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Physiological Effects during Aerobatic Flights on Science Astronaut Candidates

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***Abstract*—**Spaceflight is considered the last frontier in terms of science, technology, and engineering. But it is also the next frontier in terms of human physiology and performance. After more than 200,000 years humans have evolved under earth's gravity and atmospheric conditions, spaceflight poses environmental stresses for which human physiology is not adapted. Hypoxia, accelerations, and radiation are among such stressors, our research involves suborbital flights aiming to develop effective countermeasures in order to assure sustainable human space presence. The physiologic baseline of spaceflight participants is subject to great variability driven by age, gender, fitness, and metabolic reserve. The objective of the present study is to characterize different physiologic variables in a population of STEM practitioners during an aerobatic flight. Cardiovascular and pulmonary responses were determined in Science Astronaut Candidates (SACs) during unusual attitude aerobatic flight indoctrination. Physiologic data recordings from 20 subjects participating in high-G flight training were analyzed. These recordings were registered by wearable sensor-vest that monitored electrocardiographic tracings (ECGs), signs of dysrhythmias or other electric disturbances during all the flight. The same cardiovascular parameters were also collected approximately 10 min pre-flight, during each high-G/unusual attitude maneuver and 10 min after the flights. The ratio (pre-flight/in-flight/post-flight) of the cardiovascular responses was calculated for comparison of inter-individual differences. The resulting tracings depicting the cardiovascular responses of the subjects were compared against the G-loads (Gs) during the aerobatic flights to analyze cardiovascular variability aspects and fluid/pressure shifts due to the high Gs. In-flight ECG revealed cardiac variability patterns associated with rapid Gs onset in terms of reduced heart rate (HR) and some scattered dysrhythmic patterns (15% premature ventricular contractions-type) that were considered as triggered physiological responses to high-G/unusual attitude training and some were considered as instrument artifact. Variation events were observed in subjects during the +Gz and –Gz maneuvers and these may be due to preload and afterload, sudden shift. Our data reveal that aerobatic flight influenced the breathing rate of the subject, due in part by the various levels of energy expenditure due to the increased use of muscle work during these aerobatic maneuvers. Noteworthy was the high heterogeneity in the different physiological responses among a relatively small group of SACs exposed to similar aerobatic flights with similar Gs exposures. The cardiovascular responses clearly demonstrated that SACs were subjected to significant flight stress. Routine ECG monitoring during high-G/unusual attitude flight training is recommended to capture pathology underlying dangerous dysrhythmias in suborbital flight safety. More research is currently being conducted to further facilitate the development of robust medical screening, medical risk assessment approaches, and suborbital flight training in the context of the evolving commercial human suborbital spaceflight industry. A more mature and integrative medical assessment method is required to understand the physiology state and response variability among highly diverse populations of prospective suborbital flight participants.

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I. Introduction

EMERGING spaceflight ventures conducted by novel suborbital platforms such as Blue Origin and Virgin Galactic, are calling for new research to be conducted in suborbital space. These research platforms are both unmanned and manned, but they are being tested for manned spaceflight, and by 2021 we will likely to witness the first commercial astronauts in suborbital space. Advancement in aeromedical knowledge of the human body affected by different acceleration forces (microgravity and hypergravity) and hypoxic environments have been studied on subjects extensively for decades. These subjects are screened out and trained to sustain such stressors, such as military personnel and astronauts who follow strict guidance by either the US Air Force or NASA. But a largely uninvestigated group of subjects is represented by civilian people with no background or exposure to these environments. Previous studies [12] have revealed that young subjects with controlled medical conditions have tolerated centrifugation to $+6G_Z$ (front-to-back). This paper will analyze some physiological effects [22] under aerobatic flights environment on a civilian population. These civilians can be scientists, engineers, technologists, and educators that once day could travel to suborbital space to conduct short missions. This group of individuals may be one day referred to as commercial suborbital astronauts, payload specialists, and spaceflight participants [12].

Increasing interest has been encouraged by commercial spaceflight operations in order to enhance our knowledge in astronautics research, in-situ atmospheric science, and astronomical and astrophysics observations. Suborbital test flights are currently being conducted by Blue Origin's New Shepard and Virgin Galactic's SpaceShipTwo (SS2) vehicles. By the end of 2021, Blue Origin is planning to launch the first commercial suborbital astronauts aboard the New Shepard from West Texas Launch Site. Although flight stressors [3], such as G-forces, are well-known (about 3.5 G during ascent and 4.7 G during descent), vehicle mishaps could occur and commercial astronauts could be exposed to very high G-forces as a consequence of the Crew Capsule detaching from the main booster by a 70,000 lbs. thruster as part of the escape system. This escape system may be triggered at high-altitudes (approximately 20,000 feet or 6.1 km) reaching speeds from 475 mph (764.44 km/h), commercial astronauts will undergo Crew Capsule wobbling and rotations that would make commercial astronauts to experience high G-forces in all directions for about 15 to 20 seconds before the parachute recovery system is activated.

FAA recommends SFPs to demonstrate the ability to withstand the stresses of space flight using research platforms such as high-performance aerobatic aircraft to practice their safety-critical operations. In the future, SFPs are expected to be trained on various aspects on aerospace physiology, such as physiology stress factors due to environmental, operational and self-imposed, aerospace environment, aerospace operations, aerospace medicine and aerospace human factors issues. This training will help the crew recognize their symptoms during the various phases of flight and respond accordingly in case their ability to complete safety-critical operations is hindered by certain individual conditions [9].

FAA reference states that high rates or extended periods of acceleration in the Gz-axis can significantly increase the risk of short-term incapacitation [15] due to cerebral hypoxia, which can affect the decision-making during reentry. SSFS simulations suggested rapid oscillations (phugoid oscillations) during reentry and descent when reaching high Mach number before the gliding phase. For the aerobatic flights, candidates wore an anti-G equipment while conducting anti-G straining maneuver (AGSM) breathing techniques in the aircraft to mitigate G-induced blackouts. Participants were instructed basic AGSM and the hook maneuver before each aerobatic flight. SACs were advised to strain during a +Gz maneuver and only use the hook maneuver in case of grayout or light-headedness. Although many participants experience light-headedness, no SACs experienced blackouts. Participants were also instructed not to perform sudden head movements during +Gz exposure since various fluid movements in the semicircular canals (known as the Coriolis effect) may induce symptoms that will affect cognitive performance during flight [7].

