Life Sciences in Space Research 1 (2014) 60–66

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

# The evaluation of upper body muscle activity during the performance of external chest compressions in simulated hypogravity

Rebecca G. Krygiel [a], Abigail B. Waye [a], Rafael Reimann Baptista [b], Gustavo Sandri Heidner [b], Lucas Rehnberg [a,b,*], Thais Russomano [a,b]

[a] Centre of Human and Aerospace Physiological Sciences, Kings College London, London, United Kingdom
[b] John Ernsting Aerospace Physiology Lab, Microgravity Centre, PUCRS, Porto Alegre, Brazil

ARTICLE INFO

*Article history:*
Received 6 September 2013
Revised 10 December 2013
Accepted 15 January 2014

*Keywords:*
Cardiopulmonary resuscitation
Electromyography
Hypogravity

ABSTRACT

BACKGROUND: This original study evaluated the electromyograph (EMG) activity of four upper body muscles: triceps brachii, erector spinae, upper rectus abdominis, and pectoralis major, while external chest compressions (ECCs) were performed in simulated Martian hypogravity using a Body Suspension Device, counterweight system, and standard full body cardiopulmonary resuscitation (CPR) mannequin. METHOD: 20 young, healthy male subjects were recruited. One hundred compressions divided into four sets, with roughly six seconds between each set to indicate 'ventilation', were performed within approximately a 1.5 minute protocol. Chest compression rate, depth and number were measured along with the subject's heart rate (HR) and rating of perceived exertion (RPE). RESULTS: All mean values were used in two-tailed t-tests using SPSS to compare +1 Gz values (control) versus simulated hypogravity values. The AHA (2005) compression standards were maintained in hypogravity. RPE and HR increased by 32% ($p < 0.001$) and 44% ($p = 0.002$), respectively, when ECCs were performed during Mars simulation, in comparison to +1 Gz. In hypogravity, the triceps brachii showed significantly less activity ($p < 0.001$) when compared with the other three muscles studied. The comparison of all the other muscles showed no difference at +1 Gz or in hypogravity. CONCLUSIONS: This study was among the first of its kind, however several limitations were faced which hopefully will not exist in future studies. Evaluation of a great number of muscles will allow space crews to focus on specific strengthening exercises within their current training regimes in case of a serious cardiac event in hypogravity.

## 1. Introduction

Space is a harsh environment and the physiological effects of microgravity are well documented, with all systems being affected to some extent (Aubert et al., 2005). However, with the future prospect of interplanetary missions as well as returning to the moon, there is a need within space physiology and medicine to address the challenges of a reduced gravitational field on astronauts, to ensure safety and optimise performance in these unique environments.

There have been several documented cases of cardiac dysfunction during space missions, such as supraventricular prematurities, nodal bigeminal rhythms and prolonged QT intervals (D'Aunno et al., 2003; Hawkins and Zieglschmid, 1975; Platts et al., 2009). Whether this is a case of a failure to detect these conditions during screening, or an effect of space itself is difficult to determine but, based on mission data and ground analogues, National Aeronautics and Space Administration (NASA) data suggest that space itself does not cause potentially life-threatening cardiac dysrhythmias. NASA estimates a 1% chance annually that a life-threatening medical condition will occur during a long mission (Johnston et al., 2000). Despite being low risk, this still poses a concern regarding long-duration missions. All astronauts are trained in cardiopulmonary resuscitation (CPR) prior to their missions but, in reduced-gravity environments, it is essential for crew to have the capabilities to perform CPR techniques effectively. It is important for astronauts to be prepared for cardiac emergencies, as they are self-reliant in such an isolated environment.

Terrestrial CPR relies upon upper body weight to provide the force required for chest compression, while in microgravity the upper body is weightless, thus muscular contraction is the primary force used (Evetts et al., 2005; Jay et al., 2003;

---

* Corresponding author at: 39 Brook Square, London, SE18 4NB, United Kingdom. Tel. (+44) 07738943687.
*E-mail address:* lukirehnberg@googlemail.com (L. Rehnberg).

http://dx.doi.org/10.1016/j.lssr.2014.01.004

Johnston et al., 2004). There are several methods that have been developed for CPR performance in microgravitational conditions and each of these vary in their technique, and therefore the muscle groups used. The Evetts–Russomano (ER) method, for example, has shown an increase in the flexion angle at the elbow, suggesting that extension of the triceps brachii and use of other upper limb musculature are used to generate force for chest compressions (Rehnberg et al., 2011). To further evaluate this, these authors carried out another study, the first in a series, focusing on the EMG analysis of musculature, including pectoralis major, during chest compressions in different simulated gravitational fields. The erector spinae and rectus abdominis were also analysed to see if flexion and extension of the trunk was altered between terrestrial and microgravity CPR (Waye et al., 2013). NASA currently uses the "reverse bear hug" and "hand-stand" methods (Jay et al., 2003; Johnston et al., 2004), though a recently developed technique has been evaluated in simulated microgravity, the ER method (Evetts et al., 2005; Rehnberg et al., 2011). The CPR methods developed specifically for microgravity may not be feasible during the surface elements of these missions, as gravity is present.

