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6 authors, including:


Rafael Baptista
Pontifícia Universidade Católica do Rio Grande do Sul


Thiago Boeira Susin
Pontifícia Universidade Católica do Rio Grande do Sul


Nicholas Corrêa
Pontifícia Universidade Católica do Rio Grande do Sul


Ricardo Bertoglio Cardoso
Universidade Federal do Rio Grande do Sul

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Muscle Activity during the Performance of CPR in Simulated Microgravity and Hypogravity

Rafael Reimann Baptista*, Thiago Susin, Mariana Dias, Nicholas Corrêa, Ricardo Cardoso, Thais Russomano

Microgravity Center – Pontifical Catholic University of Rio Grande do Sul, Porto Alegre, Brazil.
*Corresponding author: rafael.baptista@pucrs.br

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Abstract Cardiopulmonary resuscitation (CPR) is a series of resuscitation actions that improve the survival chances after a cardiac arrest, maintaining tissue perfusion through sternal compressions. The aim of this study was to clarify potential differences in upper body muscle activity related to CPR in microgravity and hypogravity (Mars gravitational field). Thirty healthy male volunteers each performed 3 sessions of 30 external chest compressions (ECCs) on a mannequin, during which time the muscle activity of the pectoralis major, triceps brachii and rectus abdominis were recorded via superficial electromyography. Hypogravity and microgravity were simulated by means of a body suspension device and a counterweight system, to which the volunteer was connected via a harness. The standard terrestrial (1G) CPR position was adopted in simulated hypogravity, and the Evetts–Russomano method was used in simulated microgravity. Heart rate and perceived exertion were also measured via Borg scale. No significant difference was found between the ECCs per minute and per set of compressions when performed at 1G and in simulated hypogravity. However, the mean depth achieved during compressions showed a significant difference in hipogravity. After 3 sets of 30 ECCs, mean heart rate showed an increase from rest values to those obtained from the 3 gravitational fields, and also from 1G to microgravity, but not from 1G to hypogravity. Mean of perceived exertion presented a significant increase from 1G to hypograviy and to microgravity. Muscle activation during the performance of CPR at 1G and hypogravity was significantly higher for the rectus abdominis. All muscles were more active during CPR in microgravity when compared with 1G. These findings suggest that the rescuer should be physically well trained in order to deliver adequate CPR in extraterrestrial environments. The physical training should aim to improve muscular endurance and cardiorespiratory capacity to increase effectiveness of the rescuer emergency assistance.

Keywords: *cardiopulmonary resuscitation, hypogravity, microgravity, body suspension, electromyography*

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1. Introduction

Cardiopulmonary resuscitation (CPR) is a series of resuscitation actions that improve the survival chances after a cardiac arrest, maintaining tissue perfusion through sternal compressions [1]. The potential rescuer must recognize that the victim is in need of assistance as quickly as possible. The CPR maneuver must be started as soon as it is realized that the victim is not responding or breathing. According to the International Liaison Committee on Resuscitation (ILCOR 2010), the rescuer should perform chest compressions on the victim with a minimum depth of 50 mm at a rate of 100 compressions per minute, allowing complete chest recoil, and a compression-to-ventilation ratio of 30:2 [2]. In the United States of America there are approximately 360,000 out-of-hospital cardiac arrests a year, accounting for 15% of all deaths [3].

NASA estimates an approximate 1% chance per year of a life threatening medical situation occurring during a space mission [4]. Despite this low figure, disturbances in cardiac rhythm have been seen among astronauts. The majority of these have been attributed to cardiovascular problems but it is unclear if they are due to a pre-existing condition or acquired during a space mission. Documented observational data exists that suggests alterations in the electrical activity of the heart in long duration space missions. The QT interval, a marker of ventricular repolarization, has shown to be prolonged in some astronauts [5]. Ventricular arrhythmias were reported during the second month aboard the MIR space station [6]. Another problem observed during exposure to microgravity (microG) was the loss of left ventricular mass [7]. These factors should be studied and observed closely as they can lead to cardiac arrest [8].

It can be supposed that there will be an increased probability for the need to perform CPR in space as space tourism increases, with the average age of space tourists being 57 years [9]. Astronauts receive prior training on dealing with emergencies, with the aim of avoiding a tragedy during missions. Thus, it is important that crew members know how to adequately perform the CPR maneuver accurately and effectively, taking into account the gravitational conditions.