General medical guidelines [2] have been provided by the Aerospace Medical Association (AsMA) Task Force to individuals who may embark on short duration flights (minutes to hours). The long list of guidelines addresses several elements that could compromise safety inflight and therefore would disqualify them from these spaceflight activities. Some of these refer to the cardiovascular system, neurological, ophthalmological, ear/nose/throat, orthopedic, genitourinary, dermatology, psychiatry, oncology, gastrointestinal, pulmonary, and others such as diabetes, cancer or dental issues. The Federal Aviation Administration (FAA) also provides general guidance [8] for operators of manned commercial flights both suborbital and orbital. Prospective passengers participating in foreseeable suborbital flights with Gs up to $+3G_Z$ during any phase of the flight should provide their medical history questionnaire prior to each suborbital flight, and in case the Gs profile exceeds +3Gz, passengers should be evaluated based on the recommendations extracted from the orbital flights. A gradual onset of 0.1 G/second rate is suggested since values greater than this threshold could result in the inability of the cardiovascular system to respond to preserve a certain blood flow to critical systems, such as neurological and cardiovascular.

A recent study conducted by the Center of Excellence for Commercial Space Transportation [6] revealed four main points in regards with the medical acceptance of a spaceflight participant for a suborbital flight: 1) the flight profile should not exceed +6Gx, ±1Gy, and +4Gz. In case the acceleration exceeds the +4Gz value, the space flight participant (SPF) would need to be medically-screened to the guidelines provided for orbital passengers; 2) SFPs will participate in one flight per day, but payload scientists can fly multiple times per day; 3) time in the space vehicle (10 to 15 minutes depending on research platform), and 4) radiation dose cannot exceed 1 mSv/year. However, suborbital pilots are expected to have an annual radiation dose of about 7-15 mSv and a maximum annual limit of 50 mSv [24].

Previous publication from AsMA [23] suggests that commercial entities will carry passengers on suborbital spaceflights with maximum accelerations of 2.0G to 4.5G but these are space vehicle dependent. Positive G_Z forces are expected to cause damage to the bone and soft tissue, especially the spinal column. Consideration should be given to those individuals who have had recent surgery in the abdomen or had some sort of osteoporosis, cervical or lower spinal cord disease or any fractures. Additional consideration should be devoted to those who have mechanical valves or with prior history of dysrhythmias.

Medical and training guidelines [12] for manned suborbital flights are required, yet there is limited information about this topic [24] with a few discussions taken place at various conferences. The International Association for Advancement of Space Safety (IAASS) strongly believes in the need of setting proper medical and training guidelines based on the recommendations gathered from the safety and medical operators.

SFPs on the SpaceShipTwo (SS2) would also experience [14] very high Gs on their bodies during ascent (about 3.5 G_X and 3.5 G_Z) and descent (about $6G_X$ and 1.5 G_Z). Both pilots and passenger aboard the SS2 will feel different G loads ($+G_Z$ forces or head-to-toe on pilots and $+G_X$ forces on passengers). These high G-forces have been also been simulated while flying Embry-Riddle Aeronautical University (ERAU) static Suborbital Space Flight Simulator with the SS2, and are consistent with the G-forces (axial Gs of about -2 G_Z to +3 G_Z, and up to +6 G_X) stated in the literature review [16]. Rapid transitions from 0 G_Z or +1 G_Z to various + G_Z levels are thought to produce a push-pull effect (PPE) which is still to be understood [19], [21]. This PPE is thought to be a potential cause to Gravity induced loss of consciousness (G-LOC) as it has been identified in several United States Air Force (USAF) accidents [19], [20] and in some civilian accidents according to various reports of the National Transportation Safety Board [1]. Due to all these factors, there is a strong interest in enhancing the health status of participants to mature medical guidelines [12] for prospective commercial spaceflight operations. Recent studies have been conducted on individuals to assess the physiological effects and tolerance of centrifuge-simulated suborbital runs mimicking the SpaceShipOne test flight [4], [5], [22].

The Polar Suborbital Science in the Upper Mesosphere (PoSSUM) is a non-profit organization with a goal to study the noctilucent clouds in the mesosphere to enhance our understanding in the aeronomy and climate change science. PoSSUM program has been training over 100 subjects from different ethnicities and age since 2015. As part of PoSSUM training, subjects from across the globe meet at ERAU to conduct aerobatic flights while the hypobaric study takes place at the Southern Aeromedical Institute (SAMI) in Melbourne, Florida. This research study is dedicated to analyze the physiological effects [22] on various PoSSUM subjects during aerobatic flights, while the findings for the hypobaric will be presented in a subsequent manuscript.

Previous studies have shown that consequences of high G exposure are mainly manifested in the respiratory and cardiovascular systems [7], [11], [22]. This study will show the physiological effects of some of these simulated flight stressors on civilians or SACs.

Biometric data collection for commercial space operations relevant for short-duration space flight is associated to cardiovascular, respiratory, neurocognitive (vestibular, space motion sickness, vision, decision making, memory), musculoskeletal, hematological, and gastrointestinal systems [20]. These responses are intrinsically related with the environmental and vehicle dependent parameters, such as cabin pressurization, acceleration, vibration, noise, radiation, temperature, habitability. Critical parameters to assess and evaluate the pre-flight, in-flight and post-flight physiology of the SFP are the electrocardiogram, blood pressure and HR (cardiovascular), O_2 saturation and breathing rate (respiratory) and the psychological status [20], for which we will be providing results.

II. Procedure and Methods

A. Subjects

This study was based on a research protocol that was reviewed and approved by ERAU Institutional Review Board (IRB) in Daytona Beach campus, Florida. Each participant or subject, referred to [16] as Scientist Astronaut Candidate (SAC), provided written informed consent before taking part in the aerobatic and hypobaric runs. These SACs had previously obtained a valid FAA Class III medical certificate.