Varying degrees of hypogravity will be experienced during the planetary or lunar surface elements of future exploration missions. In addition, the standard terrestrial CPR method, which exploits the acceleration of the rescuer's weight as the compression force delivered to the sternum, may not be sufficient if the weight is reduced to an extent whereby the force achieved no longer produces adequate depth of chest compressions. There may be compensatory flexion and extension of the upper limb to help generate sufficient force in simulated hypogravity (Dalmarco et al., 2006), similar to that seen in microgravity, but not to the same degree (Rehnberg et al., 2011). The ability to achieve adequate depth is crucial to the effectiveness of external chest compressions (ECCs), since optimally performed terrestrial CPR provides, at best, only a third of normal cardiac output (Paradis et al., 1989) and even a modest deterioration in the performance of the provider may significantly reduce its effectiveness (Ashton et al., 2002). Given the importance of basic life support (BLS) in astronaut training, it is essential to accurately evaluate CPR techniques for potential use in a hypogravity environment.

Establishing the level of muscular activation in specific upper body muscles during chest compressions in simulated hypogravity may enable space crews to integrate specific countermeasures into their training regimes to prevent deconditioning of these muscle groups; this is paramount in case of an emergency situation and/or cardiac arrest in space.

The objectives of this study were:

1. To perform ECCs (depth, rate, and number) for 1.5 min at +1 Gz and at simulated 0.38 Gz.
2. To assess heart rate (HR) and rating of perceived exertion (RPE) to determine the exertion level when performing ECCs in hypogravity, compared with +1 Gz.
3. To quantify and compare the muscle activity of the triceps brachii, erector spinae, upper rectus abdominis, and pectoralis major at +1 Gz and in simulated hypogravity (0.38 Gz).

## 2. Materials and methods

### 2.1. Subject information

#### 2.1.1. Subject details

Twenty young healthy male subjects were recruited for this experiment (mean age 21.4 ± 3.7 years). Subjects' mean (±SD) height and weight were 179.9 ± 13.57 cm and 76.6 ± 6.0 kg, respectively. The experimental protocol was approved in advance by the Pontifical Catholic University of Rio Grande do Sul (PURCS) Research Ethics and Scientific Committees. Each subject provided written informed consent before participating.

#### 2.1.2. Selection criteria

Subjects were selected on the premise that they had no underlying medical problems and were not currently taking medication that could interfere with the performance of ECCs, such as treatment for cardiovascular, muscular, or bone disease. The subjects were recruited at the Physical Education, Engineering and Astronautics Faculties; they had varying fitness levels and were not trained in CPR.

### 2.2. Materials

#### 2.2.1. Body suspension device

This study used the Body Suspension Device (BSD) developed by our group (Rehnberg et al., 2011) to simulate the reduced gravitational field on Mars (Dalmarco et al., 2006; Kordi et al., 2012). The BSD consists of a harness and counterweights. The pyramidal structure of the BSD comprises steel bars of 6 cm × 3 cm in thickness. The BSD has a height of 200 cm and a rectangular base area of 300 cm × 226 cm. A steel cable connects the counterweights through a system of pulleys to the harness worn by the subject around the chest. The counterweight system comprises 20 bars with each bar weighing 5 kg.

Since the surface gravity of Mars has just over than a third of the surface gravity on Earth, it was necessary to calculate the subject's equivalent weight on Mars. The necessary counterweights were calculated using Eq. (1). The Simulated Upper Body Weight (SUBW) can be calculated by multiplying the Total Body Weight (TBW) by a percentile of 60.24% which represents the relative body weight above the waist (Hay, 1993), where SUBW = Simulated Upper Body Weight (kg); TBW = Total Body Weight on Earth (kg); MG = Mars Gravity acceleration = 3.71 m/s$^2$; EG = Earth Gravity = 9.81 m/s$^2$. Eq. (2) calculates the counterweight (CW, in kg) necessary to simulate body weight at a pre-set hypogravity level. An additional weight of 2 kg was added due to the weight of the harness.

