An Investigation of the Effects of Sustained G-Forces on the Human Body During Suborbital Spaceflight

In Fulfilment of the Degree:
Master of Science in Aerospace Engineering

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SAMMANFATTNING (SWEDISH)

Inom en snar framtid är det troligt att privata, kommersiella rymdflygningar är möjliga, där passagerarna inte kommer att vara utbildade astronauter och, till majoriteten, troligtvis äldre. Dessa personer kommer att utsättas för höga G-krafter vilket utan avancerad träning medför risker som inte beaktats i detalj tidigare.

Accelerationsprofilerna för de två rymdfarkoster som just nu utvecklas kommersiellt var analyserade utifrån officiellt tillgänglig data. Videoanalys utfördes utifrån filmer av testflygningar och mänskliga centrifugtester användes för att få fram individuell data. Dessa var sedan kombinerade för att få fram accelerationsprofiler för båda farkosterna. Baserat på dessa profiler och de maximala G-krafterna som uppnåddes analyserades de möjliga riskerna för passagerarna utifrån ett medicinsk perspektiv.

ABSTRACT

With the advent of private commercial suborbital spaceflight, a new demographic of untrained individuals will begin to travel to space. These individuals are exposed to high levels of G-forces, resulting in medical considerations which are not a normal factor with high performance fighter pilots or astronauts.

The acceleration profiles of the Virgin Galactic and Blue Origin spacecraft were obtained from publicly available data. Video analysis was performed on footage of spacecraft test launches and human centrifuge tests to obtain individual data sets. These data sets were used to develop the acceleration profiles for both spacecraft.

Based on the spacecraft's acceleration profiles and peak G-forces, medical conditions were investigated and considered to identify potential risks that may affect the passengers, particularly the elderly.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Notations

Symbol	Description
a	Acceleration
dm	Change in mass
g	Force of gravity on earth $[9.81\,\frac{\mathrm{m}}{\mathrm{s}^2}]$
G	A multiple of gravity experienced due to acceleration
I	Inertia
r	Radius
T	Torque

Abbreviations

AGARD	Advisory Group for Aerospace Research and Development
AGSM	Anti-G Straining Manoeuvre
A − LOC	Almost Loss Of Conciousness
bpm	Beats Per Minute
CAD	Coronary Artery Disease
COPD	Chronic Obstructive Pulmonary Disease
CSM	Command/Service Module
CVD	Cardiovascular Disease
G − LOC	G-force induced Loss Of Conciousness
HIVD	Herniated Intervertebral Disc
ISS	International Space Station
km	Kilometer
kph	Kilometers Per Hour
LM	Lunar Module
mmHg	Millimeter of Mercury
WHO	World Health Organization

Contents

Chapter 1

INTRODUCTION

In recent years, well funded private space exploration companies have made great strides towards successful commercially viable spacecraft opening the door to the possibility of commercial space tourism. This indicates a shift in the average demographic of those travelling to space away from the highly trained astronaut towards an average, untrained and largely unprepared Individual. Furthermore, the high cost off the flights, currently in the hundreds of thousands, will potentially shift the client age demographic towards more senior citizens. This is in general a result of the elderly likely enjoying a higher salary, or being already retired with comfortable liquid assets as opposed to younger generations who may spend their money elsewhere such as on student loans or mortgages. Consequently, medical considerations need to be re-evaluated to meet the new demographic travelling to space, and conditions which may not generally affect professional astronauts must now be considered.

After defining the thesis in Chapter 1, background information on G-forces and an overview of medical considerations will be discussed in Chapters 2 and 3 to highlight relevant material. The background overview will be followed by Chapter 4 which covers how the G-force profiles will be determined and Chapter 5 which presents the results. Finally, the results will be discussed in Chapter 6 and conclusions on the risks associated with suborbital spaceflight will be considered based on the G-force profiles found.

1.1 Background

With the advent of performance aircraft in the early 20th century, the effects of G-forces on the human body quickly came to light and research began to identify the causes, limits and training methods to minimize risk and maximize G-force tolerance. While the knowledge base has been greatly improved over the years, research has been limited in general to specialized professionals such as astronauts and military pilots. Large scale research on the effects of G-forces has been further limited to males due to the lopsided gender imbalance in these professions. This disparity has resulted in a large gap in the data on how G-forces affect different demographics with respect to physical and medical considerations.

1.2 Scope and Objectives

Before the risks can be assessed, the amount of G-forces experienced, along with the onset rate and duration must be determined for the commercial space vehicles. Given that the acceleration profiles of the remaining two commercial suborbital space tourism companies Virgin Galactic and Blue Origin are not public knowledge, video analysis will be performed on footage from test launches to develop acceleration profiles from which decisions can be made.

The current body of research on the effects of G-forces on the human body is largely the result of tests on highly trained subjects who have been cleared for flight at a high medical standard. The advent of space tourism however, is introducing average people who are well outside the scope of research that has been performed on professionals, and so come with a host of new considerations with respect to the G-forces experienced. Upon obtaining the acceleration profiles of the two spacecraft, the duration and onset rate of the largest G-forces can be determined and the standard risks from sustained G-force exposure can be investigated to determine how well the current guidelines hold up with the deteriorating health of elderly passengers. Furthermore, new conditions that are prevalent in the elderly, but non-existent in current high G-force exposure groups will need to be considered and investigated to determine if and when they become a risk and what limitations should be imposed as a result.

1.3 Method

To determine the acceleration profiles of the suborbital spacecraft, video analysis will be performed. For certain spacecraft, there is the possibility of performing the analysis several different ways in order to increase the level of confidence that the G-force profile has been properly determined. To begin, some test flight videos display output such as the speed the spacecraft is travelling. This data can be extracted frame by frame to develop a dataset which can be used to calculate the acceleration and G-forces experienced by spacecraft.

Should data output from videos not be available, it may also be possible to determine the speed and acceleration of the spacecraft by measuring its movement against a background, such as mountains or the ground. This option is more limited as some footage is shot against a featureless background, however this may provide a decent way to check if data output is correct and to identify any masking that may have been applied to the data feed to keep some of the spacecraft specifications secret.

Chapter 2

G-FORCE BACKGROUND

When considering G-forces there are in general two types to look at: Sustained and transient. Transient G-forces are generally associated with an impact such as a crash, and take place over a very short period of time. Sustained G-forces on the other hand are generally defined as G-forces that take place over a period longer than 2 seconds.

With the advent of aerial warfare, pilots were quickly exposed to G-force conditions which had never been experienced before and were not well understood. As dogfights became the norm in World War 1, reports of pilots mysteriously losing consciousness began to be reported, and by 1919, a doctor had written the first literature on what he called "fainting in the air"[1][2]. This opened the door to a whole new subset of medicine often referred to as aerospace medicine.

The term G-force is commonly used to describe how many times the amount of standard earth gravities one is experiencing. As a reference, 1G is the standard average force of gravity experienced when standing on earth and is equal to $9.81\,\frac{\mathrm{m}}{\mathrm{s}^2}$. For example, an astronaut who is experiencing 3G's during launch is experiencing three times the force of earth's gravity, and effectively weighs three times as much as he would standing on earth.

2.1 Orientation

To consider the forces acting on an astronaut, the Advisory Group for Aerospace Research and Development (AGARD) has recommended an acceleration axis convention in an attempt to unify the industry[3]. Despite these efforts, the attempt to unify the aerospace medicine industry has been met with mixed results, and various publications and groups continuing to use different axis orientations with respect to the human body. The AGARD standard has however been adopted by many important aerospace organizations such as NASA and will be used in this paper[4].

To properly discuss accelerations and G-forces in aerospace medicine, the axes are fixed to the human rather than the vehicle in which they are riding. This ensures that the accelerations experienced by a passenger accurately reflect how they are acting on the body no matter its orientation in the vehicle. The acceleration axes are defined with respect to the human body such that the +X-axis is always pointing out of the humans chest, the +Y-axis is to their right, and the +Z-axis is up through their head as shown in Figure 2.1. Counter to the acceleration axes, the G-force reference directions are directly opposite to the acceleration axes.

It is important to note here that the AGARD standard defines the aerospace medicine acceleration axes and the aerospace engineering standard differently[5]. In aerospace engineering, the +X and +Y axis remain the same, pointing through along the direction of flight, and to the starboard respectively, but the +Z axis is inverted and pointed towards earth, or the nadir. This means that acceleration experienced by a pilot seated upright in a regular airplane would match the aircraft's axis in every way apart from an inverted Z axis.

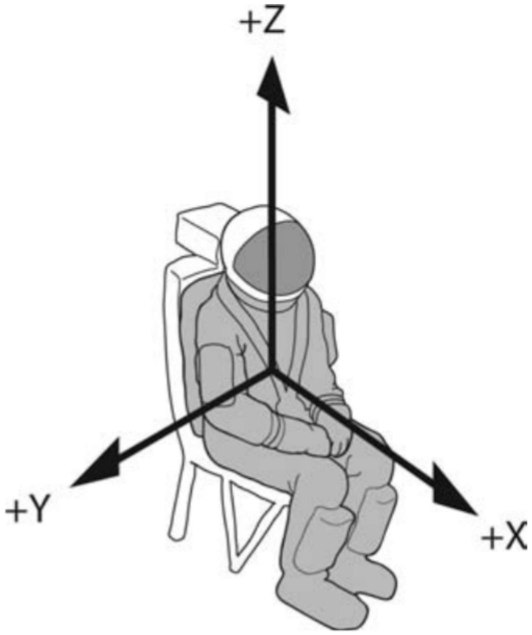


Figure 2.1: Acceleration axes placement in aerospace medicine[3]

To make sense of how forces act with respect to the axes, one can consider the astronaut from Figure 2.1 and imagine he is sitting mounted to the floor of the Space Shuttle. During launch, he would be laying on his back as the Shuttle is mounted upright, and would be pushed back into his seat by the Shuttle as it accelerated in the +X direction. This would result in him experiencing a +Gx force. During reentry, the Shuttle will use its belly to decelerate with friction against the atmosphere, resulting in the astronaut feeling pushed down into his seat on the Z axis, and experiencing a +Gz force. The same thinking can be applied to the Y-axis, however this is seldom considered in aerospace medicine due to most planes being unable to perform high-G manoeuvres that provide force in that axis.

Table 2.1 is adapted from Fundamentals of Aerospace Medicine[3] to show potential accelerations and resulting G-forces an astronaut on the Space Shuttle may experience.

Accel.	**G-force**	**Description**
$+X$	$+Gx$	Accelerating during launch
$-X$	$-Gx$	Manoeuvring with thrusters in space backwards
$+Y$	$+Gy$	Manoeuvring with thrusters in space to the right
$-Y$	$-Gy$	Manoeuvring with thrusters in space to the left
$+Z$	$+Gz$	Decelerating during reentry
$-Z$	$-Gz$	Manoeuvring with thrusters in space downwards

Table 2.1: Acceleration and resulting G-forces experienced by an astronaut on the Space Shuttle

2.2 Human Limits

The human body is highly adaptable and is capable of surviving situations well outside the environment in which it is accustomed to. In the early decades of high performance aircraft, the survivability limit was thought to be 18G's based on the limited amount of data available from crashes, and as a result, cockpits were designed to survive a crash of a maximum of 18G's[2]. Some people began to notice however that pilots were walking away from crashes with far larger estimated G-forces, and began to look into the human limits of acceleration.

To test these theories, John Stapp, an Air Force physician began researching the limits of G-force exposure using rocket sleds mounted with dummies and sensors to gain a deeper understanding. He quickly replaced the dummies with his own body and suffered a myriad of non-life-threatening injuries. Subsequent tests eventually led to him accelerating to 1,017kph over the course of 5 seconds before coming to a stop in one second, experiencing a record transient loading of -46.2Gx. This final ride left him with temporary blindness among other injuries, but he went on to make a full recovery and continued living without consequence until his death at the age of 89.