The best approach to CPR may vary, depending on the rescuer, victim and available resources. The fundamental challenge of performing CPR early and effectively, however, remains. A study conducted during parabolic flights tested three CPR methods and a mechanical device on a manikin model. Two of these studied methods were the "*reverse bear hug*" in which the rescuer compresses the chest from a position behind the victim, and the "*handstand*" in which the rescuer places their feet on one surface of the craft and performs chest compressions on the victim who is positioned against the opposite surface of the craft, by means of contraction and extension of the lower limbs [10]. A study in 2004 involving a porcine model, known to have similar hemodynamics to humans, demonstrated that CPR in a microgravity environment was possible using the handstand technique, although with the disadvantage of needing the assistance of other people and being in a spacious setting [11]. Another plausible method of providing basic life support is through use of the Evetts-Russomano (ER) technique, also tested using a manikin during microG simulated by parabolic flights. This technique consists of positioning the rescuer left leg over the right shoulder of the victim, while the rescuer right leg wraps around the torso of the victim, below the left arm. Ideally the ankles of the rescuer will cross in the interscapular region in order to give greater stability, thereby reducing the effort required to keep the legs in position and also giving resistance for the application of chest compressions. With this method it is believed that one person alone could perform basic life support, irrespective of location and specialized equipment [12].

The greater lengths of time spent by humans in space, the increasing diversity of the people who will participate in this form of travel in the near future, and taking into account all the health risks this may bring, motivated this research, whose aim was to further clarify aspects related to CPR in microG and hypofravity (hypoG). To this end, heart rate, perceived exertion, depth and frequency of compressions, and the electrical activity of selected muscles were evaluated during performance of the CPR maneuver by male volunteers using the ER technique, in order to analyze possible differences between the cardiac massage in different gravity settings.

2. Methods

2.1. Volunteers

Thirty healthy male volunteers were selected with a mean age of 22 ± 3 years, mean body weight of 78.9 ± 10.6 kg and mean height of 178 ± 7.02 cm. Exclusion criteria were considered to be the presence of disease or physical limitations that would prevent the participation of the volunteer in the research. The study was approved by the Research Ethics Committee of PUCRS and all volunteers read and signed an informed consent.

2.2. Body Suspension Device

A body suspension system built by the Microgravity Center - PUCRS was used to simulate hypoG (Mars – 3.7 m/s^2) and microG (0 m/s^2) [13]. This device consisted of a pyramidal structure with a suspended harness, similar to that used in skydiving, and a system of steel bar counterweights (CW, kg). The system of counterweights and the harness were connected via a steel cable to a pulley system. For microG simulation, the volunteer was fully suspended in the air in order to perform the CPR using the ER method (Figure 1).

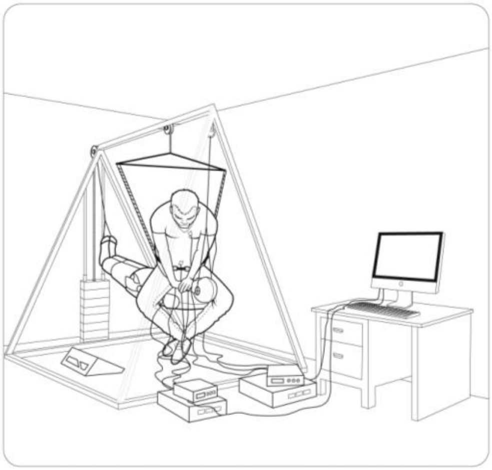

Figure 1. CPR during microgravity simulation (ER-Method) showing the body suspension device, the EMG system and the CPR manikin equipped with the system for measuring chest compressions.

In contrast, for hypoG, the counterweights were used in a way that it would simulate the decrease of Earth's gravitational force by acting vertically on the volunteer, whilst CPR was performed. In this situation, the volunteer assumed the same position as for the CPR at 1G (Figure 2).

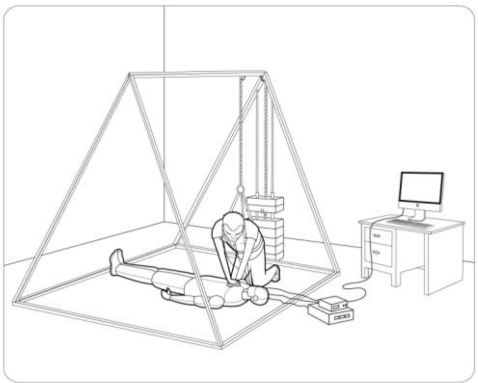

Figure 2. CPR during hypogravity simulation showing the body suspension device, the EMG system and the CPR manikin equipped with the system for measuring chest compressions.