$$SUBW = \frac{0.6024 TBW \times MG}{EG} \tag{1}$$

$$CW = 0.6024 TBW - SUBW + 2 \tag{2}$$

#### 2.2.2. Basic life support training mannequin

A full body BLS training mannequin (Resusci Anne Skill Reporter, Laerdal Medical Ltd, Orpington, UK) was used in this experiment. The mannequin was placed on the floor, perpendicular to the subject and counterweights. It was instrumented to measure depth and rate by the Microgravity Centre, PUCRS. To measure chest compression depth, the mannequin was modified with a linear displacement transducer. Its chest also contained a steel spring which retracted 1 mm with every 1 kg of weight added. An electronic guiding system (EGS) was developed to provide real-time feedback to the subject via coloured light-emitting diodes (LEDs), lit different colours according to compression depth, varying from 0–28 mm (red), 29–39 mm (yellow), 40–50 mm (green), and 51–60 mm (red). The real-time feedback allowed the subject to sustain AHA (2005) CPR standards throughout the protocol. The EGS was also featured with: 1) an electronic audio metronome configured to 'beep' 100 times per minute, guiding the subjects to maintain the AHA (2005) chest compression frequency of 100 compressions/min; 2) a visual number display descending from 30, to match the 30:2 standard compression: ventilation ratio, allowing the subject to count compressions and, again, stay within AHA (2005) standards.

#### 2.2.3. Electrode placement

Electrodes were placed on the right side of the subject's body according to the guidelines set by Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM), using anatomical landmarks in order to avoid the electrical interference of the heart. The Muscle Map Frontal from the ABC of EMG (Konrad, 2005) was used as a reference for the placement of the electrodes for the rectus abdominis and pectoralis major.

One neutral reference electrode was positioned on the cervical vertebrae 7 segment of the spinal cord. If necessary, tape was used to ensure the electrodes maintained skin contact. Protective sponge padding was used for the subject's comfort and, once prepared, the subject was secured in the harness.

#### 2.2.4. Perceived exertion and heart rate

Resting HR was measured both with an Onyx 9500 fingertip pulse oximeter (Nonin Medical Inc., Minnesota, USA) and manually by carotid palpation (60-second cycle), before chest compressions and then immediately afterwards. Both measurements were taken to ensure accuracy. The RPE was measured using a numerical scale, the Borg Score, ranging from 6–20, with verbal cues corresponding to each number (Borg, 1970). Subjects were asked their RPE after compressions were performed at +1 Gz and in simulated hypogravity.

### 2.3. Protocol

#### 2.3.1. External chest compressions at +1 Gz

In this study, the AHA Guidelines for CPR and Emergency Cardiovascular Care (AHA, 2005) were adopted, both at +1 Gz and in simulated hypogravity. Subjects knelt down, perpendicular to the BLS mannequin, in the appropriate position to commence chest compressions. The subjects firstly practised to ensure adequate ECC performance and familiarity with the protocol. The purpose was not to offer a full habituation protocol, but minor familiarisation. The subjects then performed four sets of 30 chest compressions with six seconds resting time in between sets, representing the two ventilations that would take place in reality but were not performed in this study. After the four sets of compressions were completed, HR was measured again and the subject's RPE was recorded. Subjects then rested for 15 minutes, or until their HR returned to its baseline value, in order to avoid fatigue before commencing ECCs in simulated hypogravity.

#### 2.3.2. External chest compressions in simulated hypogravity

To perform ECCs in simulated hypogravity, the subject was prepared as above. The appropriate counterweight for the subject was calculated from their weight. After being secured in the harness, the subject was partially suspended by attaching the harness to the steel wire, which was connected to the calculated counterweight. The subject knelt down perpendicular to the BLS mannequin and then performed the set CPR protocol. The subject's HR and RPE were then recorded.

### 2.4. Analysis

#### 2.4.1. Data acquisition system: external chest compressions

A DataQ® acquisition device was used in this experiment. It is featured with eight analogue and six digital channels, 10-bit resolution, a sample rate up to 14 400 samples/s and a USB interface. It supports a full scale range of ±10 V, with a measurement accuracy of ±19.5 μV.

#### 2.4.2. Data acquisition system: electromyograph device

Miograph Miotec (Miotec Biomedical Equipment, Ltd, Porto Alegre/RS, Brazil) was used for the electromyography software and equipment. Four stereo channels on the EMG device and thus four pairs of electrodes, separated by 30 mm from centre-to-centre, were used for the four muscles being evaluated. Channels 1, 2, 3, and 4, and electrode-pairs 1, 2, 3, and 4 measured the electrical activity of the triceps brachii, erector spinae (longissimus), upper rectus abdominis, and pectoralis major, respectively. Pediatric Kendall MediTrace$^{\text{TM}100}$ ECG Conductive Adhesive silver/silver chloride pre-gelled Solid Gel Electrodes (Tyco Healthcare, the Ludlow Company LP, Chicopee, MA, Canada) were used. A sampling frequency of 2000 Hz, band-pass filtering of 10–500 Hz, and a gain setting of 100 were used. An online Butter-Worth filter (50–60 Hz) was used to attenuate interference from electrical fields from AC-powered equipment in the laboratory.