While the limits of transient G-forces is very high, the limits of sustained accelerations is much lower and is dependent on several factors. The most important factors in determining the effects the sustained acceleration will have on the human body is the rate of onset and the peak sustained G-force. The rate of onset, or how fast the body accelerates dictates the ability to remain conscious, with a faster rate of onset leading to a lower G-force threshold. An average, untrained individual will likely begin to be affected by G-forces around +3Gz to +4Gz, while a trained individual using assisting equipment may be able to withstand up to +8Gz or +9Gz provided a reasonable rate of onset. Should the rate of onset be high however, the limit is significantly decreased. Professional pilots exposed to a G-force onset in excess of 1G per second for example, would see their G-force maximum decreased to somewhere around +3.5Gz. Estimates for the range of human limits from acceleration with respect to how survivable exposure time can be seen in Figure 2.2.

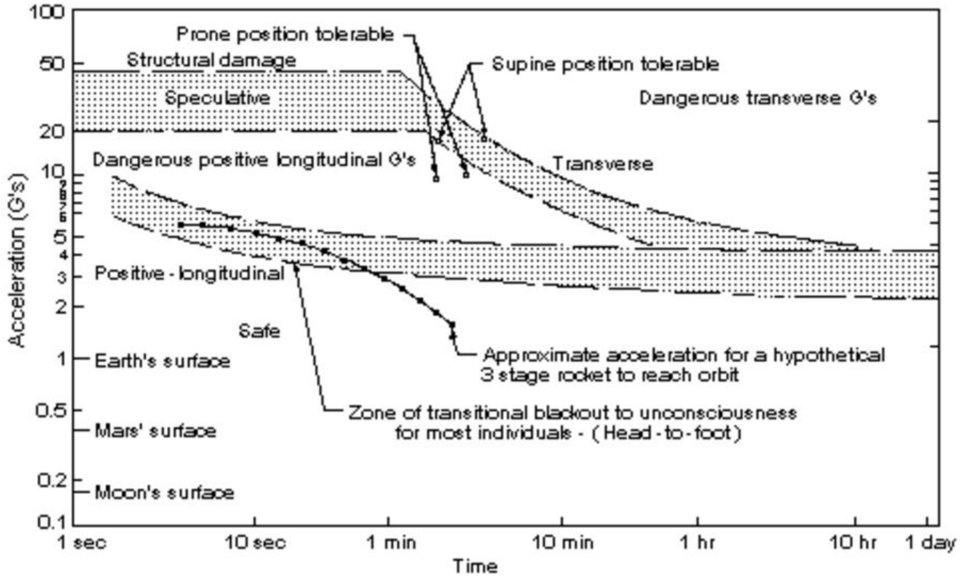


Figure 2.2: Human G-force tolerance as a function of exposure time to peak sustained acceleration[6]

2.3 Training

Training has been shown to be an integral part of improving the abilities of an individual to be able to resist the effects of high G-loads. Two training methods are regularly used in astronaut and fighter pilot training today including human centrifuges, and on occasion, 0-G flights.

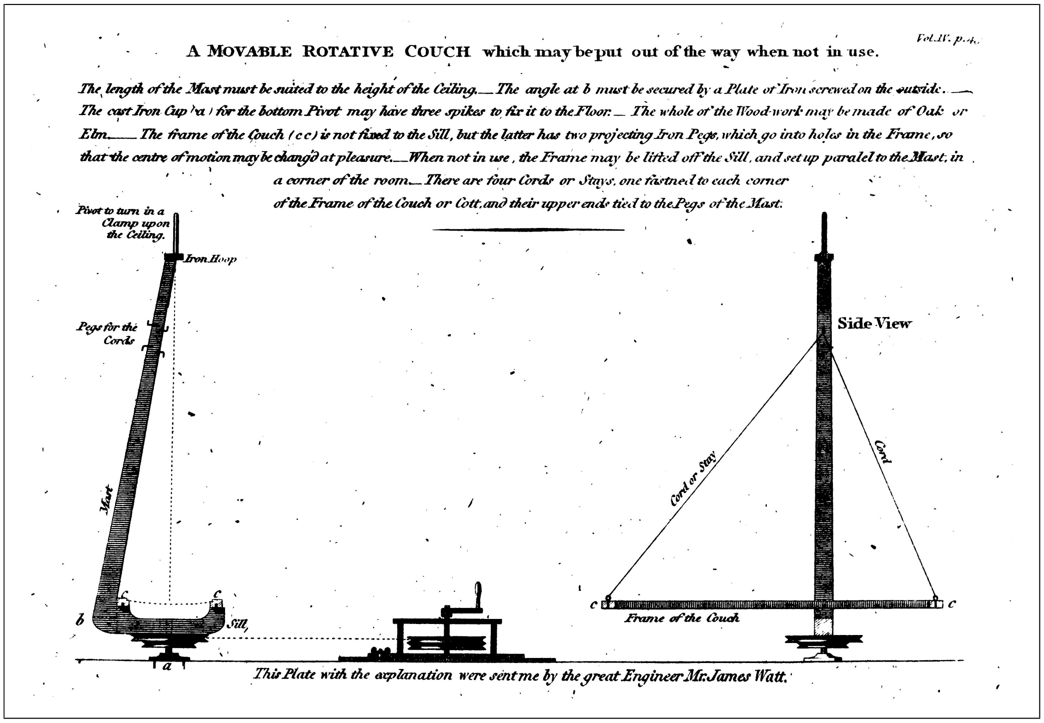
2.3.1 Human Centrifuge

With the high speeds and forces experienced by pilots engaged in aerial combat, researchers were left struggling to discover and explain the effects of G-forces on the human body. In response to the need for a research platform, scientists eventually turned to giant centrifuges which allowed for a controlled environment in which subjects could be safely tested.

The idea of a human centrifuge is not new, and has been proposed in literature as early as 1794 by Erasmus Darwin on a tip from his friend James Brindley[7]. Brindley had noted that if someone were to lay down on a large stone corn grinding wheel, he would fall asleep from the spinning motion. In 1801, Darwin went so far as to publish the design proposal seen in Figure 2.3 that laid the foundation for the use of centrifuges in medicine[8].

Throughout the 1800's the human centrifuge found occasional use as a research tool, but was predominantly used as a treatment for mental illness largely due to its ability to induce a calming effect on violent patients with less side effects than the alternatives of the time[9][10].

In 1933, the Germans built the first modern large-scale human centrifuge, followed in 1938 by the Americans. By the end of World War 2, understanding the effects of G-forces on pilots had become increasingly important as technology rapidly advanced, and at least 6 allied countries operated their own centrifuges and research teams[9].



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A MOVABLE ROTATIVE COUCH which may be put out of the way when not in use.

The length of the Mast must be suited to the height of the Ceiling.—The angle at b must be secured by a Plate of Iron screwed on the outside.— The cast Iron Cup (a) for the bottom Pivot may have three spikes to fix it to the Floor.— The whole of the Wood-work may be made of Oak or Elm.— The frame of the Couch (c c) is not fixed to the Sill, but the latter has two projecting Iron Pegs, which go into holes in the Frame, so that the centre of motion may be chang'd at pleasure.—When not in use, the Frame may be lifted off the Sill, and set up paralel to the Mast, in a corner of the room.—There are four Cords or Stays, one fastned to each corner of the Frame of the Couch or Cott, and their upper ends tied to the Pegs of the Mast.

This Plate with the explanation were sent me by the great Engineer Mr. James Watt.

Figure 2.3: Early centrifuge concept as proposed by Erasmus Darwin in 1801[8]

Human centrifuges today are used primarily as a means of researching the affects of sustained G-force loading and are an integral part of training both fighter pilots and astronauts for the G-force loads they may experience on the job. The Human centrifuge cannot be considered a comprehensive tool that encompasses the entire spectrum of G-forces scenarios, but instead a tool specifically designed to address G-forces that last longer than a second or two. Shorter periods of G-forces are instead referred to as transient loading or impact, and cannot be properly simulated using a human centrifuge. These types of transient loads are simulated in other devices, where test subjects are dropped, or accelerated linearly before being slowed in a controlled or uncontrolled deceleration to mimic an impact force over a given distance or time.

Modern human centrifuges come in a variety of configurations; from the simplest open platform to advanced computer controlled cockpits such as the centrifuge in Figure 2.4 in which pilots can experience haptic feedback during dogfight training simulations.

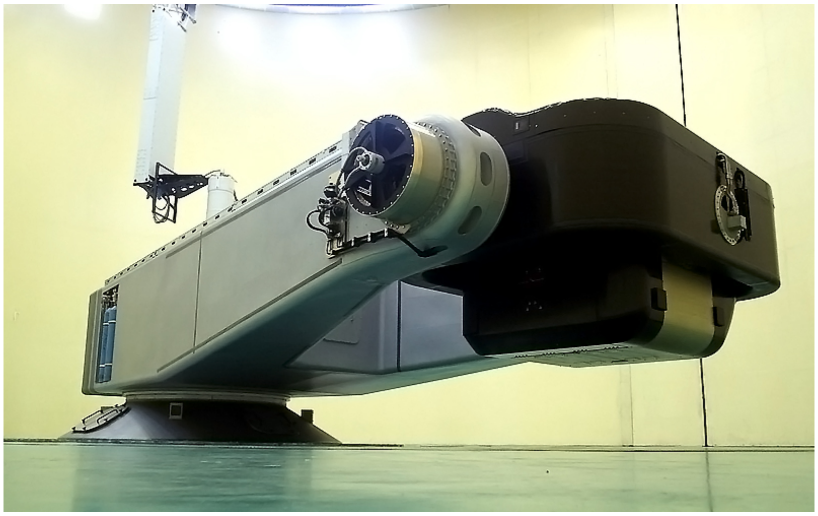

Figure 2.4: A modern dynamic human centrifuge in Moscow[11]

Two types of control, open-loop and closed-loop, are available and are dependent on the level of sophistication of the device in question[12]. The open-loop configuration allows for the control of the centrifuge by an external operator, and is the base configuration all centrifuges rely on. In this operational mode, the rider is in effect a “guinea pig” for the researcher and has no direct control over his ride. This testing method is often used in conjunction with the subject being instructed to perform a simple task or experiment while under duress to judge their level of impairment under the given load.

Closed-loop systems on the other hand gives control of the human centrifuge to the test subject sitting in it. This allows for a dynamic flight simulation in which the “pilot” has full control of the ride. The closed-loop setting is regularly used in modern fighter pilot training simulators and provides a tactile experience to emulate real life scenarios in a safe environment without the risk of crashing.

The current design, with a centrally supported rotating arm, is not without drawbacks. The short turning radius means that Coriolis forces come into effect, and a slight shaking of the head is enough to induce a tumbling or nauseous sensation. In order to reduce the effect to realistic flying levels, a much larger arm radius would need to be used as today's largest human centrifuges measure in at around 18m, still much smaller than the turning radius of an aircraft[9].

