Design and Validation of a Compact Radius Centrifuge Artificial Gravity Test Platform

by
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ABSTRACT

Intermittent exposure to artificial gravity on a short radius centrifuge (SRC) with exercise is a promising, comprehensive countermeasure to the cardiovascular and musculoskeletal deconditioning that occurs as a result of prolonged exposure to microgravity. To date, the study of artificial gravity has been done using bedrest and SRC's with subjects positioned radially with the head at the center of rotation. A recent proposal to put a human centrifuge on the International Space Station (ISS) highlighted the reality that near-term inflight SRC's will likely be confined to radii shorter than has been typically used in terrestrial analogs. The unique positioning required by such a constraint would result in physiological effects such as accelerations on the head, a change in blood pressure gradient across the body, and potential changes in muscle activation during exercise.

In this project, we define a compact radius centrifuge (CRC) as a centrifuge with a radius of less than 1.95 meters, the height of the 99th percentile male astronaut. Based on this definition, CRC's represent a class of centrifuges that cannot accommodate all subjects in a supine, radial position as is typically done in SRC's A CRC test platform is designed and fabricated on the MIT human centrifuge, which is constrained to a radius of 1.4 meters, the upper radial limit for a centrifuge to fit within an ISS module. The CRC includes a cycle ergometer for exercise during centrifugation, and also positions the subject sideways with the interaural axis parallel to the axis of rotation. Such positioning aligns the direction of the legs while exercising with the Coriolis forces, thereby eliminating lateral deflection at the knees and reducing the risk of a knee or hip injury. The CRC platform's design process is discussed, and the final design is described in detail. Finally, motor performance is characterized, and the CRC test platform and all associated systems are validated through a pilot run. The validated CRC will serve as a versatile platform on which future studies will be able to investigate physiological and mechanical responses to this unique, realistic centrifuge configuration.

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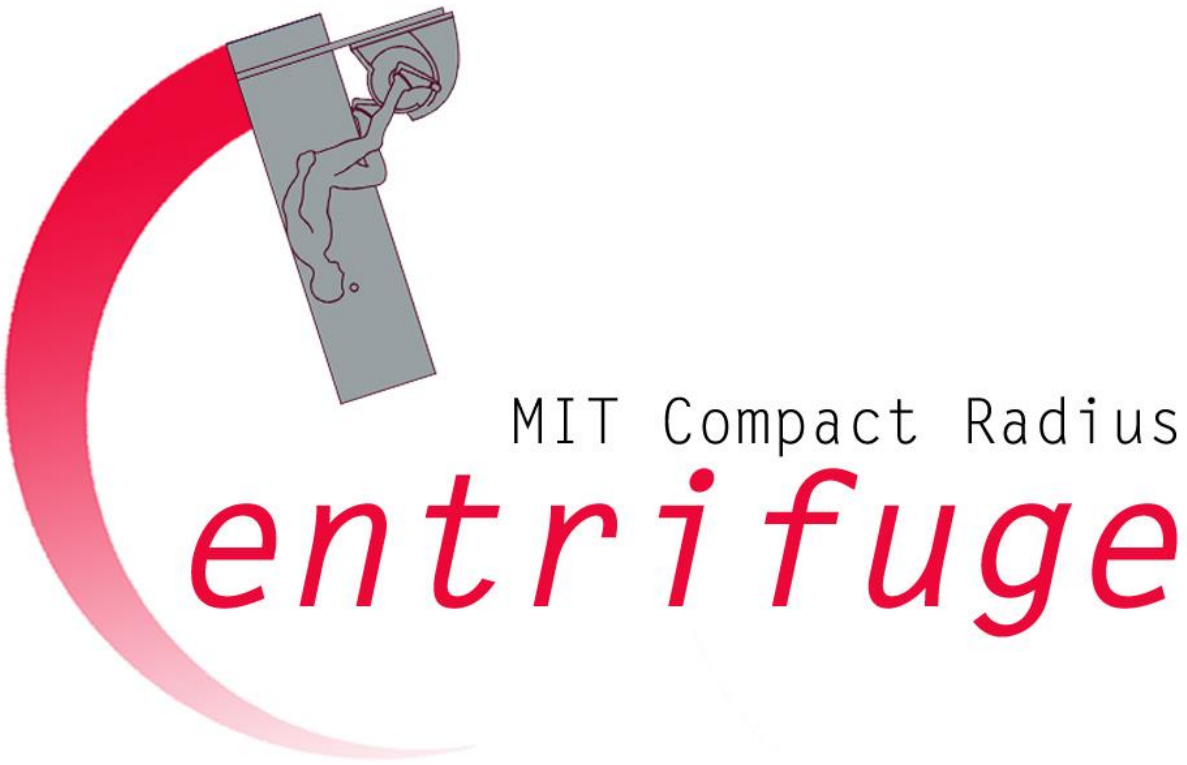
Perhaps the most important thank-you's are to my family, mom, dad, and Patrick, for all their support. And to Tim, you've been the best part of MIT, Boston, and the last two years. To many more.


MIT Compact Radius
entrifuge

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I INTRODUCTION

Humans will go to Mars. We will go back to the Moon, and we will go beyond to other planetary destinations. The timelines, financiers, and technologies behind these missions are yet to be seen, but a history of curiosity and rapid technological development foreshadows their inevitability. These missions will be long; the shortest opposition class missions to Mars would be comparable in duration to current spaceflight records, and a conjunction class mission could extend for up to 900 days. And while technology will have developed to accommodate missions of this length, human physiology will not.

Nearly a decade before the first man in space, Wernher von Braun predicted, "… it will not be the engineering problems but rather the limits of the human frame that will make the final decision as to whether manned space flight will eventually become a reality" [1]. Since then, these human limitations have manifested themselves in microgravity as deconditioning across physiological systems. Current countermeasures consisting primarily of exercise have not been shown to completely resolve these problems across all systems. Incremental improvements have been documented, but the argument for a radically different approach remains strong. One such approach is intuitively simple: to counter the detrimental effects of zero gravity exposure, provide artificial gravity (AG) via centrifugation.

While the sensation of centrifugal force was undoubtedly noted by humans long before, the study of the physiological effects of centrifugation dates back to the late eighteenth century in the writings of Erasmus Darwin (grandfather of Charles Darwin) who described it as a method of inducing sleep [2]. Aerospace applications for the centrifuge were considered as early as 1890, when a German inventor named Hermann Ganswindt proposed a spaceship that included a rotating, cylindrical chamber to produce artificial gravity for its occupants [3]. A more technically robust concept was later proposed around 1903 by famed aerospace engineer Konstantin Tsiolkovsky, who wrote about a spinning space station providing artificial gravity to astronauts as part of his science fiction novel *Beyond the Planet Earth* [3]. A number of additional space stations utilizing artificial gravity were subsequently proposed, both technically and in pop culture, most famously Wernher von Braun's torus published in Collier's Magazine in 1951 and the Discovery One spacecraft in Kubrick's 1968 film *2001: A Space Odyssey*.

It was also during the 1960's that the academic study of AG began, with a centrifuge constructed at Langley Research Center. The 20 foot radius centrifuge included a cable suspension system that allowed subjects to walk horizontally around the centrifuge and climb ladders to simulate moving to a higher deck in a rotating space station [3]. Additional studies were also done during this time by White and colleagues at the Douglas Aircraft Company [2]. Since then, centrifuges have been built at research

institutes around the globe. These include large radius centrifuges (LRC) which typically position the subject at the end of a centrifuge arm greater than 5 meters, and short radius centrifuges (SRC) which typically have radii in the range of 2-3 meters and position subjects radially with the head near the center of rotation.

There have been a number of small AG demonstrations in space. The first came during Gemini-11, when astronauts Charles Conrad and Richard Gordan tethered their spacecraft to the Agena Target Vehicle and entered a 0.15 rpm spin with the crew 19 m from the center of rotation. They continued in this spin for nearly four hours but experienced only 0.0005 G, well below the 0.22-0.50 `G AG perception threshold [4].During Skylab, astronauts ran around a padded perimeter ring, creating their own centrifugal acceleration. And during STS-90 as part of Neurolab, the Visual and Vestibular Investigation Systems (VVIS) spun astronauts about the hip inducing up to 1.0 G at the head. [5]. VVIS was the only of these demonstrations to collect any data, and none of these studied AG as a potential countermeasure to deconditioning from long-duration spaceflight. Further, the AG produced by VVIS was towards the head, and not in the typical direction towards the feet.

Centrifuges and AG countermeasure studies have also been flown with animals, including Cosmos-782 and Cosmos-936 in the 1970's [4]. More recently, the International Space Station (ISS) was originally slated to included what would have been the most robust animal centrifuge ever flown. During the late 1990's and early 2000's, the Japanese Aerospace Exploration Agency (JAXA) designed and fabricated an entire module for the ISS to house a multi-compartmental animal centrifuge, habitats, and lab equipment. The Centrifuge Accommodation Module (CAM) included a 1.25 meter radius centrifuge capable of accommodating rodents, fish, plants, insects, and cell cultures. The centrifuge was able to provide two simultaneous G-levels through radially adjustable habitats, which could experience up to 2 G at the perimeter [6]. Ultimately however, the CAM was cancelled and today sits outdoors as an exhibit.

Though a scientific loss, the CAM represents a continued recognition by the life sciences community of the need for inflight centrifuges, whether on the ISS or in future space vehicles, in order to test the effectiveness of AG as a countermeasure. As further evidence of this, a 2009 study group on AG convened by International Academy of Astronautics recommend a "substantial international effort be focused on cooperative/coordinated [artificial gravity] studies," consisting of both animal and human ground-based studies as well as flight validation tests [7]. Implementing this will require continued research efforts in the field of AG, and test platforms on which to carry out that research.

1.1 Motivation

The Artificial Gravity with Ergometric Exercise as the Countermeasure for Space Deconditioning in Humans (AGREE) was a 2011 proposed project to put a short radius centrifuge onboard the ISS in order to study the effectiveness of intermittent AG exposure at preventing cardiovascular, musculoskeletal, immunological, neurovestibular, and spatial orientation deconditioning in microgravity. The AGREE centrifuge was to have been located in the Permanent Multipurpose Module (PMM) replacing the four racks at the end of the module, as seen in Figure 1.

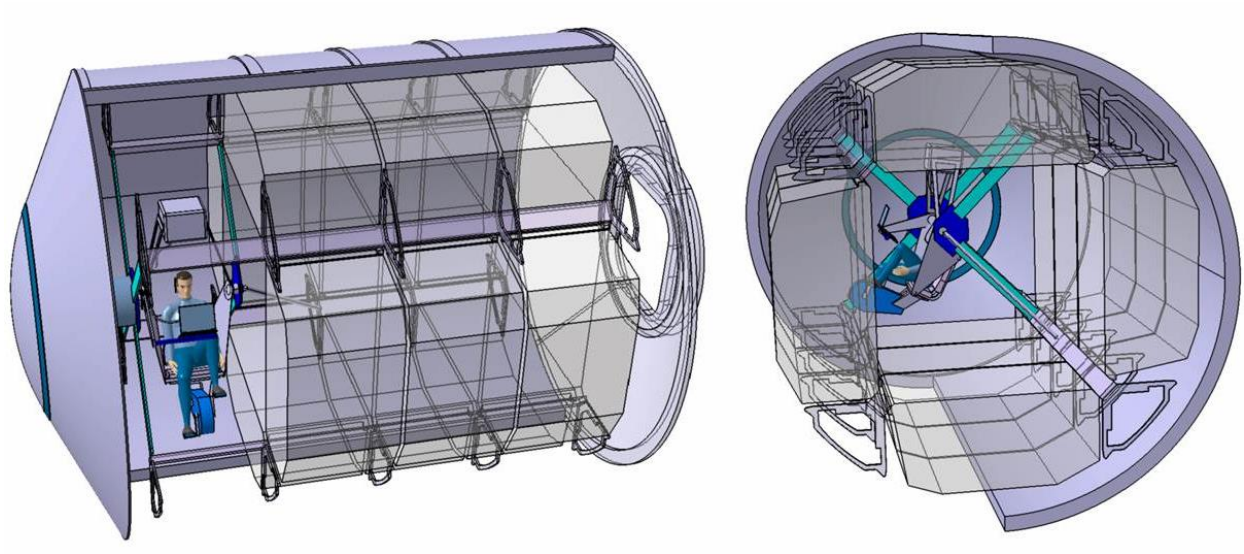

Figure 1- AGREE centrifuge in the PMM [8]

Placement within the PMM limited the maximum allowable radius of the AGREE centrifuge to 1.4 meters. This compact radius requirement necessitated that the subject be in a seated position, with the interaural axis parallel to the axis of rotation and the head slightly off-center. The AGREE centrifuge also included a counterweight, a cycle ergometer that would be interchanged with a platform for orthostatic tolerance control tests, a physiological sensor suite, and an onboard computer for data storage and centrifuge control.

Although no longer currently in development, the AGREE proposal highlighted the reality that future inflight short radius centrifuges will likely be constrained to volumes and radii significantly smaller than has been used for terrestrial designs. As a result, astronauts will be positioned differently on the centrifuge than subjects are on nearly every SRC used in AG research. In this project, we define a compact radius centrifuge (CRC) as a centrifuge with a radius of less than 1.95 meters, the height of the 99th percentile male astronaut as defined by anthropometry standards for the Constellation program and currently used by NASA [9]. Based on this definition, CRC's represent a class of centrifuges that

cannot accommodate all subjects in a supine, radial position as is typically done in SRC's. Given that CRC's likely represent a more realistic inflight centrifuge configuration, there is a need for terrestrial CRC test platforms to study the physiological responses to such a configuration. Further, as was also highlighted by AGREE, the inclusion of an exercise device is another feature of inflight centrifuges which will need further validation through terrestrial tests. Exercise during centrifugation decreases the chances of presyncope as muscle contractions and an elevated heart rate increase the venous return of blood to the upper body. The additional musculoskeletal loads and cardiovascular workout that are inherent to exercise might also enhance the effectiveness of AG as a deconditioning countermeasure. As will be elaborated in the next chapter, the current portfolio of terrestrial centrifuges includes very few that can be classified as CRC's, only one that is a CRC and includes an ergometer, and none that meet both these criteria as well as match the positioning of the subject suggested by AGREE.

1.2 Objectives and Methods

This project aims to fill the need for a terrestrial CRC test platform with an exerciser that positions subjects on Earth as they would be in microgravity. As such, the objectives are twofold:

Objective 1: Design and fabricate a compact radius artificial gravity test platform

Using the existing MIT SRC motor and centrifuge arm, design a platform which meets, to the best extent possible, the design requirements and operational capabilities of the proposed AGREE centrifuge including a maximum radius of 1.4 meters, a cycle ergometer, and a seated, sideways positioning of the subject.

