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ORIGINAL ARTICLE

# USING A STATE-OF-THE-ART HUMAN CENTRIFUGE TO SIMULATE ACCELERATION PROFILE OF ROCKET LAUNCH AND ATMOSPHERE RE-ENTRY: PROOF OF CONCEPT

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**Abstract:** Astronauts and Cosmonauts who so far were carefully selected and both highly skilled and trained will no longer be the sole space fliers. In the advent of space tourism, implementation of methods allowing for fast and cost-effective medical evaluation and preparation for space flight is inevitable. In this document, we describe a simulator training, utilizing a programmable military human centrifuge (HC), allowing for both medical evaluation and acquaintance of future space tourism. The procedures and evaluation have been implemented and flight-tested on a programmable HC. It includes elements of hypergravity training and simulations of real-life rocket start and capsule atmosphere re-entry profiles. This training was implemented on three subjects with positive results and without impacting their health, performance, and wellbeing. Such training may become disruptive innovation that reduce costs of preparing space tourists for the real space flight.

**Keywords:** ascent and re-entry into the atmosphere, flight simulator, human centrifuge, heart rate, physiological responses

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## INTRODUCTION

Historically human spaceflights were the sole domain of military test pilots [10,16]. Three years after Yuri Gagarin, in 1964 the first non-military cosmonaut Konstantin Feoktisov completed his flight. Soon he was followed by a handful of other astronauts around the world. Nowadays, most space travelers are not career military pilots [1,2,21,25]. Astronauts and cosmonauts who so far were carefully selected and both highly skilled and trained will no longer be the sole space fliers [8,10]. The next generation of space fliers will be tourists who have not pursued careers in medicine, engineering, and science [13,24]. Moreover, as we write this manuscript, European Space Agency announced astronaut selection for candidates who are psychologically, cognitively, technically and professionally qualified to be an astronaut, but have a physical disability that would normally prevent them from being selected due to the requirements imposed by the use of current space hardware [3]. This paradigm-shifting effort will transform spaceflight participation forever.

Career astronauts' basic astronaut training is two years long [8], and yet it is followed by 1.5 to 2 years of mission assignment training. Disruptive innovations are needed to accelerate the training of future space tourists, because they are not able to sacrifice several years of their life for preparation for several days long trip. In this document authors describe part of such training including both elements of hypergravity training and simulation of space flight that were programmed on a military human centrifuge. There are several factors inducing increased acceleration which needs to be taken under consideration. Those factors are: launch and ascent, violent in-flight and on-orbit maneuvers, reentry, and build-up forces due to the capsule's aerodynamic drag while slowing in Earth's atmosphere upon reentry [9]. Descent profiles can be either nominal (up to 4.5g [12]) or ballistic (up to 13g [12]). With pre-flight centrifuge training flight crew can increase its tolerance for higher g-loads up to 1.5 to 2g [9,22,29]. It should be noted that the increased tolerance for acceleration tends to diminish with time, hence the requirement of constant training. The flight profiles were based on standard gravitational training and real-life spaceship's launch and ascent, as well as atmosphere re-entry profiles. The acceleration profiles have similar features, but they are not public. Here, we utilized the acceleration profile of Soyuz FG rocket launch and the Soyuz MG capsule atmosphere re-entry profile obtained from cosmonauts participating in these flights (both rockets are not in use since 2019). Nonetheless, any flight profile could be programed on our HC. Heart rate and force exerted on a pedal by the trainees were monitored.