It has been suggested that a centrifuge with a radius in excess of 60m would be needed to approach realistic flying conditions[9]. Unfortunately, the amount of torque needed to turn the arm is related directly to the inertia of the machine as seen in Equation 2.1, and thus can be found to increases exponentially with respect to its turning radius as seen in Equation 2.2. This means that there is a functional size limit to building a conventional human centrifuge in which a reasonably sized motor can be used.

$$T = Ia \tag{2.1}$$

$$I = \int r^2 dm \tag{2.2}$$

To circumvent this problem, the US Air Force has proposed instead to build a new type of centrifuge with a capsule that attached to the inside of a circular wall, and travel on an electro-magnetic rail system[9]. This system would allow for a large enough radius to reduce the effects of the Coriolis forces to reasonable levels, and have the added benefit of a much lower moment of inertia. The low moment of inertia, coupled with electro-magnetic rails and propulsion would also allow for much faster accelerations to be achieved. This would be an added benefit as it would allow for the testing of systems such as emergency ejection seats for military aviation, and would likely provide an excellent research platform to research the effects of current and future emergency abort systems on orbital and suborbital spacecraft.

2.3.2 0-G Flight

When considering the effects of G-forces on the human body, it is important to consider all the possibilities. One case that is often overlooked when considering G-forces is microgravity, or 0-G.

It is a common misconception that in space, astronauts "float" since they are so far away from earth that they no longer feel the forces of gravity. In reality however, an astronaut on the ISS still experiences 90% of the force of gravity as felt on the surface of earth[13]. That is to say, in a microgravity environment, an astronaut continues to experience the acceleration of gravity. He does not however feel the acceleration, which is why it is called a 0-G environment.

To imagine this, one can equate it to a skydiver in free-fall in a vacuum. Given that the skydiver is in a vacuum, he would fall without experiencing any sensation that he was actually falling as there would be nothing to resist his fall. The free-fall condition is in effect what a suborbital space tourist would experience after engine cut off.

The reason suborbital spacecraft experience a limited amount of microgravity time is due to the fact that they quickly begin to fall and interact with the upper atmosphere, resulting in forces acting against the aircraft, and in turn exerting forces on its passengers. In Figure 2.5 a simplified suborbital flight can be seen depicting the period of microgravity achievable at the edge of space where the atmosphere is thin.

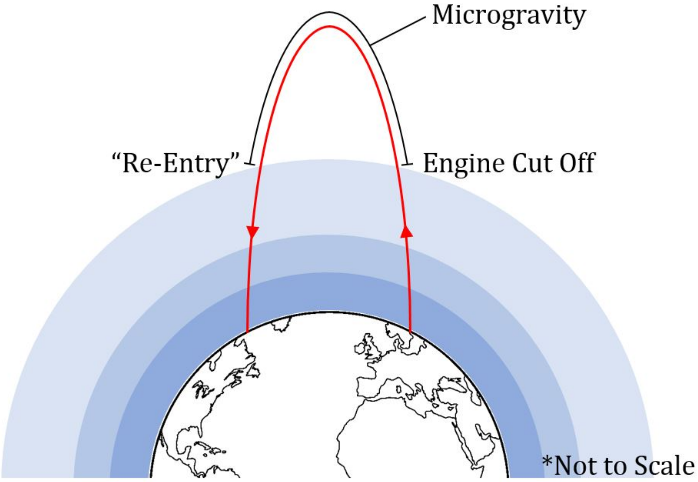

Figure 2.5: Visualization of a suborbital flight. Microgravity is experienced after main engine cut off until the spacecraft begins to fall back to earth and interact with the denser lower atmosphere

Suborbital flight is defined as any flight which reaches an altitude of 100km, and completes less than one complete orbit around earth. Suborbital flights are not limited to modern space tourism, but include high performance military aircraft and were a fixture of the early space race, with Alan Shepard, the first American in space experiencing a suborbital flight lasting 15min 28s[14].

What differentiates suborbital and orbital flight is the addition of large enough velocity component to enter orbit, the orbital velocity. With the addition of a second major force one needs to consider the astronauts position with respect to time.

In Figure 2.6 one can consider that it takes *t* time to go from position 1 to position 2. During this timestep, an object in orbit will have fallen the distance equivalent to the green line due to the force of gravity. At the same time, the object will travel the distance of the blue line due to the orbital velocity. The net result of these two motions is the *actual path* and can be seen as the segment of the orbit between position 1 and 2. From this it can be seen that an astronaut in space is not actually "floating", but instead perpetually falling towards earth while missing earth due to its orbital velocity.

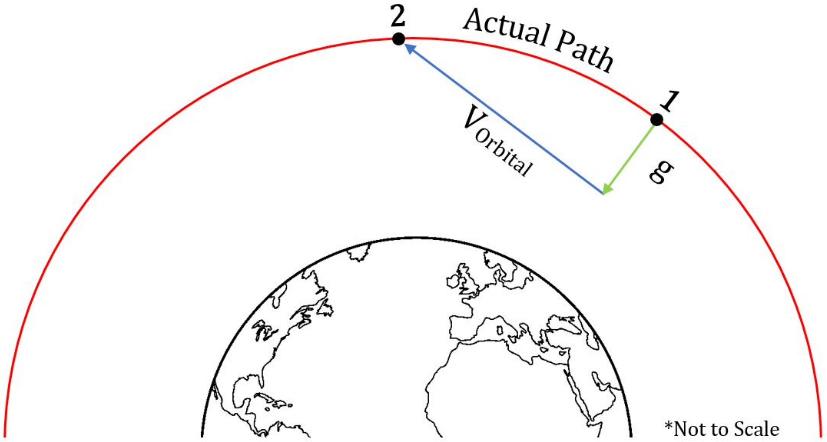

Figure 2.6: Visualization of an object in orbit. So long as orbit is maintained, the microgravity environment will continue to exist

The weightlessness experienced by astronauts in space can be mimicked on earth for short periods of time aboard an airplane flying in a parabolic trajectory. These airplanes, nicknamed “vomit comets” from their stomach churning flight path, provide from 20 to 30 seconds of microgravity depending on the company. Despite the nausea and potential medical side effects, parabolic flights are performed by space agencies and private companies around the world, and are regularly used for research, astronaut training, and thrill seekers.

To achieve the microgravity, the planes travel to a designated location, often an offshore circuit, before beginning the flight manoeuvres. Once in position, the planes accelerate upwards at a 45° pitch angle before adjusting their attitude to generate no lift. Without lift, the only forces acting on the plane are gravity and air drag which is counteracted with careful engine thrust, leading the plane to travel in a parabolic arc as seen in Figure 2.7 from which the name *parabolic flights* derives. Once the plane is over the top and approaching 45° nose down, the pilot slowly re-engages the wings and pulls the airplane out of its nose dive and back up to prepare for another round of microgravity during which the passengers will then experience up to 1.8G’s[15]. These manoeuvres are repeated with some exceptions on average 10 to 40 times and along with being able to simulate 0-G, can also simulate negative, Lunar and Martian G-forces by adjusting the angle of attack at the top of the parabola[15][16][17][18].

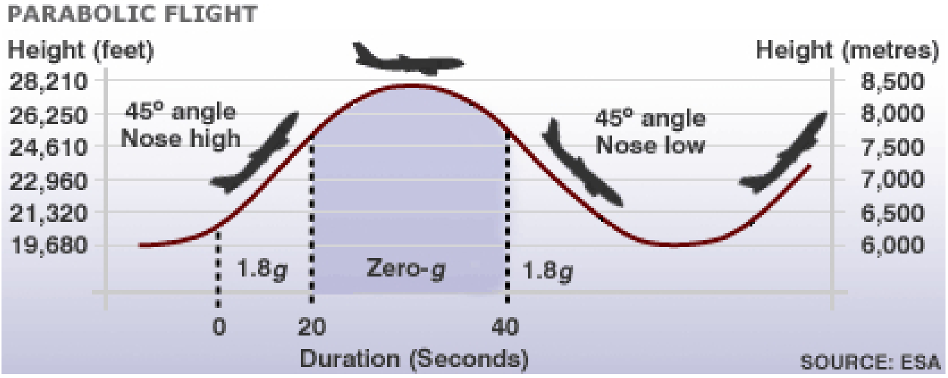

Figure 2.7: Visualization of a parabolic microgravity flight[19]

2.4 Fighter Pilots

As doctors in the 1930's and 40's began to understand how high-G manoeuvres led to a risk of unconsciousness due to a lack of well oxygenated blood reaching the brain, attempts were made to develop countermeasures. Two successful methods, anti-G suits and the Anti-G Straining Manoeuvre (AGSM), were developed and have been continuously improved upon over the years.

2.4.1 Anti-G Suits

To address the risks of cerebral hypoxia, the idea of using external pressure was proposed to constrict the pilots legs and abdomen. The idea was that by compressing the arteries in the lower extremities, blood flow resistance would be increased, and as a result arterial blood pressure would be higher allowing oxygenated blood to reach the brain. This increase in cerebral oxygenation in turn resulted in an increase in pilots ability to resist G-forces.

Initial designs consisted of several bladders filled with water and worn much like pants to cover the legs and lower abdomen with the idea that hydrostatic pressure would constricting the hardest around the areas farthest from the heart. The water filled bladder was however unpopular amongst pilots due to apparent discomfort and the added weight of wearing them[20].

In response to complaints about the initial designs, new models were developed using pressurized air bladders which connected to a bleed air system in the aircraft cockpit. These pneumatic suits were also found to have the added benefit of being capable of a higher pressurization than the previous water bladder suits, which allowed for an increase of 2.5 to 3G's of resistance. This style is still in use with most high performance aircraft flying today and some models even allow for control of the order in which different bladders are inflated, and to what pressure. These anti-G suits however often have a delay of a second or two between the initiation of a manoeuvre and the onset of the constriction. In rare cases, anti-G suits have also been linked to fractured ribs due to the force of the anti-G suit inflation experienced by the pilots.

Despite the general aversion to liquid bladders and the associated limitations, liquid bladders are still being used regularly today by professional stunt pilots such as those competing in the Red Bull air races[21]. These suits remain effective despite their low increase in G-force resistance largely due to the short duration the G-forces are held for along with the dynamic nature of the race. Furthermore, the air bleed system required for pneumatic suits is extremely costly to install and may not fit or be compatible with the airplanes used in these races.

Astronauts face slightly different circumstances when exposed to micro-gravity, where the sudden absence of gravity means that blood pools in the head. Over extended periods of time, the astronauts natural ability to resist pooling in their legs under normal 1G conditions deteriorates leading to orthostatic intolerance when they return to earth. To address this problem for returning astronauts, the Canadian Space Agency performed a study to test different types of anti-G suits and inflating models and found that the best option may be a pulsatile inflation, much as if the legs were being "milked"[22].

2.4.2 Anti-G Straining Manoeuvre

The Anti-G Straining Manoeuvre (AGSM) is a manoeuvre used by pilots to avoid losing consciousness and allowing them to fly safely under higher G-force loads. The manoeuvre consists of two parts; the tensing of the muscles and the interruption.

To begin, the AGSM should be started prior to the onset of G-forces, and continued until the flight manoeuvre is complete and the forces return to normal. The first step is to tense every skeletal muscle possible, including chest, core, arms, quads, calves, toes and anything else manageable. The tensing is then interrupted and the muscles are relaxed to allow for a breath and for pressure in the chest to drop and venous (deoxygenated) blood to circulate through the heart before re-engaging the muscle contractions[23].

An important component to the breathing motion is to ensure that the lungs are sealed off as well as possible to increase chest pressure and to avoid as much as possible air leaking while the muscles are contracted. This was previously taught with the word "Hook", but has since been replaced by "Hick" or "Hic". The word is used to make the proper movements with the glottis where after the breath is taken, the "Hi..." is said and held at the end of the inhalation closing off the throat for the 3 seconds of muscle tensing before finishing the "...ck" sound as the exhalation to begin the next short breath[24].