The relative mass of the upper body mass was calculated using equation (1). Subsequently, equation (2) was applied to define the counterweight needed to simulate body mass at a pre-determined hypoG level (Figure 2).

$$RM = 0.6BM \times SGF \div 1G \qquad (1)$$

Where RM = relative mass (kg), BM = body mass on Earth (kg), SGF = simulated gravitational force (m/s^2) and 1G = 9.82 m/s^2.

$$CW = BM - RM \qquad (2)$$

Where CW = Counterweight (kg), BM = body mass on Earth (kg) and RM = relative mass (kg).

2.3. CPR Manikin and Measurement System for External Chest Compression Depth

A CPR manikin (Resusci Anne SkillReporter, Laerdal Medical Ltd, Orpington, UK) was equipped with a system for measuring chest compressions. This system provided volunteers with a guide so that massages could be more controlled and rhythmic, delivering the depth and frequency of external chest compressions (ECCs) in real time. The visual signals were given by means of green, yellow and red LEDs (light emitting diodes), indicating the depth of compressions according to criteria set by the American Heart Association (AHA) [2]. ECC data was collected and stored on a computer through a 4 channel *DataQ DI-145* analog/digital converter with a sampling frequency of 240 Hz, and *WinDaq* software that allowed the Volt conversion to the required unit. The CPR manikin was calibrated prior to data collection for each volunteer.

2.4. Cardiac Massage Protocol and Assessment of Exertion Intensity

On the first day, volunteers were prepared with electromyography (EMG) electrodes, performed the maximal voluntary contraction (MVC) protocol, were given brief instructions as to how to perform CPR and the ER maneuver, and subsequently carried out ECCs at Earth's gravity (1G) as a control [12]. On the second day, the volunteers were randomized in relation to the order in which the ECCs would be performed in the hypoG and microG simulated environments. Volunteers had a 20 minute interval between the two simulated environments in order to permit their complete physiological recovery.

Prior to each session, volunteers were rested for 5 minutes before having their heart rate measured (preHR) using a heart rate monitor (Polar S610) positioned on their chest in line with the xiphoid process. Heart rate was again measured using this method at the end of each session (postHR). The subjective perception of exertion was assessed at the end of the session through use of the 20 point Borg Scale (BS) [14].

During the entire period, volunteers were asked to observe a rate of 100 compressions per minute and a 50mm thoracic depression for each compression [2], aided by the previously described visual signals and verbally by one of the researchers who remained by their side over the course of the 3 sessions of 30 ECCs. The data was recorded for later analysis.

2.5. Electromyography

A *Miotool* surface electromyography device with four channels and a sampling frequency of 2000Hz per channel was used (Miotec Biomedical Equipment Ltd. Porto Alegre, Brazil) to measure muscle activation (mV). The electrode placement and skin preparation followed SENIAM standards (*Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles*). Four self-adhesive infant bipolar electrodes with Ag/AgCl gel (*Meditrace*) were used on each of the evaluated muscles. The placement sites were shaved and cleaned using an alcohol solution with 95% ethanol before each pair of electrodes was positioned on the skin, with one electrode extra being placed over the C7 cervical vertebra as a reference point. The surface differential sensors were held in position using adhesive tape to prevent their detachment due to sweating and the vigorous movements required in the simulated hypoG and microG.

Data referring to the middle three compressions from the second session of ECCs (compressions 14, 15 and 16) were taken from the full sample and selected for statistical analysis; it was considered that the first compressions could be affected by familiarization and the last compressions by fatigue. The root mean square (RMS) of these three compressions for each individual was calculated, resulting in the mean and standard deviation for the muscle activity of each of the muscles involved in the CPR evaluation.

A 100 mV gain in the four channels was used and two filters for the surface electromyography (sEMG) data collection: a 20-450 Hz band-pass online filter to limit the collected signals produced by the muscles [15] and subsequently, a 50-60 Hz Butterworth online filter to remove the influence of possible electric fields generated by interference from other electrical equipment. Miograph Miotec 2.0 software was used in conjunction with MATLAB 12 for the analysis of the electromyography signals.

The *Miotool* was calibrated at the beginning of each data collection day using its own *hardware* and *software* to eliminate ambient noise.

2.6. MVC Protocol

An MVC protocol was created to enable normalization of the EMG data, based on maximum contraction tests of the rectus abdominis, triceps brachii long head and pectoralis major muscles, performing movements prioritizing contraction of the primary motors; horizontal flexion of the shoulder for the pectoralis major, elbow extension for the triceps brachii and a hip and trunk flexion for the rectus abdominis. Volunteers were asked to carry out a muscle contraction evaluated against an external resistance. The maximum value achieved by the volunteer in the test was considered as the MVC and used to normalize the EMG data.