Objective 2: Characterize performance of the CRC and validate all systems of the test platform

Using motor characterization tests and a full system pilot run, validate motor performance, human factors of the design, and the suite of associated physiological and mechanical sensors.

1.3 Thesis Organization

The remainder of this thesis is organized as follows: Chapter 2 reviews the literature on spaceflight physiological deconditioning, current countermeasures and their effectiveness, the proposed countermeasure of artificial gravity and its effectiveness in ground studies, and finally a review of previous SRC and CRC designs. Chapter 3 discusses the design of the compact radius AG platform, including an overview of the existing MIT SRC, project design requirements, concept design and design development, and a detailed description of the final design. Chapter 4 discusses the development of the Moment Minimization Tool (MMT) and the results of the motor characterization tests and the pilot run. Finally, the thesis concludes with a summary of results and suggestions for future work in Chapter 5.

2 BACKGROUND

The following chapter presents a review of relevant background literature. It begins with a discussion of the physiological systems affected by spaceflight, the countermeasures currently used on the ISS, and the reported effectiveness of these countermeasures. Next, artificial gravity is introduced as an alternative countermeasure, and its effectiveness in terrestrial studies is discussed. Finally, centrifuges with designs applicable to the MIT CRC requirements are reviewed in order to inform the design of the new platform with past lessons learned.

2.1 Physiological Effects of Spaceflight

The human body has evolved in the presence of 1 G (9.8 m/s^2), and as such, reduced or zero gravity environments induce profound changes across physiological systems. The following review focuses on the effects of spaceflight to three primary systems relevant to the current project: cardiovascular, muscular, and skeletal. Additional affected systems are also summarized.

2.1.1 Cardiovascular Deconditioning

Changes to the cardiovascular system begin immediately upon insertion into microgravity. Without the downward force of gravity there is an upward fluid shift in the body, and the normally present hydrostatic blood pressure gradient is equilibrated. As a result of the increased fluid volume in the head, many astronauts experience facial edema, headaches, nasal congestion, and venous engorgement [10]. The cephalad fluid shift also causes a sudden increase in baroreceptor stimulation, triggering a number of cardiovascular changes. Over the course of a few days, these changes adapt the cardiovascular system to its new microgravity environment. Plasma volume and red blood cell production are reduced resulting in an average 11% decrease in blood volume [11]. Venous compliance increases to facilitate pooling blood in the lower extremities, and baroreflex sensitivity is reduced [12]. Over time, the reduction in blood volume fluid pressure gradient leads to cardiac atrophy, in which mass reduction averages 8-10% [13].

Because the cardiovascular system is able to rapidly adjust to microgravity, the primary risk from cardiovascular deconditioning is not during spaceflight but rather during reentry and return to a gravity environment. The combination of reduced blood volume, reduced vasoconstriction, cardiac atrophy,

increased venous compliance, and reduced stroke volume and cardiac output, may result in orthostatic intolerance. During short-duration Shuttle missions, 63% of astronauts experienced incidences of orthostatic intolerance. Such incidents have led to lightheadedness or even syncope, as has happened to astronauts during press conferences [11]. Aerobic capacity is also reduced following return to a gravity environment. VO2max measured on astronauts after short-duration missions (9-14 days) was shown to be reduced by up to 22% [14]. Taken together, these cardiovascular changes mean an astronaut would be at risk in the event of an emergency egress or hard landing, and would be below peak cardiac fitness to begin doing work on the Martian or lunar surface immediately after transit.

An additional result of fluid shifts in the body is optical deconditioning. Through detailed examination of 7 long-duration ISS astronauts, as well as a survey of 300 astronauts, it was found that 29% of astronauts on short duration missions and 60% of astronauts on long duration missions reported degradation in vision, some of which persisted several years after missions. These changes are believed to be the result of optic disc edema induced from an increase in intracranial pressure that results from the cephalad fluid shift in microgravity [15].

2.1.2 Muscular Deconditioning

A second major physiological system exhibiting signs of deconditioning once is microgravity is the muscular system. Muscles undergo a continuous, cyclic process of remodeling in which contractile proteins degrade and synthesize, changing muscle shape, size, and myosin heavy chain isoform to match the muscles' function and level of activity. The remodeling process occurs over timescales of weeks, with proteins fully replaced approximately every two weeks under typical levels of activity. Muscle lengthening or shortening, via a change in the number of sarcomeres, can even occur in a matter of minutes [16]. In space, however, muscle activity is atypical, especially for postural skeletal muscles. The result is atrophy, loss of strength and power, and changes in myosin heavy chain composition.

Spaceflight muscular deconditioning occurs primarily in type I-fiber postural muscles in the back and lower body. On Earth, these muscles are regularly loaded as they work to keep the body upright and prevent it from tipping over due to the body's center of gravity being located forward of the ankles. Many of these muscles are also used in locomotion. Loading of the postural muscles in microgravity is essentially eliminated, both because the body no longer needs to be supported from gravity and because astronauts adapt to using their arms instead of their legs for locomotion [17]. As a result, protein degradation outpaces protein synthesis resulting in atrophy. This is further exacerbated by the

documented malnourishment of astronauts, and though not definitely proven, may also be induced by oxidative stress and hormonal changes in space [11]. Table 1 summarizes observed muscle volume change in Shuttle/Mir and ISS long-duration missions (112-196 and 166-196 days respectively) for astronaut/cosmonaut samples of N=9 and N=4 respectively. Due to differences in data collection methods, the ISS muscle samples were divided by functional group resulting in an averaging of soleus and gastrocnemius muscles which are therefore reported as equal. Although differences in available countermeasures and prescribed exercise regimens prohibit between-trial analysis, the general trends of both highlight the reality of muscle atrophy and those muscles which are more greatly affected.

Table 1- Muscle volume percent change averages and standard deviations from preflight value in long-duration Shuttle/Mir and ISS missions [18,19]

Muscle	Shuttle/Mir %change/mo	ISS %change/mo
Anterior Leg	-16.0 ± 1.2	-10.5 ± 2.9
Gastrocnemius	-23.8 ± 4.0	-15.6 ± 5.6
Soleus	-19.6 ± 4.7	-15.6 ± 5.6
Quadriceps	-12.1 ± 6.7	-5.85 ± 2.6
Hamstrings	-15.7 ± 3.9	-7.2 ± 3.9
Intrinsic Back	-20.0 ± 4.5	--
Psoas	-10.9 ± 4.2	--
Hip adductors (adductor longus, brevis, magnus)	--	-3.93 ± 2.8

As a result of muscle atrophy, decreases in muscle strength (maximum force) and power from spaceflight have also been documented. In the aforementioned ISS missions, there was an average decrease in isokinetic and isometric strength across all muscle groups as well as hip flexors and abductors, with the exception of a slight (2.00%) increase in hip extensor isokinetic strength. The magnitude of these decreases ranged from -4.00% in isokinetic strength for anterior leg muscles to -28.0% in hip flexor isometric strength [19]. In a separate study of long-duration ISS missions (161-192 day) decreases in maximal shortening velocity and peak force in the gastrocnemius and soleus across 10 studied crewmembers were also reported in addition to atrophy and peak force [20]. Muscle mass decreases are thought to be an inverse exponential function of time, eventually plateauing after approximately 270 days at an approximate 70% reduction in mass for major postural muscles [21],

though others have suggested muscle mass reaches equilibrium after just 120 days [18]. Muscle volume recovery has also been shown to occur exponentially, with near-full recovery to pre-flight values 50 days after landing from 4-6 month missions [18].

In addition to loss of muscle mass, force, and power, muscular fiber composition is also affected by weightlessness. There are three types of muscles fiber, each named for the myosin heavy chain composition: slow (type I), fast fatigue resistant (type IIA) and fast fatigable (type IIX). Type I fibers are smaller, more oxygenated fibers used for slow onset, sustained muscle activity such as supporting the against gravity, while type II fibers are larger, less oxygenated fibers for rapid, powerful, and unsustained muscle activity such as sprinting. In microgravity, reduced loading primarily occurs in muscles with predominantly type I fibers, which as a result show a change in myosin heavy change isoform as the number of type II fibers increases relative to the number of type I [11]. In essence, the muscles not only shrink and become weaker, but their functional roles also change.

2.1.3 Skeletal Deconditioning

Like muscle, bone tissue is continuously undergoing a remodeling process by which inorganic phase bone material is broken down and resorbed into the blood stream by osteocytes, followed by calcium ossification to create new bone material by osteoblasts. The process is continuous, and used by the body both to regulate calcium concentrations in the blood stream as well as to repair microdamage of the bones that occurs as the results of everyday activity. Throughout this process the material composition of the bone is not changed, only mass.

Bone remodeling is a mechanotransductional process, in which strains from stresses from ground reaction forces and muscle contractions provide the mechanical stimuli that drive osteocytes to regulate the activity of osteoblasts and osteoclasts. Below the minimal effective strain of remodeling (MESr), resorption rates outpace formation and bone mineral density (BMD) is lost. In space, the lack of gravity and reduced strain from muscle contractions causes strains on weight and load bearing bones to fall below the MESr, leading to a loss in BMD and structural changes resulting in decreased bone strength. Bone resorption is further increased during spaceflight by calcium and vitamin D deficiencies and elevated CO_2 levels [11]. Taken together, the risk of bone fracture is greatly increased. Observed BMD decreases as a result of long-duration spaceflight missions on MIR are summarized in Table 2.

Table 2- Bone mineral density changes from long-duration Mir missions [11]

Bone	% change/mo
Skull	+0.60
Humerus	+0.10
Lumbar Spine	-1.07
Pelvis	-1.35
Femoral Neck	-1.16
Greater Trochanter	-1.58
Tibia	-1.25
Calcaneus	-1.50

In addition to BMD loss and subsequent increase in risk of fracture, two other conditions associated with skeletal deconditioning can pose a risk during spaceflight. First, the imbalance of osteoblast to osteoclast activity leads to excess calcium in the blood stream and a resulting increased risk of renal stones. Second, the lack of compressive longitudinal loads on the spine causes invertebral distance to increase, resulting in height increase. Even on short duration missions of 1-2 weeks, astronauts have grown up to 3" taller than their pre-flight, early morning height [22]. This change in height causes a poorer fit of custom-tailored space suits as well as back pain.

2.1.4 Vestibular and Psychological Effects

While the cardiovascular, muscle, and skeletal systems represent the primary systems relevant to the current project, a number of other systems are also affected by microgravity. These systems are not deconditioned, in that they do not degrade over time, but are still altered and affect astronaut performance and wellbeing. The vestibular system is one example; changes in stimulation of the otolith organs cause conflicting vestibular cues in microgravity. Upon insertion into orbit a majority of first time astronauts, 75%, experience space motion sickness which can persist up to 3 days into the mission, affecting crew performance and mission timelines. Spatial disorientation both inside the spacecraft and during extra-vehicular activity (EVA) may also result, and can be exacerbated by coordination and proprioception issues also associated with vestibular impacts of spaceflight [23].

The psychological toll of long duration spaceflight serves as another possible risk to future manned missions. Confinement, Earth separation, workload (both low and high), insomnia, performance

expectations, monotony, gender and cultural differences between crewmembers, and reduced gravity conditions combine to create an extreme environment onboard spacecraft which has the potential to cause significant psychological effects. These include depression, anxiety, asthenia, interpersonal conflicts (both crew-crew and crew-ground), and cognitive task performance decrement (accuracy, speed, reaction time, time perception, and ability to perform concurrent tasks) [24]. While these may seem minor compared other types of deconditioning, it is worth noting that psychological factors are likely causes for three evacuations during the 1970's and 80's (Soyuz 21, T14, and TM2) [11], more than any other deconditioning cause. Further, the psychological issues induced by long duration space travel may persist beyond return to Earth; reintegration after extended polar missions has been reported as emotionally difficult and a further cause of anxiety [24].

2.2 Current ISS Countermeasures

In order to address these deleterious effects of prolonged microgravity exposure, the ISS currently employs a suite of countermeasures to protect astronauts who today typically spend six months onboard for each mission. The primary countermeasure used is exercise. A combination of aerobic and resistive exercises serves as a means to alleviate cardiovascular, muscular, and skeletal deconditioning. Exercise has been shown to improve mood and psychological well-being, suggesting that exercise countermeasure regimen currently used on ISS may also serve as a psychological countermeasure [25]. The exercise devices onboard the ISS include the Advanced Resistive Exercise Device (ARED), the Cycle Ergometer with Vibration Isolation System (CEVIS), the VELO ergometer, the Treadmill with Vibration Isolation System (TVIS), and the T2 treadmill (also known as the Combined Operational Load-Bearing External Resistance Treadmill, or COLBERT). Astronauts spend 2 – 2.5 hours per day (includes time for set-up and hygiene), 6 days per week on the exercise equipment, rotating between the devices each day as prescribed by individual routines developed based on astronaut preference. Figure 2 shows the exercise devices currently used on the ISS.

Figure 2- ISS exercise machines (top left to bottom right): T2/COLBERT, TVIS, ARED, CEVIS, VELO ergometer, VELO ergometer used with arm cable (NASA)

The TVIS treadmill can be used in either passive (powered by the astronaut) or active mode, in which case it is capable of up to speeds of 10 mph [26]. The updated T2/COLBERT treadmill was added to support larger crew of 6 on the ISS. It can be operated in three modes: powered, passive powered (tread is moved by the astronaut but powered motor can be used to adjust resistance) and passive unpowered. The treadmill has a maximum speed of 12.4 mph [27]. For vibration isolation, the TVIS utilizes a powered set of gyroscopes, while the T2 uses a passive system of springs and dampers. Both treadmills employ bungee cords to mimic some gravitational loading [28]. Additional aerobic exercise device options include the two ergometers onboard. The first is the Russian-designed VELO ergometer, which astronauts use in a position similar to that of a recumbent bike. The VELO ergometer uses controlled resistance to achieve workloads of 100-250 W (in increments of 25 W) as well as one setting laveled 'XX'

which is below 50 W, spinning at 40-120 rpm. The other ergometer is the US-designed CEVIS, which astronauts use in a traditional upright bicycle position. The CEVIS also uses controlled resistance to achieve workloads of 25-350 W (in increments of 1 W) at 50-120 rpm. The VELO ergometer can also be configured to be used as a cable resistive device for upper body works, at the CEVIS can be configured to be used as a hand crank [29].

Resistive exercise capabilities are provided by the ARED, added to Station in 2008 to replace the Interim Resistive Exercise Device (iRED). The ARED utilizes two vacuum cylinders to provide up to 600 pounds of resistive force through bar exercises and 150 pounds through cable exercises, which collectively allow for up to 30 different types of exercises. Another key feature of the device is the embedded sensor suite capable of measuring forces and range of motion. Along with the prescribed resistive exercise regimen, this data is available to astronauts to track their progress and is also downlinked to mission control [30].