2.5 Spacecraft G-Profiles

Over the years many different forms of spacecraft have been developed, from simple one manned capsules to complex undertakings like the Space Shuttle. Due to the difference in launch and reentry methods and approaches, each spacecraft had an individual G-force profile associated with it. To be able to compare the previous literature on the medical effects of G-forces in spaceflight to the suborbital flights proposed today, it is important to determine what forces the astronauts of the time were exposed to.

2.5.1 Soyuz (USSR/Russia)

The oldest launch system family in operation, and only human capable launch system available today to travel to the ISS, the Soyuz first launched in 1967. When seated in the capsule, the astronauts are positioned on their back on the "floor" of the capsule, aligning the Gx vector with the majority of acceleration experienced during launch an landing.

The seating orientation is of particular importance due to the peak sustained forces during launch that can be seen in Figure 2.8 are above the G-force threshold and duration known to cause the onset G-LOC. This orientation allows for the astronauts to remain alert and conscious throughout the flight.

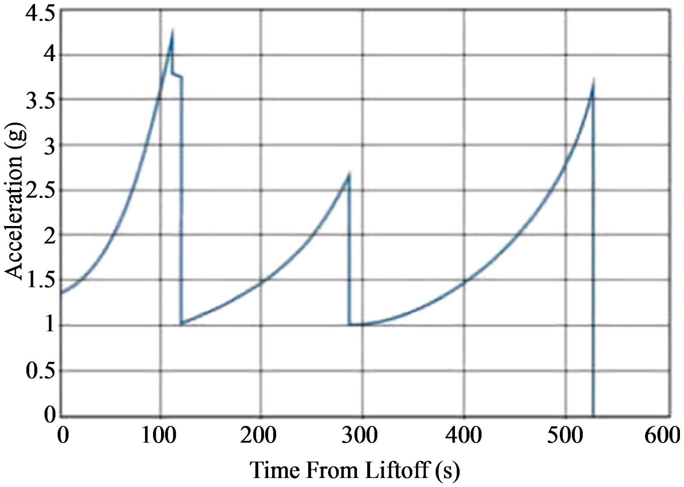

Figure 2.8: Acceleration profile of a Soyuz launch[25]

Similar forces are expected on reentry and can be seen in Figure 2.9, however the Soyuz has several possible reentry profiles to accommodate different situations, with an average reentry peak of around 5G's and a ballistic profile reaching up to 9G's that is used during emergencies to deorbit faster. The soft-landing feature on the Soyuz is also known to not provide a soft landing, however this can be considered an impact force, and not a sustained G-force [26].

Further considerations can be given to off nominal launches where the launch abort system is used. A failure and abort on the launch pad will result in the astronauts experiencing up to 10G's, with an increase in G-forces associated with an increase in flight altitude - an abort at 400s into the flight would result in a maximum of 21G's[27].

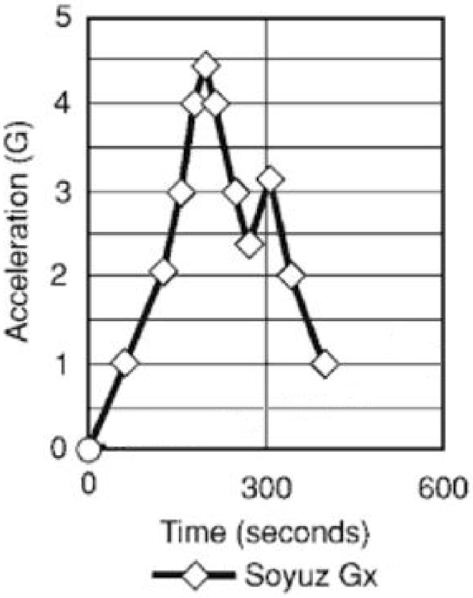

Figure 2.9: Adapted acceleration profile of a Soyuz reentry[26]

2.5.2 Space Shuttle (USA)

From Figure 2.10, it can be seen that the Space Shuttle provided a relatively reasonable launch acceleration profile maxing out at 3G's with a long slow onset.

Figure 2.10 also shows a few key points of the launch, including the solid rocket booster burnout and separation at the end of section D, and the main engine throttling occurring in section F to keep the maximum acceleration of 3G's.

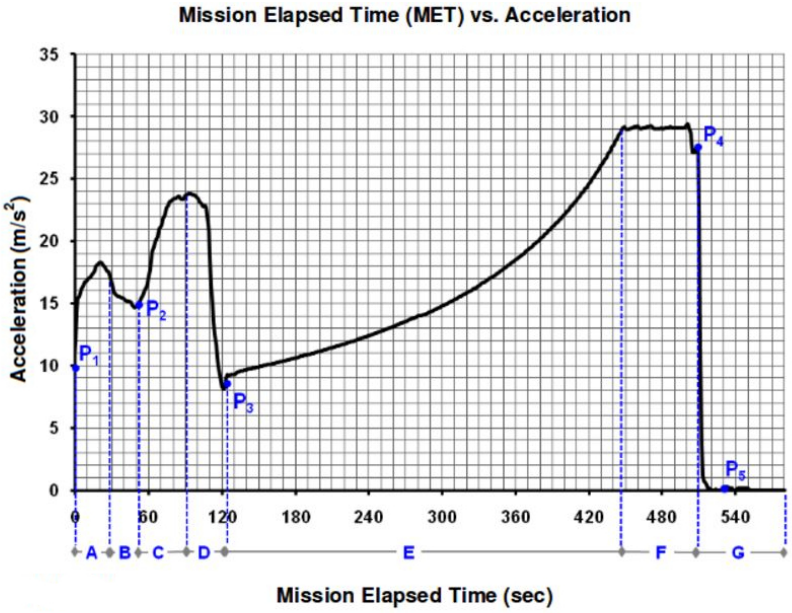

Figure 2.10: Acceleration profile of STS 121 launch[28]

The Space Shuttle alone is unique for its reentry due to the long and low G-forces experienced during reentry reaching a maximum of 1.65 +Gz[26]. These forces are however experienced building up over a period of 20 or so minutes.

2.5.3 Apollo (USA)

The acceleration profiles for the launch of the Apollo missions can be seen in Figure 2.11 and maxed out near 4G's. Astronaut seating positions limited the effects of these sustained and rapid onset G-forces by orienting them via their x-axis.

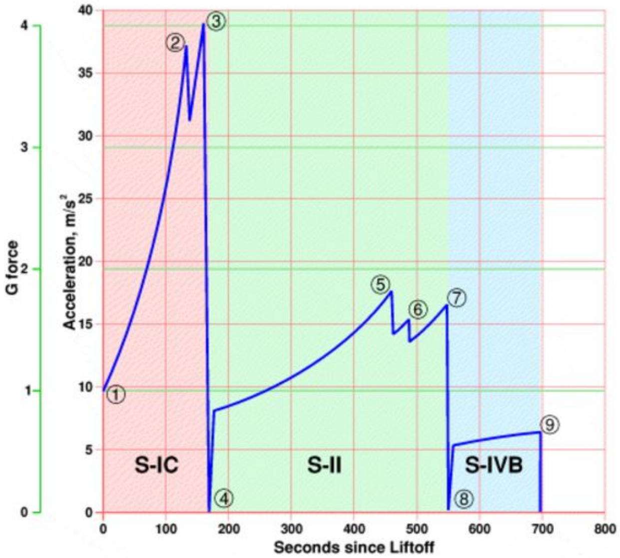

Figure 2.11: Acceleration profile of Apollo 15 launch[29]

Return to earth for the Apollo missions had two different standard reentry profiles. Two missions were flown in earth orbit beginning with Apollo 7 as the first manned launch test, and Apollo 9 which first flew with the Command/Service Module (CSM) with the Lunar Module (LM) and performed testing. Here, reentry G-forces maxed out around 3.3Gx.

The remaining Apollo missions were all lunar missions and resulted in much higher velocities for reentry leading to G-forces in the range of 6.2Gx to 7.2Gx. The sole exception to the standard reentry occurred during Apollo 13, but the G-forces were no more extreme than normal. Comparison between the earth orbit and lunar orbit acceleration profiles can be seen in Figure 2.12 and the maximums for every mission can be seen in Table 2.2.

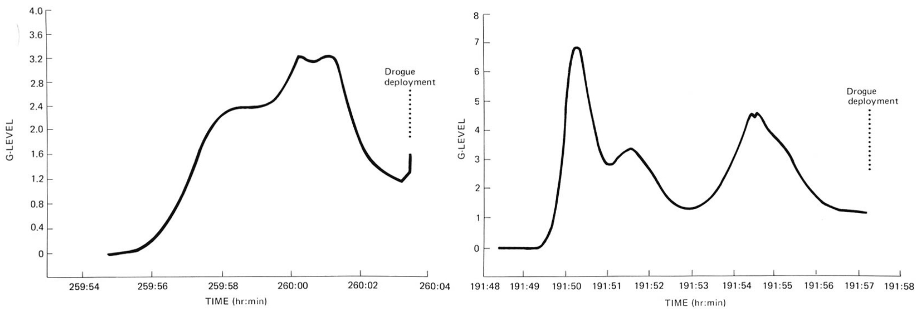

Figure 2.12: Acceleration profile of earth(left: Apollo 7) and lunar orbit (right: Apollo 10) reentry[30]

Flight	**Maximum G at Re-entry**
Apollo 7	3.33
Apollo 8	6.84
Apollo 9	3.35
Apollo 10	6.78
Apollo 11	6.56
Apollo 12	6.57
Apollo 13	5.56
Apollo 14	6.76
Apollo 15	6.23
Apollo 16	7.19
Apollo 17	6.49

Table 2.2: Apollo mission maximum experienced reentry G-force[30]

2.5.4 Mercury (USA)

While no acceleration profiles are available, two peaks were experienced averaging 6.0G for 35s and 6.4G for 54s over a period of 6min during liftoff with peaks of 8G[3]. On top of this taxing launch profile, Mercury project had abort profiles of up to 20G's, and the astronauts trained up to 16G's[31].

Chapter 3

MEDICAL BACKGROUND

Under current rules and regulations, the medical standard that astronauts and pilots must meet to be cleared for flight is extremely high. Furthermore, these individuals receive rigorous training to resist the effects of G-forces and are well versed in the procedures and manoeuvres they must perform. With space tourism quickly becoming a reality, it is likely that individuals who do not meet these stringent medical conditions will desire the opportunity to travel to space. It is therefore important to reconsider the medical risks associated with G-forces in order to assess the risk of G-force exposure for those in non flight-critical positions. The medical conditions discussed below are by no means a conclusive list, but are instead some of the most common afflictions which may result in an increased risk from exposure to G-forces.

3.1 Cardiovascular System

Under normal conditions at 1G, the body is adapted to ensure that blood can be efficiently pumped around the body and deliver adequate oxygenation. When exposed to elevated G-forces however, the circulatory system is significantly affected and the heart is no longer able to circulate enough blood for proper cerebral perfusion. This results in blood pooling in the lower extremities, and can lead to cerebral hypoxia and loss of consciousness if the duration and intensity of exposure to the G-forces is high enough. Many conditions can be related to the cardiovascular system, including the risk of blood colts and coronary artery disease as well as further conditions such as hemorrhagic strokes and cerebral hypoxia which will be discussed later in Section 3.3.

3.1.1 Clots

In a healthy body, blood clotting is a mechanism to stop bleeding and allow the healing process to begin when the human body is injured. Sometimes however, blood clots form inside a vein or artery creating a jelly-like mass made of platelets and fibrin which can partially or completely block blood flow. Blood clots can form for many reasons from sitting on a plane for a longer flight to cancer, obesity, surgery or immobility due to a cast[32].

