The Capstone Committee for Leigh Lewis certifies that this is the approved version of the following capstone:

Measurement of Head Acceleration and Angular Rate Experienced by Aerobatic Pilots

Committee:

Richard Jennings, M.D., M.S., Chair

James Vanderploeg, M.D., M.P.H.

Jonathan Clark, M.D., M.P.H.

Dean, Graduate School

Measurement of Head Acceleration and Angular Rate Experienced by Aerobatic Pilots

By

Leigh Ellen Lewis, MD

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I owe many thanks to my research team.
Pictured above: Pat Puzzuto, Sherry Puzzuto,
myself, and Dr. Charles Mathers
(Not pictured Dr. Kathleen Samsey)

Measurement of Head Acceleration and Angular Rate Experienced by Aerobatic Pilots

Leigh E. Lewis, MD, MPH

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Background: Aerobatic pilots are exposed to high levels of positive and negative G's which can be associated with career-limiting neurovestibular effects including "the wobblies." Extensive research has been conducted on the effects of positive G's in centrifuge experiments. Gz tolerances have been quantified for gray-out, black-out, and G-LOC. G-induced vestibular dysfunction or "the wobblies," though not yet well studied, is thought to affect many aerobatic pilots who are exposed to high levels of negative G's. Neurovestibular symptoms induced during flight can increase the risk of loss of aircraft control. The actual G forces experienced at head-level in aerobatic pilots have never been characterized, and this study intends to solve this knowledge gap. **Methods:** Five volunteers at the 2009 US National Aerobatic Championships were fitted with tri-axial accelerometer and angular rate earplug sensors. A second tri-axial accelerometer and angular rate sensor package was fixed to the plane. For each subject, data were collected from the two synchronized sets of hardware during a 10-minute practice session. The recordings of the maximum and minimum G values were also obtained from the aircraft's G-meter. **Results:** The maximum and minimum values obtained from the sensors measuring linear acceleration and angular rates from the pilot and the plane were well-correlated. Paired t-tests demonstrated no significant difference between head-level and plane mean linear acceleration. Angular velocity means were mixed. The Gz accelerometer values of the pilot and the plane correlated very closely with the plane's G-meter. **Conclusion:** Aerobatic pilots experience a large range of positive and negative accelerations, which appear to correlate well to those of their aircraft. Data can be successfully collected and correlated using tri-axial accelerometers and angular rate sensors. Future work in this field may involve clinical modeling of G-effects based on head-level accelerations and angular rates.

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List of Abbreviations

A-LOC	Almost loss of consciousness
BPPV	Benign Paroxysmal Positional Vertigo
deg/s	Degree per second
DTS	Diversified Technical Systems
g	Acceleration due to gravity, 9.8 m/s^2 on earth
G	Unit-less ratio of acceleration divided by g
GIVD	G-induced vestibular dysfunction
G-LOC	G-induced loss of consciousness
IRB	Internal Review Board
MD	Medical Doctor
MPH	Master of Public Health
NASA	National Aeronautics and Space Administration
NCSS	Number Cruncher Statistical System
NSBRI	National Space Biomedical Research Institute
NTSB	National Transportation Safety Board
UTMB	University of Texas Medical Branch

Introduction

Accelerometer data is currently being collected in a variety of venues. The automotive industry developed much of the instrumentation currently in use for recording acceleration data during impact testing. Data obtained from crash test dummies and automobiles have shaped how cars are built today. With time, accelerometers have decreased in size and are now so compact that they can be contained within plastic-molded ear plugs. This advancement has allowed additional human impact limits to be established. For example, in-ear accelerometers have recently been utilized to measure accelerations experienced at head-level in race car drivers, football players, and boxers. Impact models have also been established that can predict the neurological consequences of collisions at various accelerations.

Sharmila Watkins, MD, MPH devised the application of this technology to rodeo riders in her capstone, "Measurement of Accelerations Experienced in Rough Stock Riders."[1] Using tri-axial ear-molded accelerometers and angular rate sensors, she obtained data from a bull rider and from a bareback bronco rider during the 2007 Houston Livestock Show and Rodeo. Chuck Mathers, MD, MPH continued this research at the 2009 Houston Livestock Show and Rodeo.[2] Both investigators have demonstrated that earplug accelerometers can effectively measure the accelerations experienced by bare-back bronco and bull-riders.[1,2]

Aerobatic pilots are also exposed to a wide range of positive and negative G forces. Although in-flight accelerations are not due to impact, at times these forces can cause neurovestibular symptoms. Gray-out, black-out, and G-induced loss of consciousness can occur from exposure to high positive Gz. Feelings of vertigo or gait abnormalities may represent G-induced vestibular dysfunction or “the wobblies.” This condition seems to be correlated with negative G’s in the z-axis, but has not been fully characterized. While G-tolerances have been studied in centrifuges, the actual forces experienced at head level during aerobatic flight were unknown.

This area of study could be further characterized by utilizing the same accelerometers to measure the accelerations experienced by aerobatic pilots. The specific aims of this study were to: 1) measure the magnitude of linear accelerations and angular rates experienced at head-level by aerobatic pilots and 2) compare data obtained at head-level to that of the plane. Future work in this field may involve clinical modeling of non-impact G-effects based on head-level accelerations.

Background

2.1 Safety

Aerobatic maneuvers require skill, coordination, concentration, and practice on the part of aerobatic pilots. Deviation from appropriate flight control inputs can be disastrous. Although general aviation accidents from 1996 to 2005 have shown some decline, as noted in Table 1 below, injuries and fatalities during flight represent an important public health concern to individuals on the ground.[3] In 2005, 1,670 general aviation accidents representing 79% of all aviation accidents were reported by the National Transportation Safety Board (NTSB). Based on survey data, this equates to 7.20 accidents and 2.4 fatalities per 100,000 hours flown.[3] These values become alarming when compared to airline data in which 0.182 accidents and 0.016 fatalities occurred per 100,000 hours flown for the same year.[4]

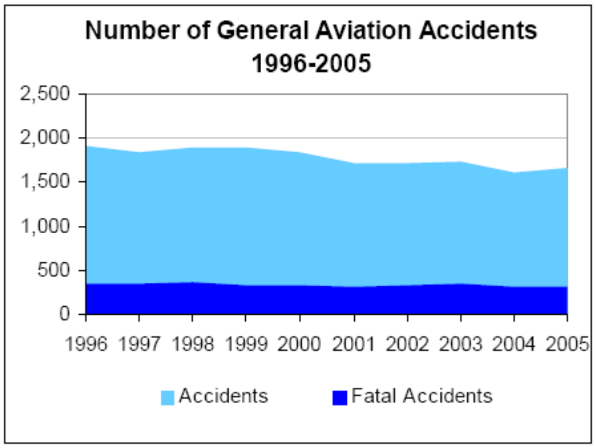


Table 1: NTSB reported number of accidents per year from 1996-2005.

Accidents that occur during aerobatic flight are often fatal. Based on review of NTSB data from 1982 to 2006, de Voogt and van Doorn[5] showed that 80% of the 494 accidents that involved aerobatic maneuvers were fatal. The main cause of aerobatic accidents was failure to maintain proper altitude.[5] Unlike many aviation mishaps, adverse weather conditions and inexperience (almost half of pilots had over 7500 hours) were not associated with aerobatic accidents.[5]

A human performance factor was noted in 82% of general aviation accidents in 2005. Aircraft handling and control were the most frequently noted causes of the accidents.[3] Similarly, the Nall Report[6] published by the Aircraft Owners and Pilot's Association (AOPA) found that maneuvering was the leading cause of fatal general aviation accidents in 2007. Aerobatics represented 6.6% of total and 7.8% of fatal accidents in this group.[6] Stall or loss of control, impact with wires or structures, and collisions with mountains or canyons accounted for the remaining types of maneuvering accidents.[6]

2.2 Acceleration

One of the physiologic environmental concerns that aerobatic pilots must contend with during flight is acceleration. Acceleration can be defined as the change in velocity over a specific time interval.[7] Velocity is a vector meaning that is has the properties of magnitude and direction. Rate of change in the magnitude of velocity over time is referred to as linear acceleration. Angular acceleration is the term used for rate of change in direction of velocity over time. Magnitude, direction, and duration affect how humans respond to acceleration. Sustained acceleration is low-magnitude and long duration.

