environmental Gravity. *Frontiers in Neural Circuits*.

Man, J., Graham, T., Squires-Donelly, G., & Laslett, A. L. (2022). The effects of microgravity on bone structure and function. *npf microgravity*.

Marušič, U., Meeusen, R., Pišot, R., & Kavcic, V. (2014). The brain in micro- and hypergravity: The effects of changing gravity on the brain electrocortical activity. *European Journal of Sport Science, 14:8*, pp. 813-822, doi: 10.1080/17461391.2014.908959.

Masatli, Z., Nordine, M., Maggioni, M., Mendt, S., Hilmer, B., Brauns, K., . . . Opatz, O. (2018). Gender-Specific Cardiovascular Reactions to +Gz Interval Training on a Short Arm Human Centrifuge. *Front. Physiol. 9*, pp. 1028, doi: 10.3389/fphys.2018.01028.

McMahon, T. W., & Newman, D. G. (2016). G-Induced Visual Symptoms in a Military Helicopter Pilot. *Military Medicine*.

Morris, C. H., & Leung, Y. K. (2006). Pilot mental workload: how well do pilots really perform? *Ergonomics 49 (15)*, pp. 1581-1596, doi: 10.1080/00140130600857987.

Pergher, V., Wittenvrongel, B., Tournoy, J., Schoenmakers, B., & van Hulle, M. (2018, doi: 10.1002/brb3.1136). N-back training and transfer effects revealed by behavioural responses and EEG. *Brain and behaviour 8 (11)*.

Rantalainen, T., Ruotsalainen, I., & Virmavirta, M. (2012, November). Effect of Weighted Vest Suit Worn During Daily Activities on Running Speed, Jumping Power, and Agility in Young Men.

Reid, M. B., & Lightfood, T. J. (2019, December). The Physiology of Auto Racing . *Med Sci Sports Exerc*.

Ross, H. (1991). Motor skills under varied gravitoinertial force in parabolic flight. *Acta Astronaut*.

Schneider, S., Brümmer, V., Carnahan, H., Dubrowski, A., Askew, C., & Strüder, H. (2008). What happens to the brain in weightlessness? A first approach by EEG tomography, Vol. 4, Issue 4. *NeuroImage*, pp. 1316-1323, doi: 10.1016/j.neuroimage.2008.06.010.

Schneider, S., Guardiera, S., Abel, T., Carnahan, H., & Strüder, H. (2009). Artificial gravity results in changes in frontal lobe activity measured by EEG tomography. *BrainResearch, Vol. 1285*, pp. 119-126, doi: 10.1016/j.brainres.2009.06.026.

Swanenburg, J., Langenfeld, A., Easthope, C. A., & Meier, M. L. (2020, September). Hypergravity Induced by Parabolic Flight Differently Affect Lumbar Spinal Stiffness. *Front Physiol.*

Wiedemann, M., Kohn, P., Roesner, H., & Hanke, R. (2011). Self-organization and pattern formation in neuronal systems under conditions of variable gravity life sciences under space conditions. *Beijing: Higher Education Press*.