Supplementing the exercise devices are a number of additional countermeasures targeted at specific physiological systems. These include leg cuffs, pharmaceuticals, and for Russian cosmonauts, continued use of the Penguin suit and lower body negative pressure (LBNP) device. The leg cuffs onboard, seen in Figure 3, are the Braslet-M thigh cuffs which are custom-tailored specifically for each astronaut. The cuffs are donned soon after reaching orbit in order to decrease the amount of upward fluid shift and retain blood in the lower limbs. Velcro straps are used to adjust the level of compression of the cuffs, and they been shown to significantly reduce the blood volume circulated. The cuffs serve only as a temporary measure however as astronauts typically wear them for no more than an hour for safety reasons, and upon removal stroke volume rapidly increases (within approximately 3 beats) before stabilizing at an elevated level [10].

Pharmaceuticals currently onboard primarily target sleep, motion sickness, nutritional, and psychological issues. These include sleeping pills (benzodiazepine, zolpidem, diphenhydramine), anti-depressants (fluoxetine, nortriptyline, dexamphetamine), anti-anxiety medication (benzodiazepines, fluoxetine), a number of motion sickness medications (scopolamine, promethazine, dimenhydrinate, meclizine, chlorpheniramine, dextroamphetamine, ephedrine, ginger, phenyltoin), saline pills for water retention, and nutritional supplements such as vitamin D to aid in skeletal conditioning [11].

Finally, the Russian Penguin Suit and LBNP suit, both seen in Figure 3, are additional countermeasures used periodically by cosmonauts. The Penguin Suit is a full-body garment imposes loads along the body's z-axis via two sets of bungee cords on the upper and lower body, anchored at a strap around the waist. Cuffs at the bottom of the suit looped around the feet transmit loads to the lower part of the body. The

upper and lower straps can be adjusted separately, with the upper body straps being capable of providing up to 40 kg and the lower straps providing additional loading. Though the suit has been in use for decades it is reported to be hot and uncomfortable and as such is rarely worn. Further, the unnatural two-stage segmented loading does not replicate the gradient loading profile exerted on the body by Earth's gravity, and there is a lack of data on the suit's effectiveness [31]. The other Russian suit, the Chibis LBNP suit seen in Figure 3, is worn by some cosmonauts beginning in the weeks leading up to reentry to stimulate cardiovascular reconditioning. The reduced pressure in the lower limbs simulates the fluid shifts experienced in a 1 G environment such that periodic use decreases the chances of orthostatic intolerance after reentry [11].

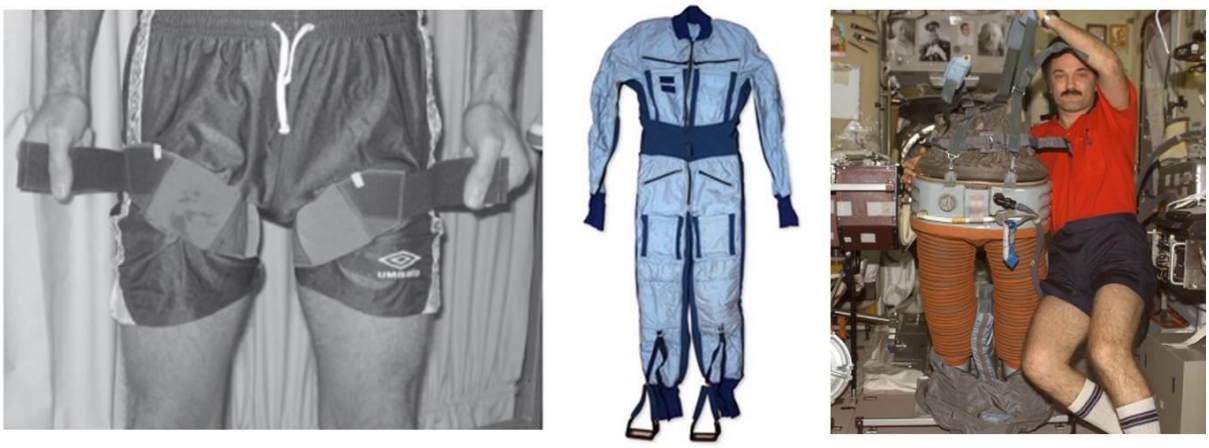

Figure 3- ISS countermeasure devices (left to right): thigh cuffs, Penguin suit, and LBNP suit [10,32], (NASA)

2.2.1 Effectiveness of Current Inflight Countermeasures

Despite the number of different countermeasures currently employed on the ISS, astronauts continue to return to Earth with demonstrated deconditioning. This includes instances of orthostatic intolerance, decreased aerobic capacity, and decreased muscle volume and strength [19]. Thus, the aerobic and resistive exercises, as well as additional suits and pharmaceuticals, are not fully effective at preventing deconditioning of the cardiovascular and muscular systems. Furthermore, exercise is the leading cause of injury for astronauts aboard the ISS [33]. There have been recent findings that show skeletal deconditioning can be successfully mitigated by the ARED and bisphosphonates, a class of antiresorptive agents. Smith and colleagues found that astronauts with access to the ARED instead of the iRED were able to maintain BMD in most weight-bearing bones when paired with adequate Vitamin D intake [34]. In a separate study, bisphosphonates were shown to help significantly reduce BMD changes compared to astronauts not taking the supplement. No statistically significant decrease in BMD was measured in

subjects supplementing ARED exercises with bisphosphonates (correlation between the ARED and bisphosphonates studies is not known). The supplements have the secondary effect of decreasing urinary calcium concentrations to a level that is not significantly different than preflight levels, thereby also reducing the risk of renal stone formation [35].

These results indicate that countermeasure effectiveness is improving and that skeletal deconditioning may be fully addressed by current practices. However, the results from ARED and bisphosphonates pertain only to skeletal deconditioning and require many hours per week for exercise. As such, a comprehensive, efficient set of countermeasures to spaceflight deconditioning has yet to be identified.

2.3 Artificial Gravity as an Alternative Countermeasure

Artificial gravity is a proposed countermeasure to spaceflight deconditioning. AG addresses the underlying problem at its source and therefore may serve as a comprehensive method of addressing deconditioning across physiological systems, as opposed to the piece-meal approach currently used.

2.3.1 Implementation of Artificial Gravity

Following the equation for centripetal acceleration:

$$a = \omega^2 r$$

where ω is angular velocity and r is radius, it stands that AG can be achieved through two approaches: a large radius centrifuge (LRC) with lower angular velocity, or, a short radius centrifuge (SRC) with higher angular velocity. The advantage of the LRC approach is its ability to closely mimic the gravity environment on Earth; a 1 G acceleration can be continually supplied and the gravity gradient from head to foot is minimized. An LRC would also allow astronauts to move and experience various G levels throughout the spacecraft, thereby allowing them to adapt to different environments depending on the mission phase. There are, however, drawbacks. In the rotating reference frame, any motion that is not parallel to the axis of rotation induces Coriolis forces, defined as:

$$F_c = 2m(\omega \times v)$$

where m is mass, ω is angular velocity, and v is the linear velocity of movement. Given that Coriolis force acts perpendicular to the direction of movement within the rotating reference frame, movement

within an LRC would be complicated. For example, astronauts moving radially would feel pushed to the side, and an astronaut jogging around the circumference would either increase or decrease the level of experienced AG. The primary disadvantage of the LRC, however, is the cost and size. As demonstrated by the ISS, such large scale projects cost in the hundreds of billions of dollars, require multiple launches, and necessitate years of on-orbit assembly. Furthermore, the size of an LRC would require unprecedented amounts of fuel should it be transported in an exploration class mission.

The SRC approach to AG has the disadvantage of producing a gravity environment less similar to that of Earth's due to intermittent use and accelerations potentially greater or less than 1 G. It also creates a high, likely 100%, gravity gradient across the body's z axis. However, given its size an SRC could fit inside a spacecraft and be carried into space with a single launch. Its lower mass would also facilitate transport as part of lunar, near Earth object (NEO), or Martian missions. Due to the SRC's increased practicality, it is generally the favored approach to AG.

Within the SRC approach there are two sub-methods to AG implementation: passive centrifugation in which the subject does not move within the spinning reference frame, and active centrifugation in which the subject does exercise while spinning. In some cases this exercise may also power the centrifuge or charge a battery. The benefits of an active SRC are twofold. First, exercise would be required of astronauts to maintain fitness regardless of the gravity environment, just as it is on Earth. By combining the time required for exercise with the time on the centrifuge, an astronaut's schedule is better utilized. Second, leg muscle contractions and heart rate elevation that result from exercise help to reduce the fluid pooling in the lower extremities that occurs with the onset of AG. Given that cardiovascular adaption to microgravity occurs over a time period of days, active centrifugation alleviates the risk of orthostatic intolerance that could otherwise occur. Numerous studies, including work by Duda, Edmonds, Greenleaf and Kreitenberg [36,37,38,39] have proven that exercises such as cycling and squats can be done comfortably and safely by subjects during AG exposure.

The potential benefits of AG over traditional exercise countermeasures are multiple. First, AG may serve as a single countermeasure to musculoskeletal, cardiovascular, and neurovestibular deconditioning which are currently addressed separately by a suite of countermeasures. Second, AG exposure may be effective at lower time intervals than the 2.5 hours currently used in exercise regimes. The reduced metabolic load required for AG compared to exercise, both as a result of time and workload, would also help to decrease oxygen, food, and water supplies. Estimates for long-duration, interplanetary missions are that for each half hour reduction in exercise time, 110,869 kcal and 91 liters of water per astronaut

per year would be saved [40]. Finally, intermittent AG exposure might allow the centrifuge to be available for research throughout the mission, thereby increasing scientific utility.

2.3.2 Effectiveness of Artificial Gravity

The effectiveness of AG exposure, both with and without exercise, has been studied on terrestrial SRC's using 6° head-down tilt (HDT) bedrest or dry immersion as analogs for microgravity exposure. Depending on the physiological system of focus, these studies range from a few days to several months. Individually, trials have shown that compared to bed rest patients with no treatment, intermittent centrifugation is effective at maintaining skeletal muscle mass during bedrest [41,42], and reducing orthostatic intolerance [43,44], as well as suppressing, and in some cases entirely mitigating, changes in heart rate [45,46], stroke volume [45], plasma volume [43], blood volume regulating hormones [46], VO2max [44,45], and baroreflex sensitivity [47]. Studies investigating the effects of AG on bones in humans are limited; in one study lasting 21 days the authors failed to find any significant difference in bone resorption markers, BMC, or BMD [48]

A confounding factor in making comparisons between these studies is the fact that the exact G-prescription (exposure time, G-level, and use/intensity of exercise) varied between each. Kaderka et al. performed a meta-analysis of 14 AG studies to compare results against 26 studies with traditional countermeasures including aerobic/resistive exercise and LBNP coupled with a treadmill. The analysis showed that AG was as effective as, though not more than, traditional measures at combating cardiovascular deconditioning, though the authors noted a higher, outlier result for a study coupling AG exposure with cycle exercise. Due to confounding differences between studies, the authors were not able to make any conclusions on the differences in effectiveness for musculoskeletal deconditioning [49]. These findings highlight the need for a more standardized approach to AG studies, which has also been called for within the research community [50] , but imply that centrifugation, as hypothesized, may be effective as a multi-system countermeasure to spaceflight deconditioning. Future studies performed at MIT on the new CRC platform are intended to compliment bedrest/dry immersion studies by better understanding the mechanical and physiological mechanisms behind AG's effect on the body, specifically given novel, more realistic subject positioning being tested.

2.4 Review of Previous SRC/CRC Designs

Before beginning design of the MIT CRC, several current and previous SRC/CRC designs were reviewed in order to glean insight into design features that have and have not worked in the past. Table 3 summarizes the SRC's currently operational at the time of writing (May 2013).

Table 3- Existing global SRC'/CRC's [51,52] (Satoshi Iwase, Oleg Orlov, Guido Petrat, and Jon Rask, email communications, March 2013)

Location	Radius (m)	Subjects	Mode	Exercise
MIT, Cambridge, USA	2.0	1	Bed	--
NASA Ames, USA	1.9	2	Bed	--
UC Irvine, Irvine, USA	1-2	2	Gondola	Cycling/Squats
IBMP, Moscow, Russia	2.5	2	Bed	Cycling
DLR, Cologne, Germany	2.8	2	Bed/Chair	--
DLR, Cologne, Germany (Opening July 2013)	3.8			Cycling
Fourth Military Medical University, Xi'An, China	2.0	2	Chair	Cycling
MEDES, Toulouse, France	2.8	2	Bed/Chair	--
Nihon University, Nishi-Funibashi, Japan	1.7	1	Gondola	--
Baylor College of Medicine, Houston, USA	2.0	4	Bed	
Aichi Medical University (Nagoya University), Aichi Prefecture, Japan	1.4	1	Chair	Cycling

As seen in the table, only one of the current centrifuges fall within the radial classification of a CRC (gondola designs do not qualify given the increased vertical component that is greater than 1.95 m). This centrifuge is the CRC at Aichi Medical University. Seen in Figure 4, the centrifuge has a 1.4 m radius and positions the subject radially with the head near the center of rotation and the feet and cycle ergometer elevated approximately 1 meter above the bed. Subjects typically ride in a near supine position, though the seat can be rotated to the typical upright position as well (Satoshi Iwase, email communication March 2013). Like the current project, the Aichi CRC was designed to meet the radial constraint imposed by AGREE. At the time of writing (May 2013) this centrifuge is still undergoing validation. However, there have been anecdotal reports of lateral deflection of the knees during cycling from Coriolis forces, indicating a need for the MIT CRC to reposition the subject in order to avoid hip or knee injuries that the deflections may cause (Satoshi Iwase, email communication March 2013).