Subjects' ages ranged between 23 and 58 years with a mean age of 35 and a standard deviation of 9 years (35 ± 9). Anthropometric measures, such as height, resting HR, suprailiac abdomen perimeter, triceps and thigh measurements, systolic and diastolic pressures, were measured one day or two days before the SACs aerobatic flight. Half of the SACs flew on the first day, and the rest on the second day. A total of 20 subjects participated in the aerobatic flights, 18 males and 2 females. No distinction was attempted to be made by sex analysis since most subjects were male.

A. Materials

SACs were given prior information and instruction as to how to use the Zephyr Bioharness (chest harness with several internal sensors) to collect subjects physiological data [17], [18] such as HR, breathing rate, posture, electrocardiogram or ECG. Other hemodynamic values, such as the systolic pressure, diastolic blood pressure and mean arterial blood pressure were studied to assess the physiological state of the participants prior and after each flight using a wgnbpa-945 sphygmomanometer.

Among the 20 subjects, 90% of these were not taking any kind of medication, 5% were taking only multivitamins and the other 5% were taking analgesics or allergy pills. PoSSUM campaigns occurred twice a year, during October and during March (strong allergy season in Daytona Beach, Florida). Only 10% of subjects stated they were current smokers and 50% of subjects said they consume alcohol between two times and six times a week. 15% of subjects stated they had some sort of oral surgery and 25% had other associated surgeries relating their knee, back, hips, shoulder or neck. 7.5% of subjects indicated they had some sort of gastrointestinal issues in the past.

C. Aerobatic Flights

Aerobatic maneuvers were performed by a certified instructor at the Patty Wagstaff aerobatic school, Florida. The SAC training was part of the PoSSUM training. SACs flew for one hour on each of the two high performance aircrafts, the Extra 300 and Super Decathlon, which have a high-power-to-weight ratio. These flights represented a significant orthostatic challenge when subjects were exposed to high G forces. Prior to flying, participants received anti-G garment training and anti-G breathing maneuver (AGSM) training, where they were instructed to conduct a combined Valsalva maneuvers with isometric contraction of abdominal, leg and arm muscles [25].

The subjects were exposed to various high G-maneuvers as displayed in Fig. 1:

1. +Gx during the takeoff, -Gx during landing.
2. Two 360 degrees loops bank angles pulling 2Gz, one left and one right.
3. Two 4Gz-0G maneuvers, each being a full 360 degrees loop of 4Gz followed by a 0G maneuver.
4. Two Gy maneuvers, one right, one left. They had little effect on subject physiology.
5. One -Gz maneuver.
6. One -2Gz maneuver.

High -Gz effects on humans are not very understood since these have caused significant discomfort in people who conducted them. Subjects in our study were affected mainly by these -Gz forces. After completion of -Gz maneuvers, participants had signs of an irregular heartbeat. An irregular heartbeat can generate stagnation of blood in the brain (heart to brain distance increases), which can induce a loss of consciousness. However, during a +Gz maneuver, the heart to brain distance decreases, decreasing the blood flow through the brain [7]. Several arrhythmias can be defined [10] as follows:

1. A sinus arrhythmia (SA) in which R-R interval varies by more than 0.16 seconds between successive beats (60-100 bpm). Below 60 bpm is a sinus bradycardia and above 100 bpm is a sinus tachycardia.
2. A repeated premature atrial contraction (PAC) where there are three or more successive but not continuous PACs.
3. A ventricular tachycardia (VT) where three or more successive ventricular ectopic beats occur.

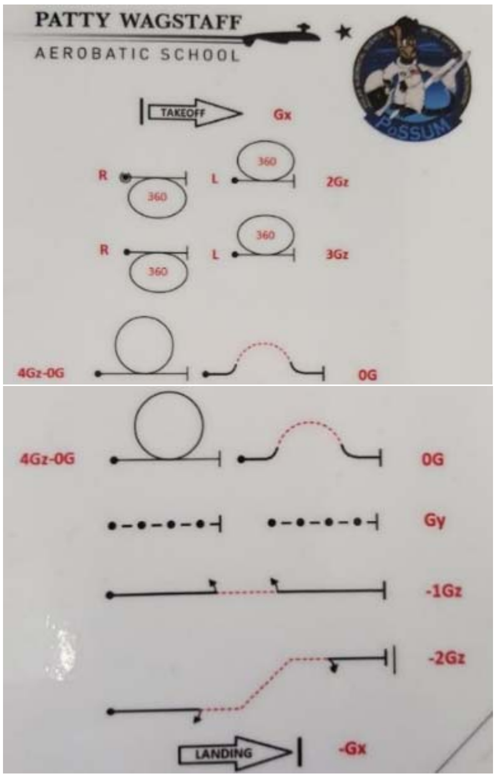


Fig. 1 Aerobatic flight timeline

III. Results

A. SAC Information

The mean of the 20 SACs was 34.8 ± 9.4 years old. The height mean was 177.0 ± 9.4 cm. The total body fat was computed using the skinfold measurement formulas for male and female [13]. Mean total body fat was 18.21 ± 5.40%. The abdomen, triceps and suprailiac were the three skinfold parameters measured in terms of percentage for each subject. For males and females, we used the three-site formulas, respectively:

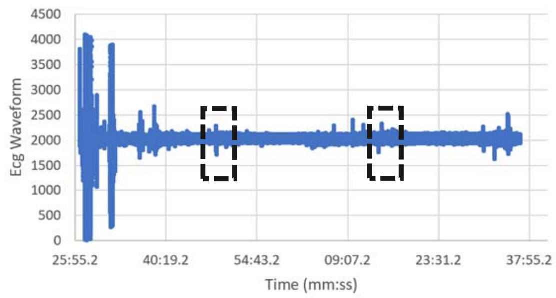
$$\text{Body Fat \% (male)} = 0.39287 \cdot [\text{sum of three skinfolds}] - 0.00105 \cdot [\text{sum of three skinfolds}]^2 + 0.15772 \cdot \text{age} - 5.18845$$

$$\text{Body fat \% (female)} = 0.41563 \cdot [\text{sum of three skinfolds}] - 0.00112 \cdot [\text{sum of three skinfolds}]^2 + 0.03661 \cdot \text{age} + 4.03653$$