Impact or transient acceleration is high-magnitude and short duration. Pilots experience sustained acceleration during normal flight and aerobatic maneuvers.[7] Transient accelerations are typically confined to durations of 1-2 seconds and can occur during flight operations and escape or crash scenarios.[7] Sustained acceleration creates challenges to homeostasis while transient acceleration may involve traumatic injury.[7] Sustained acceleration is experienced by pilots and its physiological effects will be presented here. Transient acceleration research focuses on impact data and physiologic consequences such as concussion, vertebral fractures, spinal injury, and skull fracture are not prominent features experienced during in-flight accelerations by aerobatic pilots.

Aerobatic pilots are exposed to both linear and angular accelerations as they perform maneuvers in a three-dimensional environment. Linear acceleration is the more familiar concept and involves a change in velocity without a change in direction. Accelerating a car at a green light or a pilot increasing his speed on a straight and level path are examples of linear acceleration. Angular acceleration occurs when a change in velocity involves a change in direction, such as rotation. This is the dominant form of acceleration with many aerobatic maneuvers. Angular acceleration is calculated as angular velocity measured in degrees or radians over time.[7] A roll provides an illustration of this force. The pilot can control the level of angular acceleration by altering the tightness of the roll or the degrees per second over which it occurs.

Angular head acceleration of large magnitude can cause traumatic brain injury. This is a focus of study in many fields that involve predominantly impact testing. Traumatic brain injury due to angular acceleration may be due to shear strains on the brain which have been hypothesized to be involved with axonal injury.[8]

2.3 The Vestibular System

Humans experience acceleration via inputs from the vestibular system located in the inner ear. Figure 1 and 2 depict graphic illustrations of the inner ear and vestibular system.[9] The otholith organs are composed of the utricle and saccule. These organs sense linear acceleration, specifically the utricle is sensitive to horizontal movement while the saccule senses vertical changes.[7] The three semicircular canals are oriented at approximately 90 degrees to each other and sense angular acceleration.[7] Both systems sense motion when hair-like projections from their sensory cells are deflected. Perturbation of the hair cells occurs from movement of a gelatinous layer containing calcium-carbonate crystals, or otoliths, in the otolith organs while perilymph is utilized in the semicircular canals.[7] Movement of the hair cells causes an impulse that is transferred to the brain where it is processed. In addition to the vestibular system, the visual and proprioceptive systems also provide inputs for perception of body orientation.[7] Unfortunately, having redundant systems can also cause a mismatch in signaling. When such a mismatch occurs, vertigo, visual illusions, and false interpretations can occur.[7]

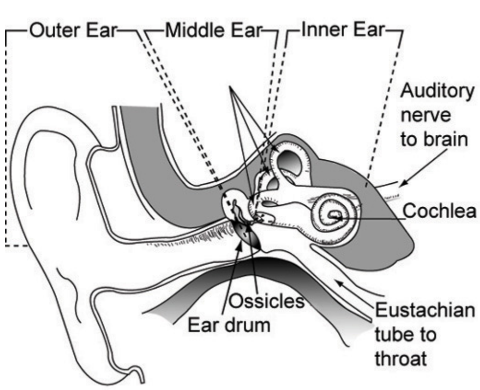


Figure 1: The Outer, Middle, and Inner Ear

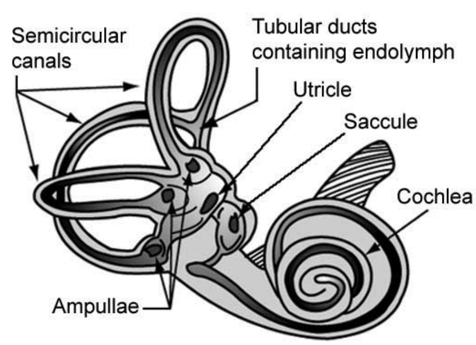


Figure 2: The Vestibular System - semicircular canals and otolith organs

2.4 Definition of G's

Acceleration due to gravity on earth is a constant termed "g" and has a value of 9.81 meters/second squared (m/s^2).[7] The pull on the body due to g is expressed as weight. Changes in acceleration experienced by an object or person are expressed in multiples of g, termed "G."[7] G is a unit-less ratio of acceleration to g. On earth, objects are at 1 G, as long as no other forces are acting on them. For example, when a plane pitches up, the pilot and occupants can experience increased or positive G's. If a pilot pulls 3 G's, for example, he/she will feel the force of three times their body weight against the seat. When a plane enters a dive, zero G's can be experienced as a feeling of weightlessness. As the footwards force increases, negative G's occur.

G is also a vector, meaning that G's have magnitude and direction.[7] The 90 degree oriented axes of x, y, and z are used to describe the orientation of G's. The positive (+) direction for x is forward, y is right, and z is upward.[7] In aviation, this orientation is applied to a seated forward facing pilot as depicted in Figure 3. The pilot experiences positive G's in the x-axis (Gx) when an aircraft accelerates forward and pressure is felt between the seat and the pilot's back. Positive G's in the y-axis (Gy) occur when the acceleration of the seat is from the right and pressure is felt between the left hip and the seat. Acceleration on the seat upwards that causes increased pressure between the buttocks and the seat pan is termed positive Gz. Negative (-) G's occur in the opposite direction for each axis described above respectively.[7]

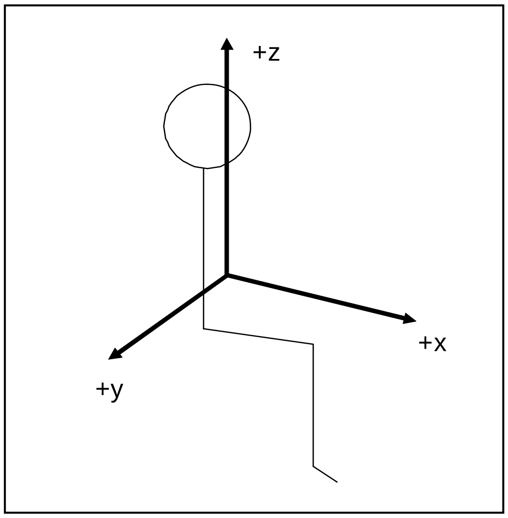


Figure 3: Human coordinate system for motion utilized in aviation.