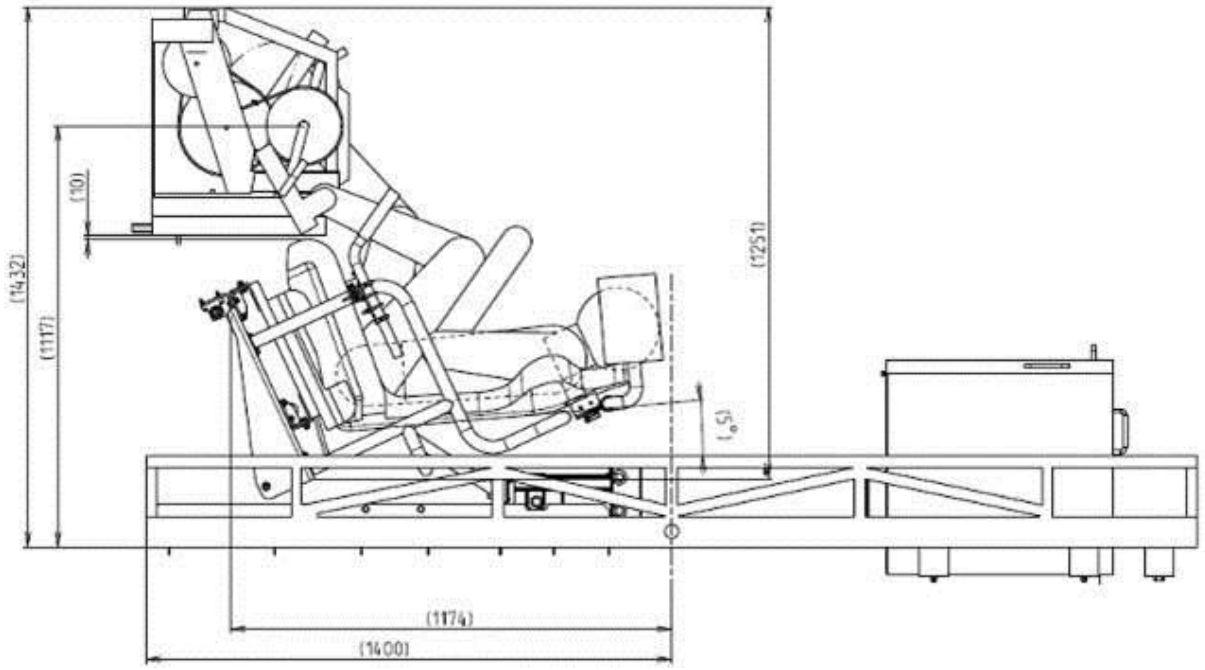

Figure 4- Aichi Medical University CRC (Satoshi Iwase, email communication, March 2013)

Due to the limited number of current CRC's, previous centrifuge designs no longer in operation but still meeting the radial requirement for CRC classification were also reviewed. One such design, seen in Figure 5, was one of the first centrifuges to be built to formally study AG. Constructed by White and colleagues at the Douglas Aircraft Company in 1965, the 1.37 m radius CRC accommodated two subjects in a sideways position with the head off-axis from the center of rotation. No further details on the design are documented, but all subjects were able to complete the White study which involved up to 30 minutes per day at 4G for 21 days, showing that such a configuration of subjects is feasible and tolerable. The design did not include any onboard exercise devices [53].

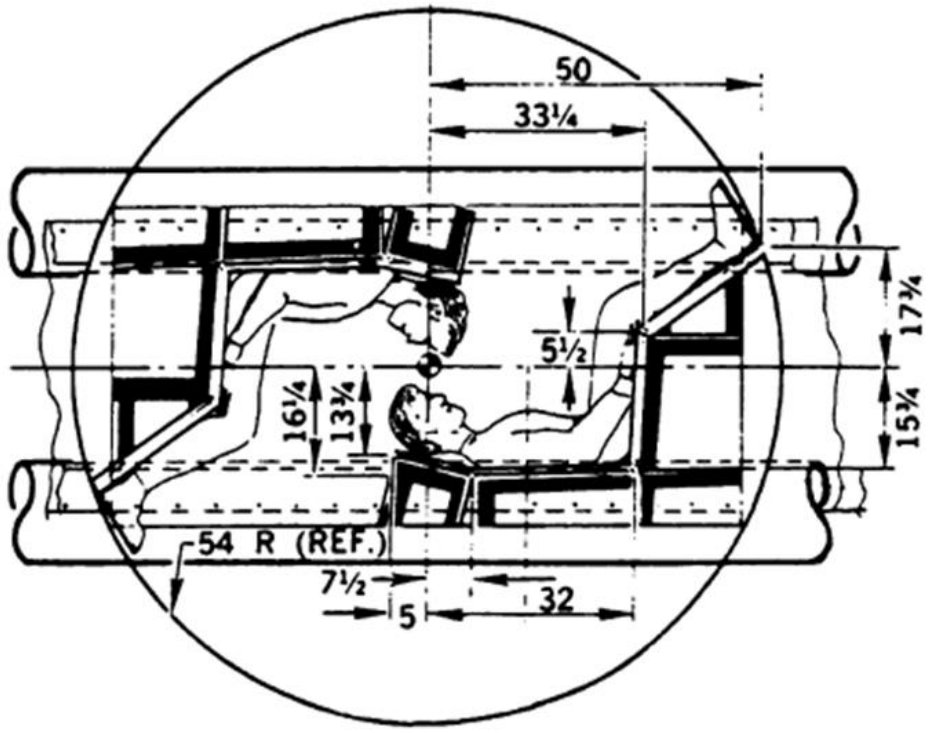

Figure 5- Douglas Aircraft Company CRC, 1965 [53]

To the best of the authors' knowledge, the only other CRC was the 1.5 m radius solid disk CRC at the University of Miami Ohio. The centrifuge was designed with the specific intention of creating a highly compact AG platform to fit inside a spacecraft. Subjects were positioned in the supine position with their legs against their chest and their head approximately 66 cm from the center of rotation. Both their feet and buttocks pressed against a seat-foot platform at the edge of the centrifuge. Studies showed that subjects were able to tolerate up to 7 G at both gradual (0.1 G/s) and rapid (1 G/s) gravitational onset with no more motion sickness than was experienced on a 6.1 meter LRC. Although only one subject rode the centrifuge at a time, a configuration in which 6 astronauts were restrained around the disk simultaneously was also proposed for use on the ISS [54].

Two additional, now dismantled, SRC designs were also reviewed because of the way in which they positioned subjects sideways while cycling, similar to the design proposed by AGREE. They include the original Space Cycle design and the Human Powered Artificial Gravity (HPAG) cycle at MIT. When the Space Cycle was originally constructed in 1997, it was a 2 meter radius SRC that accommodated two subjects, each riding a cycle ergometer with integrated generator (for both increased resistance and electricity production), pedal impact loaders, and virtual reality headset. As seen in Figure 6, subjects were positioned along the radius of the centrifuge on their side, and were spun in the forward direction. The centrifuge could also be powered by hand cranks or electrically [36].

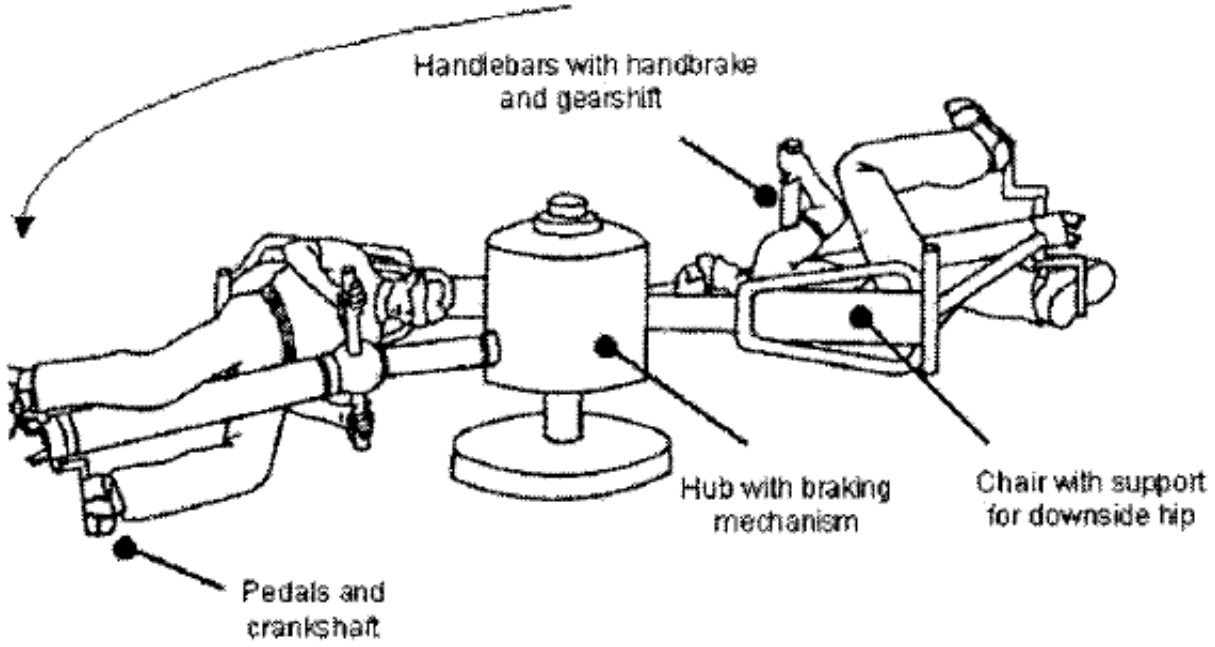

Figure 6- Original Space Cycle configuration [55]

Subsequent studies utilizing the Space Cycle noted that the sideways position of the subjects resulted in significant difficulty and discomfort when trying to pedal. As such, the Space Cycle was modified so that subjects sat upright on an ergometer in a suspended gondola able to pivot horizontally to align the gravito-inertial force vector with the body's z axis [55]. A further design modification was made to the Space Cycle in a later study, in which one of the two ergometers was replaced with a cage-like gondola, still able to pivot, that allowed subjects to perform resistive exercise (squats) [56]. This updated design no longer included a virtual reality headset, though the authors noted the importance of consistent visual cues. As seen in the original design however, subjects' legs were not supported and any support for their side was minimal, both likely contributing to the discomfort that led to a redesign.

The other SRC design that positioned subjects sideways and included a cycle ergometer was the Human Powered Artificial Gravity (HPAG) SRC at MIT, a centrifuge different from the motorized one being used in this project. As seen in Figure 7, the HPAG accommodated two subjects on their side, each pedaling a cycle ergometer used to spin the centrifuge. It was also later modified to include vibrating pedals capable of providing perceptible 30 Hz vibrations [57]. The centrifuge was noted as being unreliable and uncomfortable, and was eventually disassembled [58]. As seen in the image, the HPAG had little cushioning for the back and side, and required subjects to hold up their upper leg, both likely main contributors to the designs discomfort.

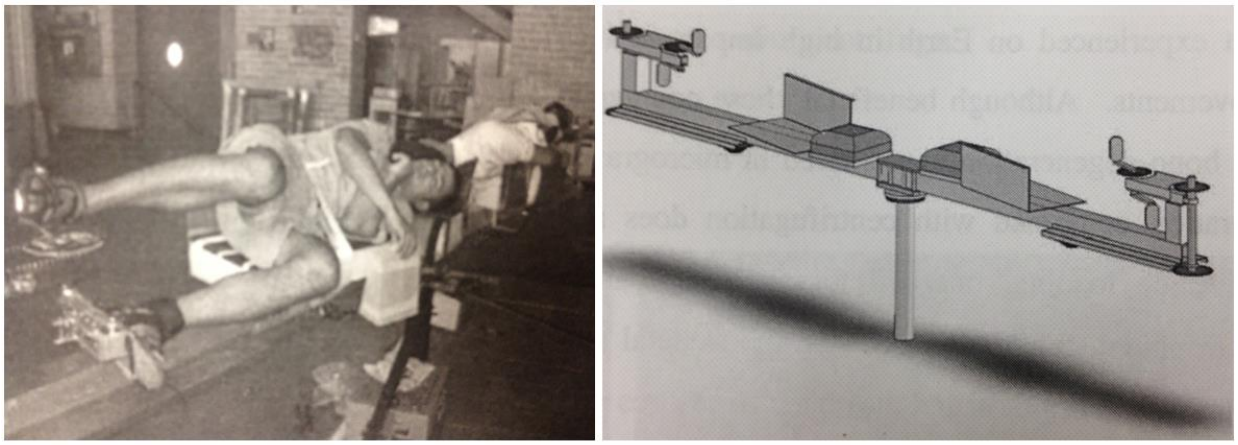

Figure 7- MIT Human Powered Artificial Gravity (HPAG) cycle [57]

The review of current and past applicable centrifuge designs reveals three key design considerations for the new MIT CRC.

1. CRC designs with radii of 1.4 meters or less are feasible and have been demonstrated passively. Further, subjects can tolerate being positioned such that there is some acceleration on the head due to the head being located slightly off of the axis of rotation.
2. Supine positioning of the subject while exercises has caused lateral deflection of subjects' knees, thus it is ideal to position subjects sideways in order to align the direction of the legs with the direction of the Coriolis forces.
3. SRC designs that have positioned subjects in a sideways position while cycling have caused significant discomfort such that the centrifuges were dismantled or redesigned. A lack of leg and side support is a probable cause for this discomfort.

By designing a CRC with ergometer that positions subjects on their side, the MIT CRC represents a novel centrifuge design and one of the most realistic in representing a likely inflight centrifuge configuration.

3 COMPACT RADIUS TEST PLATFORM DESIGN AND FABRICATION

The first objective of this project was to design and fabricate a compact radius artificial gravity test platform, specifically, one meeting the engineering requirements of the AGREE proposal. This chapter begins by detailing the existing MIT SRC design and its capabilities, on which the new platform was built. Design and operational requirements are specified, the design process is discussed, and the chapter concludes with a detailed description of the final design.

3.1 MIT SRC

The MIT SRC, as seen in Figure 8, was originally designed and built by Peter Diamandis of the Man Vehicle Lab (MVL) in 1988 as the Artificial Gravity Sleeper (AGS) to study the feasibility of sleeping during centrifugation. A waterbed was mounted on the arm, and a wind shield was erected around the subject to prevent wind motion cues while sleeping. A cycle ergometer was also added as part of the early design, as seen in Figure 9, though to the authors' knowledge no data was collected or reported from trials with the cycle [59]. The centrifuge has a radius of 2.1 meters, is 0.91 m wide and is composed primarily of an aluminum honeycomb panel surrounded by aluminum sheets.

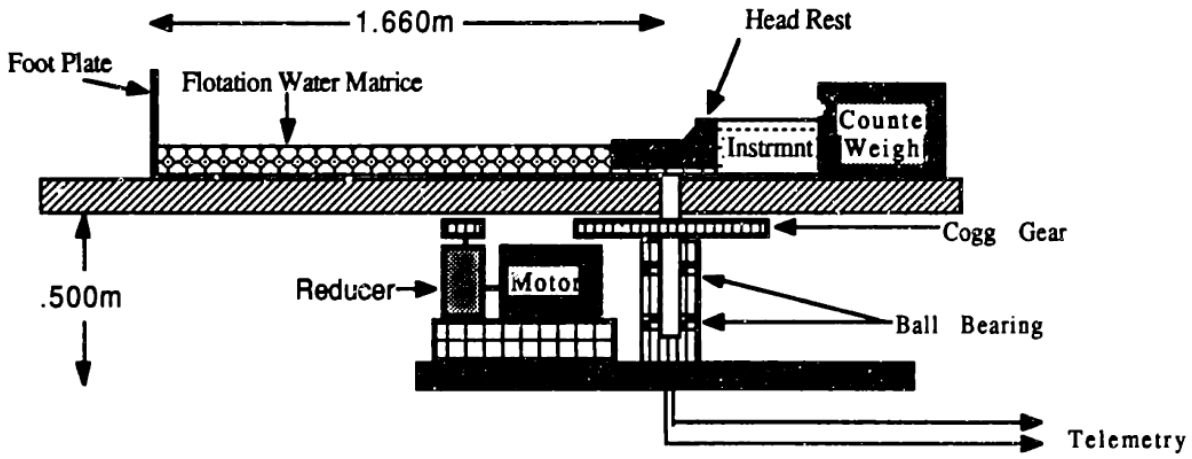

Figure 8- Original MIT MVL centrifuge design [59]

Figure 9- Original MIT AGS with cycle ergometer

In 2004, the centrifuge was updated with larger angle brackets along the sides of the main bed, new flanges and braces on the rotation support shaft to reduce vibrations, a refurbished slider bed, and a larger and more robust footplate [60]. Further modifications made between 2004 and 2010 for neurovestibular and exercise studies included an overhead frame for equipment, a helmet to control subject head positioning, an onboard Dell desktop computer with an Intel Pentium processor, 2.2 GHz, and 2.00 GB RAM running Windows XP, and a 3M MicroTouch 17" touchscreen monitor powered by an APC uninterrupted power supply and external battery pack.