## MATERIALS AND METHODS

### Participants

The profiles were first validated by a 50-years old, Caucasian pilot instructor who served as a fighter pilot for years. The two candidates: a 31 years old Caucasian male and a 24 years old Asian woman without previous experience of accelerations participated in the training. All subjects had been certified with JAR class-1 flight medicals prior to the runs and once again medically cleared on the date of the event. All participants gave written informed consent to all procedures prior to the study. The Institutional Review Board of the Military Institute of Aviation Medicine, Warsaw, Poland (decision no 01/2017) approved all procedures; they have been performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

### Equipment

A human centrifuge HTC 07 (AMST, Braunau, Austria; was programmed to produce an equivalent series of accelerations Gx, Gy, and Gz aimed to mimic the re-entry profile. The human centrifuge (HC) is a flight simulator giving opportunities for using it in operational, training and diagnostic profiles. It permits intensive pilot training providing enhanced performance of anti-G maneuvers and familiarization of aircrews with the effects of high accelerations and push-pull phenomena. Moreover, the HC provides a safe alternative to raise awareness of aircrews in case of occurrences of unwanted effects of accelerations, such as G-LOC or spatial disorientation. The gondola of the centrifuge is assembled on an 8-meter-long arm and allows Z-axis accelerations in the range from –3Gz to +16Gz with the maximal onset of accelerations over 14,5 G/s. Additionally, gyroscopic suspension of the gondola allows for achieving X-axis and Y-axis accelerations respectively in the range of the value ± 10G and ± 6G. Interchangeable parts of the centrifuge gondola facilitate functional projection cockpit equipment of the Polish Air Forces multi-purpose aircraft i.e. F-16 Block 52+ and MiG-29. In addition to simulate hypergravity [5,6,18,28], it was used to simulate parabolic flight [17]. The centrifuge is equipped with multiple devices to

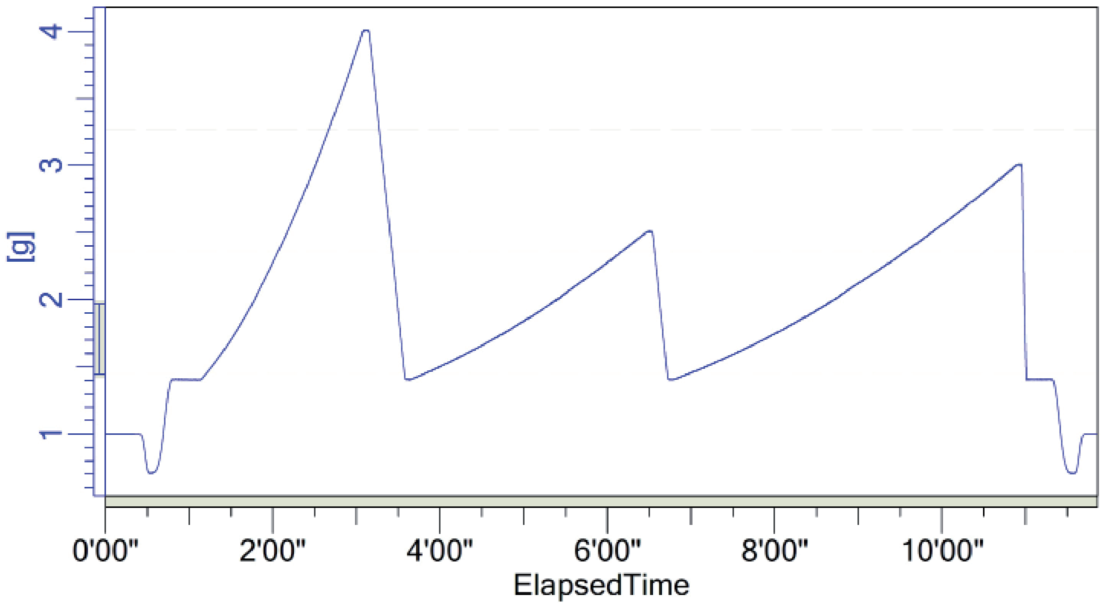


Fig. 1. Soyuz FG rocket launch profile (stage 1 and 2) and Soyuz MS orbital insertion profile [7]. The drops in G correspond to the separations of the rocket stages.

monitor the physiological effects elicited by the accelerations on the pilot [19]. The HC has implemented an optimized baseline profile to minimize incidence of motion sickness [20].