2.5 G Tolerance

Effects of +Gz, experienced along the foot-to-head axis, have been studied extensively in relation to G tolerances. The effects of sustained acceleration on the cardiovascular system can be visualized by imagining an upright person as a fluid-filled column. The head, heart, and feet are at different but ideal pressures to function at 1 G.[7] As a force is applied to this constrained volume, the body can compensate for a limited range of pressures through changes in blood pressure. At high +Gz levels, the heart is not able to pump blood sufficiently against the force to maintain cerebral blood flow. Heart-to-brain distance, blood volume, G-training, straining maneuvers, and counter pressure garments can affect how individuals respond to such forces.[7]

Blood pressure is composed of both hydrostatic and dynamic components.[7] The pressure in the cardiovascular system at various heights in the body is termed the hydrostatic blood pressure.[7] The pressure due to the contraction of the heart is termed dynamic blood pressure.[7] The hydrostatic blood pressure is lower at the level of the brain, intermediate at the heart, and high at the feet. It can be calculated by multiplying blood fluid density times g times the vertical depth of the fluid (z).[7] Using 1.06 as the typical specific gravity of blood, the hydrostatic pressure equates to 0.78z mm Hg on earth.[7] This equation can be used to calculate the pressure needed to reach a certain vertical height, for example from the heart to the brain. If the distance from the heart to the brain was 38 cm for a subject, the hydrostatic pressure to pump the blood to his/her head would be 0.78 times 38, or 30 mm Hg. As humans are subjected to additional +Gz's, the hydrostatic pressure increases in a direct fashion such that it equates to 0.78(z)G.[7] For the subject above, the hydrostatic pressure at 4 +Gz's would be 120 mm Hg (30 x 4). If the pilot's systolic blood pressure is also 120 mm Hg, this would mean that there would be little blood flow to the brain. Fortunately, physiological compensation and mitigation efforts allow humans to exceed these parameters.

As the blood supply fails to meet demand, several effects are noted. Gray-out is named for the graying of the vision that is due to reduced blood flow to the retina.[7] Black-out occurs once vision is completely lost.[7] G-induced loss of consciousness (G-LOC) then ensues as the supply of blood to the brain is further reduced.[7] Centrifuges were developed to measure such effects and develop countermeasures under controlled conditions. In a study of 1000 navy pilots and aviation personnel, average resting +Gz thresholds were found to be 4.1, 4.7, and 5.4 Gz's for gray-out, black-out, and G-LOC respectively.[10] Due to large ranges, this experiment also demonstrated the large variability of tolerance to G's. Individual tolerances to G forces have not been found to be easily predicted. However, higher G tolerances have been associated with repeated G exposure, slow onset of G's, shorter duration of exposure, decreased heart-to-brain distance, anti-G strain maneuver, anti-G suits, avoiding the push-pull effect (-Gz followed by +Gz),[7] muscle strength-training,[11] and increased baroreflex sensitivity (controls heart rate, blood pressure, cardiac output, and arterial vasoconstriction).[12] There are no known physiologic long term effects of G-LOC.[13] However, this phenomenon has been implicated in many mishaps and fatalities.

G tolerances to negative G's have been less well studied. Exposure to negative Gz may also lead to neurovestibular consequences as too much blood pools in the head and stagnates.[7] Research is limited due to discomfort experienced by study subjects. Signs and symptoms include head fullness, headache, vision changes, decreased heart rate, and arrhythmias.[7] Red-out may also occur with an increase in negative Gz.[7] During this event, vision takes on a red hue and may be due to stagnation of blood or from the lower eyelid impeding vision in high negative G-situations. Congestion of blood first becomes apparent at levels as low as -1 Gz.[7] Worsening congestion, throbbing headache, and vision changes occur from -2 to -3 Gz's.[10] Petechaie (small hemorrhages) and swollen eyelids may persist after exposure to large negative G's.[10] A new syndrome termed G-induced vestibular dysfunction (GIVD), or 'the wobblies,' has recently been described and is further explained below.[14] GIVD may lead to career-limiting symptoms for a range of durations. Few mitigation strategies to increase tolerance to negative Gz's exist. Aerobatic pilots, especially in the unlimited category, routinely experience the greatest negative G's forces in aviation.

2.6 Physiologic Effects of G's

G-forces occur in the x, y, and z axis. Positive Gz is the most well studied of the axes since occupants seated in planes are exposed to this axis routinely during banked turns and changes in pitch. +Gz makes occupants feel heavy in their seat while -Gz makes occupants feel light in their seat.[7] Exposure to +Gz can cause insufficient cerebral blood flow to the brain which results in cerebral hypoxia. The visual system provides the first indication of uncompensated +Gz exposure since the retinal artery pressure must be maintained above the internal pressure of the eye for profusion to occur.[7] As +Gz exposure continues or increases, tunnel vision occurs initially, followed by progression centrally termed gray-out, then black-out which equates to complete loss of vision.[7] Cognitive impairments do not occur during such visual changes, but if the exposure continues, loss of consciousness may occur. Almost loss of consciousness (A-LOC)[15] followed by G-induced loss of consciousness (G-LOC) result when hypoxia of brain cells occurs. G-LOC is a dreaded risk of high G maneuvers and is mitigated through countermeasures such as G-staining maneuvers, G-suits, and reclined seats.[7] With -Gz exposure, blood flow to the brain increases causing a feeling of fullness or congestion of the head and face.[7] As exposure continues or increases, head pressure can become more intense resulting in headache, red-out of vision, nose bleeds, and breakage of capillaries resulting in facial petechiae or subconjunctival hemorrhage.[7] Pilots often try to relax their muscles and fly frequently to better tolerate high -Gz, but no formal countermeasures are in routine practice.[7]

Gx or transverse acceleration has been studied intensely in automobile crash testing and the space program. Gx is a more familiar concept since it can be equated with driving a car. +Gx can be equated with the sensation of stepping on the gas while -Gx is experienced when brakes are applied.[7] Gx affects the lungs more than the cardiovascular system as compared to Gz.[7] Lung capacity is reduced and perfusion is unevenly distributed with both positive and negative Gx.[7] Symptoms include increased work of breathing and increased breathing frequency. NASA has been concerned with Gx due to the space shuttle launch and Soyuz launch and landing configurations. Astronauts and Cosmonauts are exposed to +Gx acceleration to provide familiarization with the sensation of launch and landing.[7]

Gy or lateral acceleration is the least well studied of the axes because it is not typically encountered in aviation. However, as lateral thrust -vectored jets are developed, more research will be needed into the effects of Gy.[7] +Gy results in pressure against left arm rest while -Gy results in pressure against right arm rest.[7] Gy has been shown to cause ventilation/perfusion abnormalities that cause dyspnea or shortness of breath.[7] This effect is noted more with +Gy than with -Gy.[7] Neck pain has also been reported with higher Gy forces.[7]

2.7 “The Wobblies”

Recently, a new spectrum of symptoms has been thought to be related to G forces. In 2002, Muller[14] published the first case report of G-induced vestibular dysfunction (GIVD) or “the wobblies.” A 41 year old aerobatic pilot was noted to have occasional episodes of GIVD that resolved following avoidance of aerobatic flying.[14] During the episode noted by Muller, the pilot felt a spinning sensation with nausea after performing a -7 G maneuver. The pilot immediately landed and was noted to have an unsteady gait upon exiting the airplane. On immediate evaluation, the pilot had pertinent positives of "fine horizontal nystagmus, a positive left head thrust, and a gait lean to the left."[14]

The pilot scored a 14 on the NASA neurologic function rating scale which is in the suspect range.[14] According to Clark and Meir,[16] a flight surgeon scores the subject on 1-4 scale from no symptoms to severe symptoms for 11 neurological categories. These categories include subjective neurological symptoms, motor performance skill, and gait and station.[16] A score of 11-13 is normal, 14-15 is suspect, and a score of 16 or more requires referral for additional evaluation.[16] The pilot was diagnosed with Benign Paroxysmal Positional Vertigo (BPPV) based on his findings and was treated using the Epley maneuver.[14] BPPV is a vertigo syndrome that occurs with head position changes and is diagnosed based on a history of spinning vertigo that lasts less than one minute and nystagmus that diminishes with repeated testing on physical exam.[7] BPPV is thought to be due to movement of otoconia usually found in the otolith organs to the semicircular canals, usually the posterior.[7] The pilot continued to fly, against medical advice, and completed the aerobatic competition without recurrence.[14]

Vestibular dysfunction has also been noted with exposure to high levels of positive G's. Jia et al were not able to induce vestibular dysfunction by exposing 11 pilots to +9 Gz for 10 seconds in a centrifuge.[18] However, the authors discussed the factors involved in vestibular dysfunction and proposed that GIVD is similar to post-traumatic BPPV.[18] Rather than a blunt force causing movement of the otoconia as in post-traumatic BPPV, G forces may also cause this perturbation.[18] The authors also noted that GIVD occurrence may also be related to head movements during G exposure.[18] The shearing effect of G's on the otoconia from the x, y, and z axis along with the ability of the pilot to move his/her head during maneuvers is a complex area of study that warrants further investigation.