Figure 10 shows the centrifuge configuration at the beginning of the current project in September 2012. During operation, counterweights were used as required by each subject. The counterweights included four permanent 37.3 kg rectangular masses fixed vertically at 0.86 m behind the subject's head, as well as several smaller counterweights (21.8, 20.7, 11.6, 11.4, 10.7, 7.2, and 6.8 kg) available to be placed as needed in order to minimize static and spinning bending moments. Subjects were positioned in the supine position along the radius with the head at the center of rotation, and the baseplate distance was adjusted based on the subject's height. The MIT SRC was the baseline hardware on which the CRC test platform was built. The existing arm, supports, motor and controls were considered fixed elements onto which the new test platform had to be constructed. The centrifuge is powered by the original 1 HP DC

motor, and can be controlled either manually or automatically off of a LinkMate desktop computer with AMD Duron Processor, 900 MHz, and 2.25 GB RAM running Windows XP in the adjacent control room.

Figure 10- Existing MIT MVL centrifuge at commencement of the project in September 2012

3.2 AGREE and Requirements Definition

Design of the CRC platform began with the specification of design and operational requirements. A majority of these requirements was taken directly from requirements specified as part of the Experiment Science Requirement (ESR) document for AGREE developed by the European Space Agency's European Space Research and Technology Centre (ESA ESTEC) [61]. Additional requirements specific to the existing MIT hardware were also established. Table 4 summarizes these design and operational requirements, beginning with those articulated in the AGREE proposal followed by additions for the MIT SRC. For all AGREE requirements, those not met by the final design are highlighted in red. These were not met either from constraints of the existing hardware or time/cost limitations during initial design.

Table 4- AGREE centrifuge design and in-flight operations requirements [61]

Design Requirements
1. The SRC shall have a maximum radius of 1.4 meters.
2. The SRC shall be able to accommodate one subject at a time, in a seated position facing in the direction of rotation.
3. The SRC shall be capable of being controlled by both the subject and the observer (controller).
4. The SRC shall include an exercise device (cycle ergometer) with controlled, variable resistance.
5. The displacement range of the exercise device shall be 30-34 cm.
6. The SRC design shall be modular in order to accommodate multiple exercise devices as well as a foot plate for orthostatic tolerance tests.
7. The SRC shall include a restraint to keep the torso fixed during exercise.
8. The SRC seat and restraint and shall allow for flexibility to adjust the subject's hip angle, trunk angle, and head position.
9. The seat and restraint shall accommodate all crew on the ISS by adhering to the design requirements of the Soyuz Kazbek seat.
10. The SRC shall include handle bars for the subject, capable of being fixed in variable positions allowing for shoulder angle to the torso in the sagittal plane of 0-90° and elbow angles of 0-90°.
11. The subject's inter-aural axis shall be parallel to the axis of rotation.
12. The subject's head shall be no more than 30 cm from the axis of rotation.
13. The angle of the subject's upper body with respect to the SRC radius through the hip joint shall be less than or equal to 30°. However, the seat shall be able to rapidly recline to the supine position in the event of presyncope.
14. The positioning of the subject on the SRC shall allow for near full extension of the leg and an angle greater than 45° (desired 90°) degrees to the trunk during flexion while exercising.
15.Then positioning of the subject shall be such that the distance from the center of rotation to the ankle joint shall be greater than the distance from the center of rotation to the hip joint during extension

16. The SRC shall include a video display positioned approximately 30 cm in front of the subject's face , allowing the subject to control angular velocity and acceleration as well as the resistance of the ergometer, while also showing the following real time data:

-Angular velocity

- G-level at heart

-Heart rate

-Resistance setting of ergometer

- Crank revolution speed

- Crank torque

17. The SRC shall include foot restraints to secure feet to the ergometer

18. The SRC shall include a momentum compensation device to nullify the varied angular momentum.

19. The SRC shall be surrounded by a curtain/shade to block views of the external environment (if desired by the subject). (This requirement met by ability to turn off lights in room).

20. The SRC shall provide cooling for the subject.

21. The SRC shall provide a headset for communication between the subject and observer.

22. The SRC shall include instrumentation to measuring the following during centrifugation:

- Centrifuge speed (setting and measured)
- Ergometer load (setting and resistance)
- G-force at the subject's heart
- ECG (heart rate)
- Beat-to-beat blood pressure
- Respiration frequency and depth postural
- EMG of the quadriceps, gastrocnemius, soleus, and tibialis anterior during passive/active loading
- Subject postural position (trunk, hip angles, etc.)
- Perceived postural position
- Frontal lobe blood flow and oxygenation
- Nystagmic eye movement
- Facial expression via IR video
- Force on each foot and the buttocks
- Segmental body (or chair) position
- Acceleration at seat

Performance Requirements

23. The SRC shall be capable of rotating in both directions.

24. The SRC motor and tachometer shall be able to maintain velocities of 60-200 deg/sec to an accuracy of +/- 2%.
25. The SRC motor shall maintain a constant angular velocity within 2-5% of the command velocity.
26. The SRC angular velocity shall be reproducible step-to-step, subject-to-subject, or day-to-day within 5-10% of command value.
27. The SRC motor shall provide smooth angular acceleration between 5-15 deg/sec^2 with a nominal rate of 10 deg/sec^2
28. The SRC shall be able to be stopped by both the subject and the controller.
29. The SRC shall be capable of stopping within 5 seconds in the event of an emergency.
30. The SRC shall be capable of providing up to 2 G at the heart (desired 1.2 G).
31. The centripetal acceleration at the level of the ears shall be less than 0.1 G at an angular velocity of 180 deg/sec.
32. The ergometer shall provide variable, regulated exercise up to 200 W (desired 300 W) with maximum power generated at 10-120 rpm.
33. The SRC shall be able to rotate at up to 360 degrees/sec.
MIT SRC- Specific Requirements
34. Subjects shall be oriented relative to the centrifuge the same as they would be in space despite the additional G vector. This position must be comfortable for subjects for up to 30 minutes.
35. Gross weight of the final platform (including centrifuge bed) shall be less than or equal to the gross weight of previous exercise experiments.
36. Cost shall be minimized by utilizing existing hardware whenever possible.

While the AGREE CRC used the Kazbek-UM seat dimensions for anthropometric requirements (Requirement 9), the MIT CRC expanded on this by using the most recent anthropometry standards from the NASA Human Integration Design Handbook (HIDH). Table 5 summarizes that applicable anthropometric data from the HIDH and compares it to the Kazbek-UM requirements, and Figure 11 shows the location on the body of these measurements. For all but one measurement (biacromial breadth, in which the maximum length was 0.2 inches larger for the Kazbek-UM seat), the HIDH standards were more conservative. Therefore, by modifying this anthropometry requirement to meet HIDH instead of Kazbek-UM, the MIT CRC accommodates a wider range of subjects and is able to utilize NASA-established anthropometric requirements across a larger number of dimensions.

Table 5- Seat anthropometry requirements comparison [62]

	Measurement	Soyuz Kazbek Seat Range	HIDH Range
A	Seated Height	31.4 - 39.0	30.6 – 39.9
B	Eye Height Sitting	NA	26.2 – 35.0
C	Buttock-Popliteal Length	NA	16.6 - 22.5
D	Buttock-Knee Length	NA	20.5 - 27.5
E	Popliteal Height	NA	13.0 - 19.7
F	Knee Height Sitting	NA	17.9 - 25.0
G	Foot Length	NA - 11.6	8.5 – 12.0
H	Shoulder-Elbow Length	NA	11.6 – 16.5
I	Forearm-Hand Length	NA	15.2 – 12.5
J	Biacromial Breadth	NA - 17.7	12.7 - 17.5
K	Hip Breadth Sitting	NA - 16.1	12.4 - 18.3

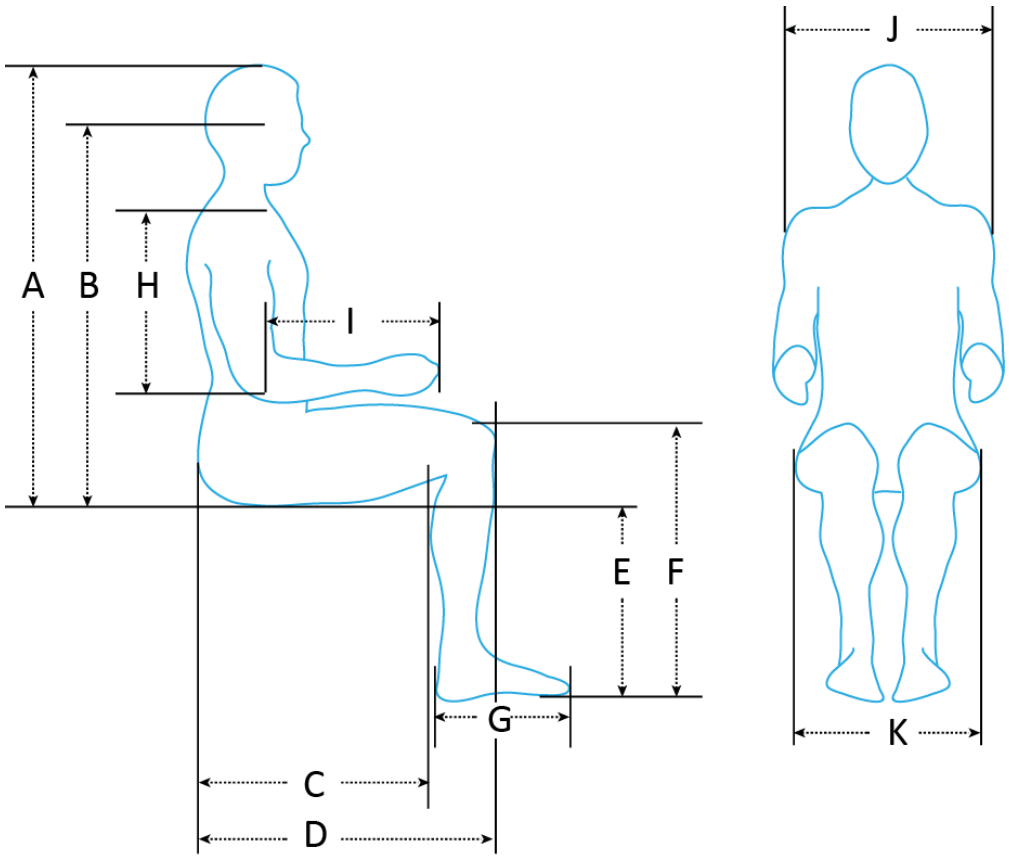

Figure 11- Anthropometry measurements

3.3 Concept Design

Concept design began by exploring the massing of new platform components within the existing centrifuge, as well as methods for comfortably accommodating the unique positioning of the subject. The proposed AGREE design, seen in Figure 12, was used as a design reference. Based on the requirements the subject was to be place subjects “sideways” on the MIT CRC, that is, with the interaural axis parallel to the axis of rotation. This positioning provides two benefits. First, it places subjects “into the wind” as they cycle, adding a motion cue to help reduce motion sickness. Second, it aligns the direction of the legs while pedaling with the direction of Coriolis forces, preventing potentially harmful lateral forces at the knees during exercise that could cause knee or hip injuries. Previous exercise studies on the MIT SRC reported knee deflections of up to 2.5 inches during exercise with subjects in the supine position [63], and deflections have also been reported anecdotally on other centrifuges (Iwase, personal email communication, March 2013). As discussed in Chapter 2, previous SRC designs that positioned subjects in the sideways position created significant discomfort to the point of being nonoperational [55]. Therefore the design of an ergonomic way of supporting the torso and legs was of primary concern.

Initial concept models of the MIT CRC design, seen in Figure 13, were done to show how a subject, sideways seat, and exerciser with baseplate might be configured within the 1.4 meter radius requirement. The models showed that achieving the design was possible but would require that components cantilever over the side of the centrifuge arm, which had not been previously done on the MIT SRC. The concept model was also used to develop two methods of leg support in order to address the discomfort associated with being sideways. The two leg support concepts are seen in Figure 14. Concept 1 used two leg plates to support the legs, and had the subject wearing low-friction leg pads. Concept 2 used a leg plate/pad for the bottom leg, but used suspended cuffs to support the upper leg. The cuffs were hung from additions to the existing frame above the centrifuge bed.