#### 2.4.3. Electromyography analysis

The 14th, 15th, and 16th contractions of each set of compressions for each muscle were analysed, in order to avoid the initial compressions, when the subject is adjusting movement, and the final compressions, when fatigue may be influential. The raw data was filtered using a band-pass filter and the root mean square was found. The mean values of the muscle electrical activity (μV) in the 14th, 15th, and 16th contraction were averaged across sets of compressions for each subject and then for each muscle (i.e. the mean of the means were found). Next, mean average muscle electrical activity from all the sets from each subject (for each muscle) were averaged together. Data was non-normalised, a decision made mainly because this research concerned the relative contribution of each muscle compared to the other three, and analysis of a muscle's activity in two different environments, rather than the relative contribution of each muscle compared to itself in the same environment. This was justified by other EMG literature which also did not normalise data for similar reasons (O'Sullivan et al., 1997; Caterisano et al., 2002; Welsch et al., 2005).

#### 2.4.4. Statistical analysis

The level of muscle activation in each muscle at +1 Gz was compared with the level of muscle activation in each muscle in hypogravity (+1 Gz triceps brachii vs. hypogravity triceps brachii, etc.). Muscle activation between muscles at +1 Gz and muscle activation between muscles in hypogravity were also examined. All mean EMG, HR, and RPE data were entered into SPSS Statistics for Windows 17.0 (SPSS Inc., Release 17.0.0, Chicago, USA, 2008) and two-tailed T-tests run, assuming equal variance and a two-tailed outcome. A one-way ANOVA and Tukey's Honestly Significant Difference Test were carried out to determine differences in muscle activity between muscle groups within each condition. Statistical significance of $p < 0.01$ was set *a priori* to examine differences in mean values between +1 Gz and hypogravity protocols.

## 3. Results

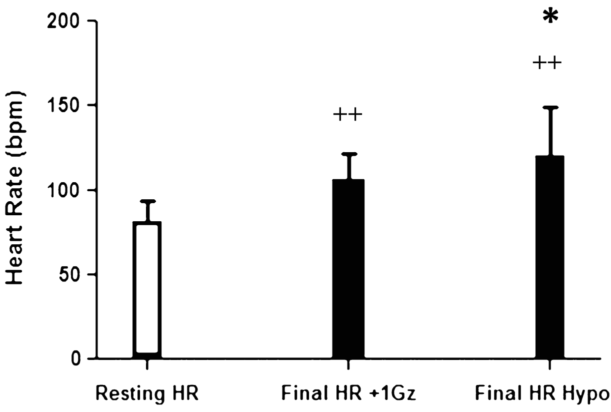
### 3.1. Chest compressions

Table 1 shows the results of ECC depth, rate, and number at +1 Gz (control) and 0.38 Gz (simulated hypogravity). The mean (±SD) compression depth, rate, and number across the four sets at +1 Gz were 47.8 (±0.5) mm, 103.3 (±0.97) compressions $\text{min}^{-1}$, and 30.5 (±0.57), respectively. The mean compression depth, rate, and number across the four sets in hypogravity were 45.7 (±0.5) mm, 103.7 (±1.8) compressions $\text{min}^{-1}$, and 31 (±0), respectively. Observations of SD show no marked variation between compression data between +1 Gz and hypogravity. There was no significant difference found in compression depth, rate, or number, when comparing +1 Gz and hypogravity.

**Table 1**
Summary of chest compression values obtained from the mannequin. Data are shown as mean (±SD).

| | Sets of 30 compressions | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| +1 Gz | | | | |
| Chest compression | | | | |
| Depth (mm) | 47 (±2) | 48 (±3) | 48 (±3) | 48 (±3) |
| Rate (compression $\text{min}^{-1}$) | 102 (±2) | 104.1 (±1.8) | 104 (±2) | 103.2 (±1.8) |
| Number (*n*) | 31 (±1) | 30 (±1) | 31 (±1) | 30 (±1) |
| HypoG | | | | |
| Chest compression | | | | |
| Depth (mm) | 45 (±3) | 46 (±3) | 46 (±3) | 46 (±3) |
| Rate (compression $\text{min}^{-1}$) | 101 (±4) | 104.9 (±4) | 105 (±3) | 104 (±2) |
| Number (*n*) | 31 (±1) | 31 (±1) | 31 (±1) | 31 (±1) |

No significant difference was found between +1 Gz control and hypogravity at $p < 0.01$, paired sample t-test.



* Significant increase in heart rate from +1Gz to hypogravity at p <0.01
++ Significant increase from resting heart rate at p <0.01

**Fig. 1.** A comparison of resting heart rate to final heart rate after the performance of external chest compressions at +1 Gz and hypogravity. Data is shown as means ±SD.