As GIVD is not well-documented in the medical literature, the extent of its incidence has not been fully established. Muller[14] conducted an informal survey during the World Aerobatics Championships in 1998. He found that "more than 75% of team members from the U.S., Britain, Australia, Russia, Switzerland, Hungary, and Slovakia had experienced at least one episode of GIVD."[14] The only team that stated GIVD was infrequent was that of France.[14] Williams et al conducted a survey among a wide range of civilian aerobatic pilots in 1996.[17] 12.7% of respondents who had a reported mean peak negative Gz exposure of 8.0 reported persistent vertigo after aerobatic flight with exposure to negative G's.[17] These figures do not include pilots who may have had vestibular problems early in their careers and never attained further aerobatic skills, nor do they include those pilots who were involved in fatal mishaps that may have been due to this phenomenon. Quantifying the number of pilots who have stopped flying or had career limitations due to vestibular dysfunction would add to this field of study.

2.8 Measuring Acceleration

G's are measured using an accelerometer or G-meter. In simple terms, acceleration can be measured by calculating displacement of a weight on a spring.[7] Exposure to high levels of positive or negative G's will cause a larger change in the displacement of the spring and can then be represented by corresponding G values. Aircraft G-meters typically measure Gz. They are usually mounted in the cockpit and measure acceleration for the frame of reference of the airplane.

Accelerometer data is currently being collected in a variety of venues. Research on racecar drivers has led the way for development and validation of earplug accelerometers.[19,20,21] In the past, models such as the head injury criterion were employed to correlate impact acceleration with concussion and traumatic brain injury. Now, head-level data obtained from earplug accelerometers will allow direct measurement of accelerative forces that result in neurologic injury. Earplug accelerometers have also been utilized in research on rodeo riders,[1,2] football players,[22] boxers,[23] and on human performance such as exercise, gait training, and other sports scenerios.[24]

Accelerations experienced in aviation are quantified by measuring the forces on the airframe. Centrifuge data has also provided quantification of physiologic effects on human subjects. However, in-flight accelerations experienced by pilots may differ from airframe or centrifuge data. To the author's knowledge, no published literature exists that quantifies the head-level accelerations experienced by aerobatic pilots. Earplug sensors can now be utilized to capture these forces. The initial step to correlating G-exposure with physiologic effects will be to examine the accelerations experienced by aerobatic pilots at head-level.

Methods

3.1 Study Design

Building on the research of Drs. Sharmila Watkins and Charles Mathers, this project was developed to evaluate the forces experienced at head-level of aerobatic pilots using the tri-axial accelerometers and angular rate sensors owned by UTMB. A review of the literature demonstrated lack of studies involving in-flight accelerations experienced by pilots. The project was presented to Patrick Puzzuto, of Diversified Technology Systems (DTS), during the 2009 Houston Rodeo and Livestock Show. With reassurances that his company could make the necessary modifications, this case-series was initiated. Dr. Richard Jennings, Chair of Aerospace Medicine at UTMB, served as the Chair of my capstone committee. Dr. Jim Vanderploeg, Assistant Director of Aerospace Medicine at UTMB, and Dr. Jonathan Clark, NASA Flight Surgeon were also committee members. The 2009 US National Aerobatic Championships were chosen as the location for data collection.

The necessary documents were drafted and submitted to UTMB's Internal Review Board (IRB) in March 2009 to conduct research on human subjects. The research protocol was approved in April 2009. Once this critical step was complete, several collaborations were formed to accomplish this project. DTS was formally contracted to provide the necessary hardware and on-site tech support. DTS was also able to loan a second set of accelerometers and angular rate sensors to mount on the plane in order to compare accelerations experienced by pilots to that of the plane. They also designed a synchronizing device so that the values obtained from the two sets of hardware could be compared. Dr. Jennings arranged for Debby Rihn-Harvey, a multi-time US National Aerobatic Champion, to also become involved in the project. She provided vital information on the sport of aerobatics, plane set-ups, and links to the aerobatic community including possible participants.

The study team was then formed to assist with outfitting of pilots and their planes along with data collection. Dr. Charles Mathers, Dr. Kathleen Samsey, Pat Puzzuto, and his wife Sherry Puzzuto all traveled to Sherman, Texas to execute the project. Five pilots were fitted with an ear-plug in each ear, one containing tri-axial linear accelerometers and one with tri-axial angular rate sensors. A second tri-axial accelerometer and angular rate package was fixed to the plane. For each subject, data were collected from the two synchronized devices during a 10-minute practice session. Funding was provided by NSBRI who awarded a grant to UTMB to continue work with the accelerometers.

3.2 Subjects

Eight aerobatic pilots were recruited for the study. Inclusion criteria included any ethnicity, either sex, age 18-65, and participation in a practice trial in the unlimited, advanced, or intermediate categories during the 2009 US National Aerobatic Championships. Exclusion criteria included any ear problems or ear pain. After written documentation of informed consent was obtained, each subject was fitted with the tri-axial accelerometer and angular rate sensors as were their planes. However, data from both plane and pilot for a 10-minute practice run was only successfully collected from five of the subjects. One trial only ran for two minutes due to the improper settings of the sensors, one only collected pilot data due to a defective battery in the plane's data recorder, and the third did not collect any data as the sensors were not activated properly. An additional volunteer was not able to participate due to poor fit of the ear-plugs. Three of the subjects were in the unlimited, one in the advanced, and one in the intermediate category. Only men where included in the final data set because there were a greater number of men at the competition and because their values were successfully collected. The average age of the subjects was 50.6 years.

3.3 Equipment

The tri-axial accelerometers, angular rate sensors, data recorders, and software utilized in this project were all designed and built by DTS. Three ADXL193 accelerometers oriented at 90 degrees to each other were contained within the left earplug. Each accelerometer is capable of measuring ranges of +/- 250 G's. The right earplug contained tri-axial ARS-8K angular rate sensors. This sensor is capable of measuring +/- 8000 degrees/second. Three sets of ear plugs were available in small, medium, and large sizes for subjects to select based on fit. The 6DX sensor contains three linear accelerometers and three angular rate sensors and was used to measure the accelerations of the plane. The 6DX accelerometers are capable of measuring +/- 200 G's. The angular rate sensors were also the ARS-8K model. The 6DX weighs 26 grams and is 28 mm x 28 mm x 16.5 mm in size.

Each set of sensors was connected to a separate but identical Slice Nano data recorder. The data recorder measured 3 cm x 3 cm x 6 cm and was powered by two 9-volt batteries housed within the data recorder case. Each data recorder sampled at a rate of 2500 samples per second. Once the pilot and plane were outfitted with the two sets of sensors, a USB cable was used to connect each data recorder to a separate laptop. Sliceware software calibrated, armed, and activated the sensors. Once activated, up to 30 minutes of data could be recorded. A synchronizing cable was connected to each data recorder as well. This cable had a button that was depressed by each pilot when he/she began her aerobatic routine. This allowed the data to be marked at the start of aerobatic maneuvers for ease of evaluation, although data was actually collected from the time the sensors were activated by each laptop computer used in this study.