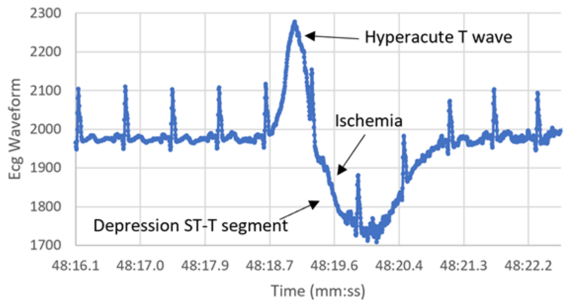
B. Preliminary ECG Data Analysis

For the first participant, Fig. 2 (a) displays a general ECG waveform highlighting a 0G and a -Gz maneuver within each dashed box. In Fig. 2 (b), we show more detail about each maneuver indicating a hyperacute T wave followed by a subsequent ischemia for the 0G maneuver. This ECG sign behaves like a myocardial infarction signature although it needs to meet at least three other criteria before concluding a myocardial ischemia event, which is highly unlikely in the scenario of the present study. A later -Gz maneuver was conducted, with another possible ischemia during a ST-T segment depression (Fig. 2 (c)).

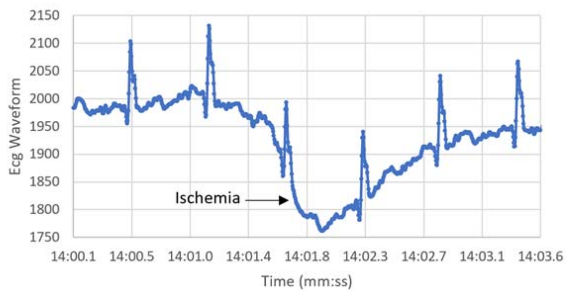
For the second participant, Fig. 2 (c) shows a general ECG waveform and a -Gz maneuver in the dashed box. This region is enlarged (Fig. 2 (d)) where a premature ventricular contraction (PVC) is observed showing abnormal asymmetric up sloping ST segment followed by subsequent curved concave-upward ST-segment depression and T wave elevations.



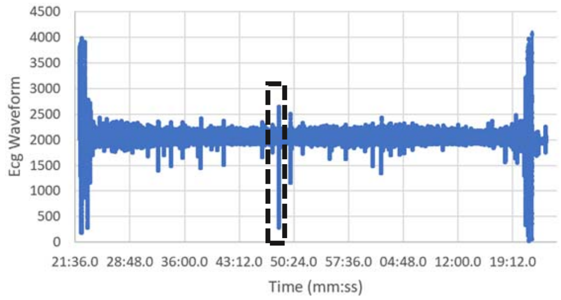
(a) ECG waveform



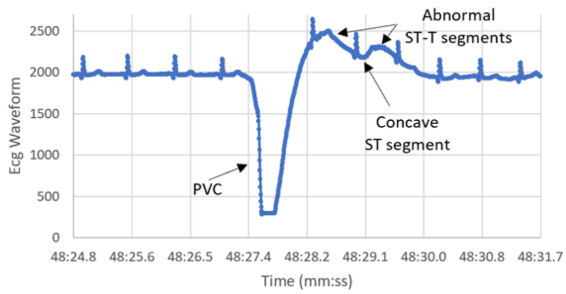
(b) Zoomed section during a 0G maneuver



(c) Zoomed section during a -Gz maneuver

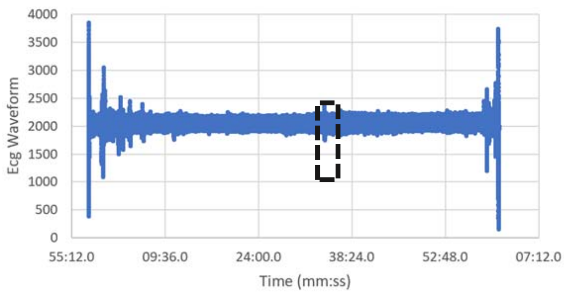


(d) ECG waveform for second subject

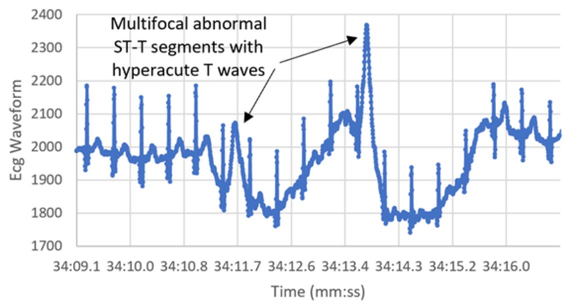


(e) Zoomed section of ECG waveform of second subject

Fig. 2 ECGs for first and second subjects showing some PVCs and ischemia during aerobatic flight training



(a) ECG waveform



(b) Zoomed section of ECG waveform

Fig. 3 ECGs for third subject during aerobatic flight

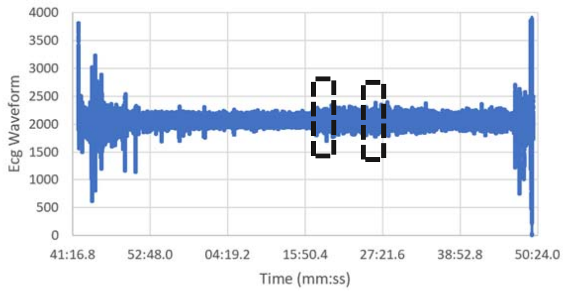
For the third participant, Fig. 3 (a) depicts the general ECG waveform indicating a region of interest in the dashed box area. This region is enlarged (Fig. 3 (b)) displaying an increase in the ECG waveform for over 2 seconds during a -Gz maneuver. Several tracings of multifocal abnormal ST-T segments with hyperacute T waves were observed in this subject in the form of couplets (Fig. 3 (b)).