### 3.2. *Rating of perceived exertion*

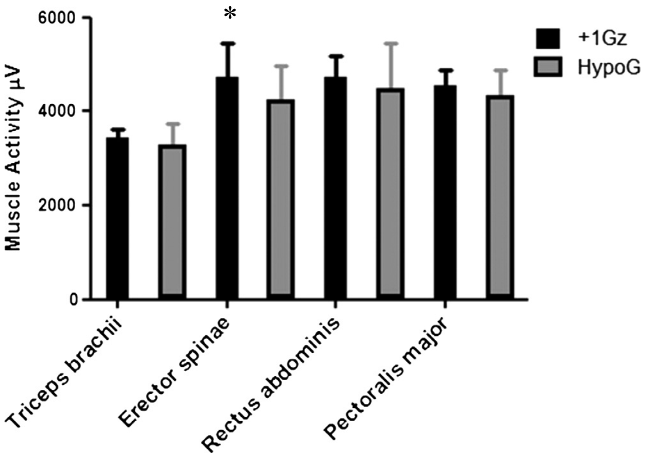
The mean RPE values at the end of 1.5 min of ECCs were significantly higher ($p < 0.001$) in simulated hypogravity when compared with +1 Gz. The RPE was 32% lower at +1 Gz (9.5 ± 2.4 'fairly light') compared with simulated hypogravity (12.5 ± 1.8 'somewhat hard').

### 3.3. *Heart rate*

Fig. 1 shows a comparison of mean HR before and after subjects performed ECCs in both gravitational conditions. HR was increased after compressions, from rest, in both +1 Gz and hypogravity, by 29% and 44.4%, respectively. HR following compressions was higher in hypogravity than at +1 Gz ($p = 0.002$).

### 3.4. *Comparison of muscle activity between +1 Gz and hypogravity*

Fig. 2 shows the mean muscle activity (µV) in each upper body muscle ($n = 20$) at +1 Gz and hypogravity. There was significantly higher mean muscle activity (−11.3%, $p < 0.05$) in the erector spinae in +1 Gz (4727.2 ± 708.1 µV) compared with hypogravity (4244.4 ± 718.4 µV). The triceps brachii, rectus abdominis, and pectoralis major showed no significant differences in mean muscle activation between +1 Gz and hypogravity.



*Significant difference p<0.01, in the Erector spinae from +1Gz to hypogravity

**Fig. 2.** A comparison of muscle activity in the triceps brachii, erector spinae, upper rectus abdominis, and pectoralis major at +1 Gz and hypogravity. Data is shown as means (±SD).

**Table 2**
Muscle activity between different muscles of the upper body at +1 Gz. Data are shown as mean (±SD).

| Comparison of muscle activity | Mean muscle activity, µV (±SD) | *p*-Value |
|---|---|---|
| Triceps brachii | 3425.8 (±205.2) | |
| Erector spinae | 4727.2 (±708.1) | 0.001* |
| Triceps brachii | 3425.8 (±205.2) | |
| Rectus abdominis | 4735.8 (±446.2) | 0.001* |
| Triceps brachii | 3425.8 (±205.2) | |
| Pectoralis major | 4551.4 (±329.6) | 0.001* |
| Erector spinae | 4727.2 (±708.1) | |
| Rectus abdominis | 4735.8 (±446.2) | 0.964 |
| Erector spine | 4727.2 (±708.1) | |
| Pectoralis major | 4551.4 (±329.6) | 0.099 |
| Rectus abdominis | 4735.8 (±446.2) | |
| Pectoralis major | 4551.4 (±329.6) | 0.229 |

* Significant difference $p < 0.01$, one-way ANOVA ($n = 20$).

### 3.5. *Comparison of muscle activity at +1 Gz and in hypogravity*

Tables 2 and 3 show the mean (±SD) values and statistical analysis of different muscle activities (µV) at +1 Gz and in hypogravity, respectively. The muscle activity of the triceps brachii at +1 Gz (3425.7 ± 205.2 µV) and in hypogravity (3287.4 ± 442.9 µV) was significantly lower when compared with all other muscles at +1 Gz ($p < 0.001$) and in hypogravity ($p < 0.001$). The compari-

**Table 3**
Muscle activity between different muscles of the upper body in simulated hypogravity. Data are shown as mean (±SD).

| Comparison of muscle activity | Mean muscle activity, μV (±SD) | *p*-Value |
|---|---|---|
| Triceps brachii | 3287.4 (±442.9) | |
| Erector spinae | 4244.4 (±718.4) | 0.001* |
| Triceps brachii | 3287.4 (±442.9) | |
| Rectus abdominis | 4493.2 (±953.9) | 0.001* |
| Triceps brachii | 3287.4 (±442.9) | |
| Pectoralis major | 4333.3 (±532.5) | 0.001* |
| Erector spinae | 4244.4 (±718.4) | |
| Rectus abdominis | 4493.2 (±953.9) | 0.413 |
| Erector spine | 4244.4 (±718.4) | |
| Pectoralis major | 4333.3 (±532.5) | 0.813 |
| Rectus abdominis | 4493.2 (±953.9) | |
| Pectoralis major | 4333.3 (±532.5) | 0.257 |

* Significant difference $p < 0.01$, one-way ANOVA ($n = 20$).

son of all the other muscles showed no difference at +1 Gz or in hypogravity.