Photo 1: Ear-plug sensors and data recorder.

Photo 2: 6DX package.

3.4 Study Protocol

Debby Rihn-Harvey provided a practice schedule and information on the category of each pilot to the research team. Subjects were approached based on their category and time of their trial as a minimum of two hours were needed between subjects to download the prior trial's data and to outfit the following plane and pilot. The project was explained and pilots were allowed to try on the various sizes of earplugs to evaluate for comfort. A research consent form was reviewed with interested volunteers. Subjects who provided informed consent by signing the form were enrolled in the study.

Approximately one hour prior to the pilot's scheduled practice session, the study team outfitted the plane by fixing the 6DX, its wire, and both data recorders to the flat area behind the pilot's seat. The 6DX was attached so that the positive x, y, and z axes were oriented as in the schema presented in Figure 3. Thirty minutes prior to the practice time, the pilot took his/her seat in the plane and was fitted with the earplug sensors. The sensors were then plugged into the data recorder that was fixed directly behind the pilot's head. The synchronizing cord was attached to each data recorder and the remaining wire was secured. The sync button was taped to the left shoulder strap of each pilot for easy access to press the button during flight. Then a laptop was attached by a USB cord to each of the two data recorders. The Sliceware program was then utilized to calibrate, arm, and then activate the sensors.

Once the accelerometers and angular rates sensors were activated, the pilot proceeded to taxi and take off. When each pilot reached the practice area ("the box") at their scheduled time, they activated the sync button and proceeded with their 10 minute maneuver sequence. Pilots were also asked to perform an aerobatic maneuver called an avalanche at the conclusion of their flight. Upon return to the ramp (parking area), the study team retrieved all hardware used in the study. A survey was also conducted to record age, minimum and maximum values recorded on the plane's G-meter, and whether or not the pilot experienced GIVD during or immediately after the flight. Each data recorder unit was then plugged into its respective laptop computer and the data was downloaded. The Sliceware program was used to determine the G-forces and angular velocities of highest magnitude and plot the pilot v plane data. Excel and NCSS were used to analyze and correlate the collected data.

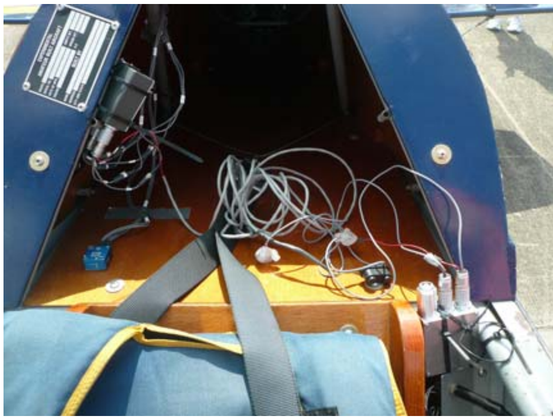


Photo 3: Example of set-up in plane.

Photo 4: Subject wearing sensors.

Results

4.1 Magnitude of Measurements

Complete readings from both plane and pilot for a 10-minute practice run were successfully collected from five subjects. The linear G's of highest magnitude measured at head-level were 6.5, 2.5, and 6.7 in the positive x, y, and z axis respectively. For the negative x, y, and z axis the G's of highest magnitude were -8.3, -13.6, and -11.4 respectively. The angular velocities of greatest magnitude in degrees per second were 356, 333.4, and 427.1 in the positive x, y, and z axis respectively. For the negative x, y, and z axis the angular velocities of highest magnitude were -402.2, -355, and -481.7 deg/s. The pilot and plane accelerometer data was highly correlated with correlation coefficients of 0.77, 0.91, 0.91, 0.90, and 0.88 for test runs one through five respectively. The sum of the linear and angular forces was greater in the pilot as compared to the plane in all of the runs except for test run one.

Table 2 demonstrates the mean magnitudes of each of the parameters, 95% confidence intervals about the means, and corresponding p-values calculated from paired t-tests. The accelerometer fixed to the plane measured higher mean linear accelerations in each axis. This accelerometer also obtained higher mean measurements in the both of the angular x axes. The head-level measurements were higher magnitude for positive and negative angular y and z parameters. The pilot and plane mean magnitudes are highly correlated with a correlation coefficient of 0.89.

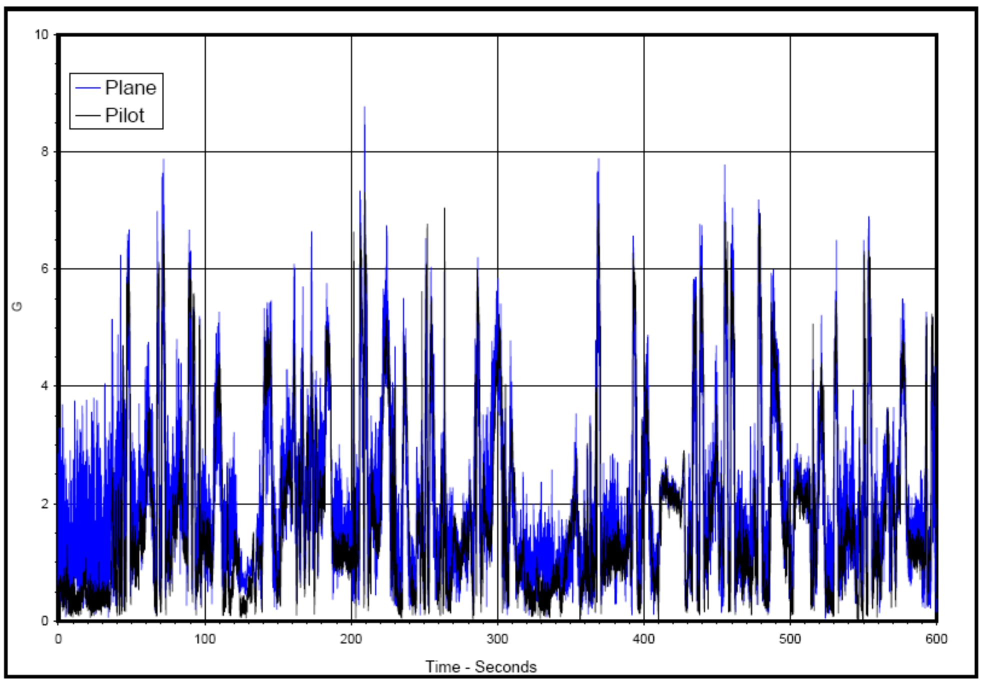
Paired t-tests were calculated for the sample means with an alpha value set at 0.05%. The null hypothesis is that the means are equal while the alternative hypothesis is that they are different. Calculated p-values less than 0.05 demonstrate that the mean pilot and plane parameter is significantly different while values greater than 0.05 demonstrate that the null hypothesis can be accepted, or more technically, there is not enough evidence to conclude that the values are different. Values were not significantly different for any of the linear acceleration parameters measured. Values for angular acceleration were mixed. Negative angular x and both angular y means were not found to be significantly different. However, positive angular x and both z means were found to be significantly different.