Blood clots often present as pain, swelling, warmth or skin discolouration, however the real risk often arises if a part of the blood clot dislodges and enters circulation. In particular, if the dislodged particles reach the lungs or brain, the clot can cause life threatening situations and result in pulmonary embolisms or strokes discussed later in Section 3.3.1.

The G-forces experienced during spacecraft launch and reentry may increase blood flow and cause blood to pool in the lower extremities if the G-forces act in the +Gz direction. This may contribute to an increased risk of dislodging a piece of a pre-existent blood clot and allowing it to enter the blood stream. High intensity vibrations during launch and reentry may also pose an increased risk of breaking of a blood clot which may lead to one of the aforementioned conditions.

3.1.2 Coronary Artery Disease

Coronary artery disease (CAD) is the most common cardiovascular disease (CVD) characterized by the narrowing of the coronary arteries. The narrowing is caused by a stiffening of the smooth, elastic interior of the coronary artery and the build-up of calcium and fatty deposits to form a plaque. This plaque can grow slowly over time as seen in Figure 3.1 leading to a decrease in the amount of blood that is able to flow through and reach the heart[3].

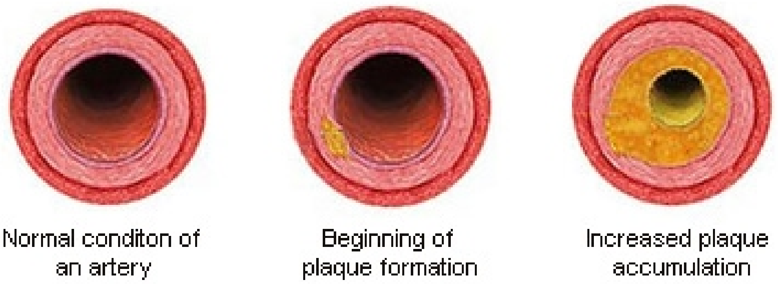

Figure 3.1: Coronary artery disease progression[33]

The presence of CAD can lead to the weakening of the heart muscles due to a lack of well oxygenated blood to certain parts of the heart resulting heart attacks, heart failure, and arrhythmias. Heart failure, the inability for the heart to pump enough blood to meet the body's needs is of particular concern when considering the implications of G-forces on the circulatory system as healthy hearts already struggle to pump enough blood to the brain when exposed to Gz forces. Studies by the WHO have found that CVD causes nearly 32% of all deaths in women and 27% in men, with CAD being the most prevalent causing an estimated 12% of the worlds deaths each year[34].

3.2 Thoracic Cavity

The chest, or thorax is the area between the neck and abdomen, with the diaphragm marking the lower end. The thorax can be subdivided into the thoracic wall which is made up of the spine, ribs, muscles and skin, and the thoracic cavity which includes the heart and lungs.

3.2.1 Heart

The heart provides the pumping motion to create pressure and circulate blood distributing oxygen collected in the lungs to tissue around the body. Once +Gz forces are involved, the heart begins to struggle to overcome the forces trying to force blood into the lower extremities and attempts to increase the blood pressure to try and overcome it. When considering an average person, there is an approximate blood pressure drop of 22mmHg between the brain and the heart due to hydrostatic forces under normal 1G conditions[2]. This means that for each additional 1G increment of +Gz force experienced, the blood pressure at the heart needs to be increased by around 22mmHg to successfully pump enough blood to the brain and avoid cerebral hypoxia.

In order to respond to the increased demand for blood pressure, there are two ways the body can address the need: An increase in cardiac output or an increase in the flow resistance. The increase in cardiac output can be changed two ways, either through an increase in stroke frequency or by an increase in stroke volume. When considering G-forces, it is generally governed by an increase in heart rate which can be considered near instantaneous. The more efficient way however is to increase the flow resistance thereby increasing the blood pressure. This reflex is unfortunately slow to respond and as a result is dependent on the onset rate of the G-forces and is why a high G-force onset rate increases the risk of experiencing A-LOC or G-LOC[35].

3.2.2 Lungs

The lungs act as a transfer mechanism, exchanging out carbon dioxide from the blood stream for fresh oxygen for the body. When in a seated or upright position, pulmonary perfusion is not constant and is gravity dependent[36]. This results in a perfusion gradient as visualized in Figure 3.2.

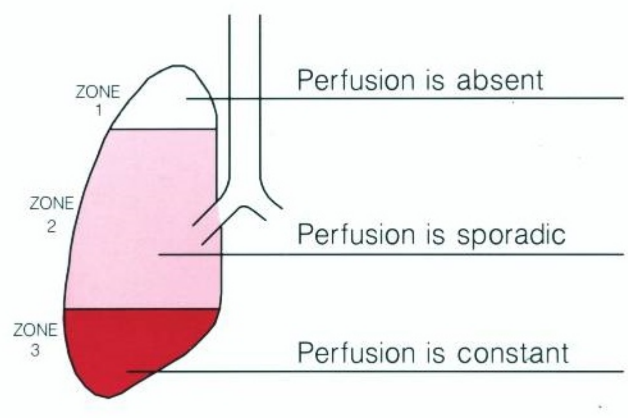

Figure 3.2: Pulmonary Perfusion[36]

When exposed to +Gz acceleration, and in more extreme cases +Gx, the gradient of perfusion is further increased as the blood becomes heavier and the heart struggles to pump against the acceleration. Furthermore, the increased weight as a result of the G-forces means that the alveoli at the bottom of the lungs, the small sacks where oxygen transfer actually happens, become compressed[20]. This means that the lower lung has essentially “collapsed” limiting oxygen from reaching the areas of the lung with the largest perfusion, and is a contributing factor to cerebral hypoxia. While this is not considered a major risk during short G-force exposure, the effects may become apparent during sustained G-forces that last in excess of a minute.

When exposed to +Gx forces, further complications may be experienced with breathing. Due to the increased weight of the chest walls, passengers may feel like they are struggling or unable to properly inhale against the G-forces. This in turn may lead to further complications, such as panic, or in extreme cases an increased chance of experiencing a rib fracture.

Furthermore, conditions such as chronic obstructive pulmonary disease (COPD) must be considered during exposure to elevated G-forces. COPD comes in various forms including emphysema and asthma, and as the name suggests limits the ability of the lungs to function properly. Many of the conditions under the COPD umbrella are linked to conditions experienced throughout life such as the exposure to chemicals or extensive dust and result in damaged alveoli. Due to the decrease in lung function, along with the difficulty in breathing experienced due to +Gx forces, it is likely that such conditions will pose an increased risk to those partaking increased G-force activities.

3.3 Intracranial

The intracranial cavity is located inside the skull and houses the brain, along with the cerebrospinal fluid and the meninges surrounding the brain. Under the effects of G-forces, the brain is among the most affected organs predominantly due to the effects of cerebral hypoxia that occurs when the heart is no longer able to pump enough blood against the increased gravity. Furthermore, G-forces in both the +Gz and -Gz greatly increase the risk of having a stroke.

3.3.1 Ischemic Stroke

An ischemic stroke can be broken down into two root causes, embolic and thrombotic, and is the most common type of stroke accounting for about 80% of all strokes experienced among Caucasians according to the WHO[37][38]. The prevalence of strokes around the world is known to fluctuate depending on location, however complete data from many countries is lacking. Embolic strokes are the result of blood clots which form elsewhere in the body and become dislodged and eventually find their way to the brain where they get stuck. Thrombotic strokes on the other hand are a direct result of a blood clot forming in the brain and impeding the blood flow. The resulting lack of oxygen rich blood flow to certain parts of the brain leads to cell death and can lead to permanent brain damage or death if it is not quickly addressed.

As discussed in Section 3.1.1, pooling blood in the lower extremities caused by high G-forces may lead to an increased risk of part of a clot dislodging itself and entering the blood stream. Furthermore, intense vibrations during launch may further lead to an increased risk of blood clots dislodging themselves and finding their way to the brain.

3.3.2 Hemorrhagic Stroke

A hemorrhagic stroke occurs when a weak blood vessel leaks or a brain aneurysm ruptures. This results in blood flooding the intracranial cavity and putting pressure on the brain tissue which can result in permanent damage or death. Under normal circumstances, hemorrhagic strokes accounts for only 20% of all strokes experienced[39][38].

When under the “eyeballs out” -Gz forces, the heart struggles to pump blood against the force of gravity and blood pools in the head resulting in an increase in blood pressure in the brain. As a result, the risk of a hemorrhagic stroke is greatly increased when exposed to -Gz accelerations as the extra blood pressure may lead to the rupture of any weak blood vessels or brain aneurysms that were semi-stable under normal conditions.

3.3.3 Cerebral Hypoxia

Cerebral hypoxia is the result of the brain not receiving enough highly oxygenated blood to meet its needs. There are many possible causes for this, but of importance is the effects of G-forces leading to the onset of cerebral hypoxia. This occurs as a result of blood pooling in the lower extremities when the body is exposed to elevated +Gz forces and the heart is unable to continue to pump enough blood to the brain. Cerebral hypoxia may lead to many of the conditions discussed in Section 3.5 including A-LOC and G-LOC which poses a severe threat to the safety of pilots. Cerebral hypoxia is not known to cause any permanent damage during sustained G-forces so long as a recovery to normal conditions is quickly made. When the G-forces are sustained on the order of minutes however, cerebral hypoxia may lead to permanent brain damage or death due to a lack of oxygen leading to cell death.

3.4 Skeletal

While incredibly robust, the skeleton is susceptible to an increased risk of injury when exposed to elevated G-forces due to a number of reasons. The risk of breaking or fracturing a bone due to G-forces can be increased by many medical conditions, with osteoporosis being the leading cause of risk.

3.4.1 Osteoporosis

Osteoporosis is a bone loss disease generally found in the elderly that results in a decrease in overall bone density and an increase in the risk of fracture. Unfortunately, osteoporosis is not typically identified by any symptoms until a fracture has occurred. While predominantly found in the elderly, it may be found in rare cases in children and begin earlier for some people in young adulthood. That being said, it should not be mistaken for an ageing disease, but instead an age-related disease.

The effects of osteoporosis can be seen globally, however a distinction in the prevalence can be identified between different ethnic and racial background. The rate of incidence is seen to have a large difference even in areas that are geographically close, with Sweden for example having a risk of a hip fracture by age 50 at 13.1% for men and 28.5% for women while Poland boasts a significantly lower risk level at 2.0% for men and 4.5% for women[40]. A decrease in bone strength and increase in risk of fractures increases exponentially with age in men and women, however the risk between men and women is not equal[41]. According to data from several developed nations, women are around 4 times more likely to experience osteoporosis as men often due to their smaller bone size and faster loss of bone density[42]. Fractures of note for G-force exposure include vertebral and rib fractures.

Causes for osteoporosis are thought to be wide spreading including both pre-existing medical predispositions and modifiable environmental factors. A few contributing factors include anorexia, gastrointestinal disease, decrease in sex hormones, alcoholism, diet, lack of proper physical activity, extended bed rest, chemotherapy, lack of calcium or vitamin D, and the extended use of certain medications[43].

Decreases or changes in the level of sex hormones found in the body often contributes to a decrease in bone mass and the onset of osteoporosis. In particular women experience a rapid decrease in the production of estrogen while going through menopause, and as a result begin to lose bone mass at an increased rate. A similar decrease in sex hormones in men occurs in their early 50's, however the decline is much more gradual[43].

It should also be noted that extended exposure to a microgravity environment has been known to lead to a decrease in bone density, and is regularly experienced by astronauts during extended stays on the ISS. While the risks are low while in space, this can cause problems once the astronauts have returned to earth and their skeleton needs to bear weight again. This is however not of importance during suborbital spaceflight as the microgravity duration is far too short to have any impact.