## 4. Discussion

Other EMG studies have been done to evaluate muscle activity during terrestrial CPR (Trowbridge et al., 2009), but this is among the first in a series focusing on the EMG analysis of musculature during ECCs in different simulated gravitational fields (Waye et al., 2013). The depth, rate and number of chest compressions performed in this study suggest this BLS manoeuvre can be performed to AHA (2005) standards in simulated Martian gravity, with no significant differences seen between +1 Gz and hypogravity.

The RPE noted in hypogravity following ECCs was higher than the RPE reported in +1 Gz following ECCs. Since hypogravity environments result in a reduction of the weight of an individual, it may be more difficult to perform ECCs while in a kneeling position, due to the reduction of force production by acceleration of the upper body. This may contribute to the practitioner experiencing fatigue and exhaustion if effective chest compressions are performed for longer than 1.5 min, which may hinder a victim's chances of survival. In a study undertaken at +1 Gz, it was found that practitioners performing ECCs experienced fatigue, and that subsequent chest compressions became less satisfactory during a 3-minute protocol (Ashton et al., 2002).

These facts highlight a limitation of this study; future studies undertaken in simulated gravitational fields should be conducted for a longer duration, such as two minutes. This is the duration stated by the AHA 2010 guidelines that rescuers should perform CPR, before rotating with another rescuer. Extending the protocol would allow a more realistic comparison of EMG activity at the beginning of CPR and at the end, to identify any deterioration in performance (Trowbridge et al., 2009). Additionally, assessment of the correlation between compression force and EMG activity could be measured in future research.

There was an increase ($p = 0.002$) in heart rate after the performance of ECCs in simulated Martian hypogravity. In the present study, HR increased to a greater extent in subjects after chest compressions were performed, compared with the study by Dalmarco et al. (2006), where HR increased by only 23% after performing chest compressions in simulated Martian hypogravity. However, Dalmarco et al. (2006) used the 2000 AHA CPR guidelines and this reduced ratio, of 15:2, could account for this difference. The loss of weight, force, and acceleration, due to the conditions of hypogravity and the restriction of the body harness, required the subject to work harder in order to maintain AHA (2005) standards; this resulted in an increased HR in order to supply the working skeletal muscles with oxygenated blood. The increase in HR correlates with the increase in RPE upon performing chest compressions in a reduced gravity environment.

This increase in HR and RPE indicates an increase in the physiological cost of performing CPR in hypogravity compared to CPR in +1 Gz. However, when combining this with the fact that there was no significant increase in the muscle activity according to the EMG data, this suggests that there is a mismatch between the increased physiological cost of CPR in hypogravity and lack of significance in the EMG data.

This indicates that either muscles that do not significantly contribute to CPR in hypogravity were measured or a more objective measure of physiological work is needed to correlate with the increased HR. There is evidence to support that CPR in hypogravity has a higher physiological cost compared with CPR at +1 Gz, using the 2005 guidelines. The study showed that there was an increased $VO_2$ in hypogravity CPR compared with +1 Gz CPR (Russomano et al., 2013). This supports the present findings that hypogravity CPR is more tiring than +1 Gz CPR. However, this study failed to determine the source of force generation for chest compressions.

In relation to muscle activity, there was a higher muscle activity in the erector spinae in +1 Gz compared with hypogravity ($p < 0.01$), as seen in Fig. 2. This is most likely due to the support given by the body harness worn by the subjects, that unloads and reduces the need for erector spinae to contract in hypogravity simulation. However, in real hypogravity, such as experienced in a Martian environment, there might be a higher muscle activity in the erector spinae due to the lack of weight. In this experiment, as a body harness was used to simulate hypogravity, the reduction of the weight, force, and acceleration of a subject was a direct result from the use of a body harness.

One might expect that the upper rectus abdominis (URA) would have increased muscle activity in hypogravity compared with +1 Gz, as the loss in weight from hypogravity would increase the need for the subject to enhance upper body acceleration (in a "crunching" movement) to generate force; thus muscle activity of the URA would increase. However, there was no significant difference in muscle activity in the URA between +1 Gz and hypogravity. This may suggest that force is being generated by hip flexors, instead of an abdominal crunching movement though, as hip flexors were not evaluated in this study, we cannot ascertain this. To further evaluate the biomechanics of CPR in hypoG, EMG analysis of hip flexors, with additional video analysis, would allow the source of force generation to be elucidated. This, in turn, would influence which muscle groups would need to be trained to perform effective CPR in a Martian environment.

During terrestrial ECCs, the pectoralis major is constantly active due to the practitioner's upright position. Therefore, it was suggested that the pectoralis major would have higher muscle activity in hypogravity, compared with +1 Gz because the subject would need to increase upper body acceleration and, thus, muscle activity, to generate force. Again, however, no significant difference was found in muscle activity in the pectoralis major between +1 Gz and hypogravity.