Axis	Pilot (95% CI)	Plane (95% CI)	P-value
Positive linear x (G)	4.76 (3.2 to 6.3)	8.24 (3.8 to 12.7)	0.100
Negative linear x (G)	-6.90 (-8.1 to -5.7)	-7.86 (-13.1 to -2.7)	0.635
Positive linear y (G)	2.28 (1.9 to 2.6)	10.44 (2.0 to 18.9)	0.053
Negative linear y (G)	-4.80 (-11.1 to 1.45)	-9.82 (-20.3 to 0.6)	0.316
Positive linear z (G)	5.30 (3.4 to 7.2)	13.96 (1.6 to 26.4)	0.129
Negative linear z (G)	-5.88 (-9.9 to -1.9)	-19.4 (-39.5 to 0.7)	0.149
Positive angular x (deg/s)	277.42 (196.6 to 358.2)	460.66 (305.1 to 616.2)	0.013
Negative angular x (deg/s)	-384.66 (-404.6 to -364.7)	-425.64 (-649.3 to -201.9)	0.653
Positive angular y (deg/s)	255.98 (172.7 to 339.2)	190.46 (121.0 to259.9)	0.154
Negative angular y (deg/s)	-282.64 (-335.4 to -229.8)	-185.68 (-281.1 to -90.3)	0.058
Positive angular z (deg/s)	294.22 (184.0 to 404.4)	154.1 (111.4 to 196.8)	0.014
Negative angular z (deg/s)	-382.8 (-473.1 to -292.5)	-137.68 (-220.1 to -55.6)	0.004

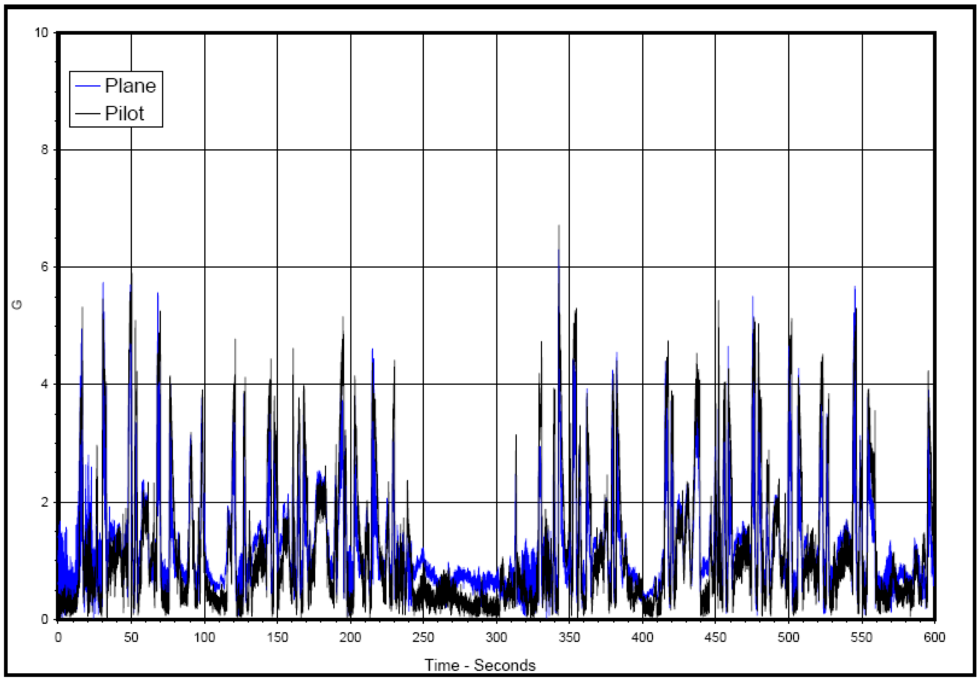
Table 2: Comparison of mean linear acceleration and angular velocity for pilot v plane.

4.2 Accelerations Experienced by Pilot v Plane

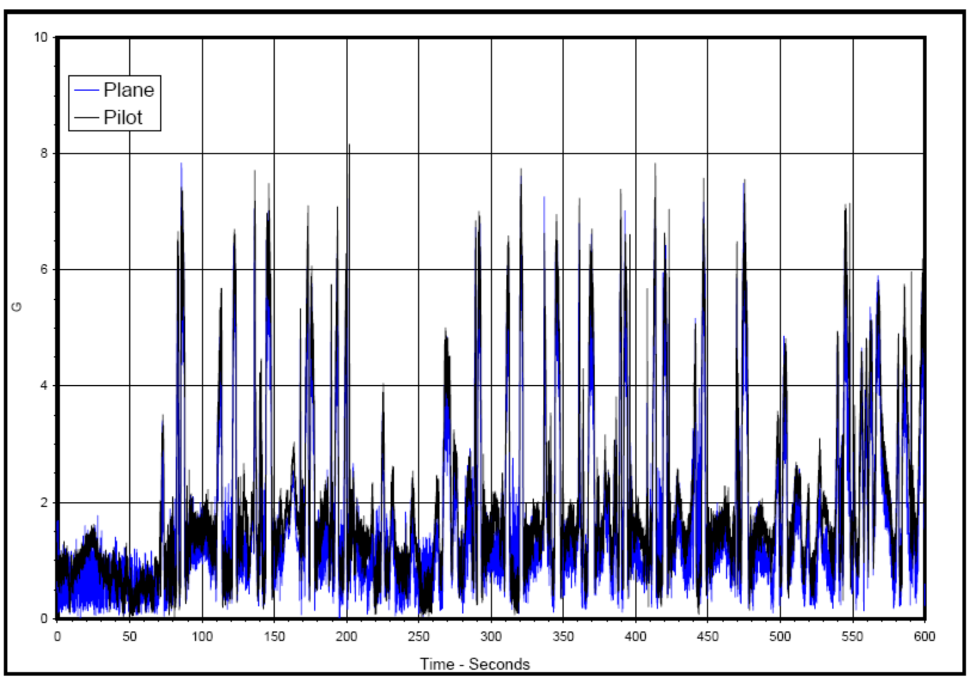
In order to compare the data obtained from the plane and the pilot, resultant linear accelerations were computed and plotted. The resultant represents the sum of the squares of the x, y, and z axis. This allows the magnitude of the forces to be seen rather than the positive and negative G's. Plots 1-5 demonstrate the resultant linear accelerations experienced by the pilot and the plane in each of the five test runs. The data was sampled and filtered in an attempt to encompass more manageable data and exclude outlying values due to vibration in the following plots. The data were sampled at intervals of 50 data points and filtered at 60 Hz. The pilot resultant for each of the 5 runs was 7.31, 6.71, 8.16, 7.89, and 8.53 G's respectively. The plane resultants were 8.77, 6.30, 7.83, 8.48, and 8.16 respectively. On average, the resultants for the plane and pilot are nearly equivalent.



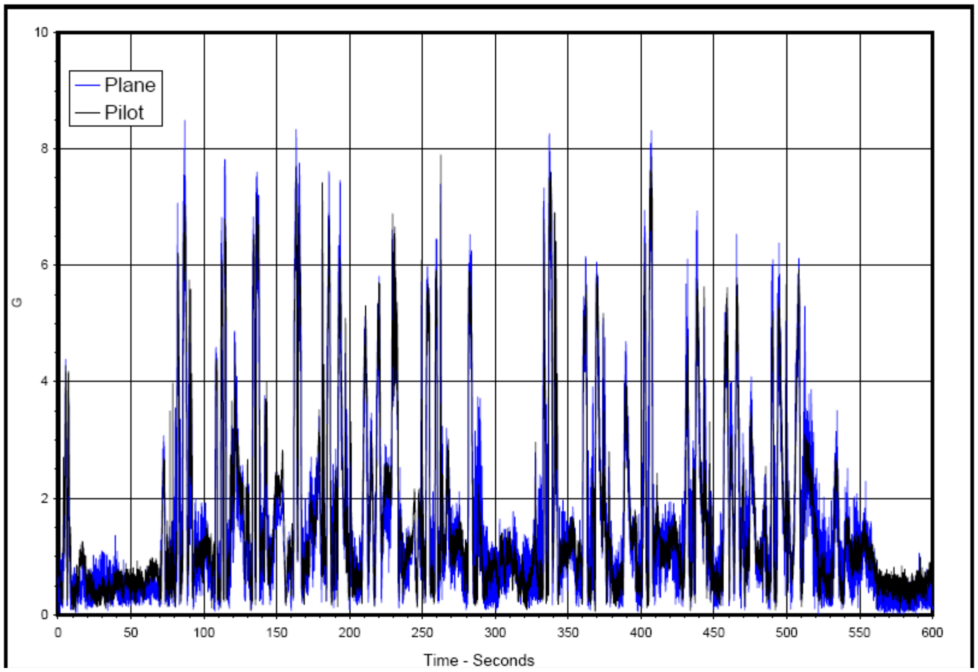
Plot 1: Resultant accelerations of pilot v plane for test run 1.