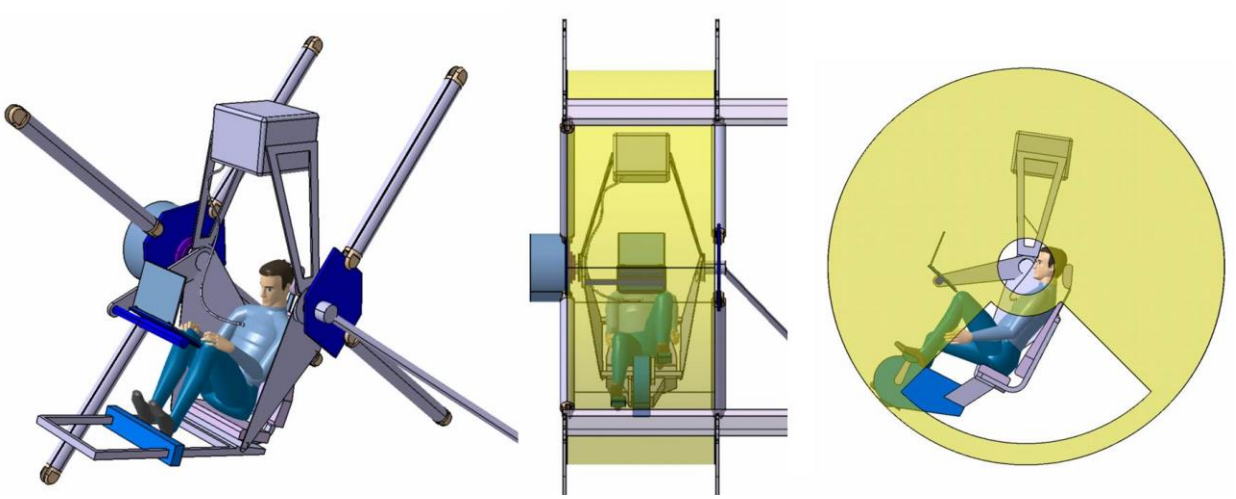

Figure 12- AGREE CRC concept renderings [64]

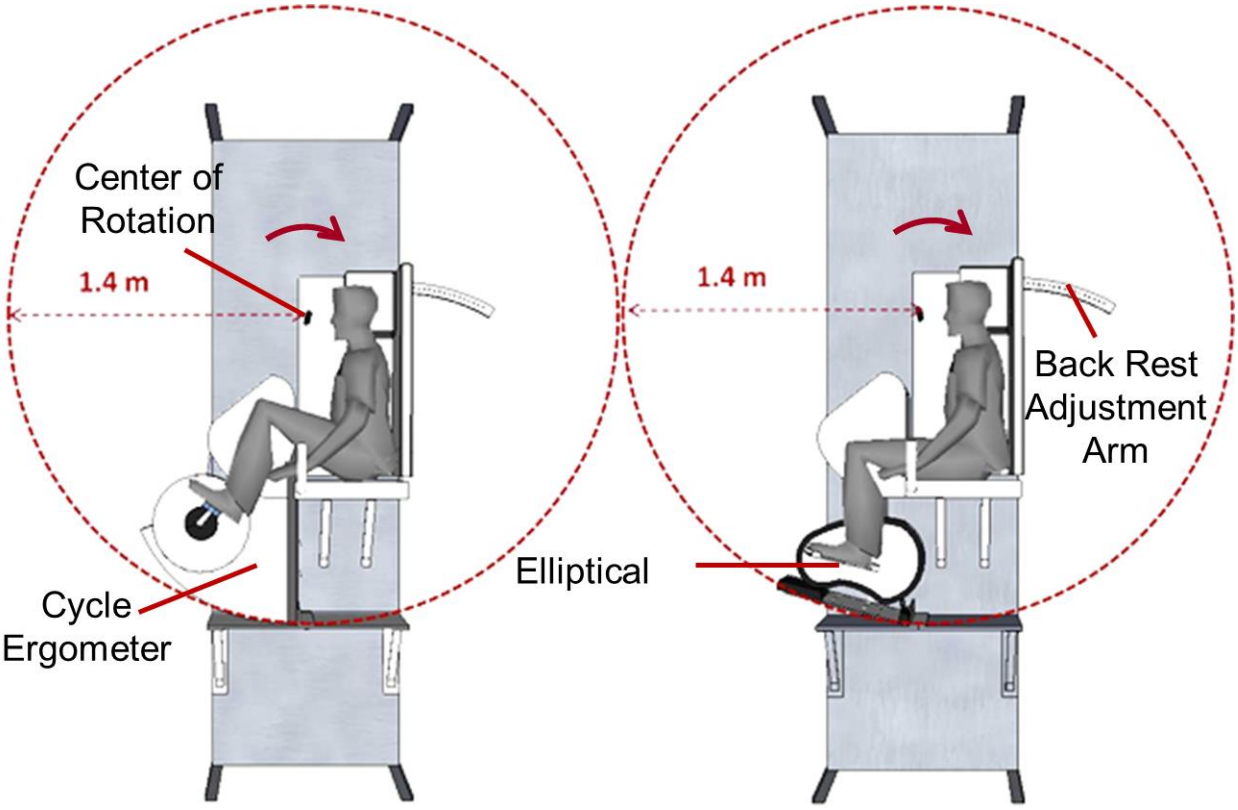

Figure 13- Massing of components onto the existing centrifuge, shown with two types of exercise devices: cycle ergometer (left) and elliptical (right)

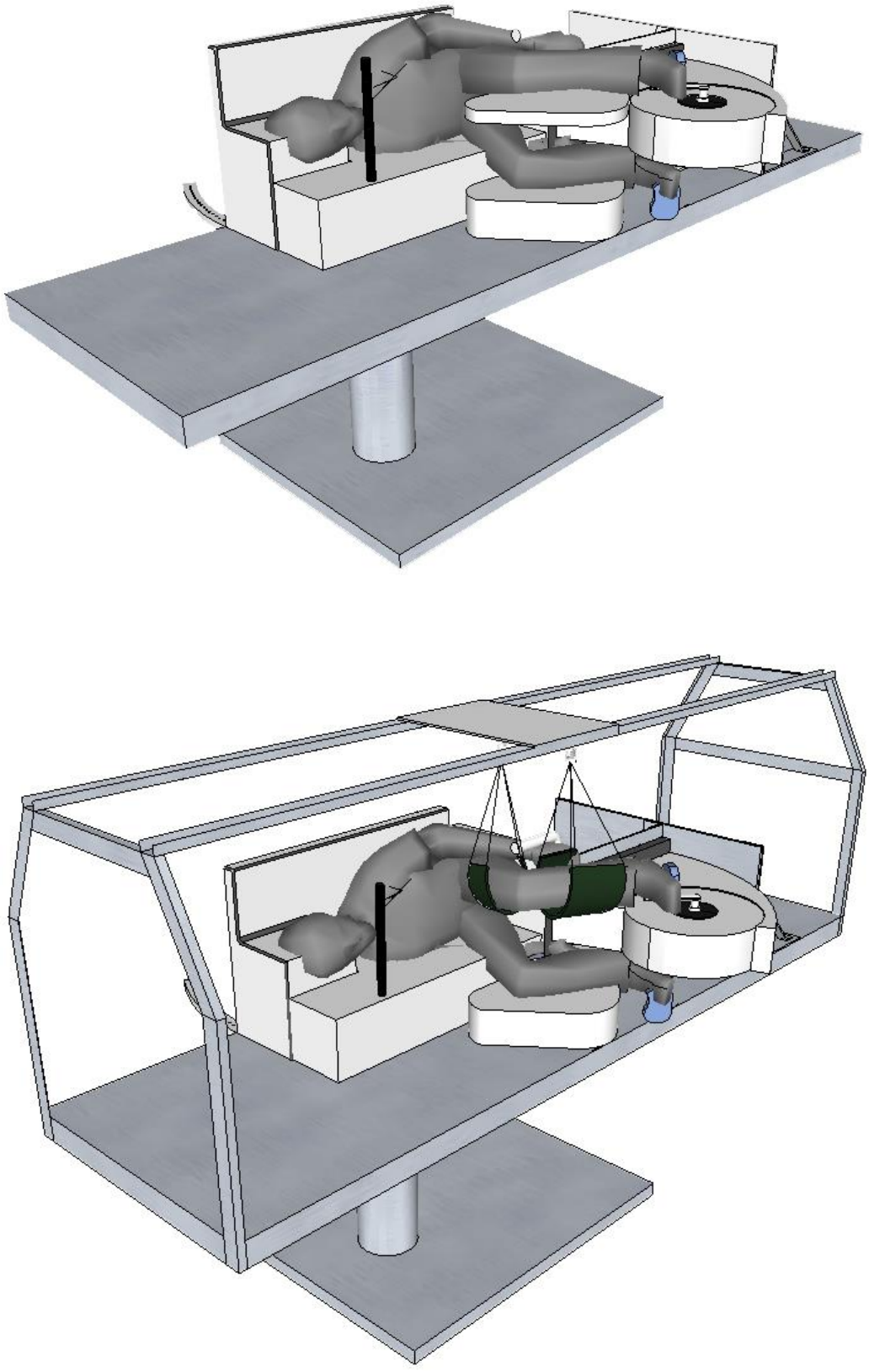

Figure 14- Leg support concept 1, leg plates (top) and concept 2, leg cuffs (bottom)

3.4 Design Development

Following concept design, design development began with the construction of a mockup to test Concepts 1 and 2. The mockup consisted of three components: the chair, a mounted ergometer, and leg pads. As seen in Figure 15, the chair was created using ¾" plywood, 3" thick memory foam, 0.0015"Teflon film over the leg plates, and a memory foam pillow. The chair's back measured 43" x 24", the seat (portion supporting buttocks) measured 18" x 24", and the side rest (portion on the ground) measured 43" x 23" at the top and 15" at the bottom. The leg plates measured 20" x 22.5" with rounded corners. For Concept 1, the top leg plate was hinged to facilitate getting into the chair. The ergometer used with the mockup was the Drive Medical Folding Deluxe Pedal Exerciser (Drive Medical Design and Manufacturing, Port Washington, NY) mounted on an aluminum base, as can be seen in Figure 15.

Figure 15- Seat and ergometer ground mockup in operational configuration (left) and with upper leg plate raised for subject seating (right)

The leg pads measured 6" wide x 17.5" long by 1.5" thick. The pads consisted of 1.5" thick memory foam, duct tape backing, and 0.015" thick Teflon surface, and Camco 42503 Velcro straps (Camco Manufacturing Inc, Greensboro, NC). The lower leg pads were cut with a curved indentation to allow for the upper and lower pads to adjoin at the knee, as seen in Figure 16.

Figure 16- Ground mockup leg pads front and back (left) and worn by subject (right)

Formative evaluation was first done with the mockup on the ground. Four subjects (2 male, 2 female) ranging in height from 5’ 3” to 6’ 5” were strapped into the chair and cycled. This formative evaluation led to a number of changes, including:

- A switch from a vertical rising upper leg plate to horizontal rotation
- A reduction in the length of the leg pads
- A reduction in the height of the lower leg plate with respect to the side rest
- A reduction in the width of the upper leg plate to avoid interference in the groin area
- An increase in the diameter of the Velcro bands for pads on the upper leg plate

Following ground evaluation, the chair was moved onboard the centrifuge and fitted into the existing sliding frame. Once onboard, and with changes from ground testing implemented, the mockup was used to prototype both the leg plate and leg cuff concepts during centrifugation, as seen in Figure 17 and Figure 18.

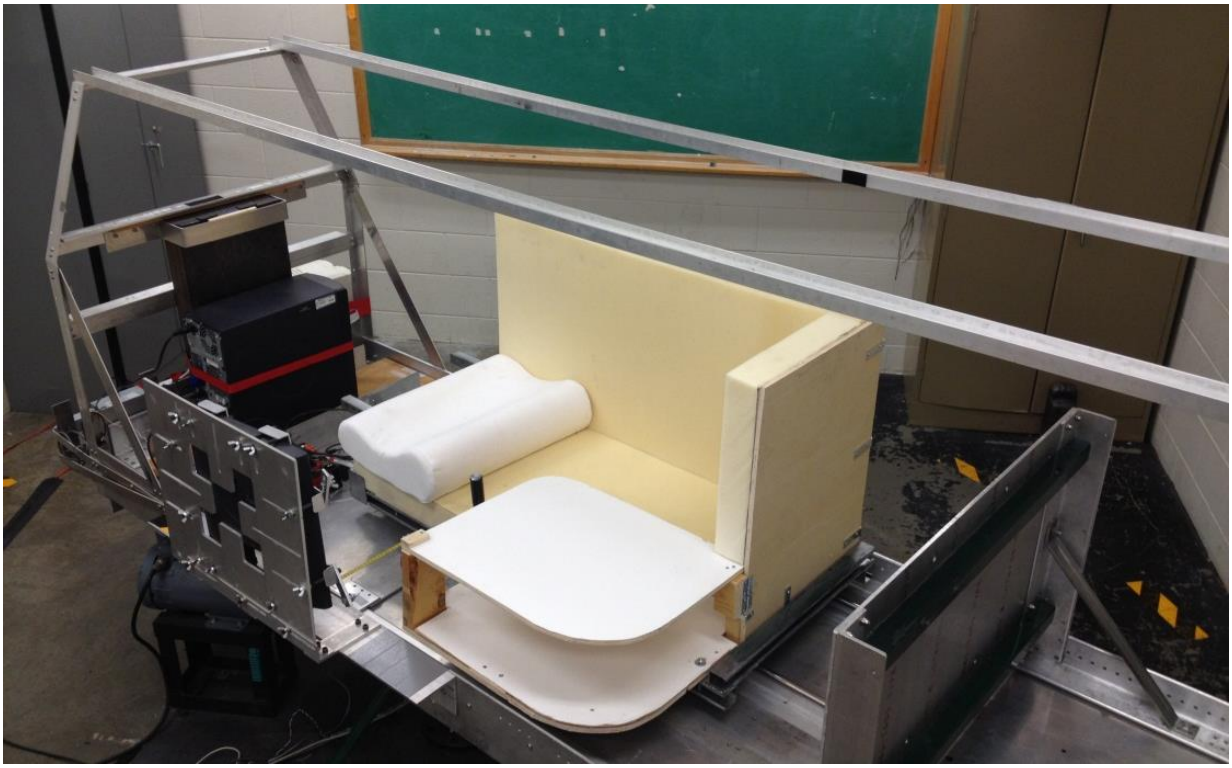

Figure 17- Leg plate concept mockup on centrifuge

Figure 18- Leg cuff concept mockup on centrifuge (front vertical leg cuff support beam not shown)

For the onboard evaluation, the leg pads were reduced in length to 7” (width and depth remained the same). The leg cuffs, seen in Figure 19, were made from canvas and measured 5.5” wide by 24” and 17.5” long for the upper and lower leg cuffs respectively. Each cuff was suspended from the overhead frame by two CamLok 3039DAT Adjustable Steel Cord bungee cords (Master Lock Company, LCC, Oak Creek, WI). The pairs of bungees were looped at the top through a 2” diameter stainless steel ring bolt. Additions were made to the centrifuge’s overhead frame to support the leg cuffs; added supports were constructed from3.5” wide, ¼” thick aluminum (alloy 6061) beams as seen in Figure 18 (with one additional vertical beam in front of the subject, not shown for photo clarity). The final addition to the chair was a 5-point Netami 25-0045 cam lock safety harness (Netami USA, Flushing, NY) of which 3 of the 5 points were used.

Figure 19- Leg cuffs

As seen in Figure 20, the same prototype ergometer used on the ground was also used for onboard testing. In order to mount it on the centrifuge and allow its position to be adjusted in two directions, modifications were made to the existing baseplate. First, the baseplate was “inverted” to move the corner brackets from the front to the back. Two 60” strut channels were then bolted to the front of the baseplate, and the pedal exerciser and its 1/8” aluminum base were attached to the struts by 5.5” sections of strut telescoping tubes and two 1.25” long trolleys. This allowed the exerciser to be moved up to 20” perpendicular to the radius, and be secured through the telescoping tubes and strut channels by locking pins. During initial runs, the trolleys used to secure half of the exerciser’s aluminum plate to the struts were found to be inadequate and the cause of vibrations, so clamps were added for a majority of trials.