It was suggested that at +1 Gz, the erector spinae and rectus abdominis would show the highest electrical activity, followed by the pectoralis major, and lastly the triceps brachii (i.e. erector spinae = rectus abdominis > pectoralis major > triceps brachii). However, the only significant differences in muscle activity were observed in the triceps brachii when compared to the other muscles, and in the rectus abdominis when compared to the pectoralis major. The triceps brachii had lower muscle activity than the erector spinae ($p < 0.01$), rectus abdominis ($p < 0.01$), and pectoralis major ($p < 0.01$). Trowbridge et al. (2009) noted that there was no change in EMG activity of the triceps brachii between conditions; however it is difficult to make a direct comparison with our hypogravity data as the biomechanics of CPR performance could have been different.

There was no significant difference in muscle activity between the erector spinae and rectus abdominis, or between the erector spinae and the pectoralis major. It should also be noted that the rectus abdominis and erector spinae had almost equivalent muscle activity at +1 Gz (4735.8 ± 329.6 and 4727.2 ± 708.1, respectively), suggesting that muscle co-contraction is generated to stabilise the lumbar spine.

EMG activity of the erector spinae has been shown to be dependent on posture. The mean value for the anterior lean was larger than for the posterior lean and was neutral (Zimmermann et al., 1993). In this experiment, subjects forcefully propelled forward each time a compression was performed. Thus, EMG activity was more profound due to anterior leaning. Erector spinae EMG activity was higher than the EMG activity of the triceps brachii. These data also suggest that the triceps brachii may have lower muscle activity than the erector spinae because the postural properties of the erector spinae function to support the torso and maintain the upper body in the upright position, particularly during the performance of ECCs, as the practitioner's upper body was quickly and continuously moving forwards and backwards in a stabilised manner.

The triceps brachii had lower muscle activity than the pectoralis major, most likely due to the triceps brachii dynamic action during compressions; the elbow has flexion-extension movements, in other words, concentric and eccentric contraction. Eccentric contraction is known to show lower EMG activity than concentric or isometric contraction (Grabiner and Owings, 2002; McHugh et al., 2002). Furthermore, the shoulder position, when compared to the elbow position during ECCs, is constantly elevated and undergoing isometric contractions, which increases EMG activity.

During hypogravity, the triceps brachii also had lower muscle activity compared with the erector spinae ($p < 0.01$), rectus abdominis ($p < 0.01$), and pectoralis major ($p < 0.01$), as seen in Table 3. This could most likely be attributed to the fact that the rectus abdominis and erector spinae are postural muscles and are, therefore, always active. This is particularly the case when the practitioner attempts to overcome the loss of mass and increase acceleration to force the upper body forwards and backwards, while maintaining an upright, stable position in conditions of reduced gravitational force.

There were no other significant differences in muscle activity between muscles. A similar pattern of muscle activity was observed in microgravity CPR, with the triceps brachii having lower activity compared with the other muscles, and no other significant difference identified in muscle activity (Waye et al., 2013). The results of the present study combined with data of microgravity CPR suggest that these four muscle groups do not significantly contribute to force generation in extraterrestrial CPR, despite the increased physiological cost of performing CPR. Future research investigating muscle activation in CPR should broaden to record a greater number of major muscle groups, most notably the abdominal and lower limb muscle groups, as studied by Trowbridge et al. (2009). By doing so, there would be a more complete picture as to which muscle groups are recruited in CPR performance in simulated hypogravity; this would facilitate more detailed comparisons.

This research suggests that space crews may consider focusing on abdominal and back strengthening exercises within their current training regimes, in the rare instance of a serious cardiac event occurring in hypogravity. However, further research is required to study muscle activation in a wider variety of major muscle groups; this will allow a better understanding of the biomechanics involved in CPR performance in hypogravity, and therefore optimise countermeasures. Despite this, the current study can be used as a reference for future research regarding EMG activity during chest compressions in different simulated hypogravity environments.

## Acknowledgements

We would like to thank King's College London, the Colt Foundation and the John Ernsting Aerospace Physiology Lab, Microgravity Centre, PUCRS, for their support in undertaking this study.

## References

American Heart Association (AHA), 2005. Guidelines for cardiopulmonary resuscitation and emergency cardiovascular care—IV. Circulation 112, 19–34.

Ashton, A., McCluskey, A., Gwinnutt, C.L., et al., 2002. Effect of rescuer fatigue on performance of continuous external chest compressions over 3 min. Resuscitation 55 (2), 151–155.

Aubert, A.E., Beckers, F., Verheyden, B., 2005. Cardiovascular function and basics of physiology in microgravity. Acta Cardiol. 60 (2), 129–151.