2.7. Statistical Analysis

The data was analyzed using the statistics program GraphPad InStat version 3.10, (GraphPad Software, San Diego California, USA). The Kolgomorov-Smirnov test was used to verify normality of the data. Descriptive statistics are given as mean ± standard deviation. Friedman Test (Nonparametric Repeated Measures ANOVA) with Dunn's multiple comparisons post hoc test was used for comparisons between all the study variables except for heart rate data which repeated measures ANOVA with Bonferroni ́s multiple comparisons post hoc test was used to compare gravity, hypogravity and microgravity situations, using a significance level of $p<0.05$ for all analyses.

3. Results

3.1. External Chest Compressions

In a comparison between 1G and hypoG environments, no significant difference was shown in the data related to compressions performed on the CPR manikin in terms of the number of compressions per minute and the number of compressions per set. However, the mean depth achieved during compressions showed statistical significance (p<0.05), reaching 48.09 ± 2.61 mm at 1G and 45.92 ± 2.84 mm in hypoG. In a comparison between 1G and microG environments mean figures, both the number of compressions per set and the depth of ECCs showed statistical significance, as can be seen in Table 1. The number of compressions per minute, on the other hand, showed no significant difference (*p>0.05*).

Table 1. Mean of variables related to physical exertion

Condition	preHR (bpm)	postHR (bpm)	Borg scale	Compression depth (mm)
1G	82.47 ± 10.79	107.43 ± 17.12	9.33 ± 2.29	48.09 ± 2.61
HypoG	83.61 ± 14.31	121.29 ± 27.03 *	12.42 ± 1.78 *	45.92 ± 2.84 *
MicroG	83.95 ± 11.61	160.86 ± 19.41 †	17.04 ± 2.53 ǂ	44.15 ± 4.56 ǂ

* 1G - HypoG (P<0.05), † 1G - MicroG (P<0.05), ǂ 1G – MicroG (P<0.001).

3.2. Heart Rate and Perceived Exertion

The preHR measurement was taken before the start of testing with all the volunteers being in a similar state at rest, with a mean of 82.47 ± 10.79 bpm at 1G, 83.61 ± 14.31 bpm in hypoG and 83.95 ± 11.61 bpm in microG. The postHR measurements after three sets of ECCs presented a pattern of increase, with significant (*p<0.001*) differences between 1G (107.43 ± 17.12 bpm) and microG (160.86 ± 19.41 bpm), and no significant differences when compared to hypoG (121.29 ± 27.03 bpm) as shown in Table 1.

Corroborating this data and following the same behavior, the perceived exertion evaluated by the Borg scale presented significant differences between the means at 1G (9.3 ± 2.29), hypoG (12.42 ± 1.7) and microG (17.04 ± 2.53). The difference between 1G and hypoG was considered less significant (*p<0.05*) then the difference between 1G and microG (*p<0.001*). Table 1.

3.3. Muscle Activation

The data showed no statistical difference in the comparison of muscle activation during execution of the CPR maneuver at 1G and hypoG for the triceps brachii and pectoralis major muscles, but it was significantly higher (p<0.01) at hypoG for the rectus abdominis as well as significantly higher at microG in all muscles when comparing with 1G (p<0.001) (Table 2).

Table 2. Mean of all normalized (mV) muscle activity.

Condition	Pectoralis major	Triceps brachii	Rectus abdominis
1G	0.06 ±0.04	0.04 ±0.03	0.07 ±0.18
hypoG	0.16 ±0.40	0.11 ±0.27	0.25 ±0.74*
microG	0.16 ±0.11†	0.09 ±0.07†	0.35 ±0.68†

* 1G - HypoG (P<0.01), † 1G – MicroG (P<0.001)

At 1G, a significant difference was seen in the muscle activation means between the pectoralis major (0.06 ± 0.04 mV) and the triceps brachii (0.04 ± 0.03 mV) (p<0.05), and between the pectoralis major and the rectus abdominis (0.07 ± 0.18 mV) (p<0.01), whereas the comparison between the means of the triceps brachii and rectus abdominis showed no significant difference. In hypoG, the means for muscle activation were also compared, only presenting statistically significant differences between the pectoralis major (0.16 ± 0.40 mV) and triceps brachii (0.11 ± 0.27 mV) (p<0.05). In microG, statistical difference was observed between the pectoralis major (0.16 ± 0.11 mV) and triceps brachii (0.09 ± 0.07 mV), and between the triceps and rectus abdominis (0.35 ± 0.68 mV).