## Soyuz Launch Profile

The ascent acceleration profile curve (Fig 1.) is analogous to Soyuz FG rocket launch profile (stage 1 and stage 2) and Soyuz MS orbital insertion profile [7,23]. Just after start, the rocket velocity increases proportionally inducing higher g-loads up to 117th second, where it peaks at 4g. Then at booster separation acceleration decreases to 1g. This is followed by monotonic linear increases to 2.5g in the 285th second. Once again, the second stage separation decreases acceleration to 1g, and it's followed by ignition of the third stage engine. Last stage increases spacecraft velocity to achieve orbital insertion in the 525th second. At this precise moment spacecraft computer commands Main Engine Cut-off (MECO) and leaves astronauts and cosmonauts in microgravity [4,12,26].

## Re-entry profile

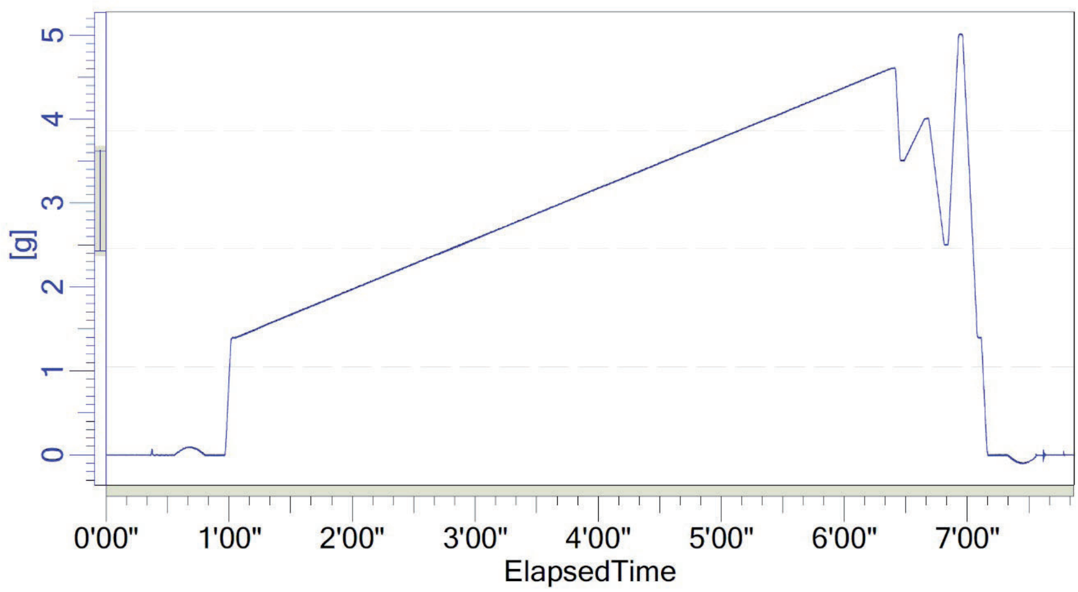


Fig. 2. Reentry profile during descent of Soyuz MS-09 mission. At the 7th minute, the "soft landing" takes place. It is accompanied by increase of acceleration to 5G about one meter above the Earth surface (additional jet engines started) (courtesy gen Mirosław Hermaszewski, [14]).

The Gx components are created by aligning the gondola of the HC as presented in Fig 3. Fig 4 presents profiles of all G components. Please note that the Gz is equal to roughly 1.4 g due to rotational motion of the centrifuge in Earth's gravitation environment.

## Physiological responses

Fig. 5 and Fig 6. depict changes in heart rate and the force exerted by the pilot's leg on the pedals during the descent. Please note no significant changes in heart rate and the force, as compared to hypergravity warm-up training.