3.4.2 Spinal

Spinal injuries in high G-force environments make up a significant portion of the reported discomforts and injuries. Proper supportive seating and restraint systems may mitigate the risks of G-force loading on the back in the Gx and Gy directions, but Gz compression loading still bears an elevated risk, along with neck injuries resulting from insufficient head support.

At elevated +Gz accelerations of 8 to 9g during a triennial high G centrifuge training exercise by the Korean Airforce, the incidence rate of acute spinal injury to the cervical and lumbar spinal area was found to be 2.3% among professional pilots[44]. Unfortunately, due to the limits of the age of active duty pilots the study was forced to conclude that while there was no correlation, there was also no consensus on whether age could be linked spinal injury.

Minor injuries were found to be the most common and included cervical and lumbar soft tissue injuries while more severe injuries were less common and included cervical and lumbar herniated intervertebral discs (HIVD). It should be noted however, that herniated disks are often symptomless or misdiagnosed, and as a result imaging must be performed before and after the tests are administered to rule out pre-existing conditions.

Furthermore, it is of importance to consider that the participants in this study are trained professionals, and may be unlikely to report minor injuries or pain due to prior experience or being unwilling to receive a mark on their medical record and risk their flight ready status. This means that it is likely that a group of untrained individuals in a comparable situation may report a higher instance of experienced pain or injury.

Data on the effects of G-force loading is unfortunately only available for trained professionals in their physical prime, and any significant amount of data for untrained or elderly passengers is not available. Spinal disk degeneration and injury risk may be increased by a number of factors including smoking and ageing, and will likely increase the risk of spinal injury to passengers exposed to high risk situations[45][46].

Spinal fractures due to osteoporosis are furthermore a common occurrence and are thought to be present in 35 to 50% of women over the age of 50. While prevalence rates may be high, only around one third are clinically recognized, and many are often misdiagnosed as other ailments. Given the high rate of incidence that can be found in the general population, along with the increased risk of another fracture after experiencing a first, it is possible that the added stress from elevated G-forces will contribute to the risk of suffering a vertebral fracture during launch or reentry of a spacecraft, however research in this area is currently lacking[47].

3.4.3 Ribs

Ribs, much like the spine are at increased risk of suffering from fracture when exposed to elevated G-forces. Numbers were not available to link rib fracture risk related to osteoporosis, however fractures from osteoporosis can occur in any bone in the body[43]. Given that everyday activities can lead to fractures with osteoporosis, it can be postulated that in particular, Gx forces may lead to an increased risk of suffering from a fractured rib. Ribs also face a risk of injury during the inflation of anti-G suits, which have been known to cause rib fractures in healthy individuals.

3.5 Ophthalmology

When exposed to high levels of sustained +Gz acceleration, the body experiences a drop in blood pressure causing a lack of cerebral blood perfusion which can lead to incapacitation, and if sustained long enough, death. The effects from a lack of cerebral blood pressure often presents through the ocular system due to the retinas high sensitivity to oxygen content. This happens when the local arterial blood pressure is no longer higher than the intraocular blood pressure meaning it is unable to perfuse the retina. These anomalies result in no permanent damage to the visual or cognitive systems according to the current body of research on the subject.

Sustained -Gz forces on the other hand result in blood pooling in the head, which can cause permanent damage to the eyes and brain, and may result in serious medical conditions or death.

3.5.1 Tunnel Vision

Tunnel vision, sometimes referred to as greyout, is caused by high sustained +Gz acceleration forces and is the gradual loss of peripheral vision which will slowly narrow down until only the macular (central) vision remains. This happens when the local arterial blood pressure is no longer above the intraocular pressure of approximately 20 mmHg[48] and the difference in pressures results in a reduced retinal blood flow leading to tissue ischemia. The high intraocular pressure is also the reason visual obstructions such as tunnel vision and blackout can occur while maintaining consciousness and why it can be a precursor to more dangerous conditions such as A-LOC or G-LOC.

3.5.2 Blackout

A blackout is the complete loss of vision as a result of G-forces while retaining the use of all other senses. Care must be made to ensure that a blackout is not incorrectly referenced while referring to A-LOC and G-LOC.

3.5.3 A-LOC

A-LOC, or “almost loss of consciousness” is a dangerous state characterized by a decrease in motor functions and cognitive abilities while remaining conscious[49]. While impaired, pilots often fail to be able to take the correct actions, which can result in loss of aircraft control, and crashing. Visual precursors are often thought to be a good way of detecting the approach of A-LOC, however research has shown that this is a poor indicator, and only 58% of reported instances were found to have experienced greyout or tunnel vision prior to entering A-LOC[50]. A high rate of onset may also means that A-LOC or G-LOC may happen without warning.

3.5.4 G-LOC

G-LOC, or “G-force induced loss of consciousness” is a state of unconsciousness lasting 2 to 28 seconds (12 seconds average) as the result of exposure to high +Gz forces, often including a high rate of onset. G-LOC can be visually identified by an observer as a relaxation of voluntary muscle control resulting in a loss of posture which presents as a head and neck slump[49]. Subjects are often unaware that the event has occurred, and sometimes report short, but vivid dreams or dreamlets. The period immediately after the G-LOC is characterized by a state of general confusion and disorientation for a further 2 to 97 seconds (15 seconds average) in which the pilot can be considered incapacitated. The resulting total of 9-110 seconds (28 seconds average) poses an extreme threat to pilot safety, and can result in loss of aircraft and life[3]. Several modern high performance aircraft have automated ground avoidance systems that activate in the event of an incapacitated pilot to avoid crashing.

3.6 Dermatology

A common side effect of high +Gz exposure is the appearance of petechiae or "G-measles" on the lower extremities[51]. Petechiae seen in Figure 3.3 presents itself as small red, purple or brown dots found on the arms, legs and abdomen of fighter pilots and is associated with blood pooling due to the accelerations. The spots themselves are a result in the increase of blood pressure causing capillary blood vessels to burst resulting in a small accumulation of blood under the skin resulting in the blemishes. Petechiae caused by G-forces is not considered to be of danger, and will heal on its own.

Figure 3.3: Petechiae or "G-measles"[52]

Under normal circumstances in healthy people, these spots begin to appear in dependent body parts at anywhere between +5Gz to +9Gz depending on the subjects susceptibility, and acclimatised resistance has been known to occur in professional pilots[53]. The accepted G-force onset limit of +5Gz at which petechiae generally begins to occur may potentially be lowered for elderly citizens, however the data does not currently exist to determine if there is an increased risk in the elderly.

3.7 Cancer

In spite of the lack of direct reports of the effects of G-forces on cancer patients or those who have recently completed certain cancer treatments, some of the known side effects can be expected to have an impact on the passengers safety during suborbital flight.

Chemotherapy treatment presents a host of side effects to be considered including, but not limited to, nausea, easy bruising and bleeding, and an increased risk of bone loss or fracturing[54]. The increased risk of bruising and bleeding may lead to larger or more prevalent petechiae in +Gz accelerations, and an increase in the risk of a hemorrhagic stroke in the case of -Gz. The risk of bone loss may be mitigated in the case of many cancers with the use of specific rugs to address the issue[55].

According to the Harvard medical school, cancer also has an increased chance of allowing deep vein thrombosis to develop[32]. As discussed in Section 3.1.1, blood clots may pose an elevated risk of becoming dislodged due to the G-forces or vibrations experienced during suborbital spaceflight.

Suborbital spaceflight must also address the public fears of travelling through an area of elevated radiation, and the consequent worries passengers may have with respect to it potentially causing cancer. The fears associated with radiation exposure during spaceflight however appears to be unsubstantiated for suborbital spaceflights, as the time the passengers will spend exposed to elevated radiation is negligible. Care should be taken to address the concerns of passengers and provide proper education to alleviate fears.

3.8 Medical Drugs

When considering the ability of an individual to partake in elevated G-force flights, the medications that the patient is currently taking or has recently completed should be considered. This is a particularly important area to consider due to the individual side effects and risks associated with each drug, and thus must all be considered individually. A few of the most common conditions and medications to consider include those used for chemotherapy, anti-clotting medication and blood pressure medication.

3.9 Pregnancy

The effects of G-forces on pregnancy have not been investigated due to the ethical concerns, however there are notes on the potential risk of exposing an unborn foetus the effects of G-forces during bungee jumping, and regulations in place in the US Air Force that a pregnant woman may not fly ejection seat aircraft[56][57]. The foetus itself is encased in liquid which allows for protection against the compression forces experienced during G-forces, however risk remains in the form of elevated blood pressure from the mother along with potentially a lack of well oxygenated blood being available. There is furthermore the potential risk to the mother from the extra mass of the womb and foetus may cause damage to other organs as it is pushed against them. If pregnancy is suspected during the pre-flight physical, a pregnancy test should be administered to avoid potential damage to the unborn baby.

3.10 Supplements

A case has been made by the Aerospace Medical Association for the risks of lower G-force tolerance associated with the consumption of certain dietary supplements[58]. The 2011 case report details the suspected effects a US Navy F/A 18E pilot experienced after starting a new supplement, and subsequent improvement after product discontinuation.

The Navy airman reported a blackout event that occurred during a sustained 5g pull up manoeuvre, and aborted the manoeuvre to retain consciousness. The pilot denied the possibility of a push-pull manoeuvre, and was subsequently medically cleared as healthy and in good shape. A similar episode was reported on his next flight between 4 and 5G's and the pilot immediately returned to base. The medical prognosis was once again clear, however he mentioned he had begun taking a new supplement two weeks prior. An investigation into the supplements components revealed the inclusion of Coenzyme Q10, a banned substance for Naval pilots. The pilot was advised to discontinue the use of the supplement, and cleared for flight a week later. He was subsequently able to easily withstand sustained manoeuvres of up to 7G with no problems.

In the paper, two ingredients, Niacin and Coenzyme Q10 are flagged as worrisome due to their potential medical applications in lowering blood pressure. The author postulates that while the consumed quantities were well below what would be considered a full dose, theses small amounts combined with the stresses of the job were contributing factors to lowered tolerance of G-forces experienced by the pilot.

3.11 Physiological Differences Between Men and Women

According to a paper from the Australian military, small scale studies have not found any major differences in women's ability to withstand G-forces, despite physiological differences including lower haemoglobin counts, and smaller lung parameters[57]. The study did however mention that there may be evidence of a decrease in G-force resistance when comparing heightwise between the sexes. This is however of little consequence due to the large variability in G-force resistance in a homogeneous sample.

Of note for women who have been treated for breast cancer is the increased risk of low bone density due to osteoporosis[59]. This may occur due to the treatment leading to a loss of ovarian function resulting in a potential early onset of menopause, and as a result lowered levels of estrogen.

3.12 Age

No information was available on the effects of G-force with respect to age, however it can be postulated that risk will increase with age due to a number of reasons. In direct relation to withstanding G-forces, the strength needed to properly execute an AGSM will diminish as age progresses directly resulting in a lower G-force threshold. Along with deterioration of strength, many of the above discussed medical conditions worsen or begin to appear with age as well, significantly raising the medical risk for more senior passengers and flight crew on suborbital space flights.

Chapter 4

METHOD

Blue Origin and Virgin Galactic are unique in the fact that they take solutions from opposite ends of the spacecraft spectrum to accomplish the same goal. Blue origin takes a more conventional approach, using a rocket and capsule to reach space, while Virgin Galactic takes advantage of a mothership to lift their spaceplane up above the dense lower atmosphere before launching it to space.

4.1 Spacecraft Specifications

Prior to beginning analysis of the Blue Origin and Virgin Galactic spacecraft to determine their G-force profiles, the initial measurements of the spacecraft need to be determined. This may be completed in a number of different ways depending on the available data, and if no published numbers are available, calculations will need to be made.