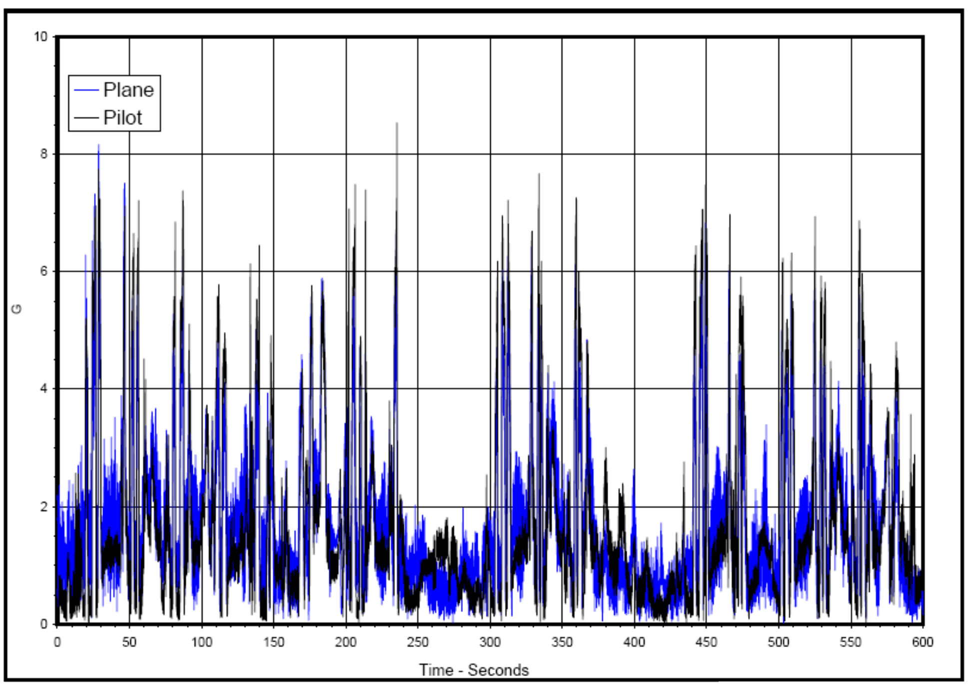
Plot 2: Resultant accelerations of pilot v plane for test run 2.



Plot 3: Resultant accelerations of pilot v plane for test run 3.



Plot 4: Resultant accelerations of pilot v plane for test run 4.



Plot 5: Resultant accelerations of pilot v plane for test run 5.

4.3 Comparison of Measured Acceleration v G-meter

Comparing the experimental Gz values obtained from the accelerometers to the G values obtained from the planes' G-meters provides another mechanism of analysis. Table 3 summarizes the findings for the maximum and minimum values obtained. The correlation coefficients are high between the G-meter values and the recorded pilot accelerations with a value of 0.79 for +Gz and 0.76 for –Gz. However, with correlation coefficients near zero, the G-meter and plane accelerometer data was not well correlated. The data from the plane's test accelerometer for test run one contained very extreme data points. When test run one is excluded, the correlation coefficient between the G-meter and the plane accelerometer values is 0.70 in the positive axis and 0.99 in the negative axis.

	G-meter	Pilot	Plane	G-meter	Pilot	Plane
Test Run	max	max z linear	Max z linear	min	min z linear	min z linear
1	8	4.7	31.2	-4	-4.81	-48.2
2	7	3.4	5.2	-2.5	-3.35	-8.9
3	10	7.0	10.3	-4.9	-4.7	-13.1
4	8.3	6.7	11.4	-5	-5.88	-12.8
5	8.8	4.7	11.7	-6	-4.4	-14

Table 3: G-meter v accelerometer measurements of the Gz axis reported in G's.

4.4 Comparison among Pilots

Each subject was asked to complete a maneuver called an avalanche at the end of their routine. By completing the same series of inputs, it was hoped that the subjects could be compared to each other. Unfortunately, no mechanism was devised to mark when the maneuver was initiated or completed during the data collection. The data provided no clear indication of when the maneuver occurred. Thus, the pilots could not be compared to each other during a similar maneuver.

4.5 "The Wobblies"

Each subject was surveyed after the performance of their test run. None of the subjects reported symptoms of GIVD upon landing or walking away from their aircraft. Therefore, pilots were asymptomatic over a range of -2.5 to -6 G's as recorded by each aircraft's G-meter. Several subjects did report symptoms that may have represented "the wobblies" in the past. G-levels at which these symptoms occurred were not collected or analyzed.

Discussion

5.1 Outcome

The first aim of this study was to measure the magnitude of linear accelerations and angular velocities experienced at head-level by aerobatic pilots. This was successfully accomplished during five practice runs at the 2009 US National Aerobatic Championships. The accelerometers and angular rate sensors captured values over 10 minutes for positive and negative linear acceleration in the x, y, and z axis as well as positive and negative angular velocities in the x, y, and z axis.

The second aim of this study was to compare the data obtained at head-level to that of the plane. This was accomplished in several ways. First, correlation coefficients between the pilot and plane accelerometer data of greatest magnitude for the positive and negative linear and angular values in the x, y, and z axis were calculated. The values were found to be highly correlated with correlation coefficients of 0.77, 0.91, 0.91, 0.90, and 0.88 for test runs one through five respectively. Second, paired t-tests were computed to evaluate if the mean plane and pilot values were significantly different. None of the linear acceleration parameters were found to be significantly different. Angular velocities were found to have mixed results with values for the positive x and both z values to be significantly different, while the negative x and both y values were not significantly different. This may be due to the relatively low magnitudes of angular velocities that were measured. Differences may also exist due to the variation created from head turning during maneuvers. Lastly, the plane and pilot accelerometer data was compared to the plane's G-meter. The G-meter values were highly correlated to the values obtained at head-level with correlation coefficients of 0.79 for +Gz and 0.76 for

-Gz. The G-meter values and experimental plane accelerometer values did not correlate. However, with the exclusion of test run one, there was good correlation between the two values obtained from the plane with correlation coefficients of 0.70 in the positive axis and 0.99 in the negative axis. The plane's accelerometer in test run one recorded very extreme values. Although these numbers may have been valid, they could have been fleeting values that were not captured by the plane's G-meter. Increased sample size would also be helpful to determine if data collected during this trial was plausible.

5.2 Context

The goals of measuring the magnitude of linear accelerations and angular rates experienced at head-level by aerobatic pilots and comparing this data to that of the plane were met during this study. The linear G's of highest magnitude measured at head-level were 6.5, 2.5, and 6.7 in the positive x, y, and z axis respectively. For the negative x, y, and z axis the G's of highest magnitude were -8.3, -13.6, and -11.4 respectively. The angular velocities of greatest magnitude in degrees per second were 356, 333.4, and 427.1 in the positive x, y, and z axis respectively. For the negative x, y, and z axis the angular velocities of highest magnitude were -402.2, -355, and -481.7 deg/s. No prior similar studies have measured accelerations at head-level with which to compare the results obtained here. To gain perspective on the magnitude of linear acceleration and angular rates measured for aerobatic pilots, comparison can be made with centrifuge data and values obtained from studies which utilized similar sensors.