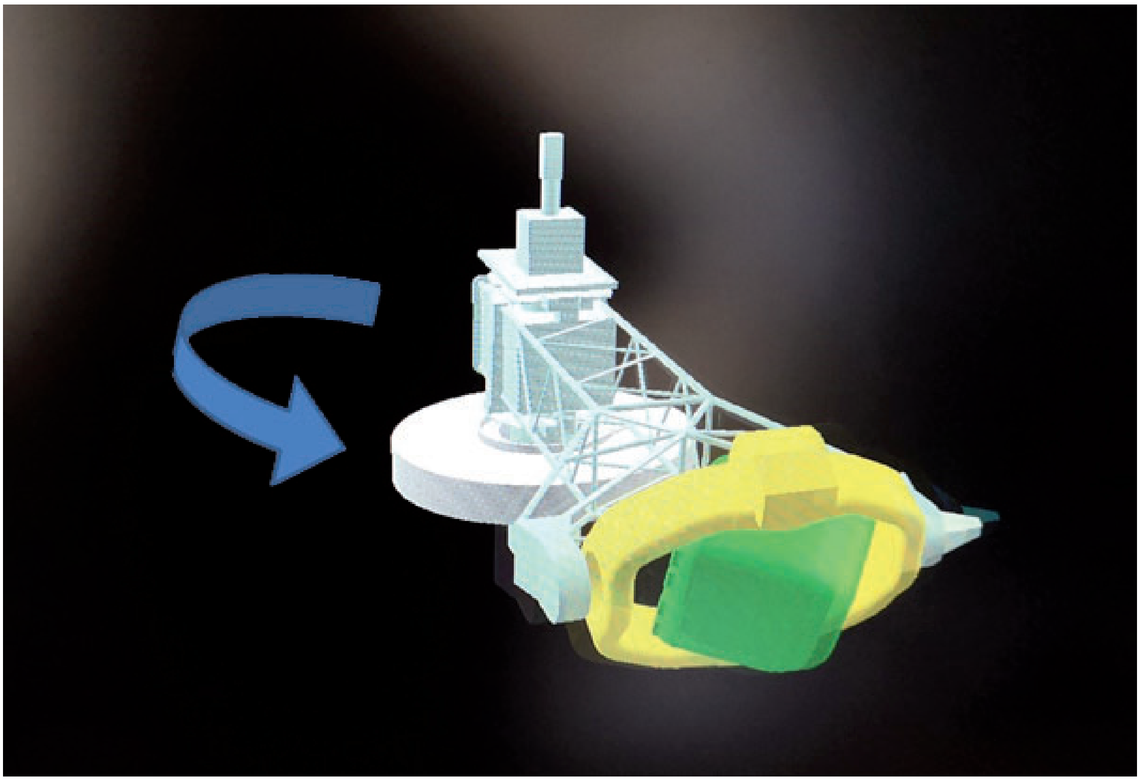

Fig. 3. Alignment of the gondola (green) on the arm (yellow) of human centrifuge to produce supine acceleration (Gx). The blue arrow depicts the rotation.