The ECG waveform for participant 4 in Fig. 4 (a) shows two regions of interest indicated by the dashed boxes. These regions are enlarged in Figs. 4 (b), (a), where the participant may have experienced two PVCs may have occurred during several -Gz maneuvers.

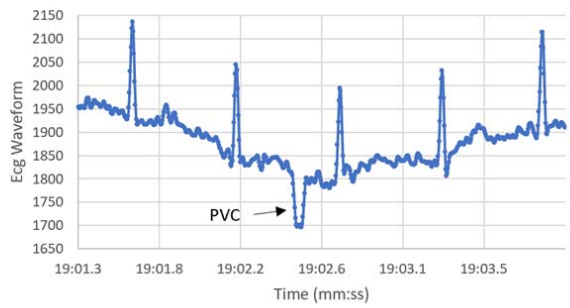
Fig. 4 (d) shows another generic ECG waveform for participant 5. Several boxed regions show regions of interest displayed in Figs. 4 (e), (f) during -Gz maneuvers. In the first region (Fig. 4 (e)) it a regular rhythm for several cycles with various episodes of abnormal ST-T segments was observed, while the second region (Fig. 4 (f)) shows a signature with variable times between each ECG waveform, being these longer during the maneuver. For example, the time between the peaks is about 0.75 seconds, this time is about 1.2 seconds at the peak of the maneuver, then it goes back to 0.75 after a few cycles.

In general, about 15% of the participants showed some sort of dysrhythmic patterns (PVC s-type or shaped disruptions) in the ECG waveforms, some of which may have triggered physiological responses caused by high-G attitude training, but other may have been caused by the sensor artifact.

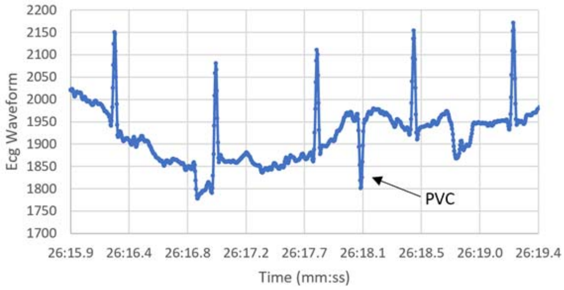
There was no G-LOC observed in any of the aerobatic maneuvers for the 20 subjects. SA has often been recorded after high-G stress when HR is returning to normal form a more rapid rhythm. Some pilots showed marked respiratory dysrhythmias even before undergoing high-G stress.



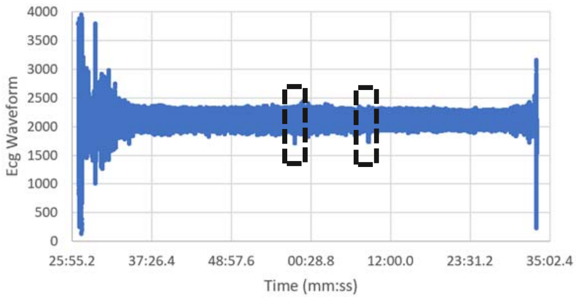
(a) ECG waveform



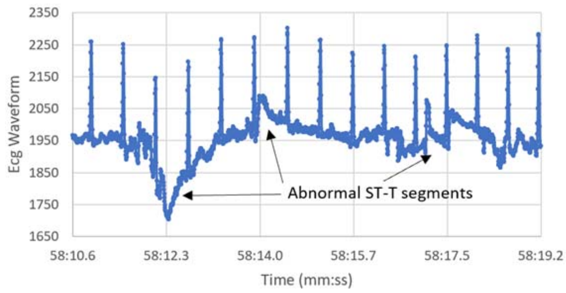
(b) First boxed region of waveform during a -Gz maneuver



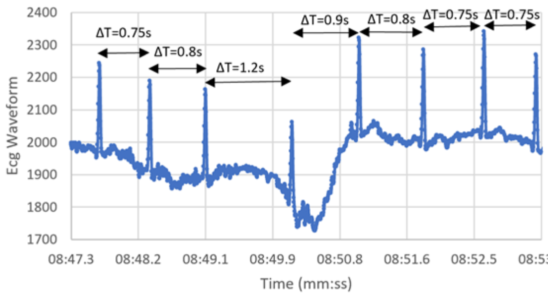
(c) First boxed region of waveform during a -Gz maneuver



(d) ECG waveform



(e) Zoomed section of ECG waveform



(f) Zoomed section of ECG waveform showing various time differences between each wave

Fig. 4 ECGs for third and fourth subjects during aerobatic flight

Nearly 40% of the subjects decided not to conduct the +Gz or -Gz maneuvers or reduce the time of these maneuvers from about 20 seconds (typical time for these maneuvers) to just about 10 seconds because they experienced the start of a graying of vision symptom, caused by a lower blood flow to the head, and therefore to the eyes. Although vision was not completely lost, it gave subjects a sign of impairment and had to call the maneuver off.

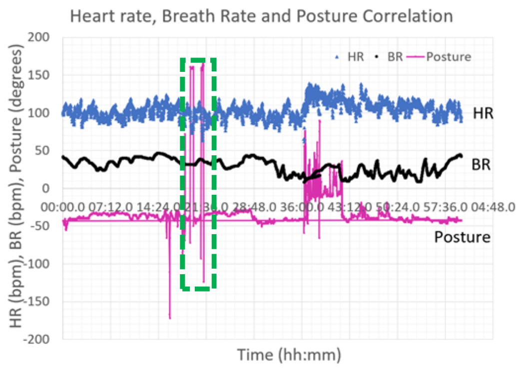
Only four out of 20 subjects experienced very nauseated symptoms after the flight. No episodes of tachycardia or bradycardia were observed in any of the participants.