Centrifuge studies have provided extensive evidence of the neurovestibular effects of positive G's. Mean +Gz levels of gray-out, block-out, and G-LOC have been found to be 4.1, 4.7, and 5.4 G's respectively.[10] Negative Gz have not been as well characterized, but worsening congestion, throbbing headache, and vision changes have been shown to occur at levels from -2 to -3 Gz.[7] Aerobatic pilots were able to tolerate G's in the range of 6.7 to -13.6 during this study. This range demonstrates that the aerobatic pilots involved in this study have developed G tolerances. The large magnitude of negative G's in all three axes experienced by aerobatic pilots is also apparent from this comparison.

Accelerometer research from a variety of venues has helped to correlate impact forces with injuries. The magnitudes of the forces involved provide an interesting comparison to the numbers obtained in aerobatic pilots. Much of the initial research using accelerometers was conducted in race cars. Weaver et al. analyzed 374 crashes that occurred in the Indy Racing League from 1996 to 2003.[25] Three-axis accelerometers were mounted on the floor of the car's chassis and recorded a range of 5 to 239 G's during impact.[25] The authors found that drivers involved in a crash with impacts greater than 50 G's developed head injury 16% of the time, while those involved in impacts of less than 50 G's were only reported to suffer from head injury 1.6% of the time.[25] Rowson et al. used helmet accelerometers to measure the force of 1712 impacts in Virginia Tech football players during the 2007 football season.[22] The range of linear accelerations was found to be 9 to 137 G's.[22] Average head accelerations were 12.8, 10.0, and 16.5 G's in the x, y, and z axis respectively.[22] Angular acceleration was also measured, but values of angular velocity are not provided. No players were diagnosed with concussion during the research study.[22] Another interesting study was conducted by measuring punches thrown by Olympic boxers. Walilko et al. instrumented the boxer's hand and a Hybrid III dummy with accelerometers.[23] The average head acceleration was found to be 58 G's while the average angular velocity, after unit conversion, was 1145.9 degrees per second.[23]

Using the same earplug sensors, the studies of Sharmila Watkins, MD, MPH and Charles Mathers, MD, MPH evaluated acceleration and angular rate values for rough stock riders.[1,2] Dr. Watkins obtained data from a bull rider and bareback bronco rider during the 2007 Houston Livestock Show and Rodeo. The peak resultant linear acceleration for the bull rider was 26 G's and 46 G's for the bareback rider.[1] Dr. Mathers continued this work by obtaining data from 10 bull and 10 bareback riders at the 2009 Houston Livestock Show and Rodeo. Bareback riders experienced higher linear accelerations than bull riders in all axes, with the maximum the x, y, and z axis recorded at 27.6, 17.5, and 24.9 G's respectively.[2] The angular rates of bareback riders were also larger than bull riders at 2109.7, 2864.7, and 2228.7 degrees/s in the x, y, and z axis respectively.[2] The data demonstrated that rough stock riders are exposed to high levels of linear acceleration and angular rates, with bareback riders experiencing almost twice the level of accelerations as bull riders.[2]

These examples provide context for the measurements obtained in this series of aerobatic pilots. Overall, the positive accelerations experienced by aerobatic pilots are not as great as many of the other studies. However, most of the values obtained in prior studies are from short duration impact data. While some impact studies are set up to measure impact at a specified negative G level,[19] no comparison of the negative G's experienced by aerobatic pilots could be made with the existing literature. Thus, aerobatic pilots represent a unique population for measuring negative G's and for continuing correlation to neurovestibular symptoms in disorders such as "the wobblies."

The angular rates measured in aerobatic pilots were small compared to rodeo riders who were reported to experience angular velocities that were several orders of magnitude higher than those of the aerobatic pilots. As angular rates are measured in degrees per second, a complete turn in one second would equate to 360 degrees/second. This level is easily reproduced on the ground and intuitively does not cause any adverse effects. However, the angular velocities reported here do not include an analysis on the length of time each force was sustained, and increased duration of angular velocities may be an important clinical consideration.

5.3 Limitations

The small number of subjects in this study led to limitations in this research. No women were included in this project. Participants were only obtained from one event and do not include air show performers who may pull varying amounts of G's. Test run one had several outlying values and analysis after additional test runs would help to explain the accuracy of the recorded values. On table 2, the confidence intervals demonstrated wide ranges and several included zero. Increasing the sample size through further testing would also improve the statistical power of this study. As additional data is collected, the epidemiological characteristics of GIVD may also be elucidated.

The settings of the accelerometers and angular rate sensors could be modified in future studies. The experimental devices were set to record 2500 values per second. This over-sampling made the data hard to analyze and individual values could not be compared. The sensors should also be set so that only values that are sustained for a specified period of time are collected. This may have been one of the problems with test run one. In this case the outlying values may have occurred, but may have not lasted longer than $1/2500^{th}$ of a second. Angular acceleration could be measured by adding a second angular rate sensor to each package or through the addition of an angular rate acceleration sensor. DTS is developing devices on the scale of the ear-plug sensors used in this study. Angular acceleration is more often reported in the traumatic brain injury and impact acceleration literature and would provide another useful comparison. Time-lapse video could be use to capture each test run and to compare maneuvers between planes such as that attempted through the avalanche in this study. Another sensor could also be created to mark the beginning and the end of an aerobatic maneuver performed by each participant.

Hardware configuration may have also caused inaccurate recordings. The plane accelerometer and angular sensor data were collected using the 6DX package borrowed from DTS. This package contained similar, but not the same tri-axial accelerometer model used in the ear-plug sensor. This could have led to differing values in each set of sensors. The 6DX package also needed to be oriented parallel to the ground. The panel behind the pilot's head did not always allow this set-up as it was sometimes at an angle. It is unknown if the G-meters of the aircraft used in this study were accurate as there is no requirement to have them routinely calibrated. This could lead to errors in how closely the data were correlated.

5.4 Future Applications

Aerobatic pilots experience a large range of positive and negative accelerations, which appear to be well correlated to their aircraft. Head-level data can be successfully collected and correlated using tri-axial accelerometers and angular rate sensors. Future work will involve further data collection in this group and hopefully capture levels that are associated with neurovestibular effects such as GIVD. The tri-axial accelerometers and angular rate sensors used in this study are capable of measuring a large array of forces that have not been routinely captured from G-meter data. Once values for neurovestibular effects are quantified, clinical models can be devised to predict adverse effects for certain head-level accelerations and angular rates. Such modeling will be a novel undertaking as past-models have dealt with impact data. Mitigation strategies can then be further developed and employed to prevent such occurrences.

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Vita

Leigh Ellen Lewis was born on 4/27/1979 in Orange Park, Florida to Dan and Sonja Lewis. She received a Bachelor of Science in Biochemistry in 2000 from Eckerd College. In 2004, she was named a Medical Doctorate after attending the University of Miami School of Medicine. Leigh then served four years in the United States Navy, the majority of which was as a Flight Surgeon. She is currently a second year resident in the Internal Medicine/Aerospace Medicine Residency Program at UTMB. She was recently named Chief Resident of Aerospace Medicine for the 2010-2011 academic year.

Permanent address: 921 Marine Drive, #301, Galveston, TX 77550

This capstone was typed by Leigh Ellen Lewis