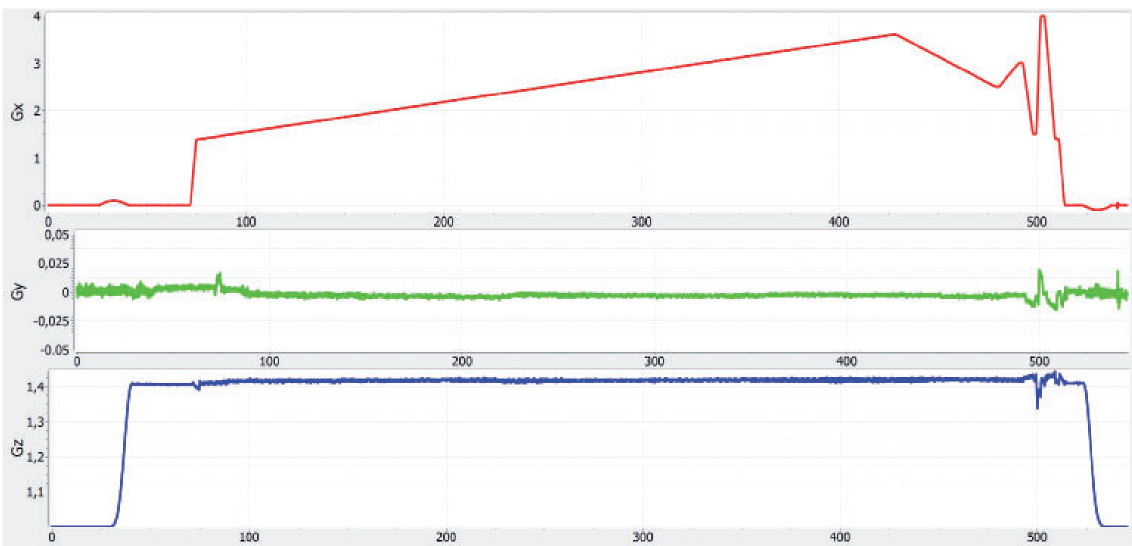


Fig. 4. The re-entry profile. Gx, Gy, and Gz are multiples of Earth's gravity. Gz≈1.4 is the baseline acceleration of rotation a human centrifuge.

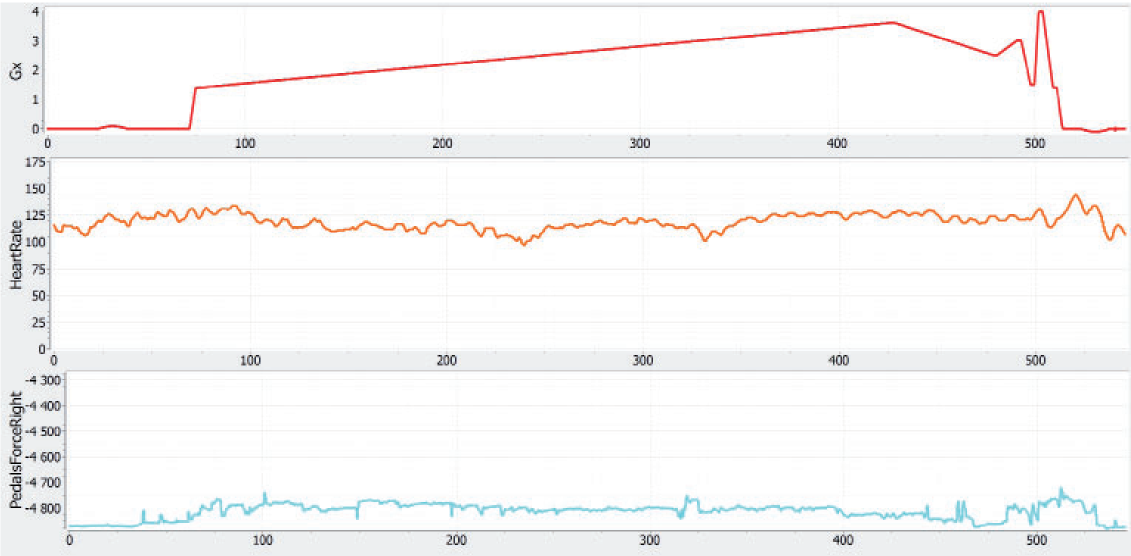


Fig. 5. Heart rate change and force exerted by the male participant during descent. Please note that Gx was limited to 4G during this run for safety reasons. No abnormal reactions observed.