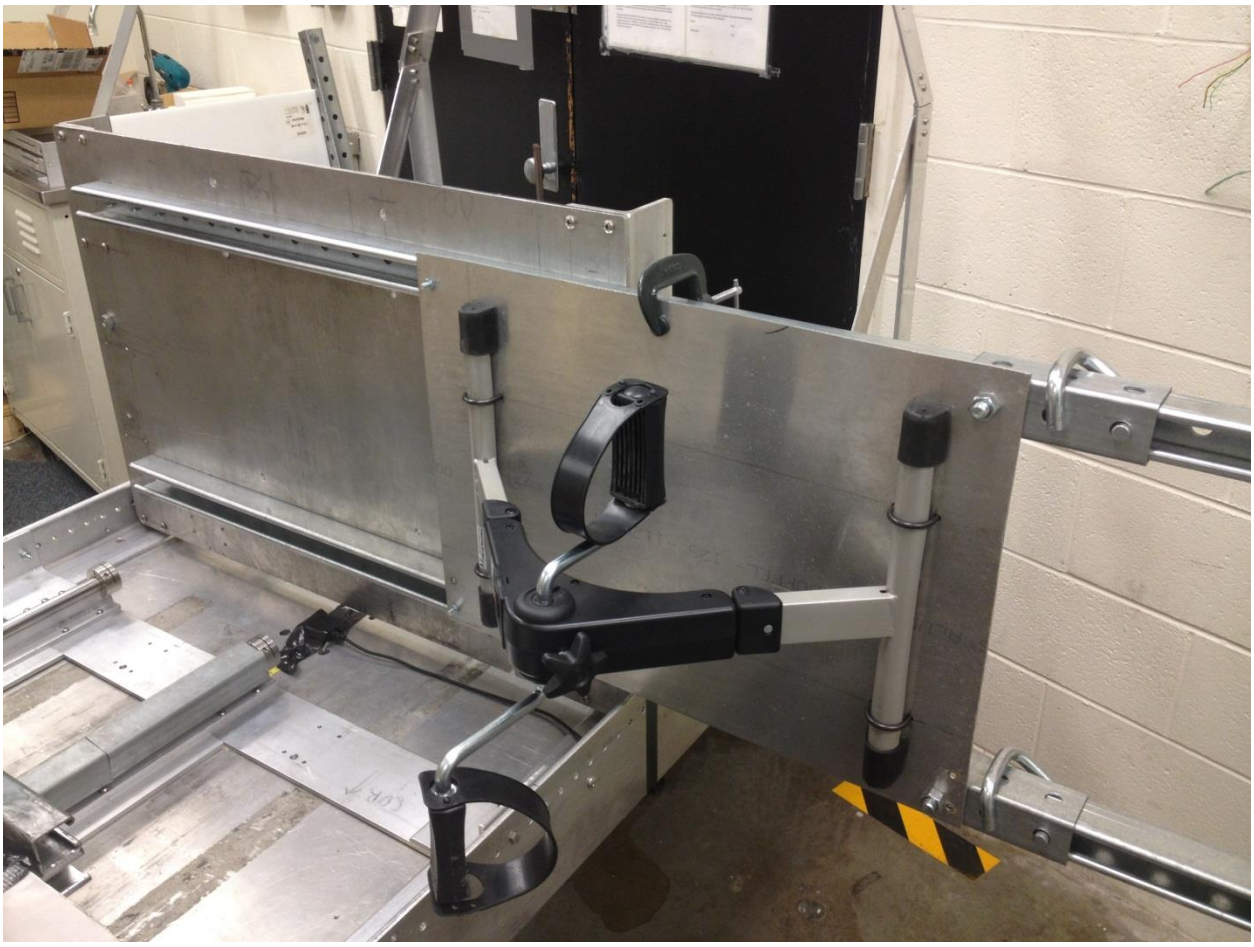

Figure 20- Mockup exercise device and baseplate

Six subjects, 3 men and 3 women, tested the onboard mockups. Subjects were exposed to 1 G at the feet (approximately 25 revolutions per minute [RPM]) for 5-10 minutes, during which they cycled at a subjectively comfortable rate with minimal resistance. They were also specifically asked to pedal as fast as possible for 1-2 minutes of their trial. After each trial, subjects were asked for their feedback on operations (getting in and out of the centrifuge) and design of each component. The subjects ranged in weight from approximately 115-200 lbs, and in height from 5'0" to 6' 5". Appendix A summarizes the results of these user tests. Early on, significant issues were identified with the leg plate concept including difficulty and discomfort while loading in and out of the chair, and the inability to fine tune the height of the upper leg resulting in discomfort while cycling. The leg cuffs, however, were found to be both easy to get into and easy to adjust. As such 4 of the 6 subjects only used the leg cuffs, and all found them to be comfortable.

One subject (male, age 26) participated in three extended trials lasting 10- 18 min with alternating periods of rest, "slow" pedaling (~1 Hz), and "fast" pedaling (~2 Hz). Though the ergometer was set on its maximum resistance setting there was minimal resistance. The purpose of these trials was to evaluate the mockup for the extended time periods expected to be used during actual trials. The subject also wore a heart rate belt (Vernier Software and Technology, Beaverton, OR) to simulate one of the more physically obtrusive physiological sensors and evaluate what impact, if any, that would also have on user comfort.

Figure 21 shows the results of heart rate during one of the long-duration tests. Trials began with a period of rest once the centrifuge had stabilized at 1 G at the feet. Despite minimal resistance, the subject's heart rate rose to within the target heart range during both fast and slow pedaling (maximum heart rate is defined as 220-subject's age in beats per minute [BPM], and target heart rate is defined at 50-70% of the maximum heart rate [65]). Two additional trials, each lasting 18 minutes, yielded similar results. Qualitatively, the subject reported that cycling was comfortable overall. There were some periods during which the upper leg began to feel numb which was attributed to the leg cuffs being too tight and lifting the leg too high. The cuffs were subsequently adjusted during rest periods and the issue was alleviated. The subject also reported some pain on the right shoulder after the trails, which was attributed to the safety harness. This was adjusted during subsequent trials which again alleviated the problem. The heart rate belt caused no discomfort and was reported as being nearly undetectable during trials.

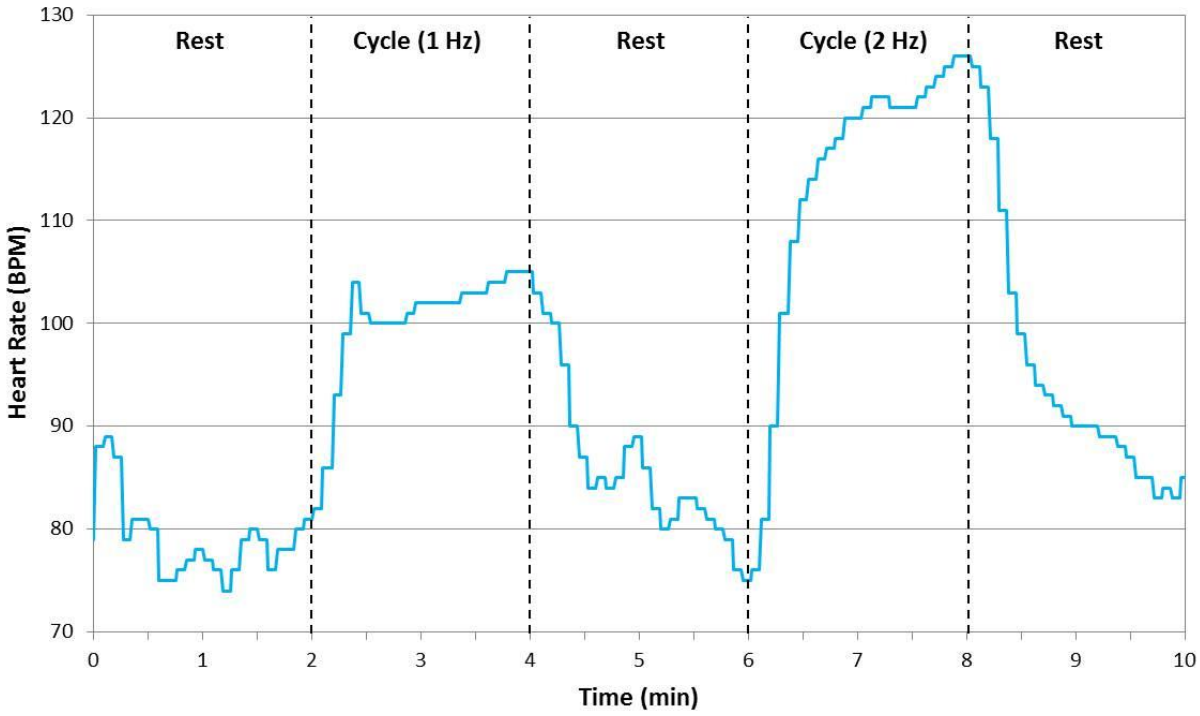

Figure 21- Heart rate during example long-duration mockup user testing

Together, both long and short-duration user testing found that the leg cuffs were the preferred design for upper leg support, that the design was able to accommodate a wide range of anthropometry, and that the design could be used with instrumentation for extended periods of time. Given these findings, along with the design improvements identified and listed in Appendix A, the design process moved into final design and fabrication.

3.5 Final Design and Fabrication

Based on findings from user testing, the final design of the test platform was done using the leg cuff method for supporting the upper leg. The final design consisted of six components: four main parts of the physical platform (sliding base, chair, exerciser baseplate, leg cuffs/frame), the cycle ergometer, and the instrumentation suite. Figure 22 and Figure 23 show the final design. The cushions which are located on the side and base of the seat are not shown. Technical drawings of machined components can be found in Appendix B, the bill of materials including part numbers in Appendix C, and each of the six components is detailed in subsequent sections

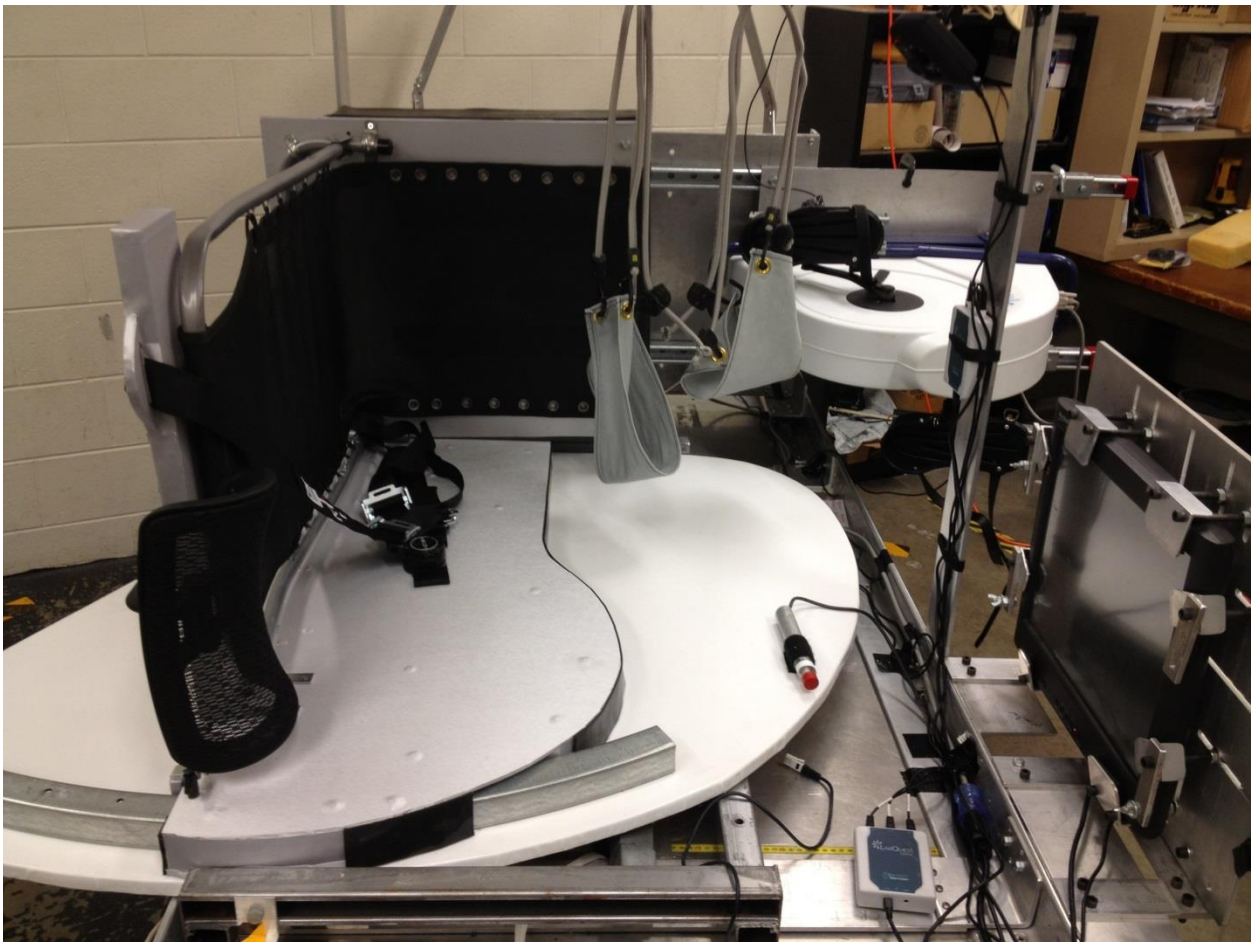

Figure 22- Final CRC platform (I)

Figure 23- Final CRC platform (II)

3.5.1 Sliding Base

The sliding base, seen in Figure 24, is the component of the main platform that mounts directly to the centrifuge arm and serves as the surface on which both the subject's leg as well as the adjustable side rest can slide. The entire surface can also glide along guiderails to adjust its radial position based on the subject's height. The sliding base is held in place radially by 2" incremental strut sections that are placed over the guiderails.