4.1.1 Blue Origin

The Blue Origin spacecraft is a surface launched capsule spacecraft capable of bringing 6 passengers up to 100km in altitude and allowing them to experience up to four minutes of microgravity. Reentry is performed much like the current Soyuz spacecraft using parachutes to safely return the capsule to the ground.

Despite the endless publicity and ample exposure, Blue Origin has no published numbers for the size of the "New Shepard" launch configuration. Their website however boasts they will have "the largest windows in spaceflight history"(Figure 4.1) with window nearly 108.5cm high and 72.5cm wide[60].

Figure 4.1: Blue Origin window size[60]

From this, it is possible to perform image analysis on a picture of the capsule in production. Using the picture in Figure 4.2 it is possible to determine the dimensions by finding the pixel to length ratio. To account for the point of view of the camera, the height of the front and rear windows can be averaged to find their height in pixels as if they were situated on the side, where the widest point is. Finding that the average window height would be 720px, and equating it with the height of 42.7" from Figure 4.1, an estimate of the base diameter can be found to be around 134". Given the inexactness of the estimates and when compared to similar estimates found online, a round number of 132", or 11' will be used.

Figure 4.2: Blue Origin image analysis[61]

4.1.2 Virgin Galactic

Virgin Galactic's launch system comprises of a two-stage launch sequence with a mother ship and a space plane as seen in Figure 4.3. Initially, the spacecraft "Space Ship Two" is attached to the center of a larger mothership called "White Knight Two" which is a custom designed dual hull fixed wing aircraft. The White Knight Two is used to carry the spacecraft from a runway and deliver it up to an altitude of 15km before it releases the spacecraft. The spacecraft then fires its rocket propulsion system taking it up to space. Reentry is completed by gliding back to the runway much like the Space Shuttle.

Figure 4.3: Model of “Space Ship Two” mounted to the mothership “White Knight Two” as seen from below[62]

Dimensions for Space Ship Two have a cabin diameter of 7 foot 6 inches and a length of 12 feet, and an exterior wing span of 27 feet and a length of 60 feet. The personnel capacity of the Virgin Galactic spacecraft is slightly larger than that of Blue origin, allowing for the seating of six passengers along with two crew members.

4.2 Video Analysis

Given that the acceleration profiles of the Virgin Galactic and Blue Origin spacecraft are not public knowledge, other methods for analysing and determining the acceleration profiles was needed. To obtain the data needed to create the G-force flight profiles, video footage covering large portions of the flights was found and video analysis was performed in various methods depending on video source.

4.2.1 Blue Origin

To determine the acceleration profile for the Blue Origin spacecraft, two video analysis methods were used. The initial approach was to perform frame by frame video analysis and measure the displacement of the spacecraft against the background.

To make frame by frame analysis viable, the dimensions of the spacecraft first needed to be found as done in Section 4.1.1 in order to determine how many pixels were equivalent to what distance. Test launch video was then broken down and every fourth frame was extracted. Using the knowledge that the capsule was 11 feet wide, it was found using the test footage that 1 pixel is equal to 0.039m. From analysing the extracted frames, the pixel to distance ratio could be used to determine how far the spacecraft had advanced for the interval. Once the displacement data had been extracted and tabulated, the velocity could be calculated using the timestep, and in turn the acceleration can be found. An annotated frame from the video analysis can be seen below in Figure 4.4

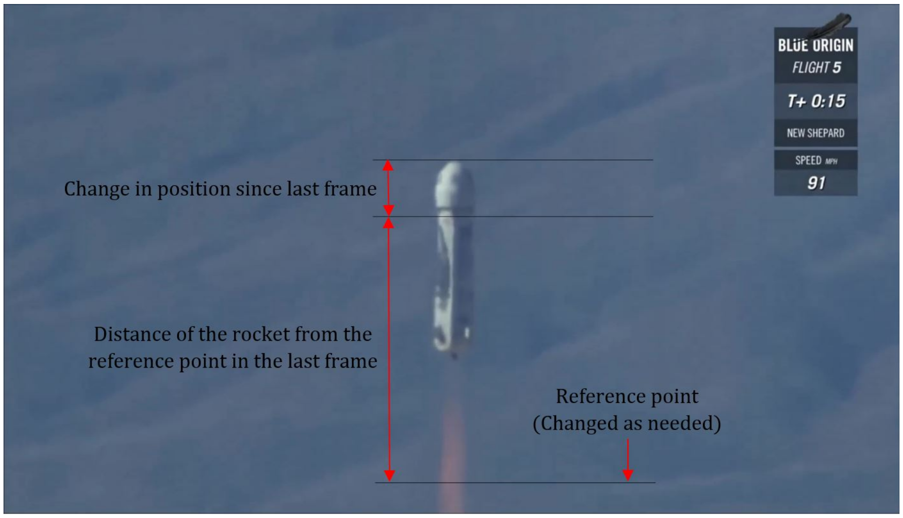

Figure 4.4: A visualization of the method one frame by frame video analysis of a Blue Origin test launch. The speed readout in the upper right was used for analysis method two[63]

Several factors however were found to decrease the level of accuracy below an acceptable range including atmospheric disturbances, video resolution, change in observation angle and insufficient background reference points during certain segments of flight. The atmospheric disturbance was not visible during regular video playback, however once the footage was parsed, the frame by frame difference was readily apparent. This resulted in the calculated displacement being very large between some frames while a subsequent interval would find a very small displacement. This condition is likely due to a combination of the heat in the desert environment as well as the fact that the cameras had to be placed very far away to provide safety for the crew as well as to accommodate for the focal length of the lens so it could be used from launch to apogee in one continuous shot.

Furthermore, when combined with the atmospheric disturbances, the low resolution of the video, along with the lack of clearly defined (blurry) edges on the spacecraft led to difficulties consistently selecting reference points accurately. Difficulties selecting reference points on the rocket was compounded by the fact that the perspective on the rocket was changing as it rose in altitude, meaning that the reference points changed, and the ratios were no longer the same lengthwise along the rocket.

To address the shortcomings of frame by frame analysis a second method was applied to take the speed readouts provided throughout the video. This method was initially not used over concerns about breaks in the footage where the speed did not update for a period of the flight along with the worry that Blue Origin may have been distorting the readout to protect proprietary information.

Once the flight data was extracted for the duration of the flight, the acceleration could be calculated and the G-force profile plotted. This method allowed for the profile to be developed from launch to main engine cut off at which point the microgravity experience began. Data on the G-forces during reentry was not able to be recovered due to the videos focusing on the landing of the first stage, not the crew capsule.

Time (s)	**Delta T (s)**	**Speed (MPH)**	**DeltaV (m/s)**	**G-force**
25.00	0.25	296	2.235	1.911
25.25	0.25	298	0.894	1.364
25.50	0.25	302	1.788	1.729
25.70	0.25	305	1.341	1.546
26.00	0.25	309	1.788	1.729
26.25	0.25	312	1.341	1.546
26.50	0.25	315	1.341	1.546
26.75	0.25	319	1.788	1.729
27.00	0.25	322	1.341	1.546

Table 4.1: Example excerpt of the data collected from Blue Origin

To address the glitches in the live feed where the velocity did not update, a linear progression was added to replace the corrupted data. This resulted in a clean data set from which the G-force profile could be plotted.

4.2.2 Virgin Galactic

The Virgin Galactic "Space Ship Two" provided a unique challenge compared to Blue Origin due to the fact that they did not provide a live speed readout and nearly all footage available was shot from beneath against a clear, blue sky background. This meant that no background reference points could be used to calculate how fast the spacecraft was going, and by extension determine the G-forces the occupants may experience.

Fortunately, footage of a training centrifuge ride was found which had G-force readouts for both Gx and Gz forces. Much like with Blue Origin, the video was parsed and a frame was extracted every quarter-second from which the Gx and Gz data was catalogued.

Figure 4.5: A frame from which the G-force data was extracted to develop the G-force profile[64]

Before the data could be plotted, several considerations and adaptations had to be made. Firstly, the microgravity environment which generally fills the center portion of the flight could not be replicated in the centrifuge leading to a readout which was not zero. This meant that the data approaching and leaving the microgravity period had to be estimated. Furthermore, to speed up the simulation and avoid boredom of the passenger in the centrifuge, the microgravity period appears to have been shortened during the simulation resulting in a microgravity interval which was too short. The interval was increased manually in the data in order to match more realistic flight conditions based on the expected length of the microgravity flight.

This data ended up providing additional insight into the G-forces experienced by the passengers due to the reconfiguring seats which change depending on what part of the flight they are in. The changing seat configuration is designed to limit the G-forces experienced by the passengers, and will greatly change the effects of the G-forces versus to assuming static seating.

Time (s)	**Delta T (s)**	**Gz**	**Gx**
35.00	0.25	3.3	2.7
35.25	0.25	3.4	2.7
35.50	0.25	3.4	2.7
35.75	0.25	3.4	2.7
36.00	0.25	3.4	2.7
36.25	0.25	3.5	2.7
36.50	0.25	3.5	2.7
36.75	0.25	3.5	2.7
37.00	0.25	3.5	2.7

Table 4.2: Example excerpt of the data collected from Virgin Galactic

Chapter 5

RESULTS

The data acquired in Chapter 4 was plotted to develop the G-force profiles of the Blue Origin and Virgin Galactic spacecraft seen below in Figure 5.1 and 5.2. These graphs are formatted to have mission elapsed time along the bottom on the x-axis while the G-forces experienced are measured on the y-axis.

5.1 Blue Origin

In the results for Blue Origin in Figure 5.1, the “New Shepard” spacecraft is found to experience a maximum G-force of proximately 3G’s during launch. The seating configuration for Blue Origin is unknown however, resulting in the inability to determine the angle through which the G-forces will act on the passengers. Consequently, a worst-case scenario must be assumed where the G-forces act entirely in the Gz direction. In a more realistic attempt to assess the situation, some assumptions can be made based on available renderings of the “New Shepard” interior. Estimates can be made for different seating configurations such as a reclination angle of 45° in which case Gx and Gz would both be a reasonable 2G’s or 90° where the G-forces would be entirely Gx.

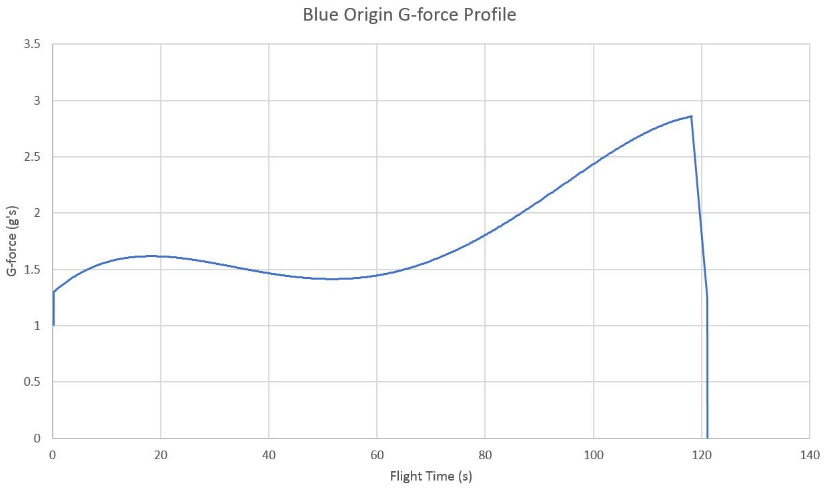

Figure 5.1: G-force profile for Blue Origin

Due to the limitation in the video footage available, the reentry profile for the "New Shepard" spacecraft cannot be determined in its entirety. It has however been noted during a live feed of a Blue Origin test launch that the G-forces momentarily peak around 5G's during reentry[65].