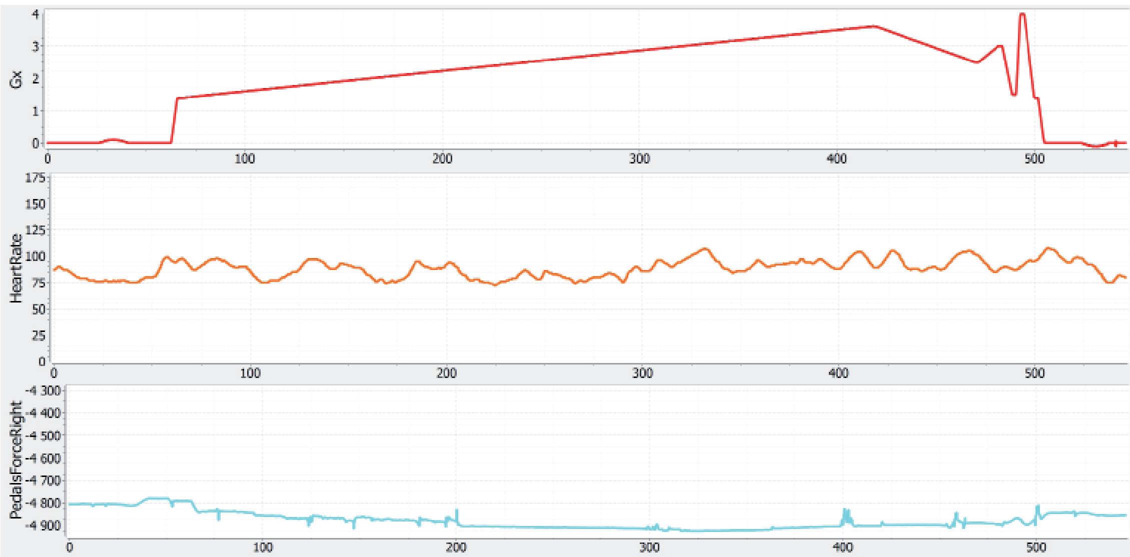


Fig. 6. Heart rate change and force exerted by the female participant during descent. Please note that Gx was limited to 4G during this run for safety reasons. No abnormal reactions observed.

For comparison, Fig. 7 and Fig. 8 show typical changes in heart rate and force exerted on pedals during acceleration.

## DISCUSSION

Exemplary ascent and re-entry profiles were programed on a military grade human centrifuge and training was successfully performed on three subjects. It allowed the trainees to get acquainted with the acceleration characteristics. The profile did not induce significant cardiovascular responses associates with hypergravity [13,18,19].

Business enterprises that see an opportunity in space tourism will need to develop short and condensed training programs to adapt and pre-train non-professional space travelers. This is not only due to the extreme cost of training for career-astronaut, but also the time required to complete both basic and mission assignment trainings [13]. Typically, those processes take around two years followed by specialized 1.5-2 years flight assignment training [8,10]. However, the physiological effects on the human body will not change depending on what role one will play in a crew. Therefore, it is safe to assume that the same procedures and training,

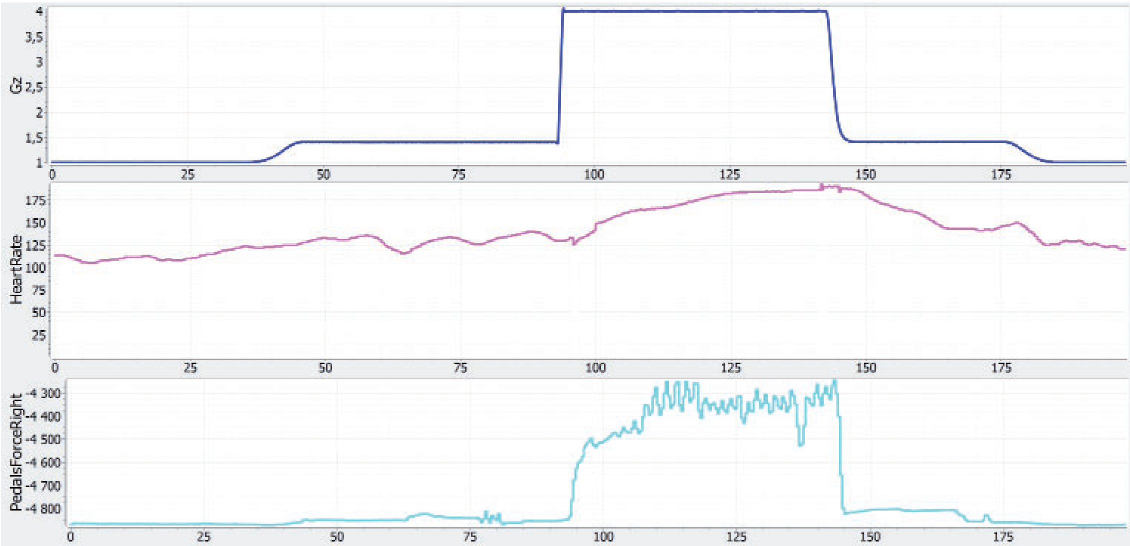


Fig. 7. Heart rate change and increase in the force exerted on pedals during acceleration to 4G in the 31 years old male.