4. Discussion

This study found similar results to researches by Dalmarco et al. [16] and Krygiel et al. [17], in which they observed that the frequency of ECCs was no different between the 1G and hypoG (Moon and Mars) male groups, whilst maintaining an adequate depth according to AHA 2005 recommendations [18], where the ideal depth for ECCs was considered to be between 40-50 mm. Following the same recommendations, the results of Waye et al. fitted the boundaries in microG. Although this present study observed values close to those of the previous researches, achieving a mean depth of 47.07 ± 2.08 mm in hypoG and 43.07 ± 5.08 mm in microG, these values remain slightly below those advocated by the AHA 2010 guidelines in which compression depth should be at least 50 mm. Even so, blood perfusion to the brain and heart remains, which although decreased, is important for the cardiac arrest victim.

A factor that should be taken into account, as this alteration in depth occurred between simulations, is the physical effort needed to maintain adequate CPR. Fatigue is reached after just a few minutes, not only in environments simulated by suspension, but also in parabolic flights [19]. Supporting this statement are the results obtained from the HR and BS data recorded after completion of the tests, which suggest that performing the compressions required a great effort, reaching means of 12.42 ± 1.7 in hypoG, and 17.04 ± 2.53 in microG on the Borg scale. Reinforcing this also, the data means for postHR in hypoG and microG were 121.28 ± 26.38 bpm and 160.62 ± 20.92 bpm, respectively, showing a high physical demand [20]. In addition to this, the lack of both physical and motor coordination training of the volunteers may have affected the results, although during astronaut training, the candidates undergo a number of tests on such matters, so the ER technique could be more effective when performed by better trained individuals [21].

These findings may be related to the difficulty in performing compressions, inasmuch as the volunteers were suspended and in a simulated gravitational environment involving a reduced body weight. Based on the principles of classical physics, where weight is equal to the product of the mass and gravitational acceleration (W=mg), it is evident that the lower this acceleration, the more difficult it will be to maintain the required depth as the individual can no longer count on the help provided by their own upper body weight [22]. As such, the volunteer ends up increasing muscle activation to compensate for this disadvantage in order to achieve the optimum depth (Table 2).

The results of this present study are compatible with those presented by Tsou et al. [23], in which during the CPR maneuver in a terrestrial environment they observed high muscle activation of the pectoralis major and rectus abdominis, the former being the one with the highest mean for muscle activity among the ten muscles analyzed. Triceps brachii presented the lower activation observed, corroborating with Krygiel et al. [17] results in hypoG and Waye et al. [24] in microG. Additionally, data obtained from researches by Krygiel et al. [17] and by Waye et al. [24] also showed a dependency on the contraction of upper limb and abdominal muscles to perform CPR in hypoG and microG, hence, agreeing with the results of normalized muscle activity of this present study, where the same muscle strategy to compensate for the simulated lack of gravity was noted. Therefore, identifying the primary muscles used for performing the CPR technique in hypoG and microG can ensure that these muscles can be sufficiently trained, in order that adequate CPR could be performed on a space mission.

5. Conclusion

This research provides important information with regard to training for the ER resuscitation maneuver. The rescuer should be physically well trained and familiar with the proposed technique. The physical training should aim to improve muscular endurance and cardiorespiratory capacity, as otherwise, the effectiveness of the assistance may be compromised. For this, both the upper limbs and the abdominal region must be worked, with the latter being of fundamental importance for the stabilization and production of the chest compression movement, together with the pectoral muscles. It was also observed during the study that volunteers used the strength of their lower limbs to counter-support the manikin and bring it towards the extended arms in order to achieve optimal compression. In addition to these factors, greater familiarity with the ER technique and a longer period of training would be beneficial for a more effective maneuver. With better adaptation to the technique, the rescuer could have improved control over their own positioning and movements, such that the effort required to perform the ER maneuver would tend to be less.

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Statement of Competing Interests

The authors have no competing interests.

List of Abbreviations

AHA - American Heart Association
BM - body mass on Earth
BS - Borg Scale
CPR - Cardiopulmonary resuscitation
CW - Counterweight
EMG - electromyography
ER - Evetts-Russomano
ECCs - external chest compressions
hypoG - hypofravity
LEDs - light emitting diodes
MicroG - microgravity
mV - muscle activation
MVC - maximal voluntary contraction
NASA - National Aeronautics and Space Administration
postHR - post session heart rate
preHR - pre session heart rate
RM - relative mass
RMS - root mean square
sEMG - surface electromyography
SENIAM - Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles
SGF - simulated gravitational force

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