To corroborate the results, it is possible to perform some basic math on the data acquired and find out at what altitude the engine cuts off. From there, using the known peak velocity, it is possible to calculate how far the spacecraft will continue to travel. This finds that the spacecraft travelled proximately 90km, however there is some discrepancy as the data was extracted until the spacecraft began to decelerate, but powered flight continued for a few seconds after this. This extra powered at just over 1km/s flight time is sufficient to bring the total distance covered to near 100km, the actual expected altitude.

5.2 Virgin Galactic

The Results for Virgin Galactic provide a much deeper insight accounting for both Gx and Gz acceleration components. Unlike the results from Blue Origin, Virgin Galactic provides a full acceleration profile from the point of mothership release until reentry is complete. To lessen the risks to the passengers, the Gz forces are seen to be minimized by careful manipulation of dynamics seats to ensure that the largest and longest sustained forces act through the Gx axis.

Looking at the G-force curve for Virgin Galactic in Figure 5.2, the G-force spikes can clearly be linked with their associated phases of flight. To begin, during the launch phase the seat is in an upright position aligning the passengers Gx axis with the direction of flight. The first drop on the plot where Gz forces to zero is where the mothership releases the spacecraft resulting in approximately 4 seconds of free fall. This produces a near weightless state for the passengers before the rocket booster kicks in. On booster ignition, the passengers will be pushed back into their seats (Gx) as the rocket accelerates for the duration of the rocket burn. Simultaneously, the spacecraft will pull up to change its trajectory from an initial horizontal flight to vertical flight away from earth surface heading towards space. This turn will apply centrifugal force to the passengers in the Gz direction which can be seen as the shorter spike during the launch phase of the spacecraft.

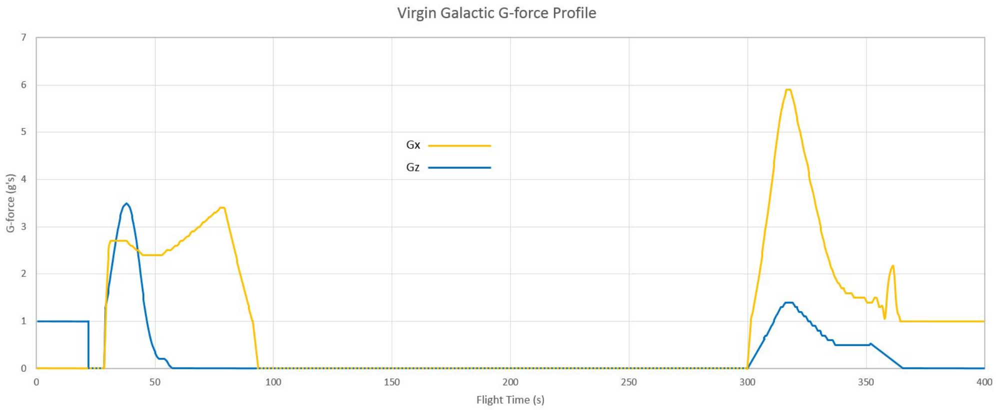

Figure 5.2: G-force profile for Virgin Galactic

Booster cut off will signal the beginning of the microgravity experience and the seats will recline out of the way to allow for an estimated four minutes of weightlessness. Upon completion of the microgravity flight segment, the passengers will strap themselves into their reclined seats.

To reenter earth's atmosphere and return for landing, the spacecraft begins by falling straight down belly first towards earth. As it falls, the spacecraft begins to interact with the atmosphere which drastically slows down the descent of the spacecraft attributing to the large G-force spike in the decent stage. The purpose of reclining the seats during reentry is to ensure that the high G-forces experienced as the spacecraft decelerates against the atmosphere are in the preferred Gx direction. Once enough speed has been shed, the wings will feather allowing the spacecraft to transform into a glider and return to the runway from which it was launched.

It should also be noted that industry rumors exist stating that the +Gz forces experienced during the launch of the spacecraft are in reality much higher at +5Gz, and that the centrifuge tests are modified to keep the maximum Gz's low to avoid loss of consciousness.

Chapter 6

DISCUSSION

When comparing the G-forces between the two spacecraft, the launch and reentry must be compared separately. From the data accumulated, it can clearly be determined that Blue Origin exerts much lower peak G-forces during launch when compared with Virgin Galactic. This can likely be attributed to the fact that the Blue Origin spacecraft has 15 vertical kilometres more distance over which it can accelerate and build up speed. This is a result of Blue origin choosing to launch the spacecraft from the ground while Virgin Galactic uses a mothership to launch their spacecraft from an altitude of approximately 15km. Conversely, the longer distance to travel means that these lower G-forces are sustained much longer, a total of just over 120 seconds compared to Virgin Galactic's 70 or so seconds of rocket powered flight.

While the Blue Origin reentry profile is not known, G-forces in a best-case scenario will result in elevated G-forces in the range of 5Gx to 6Gx and worse case 5Gz for Blue Origin. Assuming the best case, the Gx loading forces are reasonable and should not pose any risks of loss of consciousness.

The differences observed are largely a result of the spacecraft launch design trade-offs that were made by each company. Blue origin for example is able to mitigate the peak G-forces experienced by the passengers by allowing for a longer acceleration distance with a takeoff from the ground. This means however, that the spacecraft must contend with having to pass through the dense lower atmosphere under fuel intensive rocket power. The huge fuel demand presented by this means that the majority of the mass of the launch vehicle must be dedicated to fuel leaving only a small capsule to reach space and a parachute to land. The parachute itself may also pose an interesting consideration when opening, as it may induce a short but significant G-force event. This event is however largely dependent on the altitude and speed at which the parachute deploys, along with how it unfurls.

Virgin Galactic on the other hand uses a mothership to lift their spacecraft up above the dense lower atmosphere, and as a result needs much less fuel to achieve their target altitude. This also means that their spacecraft can dedicate a much larger percentage of the total flight mass to crew area, and is able to incorporate wings which allow for a controlled landing on a runway. As a result of launching higher, dedicating less structural mass to fuel storage and saving on fuel costs, the spacecraft however needs to perform a 90° direction change under rocket power and accelerate over a shorter distance. This in turn results in the higher observed G-forces experienced by pilots and passengers on this spacecraft.

From a medical standpoint, the G-forces experienced on both spacecraft are reasonable when compared to the forces professional astronauts and fighter pilots are trained to operate under. Considerations for different demographics within the population however are less conclusive. This is due to the majority of the research being centred around fit males in their medical prime who make up the large majority of the employees in G-force related occupations.

In particular, age consistently stood out as the single largest unknown when considering the effects of G-forces on a multitude of medical conditions and diseases. This is a result of the limited average demographic of those working in high G-force environments, thus limiting the extent of the research performed. Alternately, many of the diseases and afflictions can be determined with confidence to pose an elevated risk of injury or death despite the lack of direct research into the matter. Those with advanced osteoporosis for example, can be considered a higher risk as it is known that simple movements in everyday life are sufficient to cause fractures.

The diseases and conditions covered in Chapter 3 should all be considered during the pre-flight medical clearance. Particular care should be made to assess for cardiovascular disease, pulmonary disease and osteoporosis, particularly if a family history exists, as well as ongoing or recently completed cancer treatment and unknown pregnancies. Many external factors such as smoking and even the consumption of certain off-the-shelf supplements have been linked to a reduced ability to resist the effects of G-forces. This can in turn lead to an increase in the chance of experiencing symptoms such as tunnel vision, greyout, blackout, A-LOC or G-LOC during launch or landing and result in a state of disorientation which may cut into or reduce the passengers ability to enjoy or partake in the limited time spent in the microgravity environment. Furthermore, clients should be made aware of the risks associated with the elevated G-forces experienced during the flight, and prepared for the medical side effects they may experience such as nausea and disorientation during the flight, and the possibility of developing petechiae.

Despite decades of research into the effects of G-forces on the human body, there is still a large gap in the understanding of many of these diseases in the larger population when G-forces are considered. As a result of the lack of direct research to support the risks of various diseases on different demographics of the population as a result of G-forces, the pre-flight medical clearance should use a level of discretion to assess the risks for each individual. Post-flight physicals should also be considered both to ensure the safety of the passengers, and with permission, to allow for data to be collected to further the understanding of G-forces on the various demographics.

Chapter 7

CONCLUSIONS

The G-force profiles developed in Figure 5.1 and 5.2 show that the G-forces experienced during launch and reentry are constrained to reasonable Gx and Gz components when compared to previous human capable manned launch systems. From the G-force graphs, it can be seen that during launch the maximum G-force experienced in nominal flight conditions is around +3Gz to +3.5Gz, and is rumored to be higher for Virgin Galactic, peaking around +5Gz. This elevated Gz force is high enough and sustained long enough that it is likely that some passengers will experience G-LOC without the use of AGSM or anti-G suits. If the rate of onset is in excess of 1G per second, even trained professionals will reach their lowered G-force tolerance. Sustained elevated Gx is also present for well over a minute which may result in passengers feeling like air is being forced out of their lungs and they are struggling to breathe.

Contrary to popular belief, the reentry will exert much higher G-forces on the passengers than the launch, however this will be for the large part translated to Gx forces eliminating the risk of G-LOC. Many passengers will again experience trouble with breathing, particularly while inhaling as they must work against the weight of their chest which may be up to 6 times heavier than they are used to. This will be particularly difficult for those with COPD who may experience increased complications of their condition and struggle to breath.

Due to the limited demographics on which G-force research has been performed, the exact risks of G-forces are unknown for large parts of the population, particularly with respect to ailments which present later in life. Despite the lack of actual data, common conditions such as cardiovascular disease, blood clots and osteoporosis will pose a large risk particularly with more senior passengers. Many diseases and conditions which are often a part of everyday life become much more dangerous when G-forces are involved, leading to an increased risk of injury or death. As a result, medical flight guidelines must consider the risks associated with diseases based off current understanding, and estimate the potential effects each disease will have based on the knowledge available.

Chapter 8

FUTURE WORK

Many, if not all of the medical conditions considered lack research and data for large swaths of the population. To date most research affecting G-forces has been focused on healthy, fit men in their prime due to the demographics who make up a large part of the space programs and air forces performing these tests. Limited research with small numbers has been performed in some areas for women, and no research is available to consider the ramifications for elderly people. Ample research opportunities exist to investigate any number of the above mentioned medical conditions with respect to both sex and age to create a more homogeneous understanding of the general population. Fortunately, data will likely begin to accumulate once suborbital spaceflight tourism begins, and new insights into the effects of G-forces on different conditions will likely become apparent. Opportunities however to test or obtain data under controlled conditions in a human centrifuge may be hard to come by due to the ethical considerations of exposing test subjects needlessly to such conditions.

From the spacecraft perspective, the knowledge of certain parameters including the seating angle in the Blue Origin spacecraft would allow for more accurate conclusions to be drawn from the G-force profiles. Measurements for the seating could allow for determining through which axis the G-forces will act on the human passengers, and by extension determine the risks associated with the G-forces.

With respect to Blue Origin again, there is still a gap in the data for the capsule reentry of which no complete video footage exists to date. While it is known that the reentry peaks around 5G's the onset rate and duration of the experienced G-forces is still unknown. This presents an opportunity for a more complete G-force profile to be developed at a later date in conjunction with the knowledge of the seating configurations to determine Gx and GZ components should it become public knowledge. The publication of full G-force data by either launch provider could be used to make more accurate safety judgements and verify that the G-force profiles that have been developed are an accurate representation of reality.

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