Borg, G., 1970. Perceived exertion as an indicator of somatic stress. Scand. J. Rehabil. Med. 2 (2), 92–98.

Caterisano, A., Moss, R.F., Pellinger, T.K., et al., 2002. The effect of back squat depth on the emg activity of 4 superficial hip and thigh muscles. J. Strength Cond. Res. 16 (3), 428–432.

Dalmarco, G., Calder, A., Falcão, F., et al., 2006. Evaluation of external cardiac massage performance during hypogravity simulation. Conf. Proc. IEEE Eng. Med. Biol. Soc. 1, 2904–2907.

D'Aunno, D.S., Dougherty, A.H., DeBlock, H.F., et al., 2003. Effect of short- and long-duration spaceflight on QTc intervals in healthy astronauts. Am. J. Cardiol. 91 (4), 494–497.

Evetts, S.N., Evetts, L.M., Russomano, T., et al., 2005. Basic life support in microgravity: evaluation of a novel method during parabolic flight. Aviat. Space Environ. Med. 76, 506–510.

Grabiner, M.D., Owings, T.M., 2002. EMG differences between concentric and eccentric maximum voluntary contractions are evident prior to movement onset. Exp. Brain Res. 145, 505–511.

Hawkins, W.R., Zieglschmid, J.F., 1975. Clinical aspects of crew health. In: Johnston, R.S., Dietlein, L.F., Berry, C.A. (Eds.), Biomedical Results of Apollo. Scientific and Technical Information Office, NASA, Washington, DC, pp. 71–73.

Hay, J., 1993. The Biomechanics of Sports Techniques, 4 ed. Prentice Hall, New Jersey, USA. 410 pp.

Jay, G.D., Lee, P.H.U., Goldsmith, H., et al., 2003. CPR effectiveness in microgravity: comparison of three positions and a mechanical device. Aviat. Space Environ. Med. 74, 1183–1189.

Johnston, S.L., Campbell, M.R., Billica, R.D., et al., 2004. Cardiopulmonary resuscitation in microgravity: efficacy in the swine during parabolic flight. Aviat. Space Environ. Med. 75 (6), 546–550.

Johnston, S.L., Marshburn, T.H., Lindgren, K., 2000. Predicted incidence of evacuation-level illness/injury during space station operation. Aviat. Space Environ. Med. 71, 333.

Konrad, P., 2005. The ABC of EMG: A Practical Introduction to Kinesiological Electromyography. Noraxon EMG & Sensor Systems, Boston.

Kordi, M., Kluge, N., Kloeckner, M., et al., 2012. Gender influence on the performance of chest compressions in simulated hypogravity and microgravity. Aviat. Space Environ. Med. 83 (7), 643–648.

McHugh, M.P., Tyler, T.F., Greenberg, S.C., et al., 2002. Differences in activation patterns between eccentric and concentric quadriceps contractions. J. Sports Sci. 20 (2), 83–91.

O'Sullivan, P., Twomey, L., Allison, G., et al., 1997. Altered patterns of abdominal muscle activation in patients with chronic low back pain. Aust. J. Physiother. 43 (2), 91–98.

Paradis, N.A., Martin, G.B., Goetting, M.G., et al., 1989. Simultaneous aortic, jugular bulb, and right atrial pressures during cardiopulmonary resuscitation in humans. Insight into mechanisms. Circulation 80, 361–368.

Platts, S.H., Martin, D.S., Stenger, M.B., et al., 2009. Cardiovascular adaptations to long-duration head-down bed rest. Aviat. Space Environ. Med. 80 (5 Suppl.), 29–36.

Rehnberg, L., Russomano, T., Falcão, F., et al., 2011. Evaluation of a novel basic life support method in simulated microgravity. Aviat. Space Environ. Med. 82, 104–110.

Russomano, T., Baers, J.H., Velho, R., et al., 2013. A comparison between the 2010 and 2005 basic life support guidelines during simulated hypogravity and microgravity. Extrem. Physiol. Med. 2 (11).

Trowbridge, C., Parekh, J.N., Ricard, M.D., et al., 2009. A randomized cross-over study of the quality of cardiopulmonary resuscitation among females performing 30:2 and hands-only cardiopulmonary resuscitation. BMC Nurs. 8, 6.

Waye, A.B., Krygiel, R.G., Susin, T.B., et al., 2013. Evaluation of upper body muscle activity during cardiopulmonary resuscitation performance in simulated microgravity. Adv. Space Res. 52, 971–978.

Welsch, E.A., Bird, M., Mayhew, J.L., 2005. Electromyography activity of the pectoralis major and anterior deltoid muscles during three upper body lifts. J. Strength Cond. Res. 19 (2), 449–452.

Zimmermann, C.L., Cook, T.M., Goel, V.K., 1993. Effects of seated posture on erector spinae EMG activity during whole body vibration. Ergonomics 36 (6), 667–675.