C. BioHarness Data Analysis

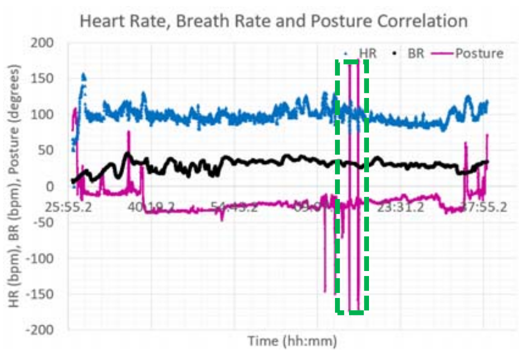
The evolution of the HR, breathing rate (BR) and posture for some subjects during the aerobatic flights is displayed in Fig. 5. HR is depicted in blue, BR in black and posture in magenta, and the boxed section is a region of interest during -Gz maneuvers for each of the subjects. The HR and BR (mean ± standard deviation) for all subjects was 93.9 ± 16.7 bpm and 21.0 ± 4.0 bpm, respectively. Maximum HR and BR values of these mean parameters found for all subjects were 127.0 bpm and 30.0 bpm, respectively. Minimum HR and BR values of these mean parameters for all subjects were 60.0 bpm, and 14.0 bpm, respectively. Some conclusions can be extracted from this analysis. The first one is that the maximum mean HR increased 35.3% among all subjects during the aerobatic flight, and the maximum mean BR increased 48.0% for the 20 subjects.

The boxed region in Fig. 5 (a) shows a decrease of HR from about 100 bpm to 75 bpm during an aerobatic flight maneuver that lasted 25 seconds for one subject. A subsequent 20 seconds maneuver (85 seconds after completion of first maneuver HR recovers to about 100 bpm again) dropped the subject's HR from about 100 bpm to 65 bpm. This approximately 25% to 35% decrease in the HR is observed across each of the subjects during the -Gz maneuvers, when their bodies are inverted in the aircraft as indicated by the high peaks (magenta), also depicted in the green boxes in Figs. 5 (a)-(h). These two maneuvers lasted about 18 to 25 seconds for most of the subjects; these maneuvers were spaced between 1 minute and 2 minutes. For other subjects this HR variability can be more significant with approximately 45% HR decrease. This phenomenon is referred to as preload and afterload related events.

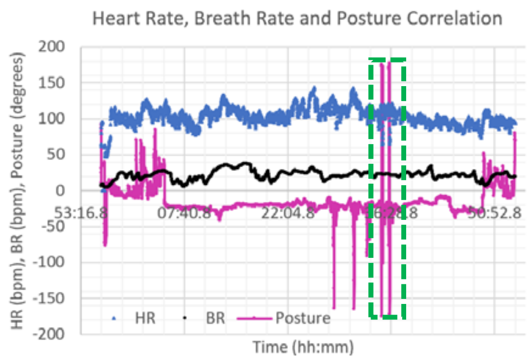
Other observations in Fig. 5 were observed during aerobatic flights. The first observation is a decrease of HR when the SACs were exposed to -Gz maneuvers, which corresponds during the inverse position of the SAC in the aircraft (Fig. 5). Before the -Gz maneuver, about 62% of SACs had an HR above 110 to 120 bpm, and during the maneuver, their HR was decreased in cases down to 60 to 70 bpm. After the maneuver, their HR increased back to above 110 bpm. There were no significant changes in the BR immediately before, during and after performing the -Gz maneuver.



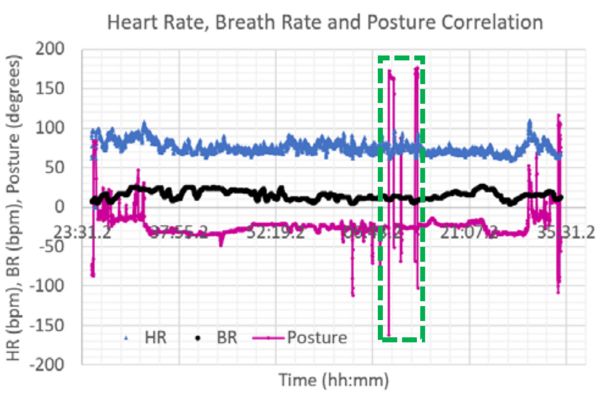
(a) HR, BR and posture (subject 1)



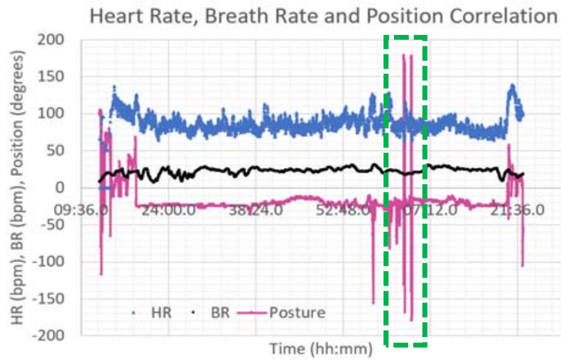
(b) HR, BR and posture (subject 2)



(c) HR, BR and posture (subject 3)



(d) HR, BR and posture (subject 4)



(e) HR, BR and posture (subject 5)

(f) HR, BR and posture (subject 6)

(g) HR, BR and posture (subject 7)

(h) HR, BR and posture (subject 8)

Fig. 5 Heart and breath rates, position correlation for eight subjects

During aerobatic flight, the HR and BR values were collected for each subject (Fig. 6). The mean of the maximum HR and BR values for all subjects was 135 ± 25.1 bpm with maximum and minimum values of 211 bpm and 93 bpm, respectively. The mean of the maximum BR value was 34 ± 5.7 bpm, with a maximum BR of 47 bpm, and a minimum BR value of 26 bpm. Similarly, the mean of the minimum HR for all subjects was 63.6 ± 12.5 bpm with maximum 86 bpm and minimum 39 bpm. When comparing the mean HR and the mean maximum HR values, we observe a 43.4% increase in the maximum HR and a 64.6% increase in the maximum BR for all subjects.