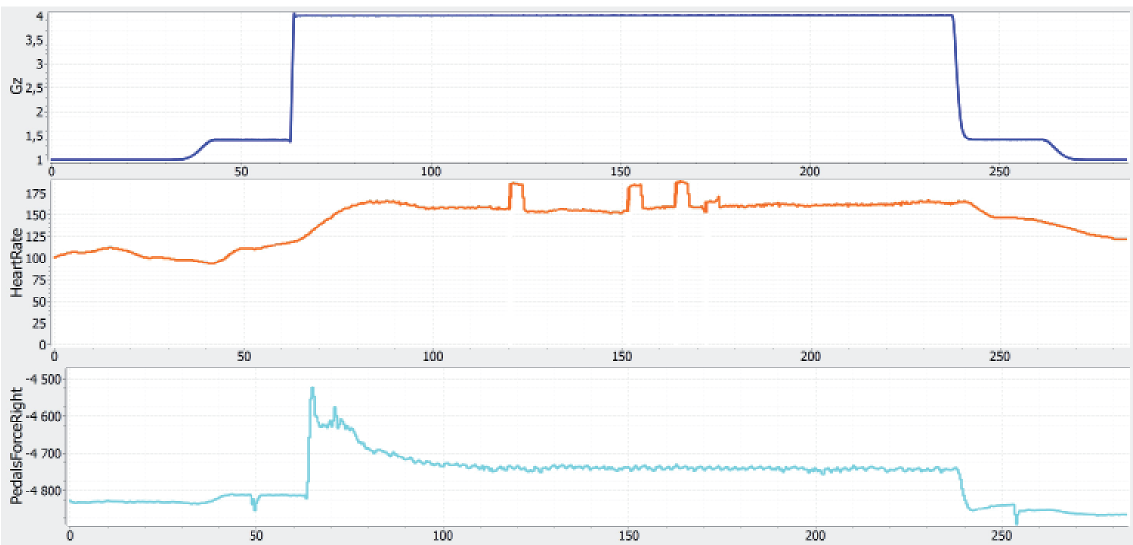


Fig. 8. Heart rate change and increase in the force exerted on pedals during acceleration to 4G in the second candidate. Please note the differences in muscle strain in response to sudden onset of Gz. There are some artifacts (sudden, short jumps) present on HR graph.

at least in that regime, should be, in our opinion, applied to both professional and commercial personnel. The simulator could be also used to train some emergency procedures during takeoff and landing.

The feasibility study has indicated, that despite the earlier precautions about the atrial fibrillation, there were no immediate danger or any indication of irregular heart rhythm [11,27]. Due to the fact, that two subjects of different ethnicity, gender, and age they are not a representative group for the population. Therefore such study should be considered only as a proof of concept or a preliminary study [14,15]. Larger studies involving more candidates without piloting experience are warranted to evaluate their physiological reactions to accelerations encountered during launch and ascent, as well as during reentry into the atmosphere.

## CONCLUSION

The expected result has indicated that the nominal ascent and re-entry profiles of Soyuz MS were not indicating immediate danger to the untrained subjects. In the follow-up, researchers plan to increase acceleration in the +Gx axis and recreate ballistic reentry profiles to test behavioral and cognitive response in time-critical contingency procedures. Such trainings using simulated conditions of space flight may be disruptive innovations reducing costs of preparing space tourists for the real space flight.

## AUTHORS' DECLARATION:

**Study Design:** Mateusz M. Harasymczuk, Agata M. Kołodziejczyk, Arkadiusz Trzos, Robert Kilian, Tadeusz Grzeszuk, Krzysztof Kowalczuk. **Data Collection:** Mateusz M. Harasymczuk, Robert Kilian, Tadeusz Grzeszuk, Marek Gąsik, and Krzysztof Kowalczuk. **Manuscript Preparation:** Mateusz M. Harasymczuk, Stefan P. Gaździński, Agata M. Kołodziejczyk, Arkadiusz Trzos, and Krzysztof Kowalczuk. The Authors declare that there is no conflict of interest.

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