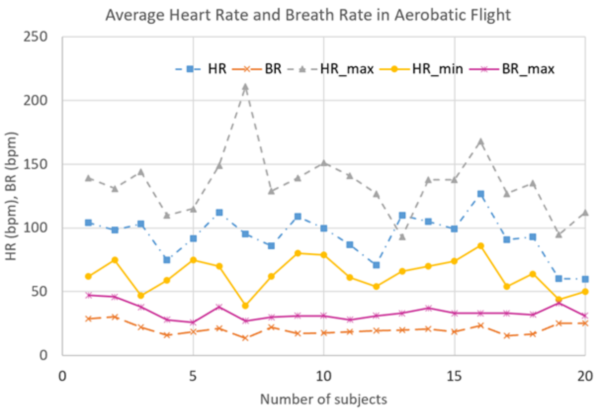
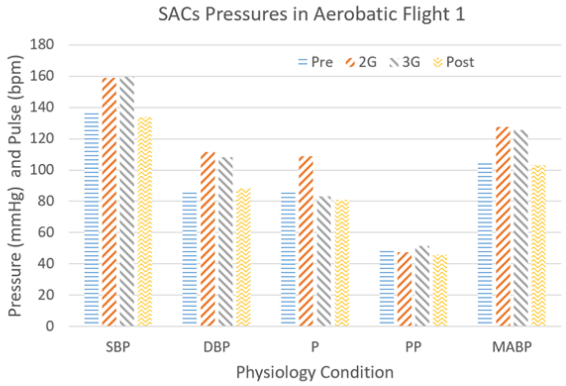


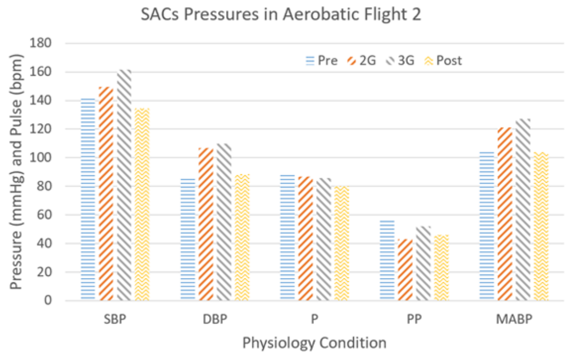
Fig. 6 Mean HR (beats per minute) and breathe rate (breaths per minute) during aerobatic training for 20 subjects.

In this study, systolic blood pressure (SBP) and diastolic blood pressure (DBP) were also measured before flight, during an aerobatic maneuver, and after the aerobatic flight (Fig. 7). The pressure (P) for each subject was taken 10 minutes before the takeoff while seated in the cabin. Pulse pressure (PP) is then obtained by subtracting the DBP from the SBP. Finally, the mean arterial blood pressure (MABP) was obtained by dividing the PP by 3, then adding this value to the DBP. During flight, not every subject was able to collect a reading during every single G-maneuver. After aerobatic flight and 10 minutes after landing, the pressure for each subject was taken when the subject was seated in the aircraft. Figs. 7 (a)-(c) depict the physiological parameters for each subject for aerobatic flight 1, aerobatic flight 2 and average of both flights, respectively.

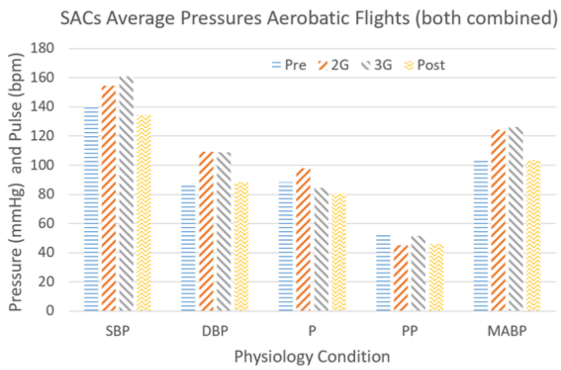
Fig. 7 (d) displays the comparison of the average pressures pre, post and during the 2G and 3G aerobatic maneuvers for all the subjects combined. Additional analysis was conducted for different age groups: 20-29 years old (group 1: 7 subjects with 27.1 ± 1.9), 30-39 years old (group 2: 8 subjects with 32.8 ± 2.6) and 40 to 60 years old (group 3: 4 subjects with 50.3 ± 5.9). The pressures were analyzed for each of these groups and for each flight on both aircrafts. Then the average was obtained. Finally, the difference among groups was computed for all variables (SBP, DBP, P, PP, and MABP) pre, 2G, 3G and post. Some observations were extracted from this comparative analysis:



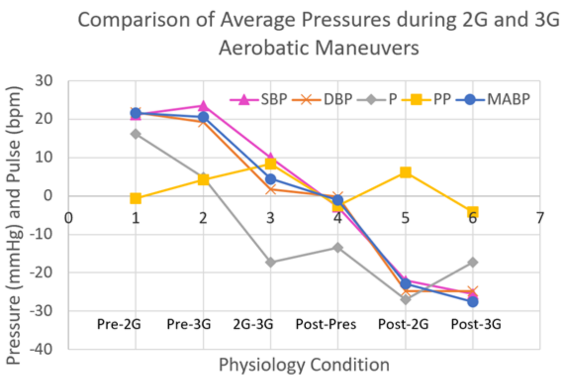
(a) Pressures and pulse during aerobatic flight 1



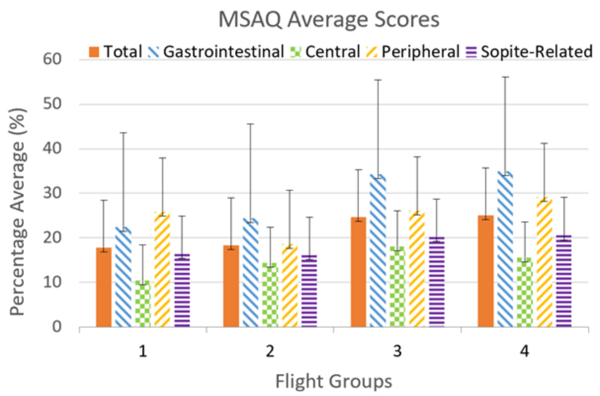
(b) Pressures and pulse during aerobatic flight 1



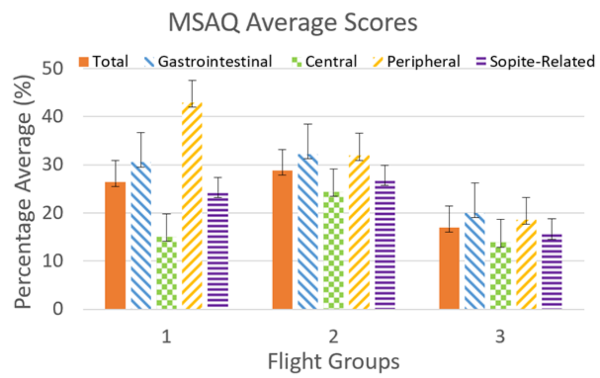
(c) Average pressure and pulse for both flights



(d) Comparison of pressure and pulse for different maneuvers



(e) MSAQ of 20 subjects (two aircraft)



(f) MSAQ of 10 subjects (two aircraft) for flight groups 1 and 2, 8 subjects (two aircraft) for flight group 3

Fig. 7 (a)-(d): Effects of aerobatic maneuvers (2G and 3G) on the several physiologic parameters and comparison with pre and post flight measurements for all subjects. (e), (f): MSAQ scores for various flight groups

The first observation is that the relative error for PP (pre-flight) between groups 1 and 2, groups 2 and 3 and groups 1 and 3 is about 12.5%, 12.6%, and 28.6%, respectively. Relative error for PP (2G aerobatic) was about 20.0%, 5.7%, and 12.0%, respectively, when comparing the same groups. The relative error for PP (3G aerobatic) was about 2.5%, 4.7%, and 7.0%, respectively, when comparing these groups. Finally, the relative error for PP (post-flight) was 1.9%, 8.9%, and 10.6%, respectively when comparing these groups. A second observation (when comparing all these groups in the same order) is that the pulse (P) pre-flight is 13.5%, 5.0%, and 16.2%, respectively; 18.9%, 3.6% and 18.9%, respectively for 2G; 17.4%, 14.9%, and 27.5%, respectively; and 12.0%, 4.3%, and 14.6%, respectively for post-flight. A third observation is that the relative error of MABP pre-flight was 50% higher between groups 1 and 3, than the relative errors between groups 1 and 2, and groups 2 and 3. The relative error of MABP during the 3G maneuver between groups 1 and 2 was 3.2%, 11.0% between groups 2 and 3, and 13.7% between groups 1 and 3.

Next we provide a statistical analysis for the motion sickness assessment questionnaire (MSAQ) (Fig. 7 (e)) for 20 subjects (4 groups). The mean and standard deviations for the gastrointestinal, central, peripheral and sopite-related scores for each flight group were 22.5 ± 17.9, 10.44 ± 3.15, 25.93 ± 12.51, 16.39 ± 6.39 (group 1); 24.44 ± 24.53, 14.44 ± 6.78, 18.61 ± 10.26, 16.11 ± 7.74 (group 2); 34.33 ± 20.91, 18.1 ± 10.41, 26.11 ± 10.26, 20.28 ± 10.10 (group 3); and 35.00 ± 15.63, 15.6 ± 7.27, 29.17 ± 14.55, 20.56 ± 7.78 (group 4).

Fig. 7 (f) displays 10 subjects for each group that flew the two different aircrafts, and the last group represents another group of 8 subjects that flew only on one aircraft because of time constraints to collect the data. Thus, for analysis, we will keep them separated too. Mean and standard deviations for the gastrointestinal, central, peripheral and sopite-related scores for each flight group were 31.4 ± 22.4, 19.8 ± 12.5, 37.5 ± 20.4, and 25.4 ± 13.3, respectively. The mean for the total score is 27.6 ± 14.1. The third group's mean total score is 17.0 ± 15.5, and their individual scores were 20.0 ± 20.8, 13.9 ± 11.0, 18.6 ± 18.3, and 15.6 ± 13.4, respectively. Positive error bars were added based on the standard deviation value obtained from all four flight groups.

IV. Conclusion

The goal of this research was to gain insight of the physiological effects on various subjects during aerobatic flights indoctrination to aid in the development of more mature medical screening, medical assessment methods and suborbital flight training for prospective commercial astronauts in the rising suborbital spaceflight industry. Prospective training guidelines for suborbital flights are still being developed by various flight operators, and length of training is expected to be around a few days to one week depending on the flight operator. These medical and training guidelines will be tailored to civilians –people who do not follow strict training such as military personnel, professional NASA/ESA astronauts or Russian cosmonauts. Our data presented in this study suggest that ECGs, HR, and PP monitoring could be considered a surrogate for dysrhythmias development and flight stress. We suggest that these medical variables to be monitored at least 3 days before suborbital flight, during the 10-12 minutes suborbital flight and post-flight within one hour of the flight and 2 days after suborbital flight. Aerobatic training flights effects induced several other effects on subjects while performing unusual high-G forces maneuvers (2G-3G and short periods of microgravity), such as gastrointestinal disruptions and pulmonary capacity that may affect commercial astronauts during flight.

Our findings reveal that about 15% of participants experienced PVCs during training flight, while about 40% of subjects who flew shortened their +Gz/-Gz maneuvers due to grayout vision, nausea symptoms or decided not to perform these last physiological demanding maneuvers. Although HR was monitored before, during and after flight, especial attention was focused on the +Gz and –Gz maneuvers during training. Preload and afterload events were experienced by subjects during these maneuvers lasting approximately 20 seconds, yielding to a decrease of the HR of about 25% to 45% in some subjects. A more refined analysis on the HR behavior and its evolution is suggested to be conducted for each participant throughout the entire training flight in future studies to better understand trends across different age groups. For this reason, this study suggests that a certain level of screen for health and fitness should be required to pre-adapt these suborbital passengers to prospective suborbital flights in order to minimize possible physiological disruptions that could jeopardize the success of the mission in the context of safety and science.

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