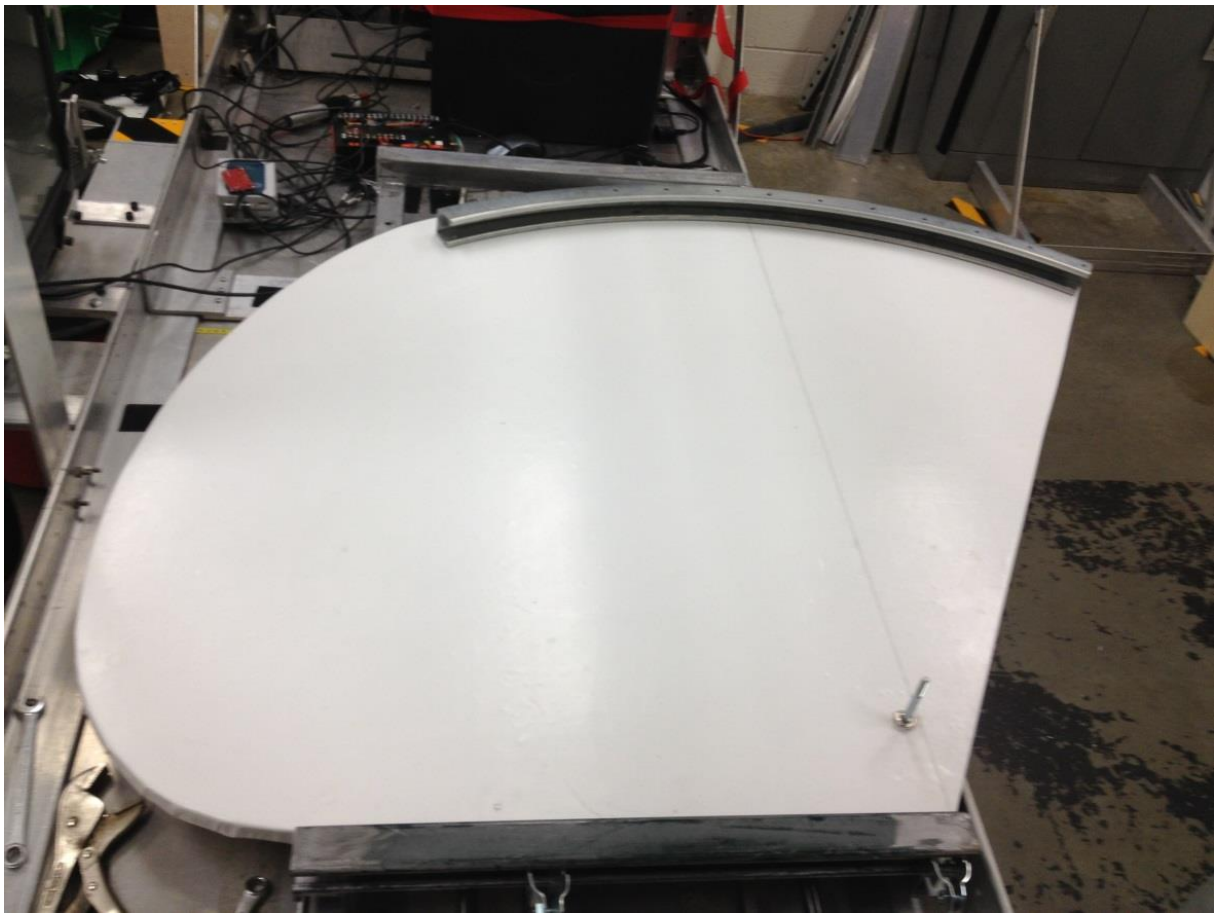

Figure 24- Sliding base

The sliding base consists of two subcomponents: a steel frame with linear bearings, and a slider board mounted on top. The frame and linear bearings are primarily the existing hardware from the previous centrifuge back rest, with a single additional strut for support at one end. The bearing tracks were also moved to the side of the centrifuge arm such that they are not centered along the radius.

The slider board is made of 3/4" spruce coated in two layers of white enamel and then covered by 0.01" thick, adhesive-backed PTFE film. Wood was selected as the primary material, replacing the previous HDPE board, because of lower weight and cost. The board was attached to the frame via 5/16" bolts

mounted into inserts. The arched strut at the top measured 1 5/8” x 1 5/8” along the edges and had an inner radius of 36”. Ten holes space 5 degrees apart were milled across the top of the curved beam to serve as pin holes for adjusting the side rest.

The shape of the slider board was derived from three curves, as seen in Figure 25. The first was a 60° sweep of a 41.6 inch radius curve from the point of rotation, which was the portion of the slider board used for the side rest to be adjusted. The second curve was a 60° sweep of a 9 inch radius for the lower leg while cycling, and the third curve was a tangential curve between the two. This tangential area was included both to increase the structural stability of the slider board as well as to cover the underlying frame to prevent pinching or other injuries.

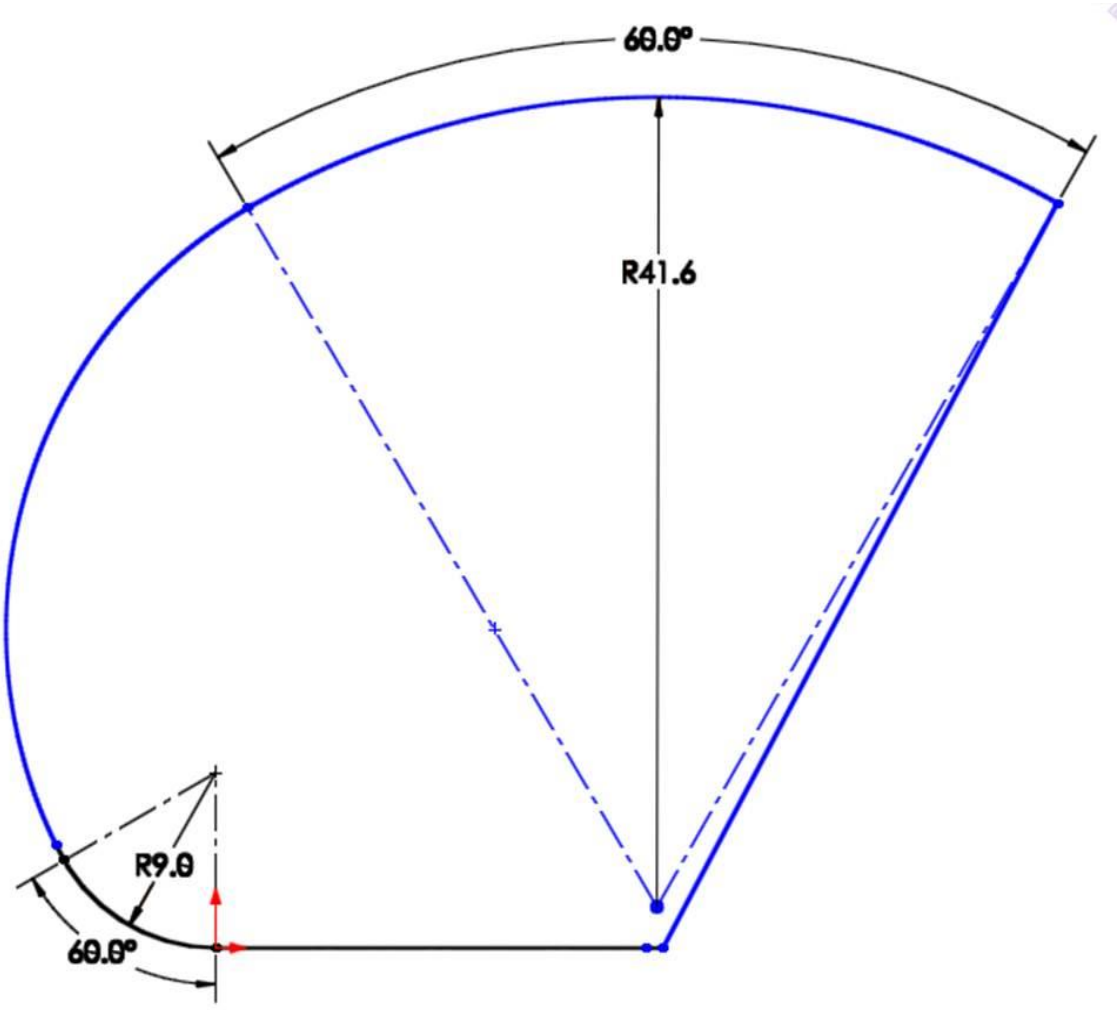

Figure 25- Slider board geometry (lengths in inches)

3.5.2 Chair

The chair of the test platform consists of three subcomponents: the back rest, the side rest, and the base. Figure 26 shows both sides of the final seat design with the subcomponents labeled.

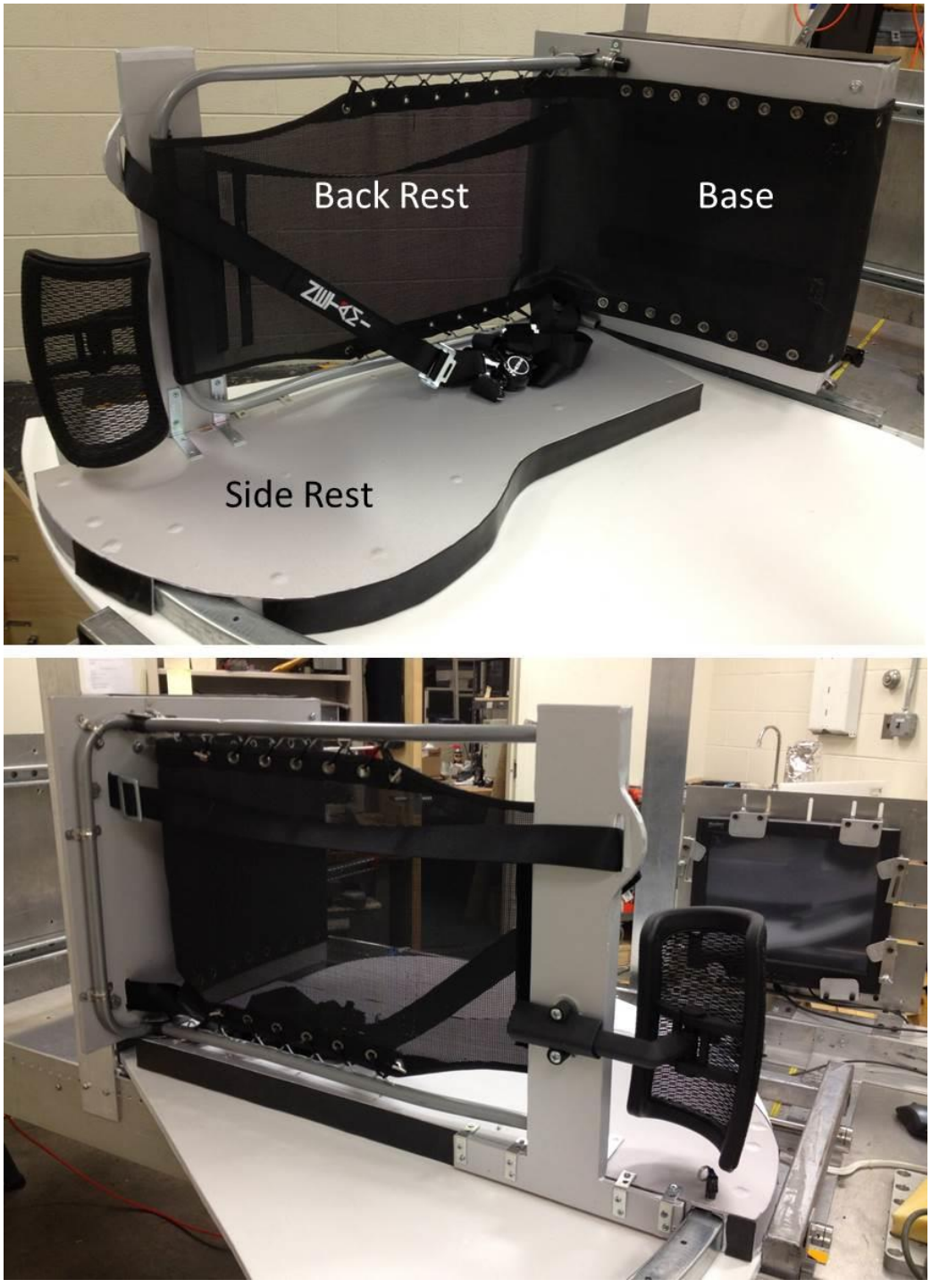

Figure 26- Final seat design, cushions not pictured

The base and side rest consist of layers of rigid foam, wood, adhesive aluminized vinyl covering, and adhesive rubber. The side rest also has a layer of 0.01” adhesive-backed PTFE film on the bottom to facilitate sliding along the surface of the slider board. Figure 27 shows a diagram of the layered composition of these two components. The core foam material was chosen in order to achieve the necessary thicknesses at minimal mass. Wood was used on either side of the foam both to better distribute loads on the foam as well as to serve as material into which additional components could be secured. The aluminized vinyl was used to reduce wear and allow for easier maintenance, and the rubber was used in areas where the foam was not covered by wood, in order to increase durability.

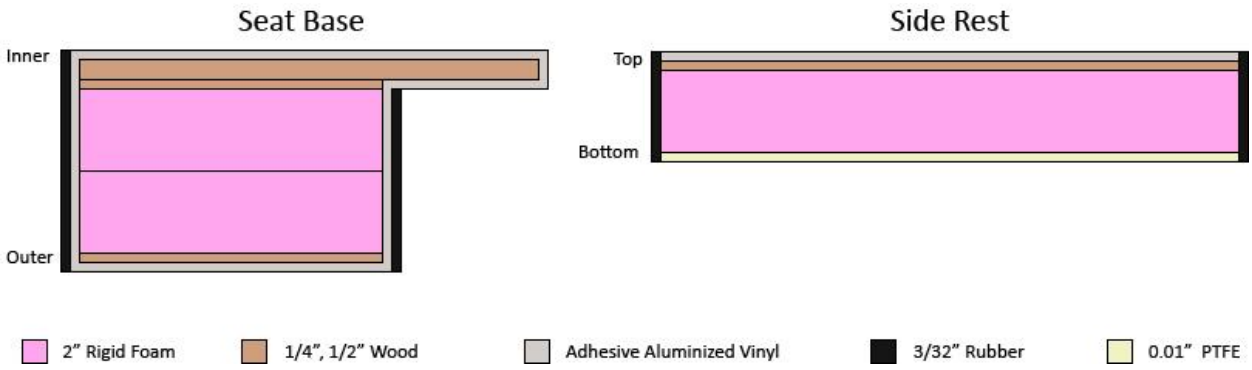

Figure 27- Seat base and side rest material diagram (not to scale)

The seat is affixed to the frame of the sliding base via clamps and two 7/8” aluminum tubes. The side rest lies on top of the slider board and includes a cut-out for the curved guide strut. The side rest pivots around a screw that is permanently affixed to the sliding base.

The back rest component is made with the back portion of a Strathwood Basics Anti-Gravity Adjustable Recliner (Amazon.com, Seattle, WA) which is fixed to the seat base. The upper part of the backrest (at the neck) is supported by a vinyl-covered wood beam onto which the adjustable, Space Seating breathable mesh headrest (Office Star Furniture Direct, Wichita, KS) is affixed. The safety harness is the same 5-point Netami cam lock harness used in the mockup, and is secured to the seat base.

Trunk angle of the subject can be adjusted by changing the angle of the side/back rest of the chair. The trunk can be adjusted from +15° (leaning forward) to -30°. As seen in Figure 28, the side rest can be locked into place via a pin that is inserted into one of the holes along the sliding base’s curved strut.

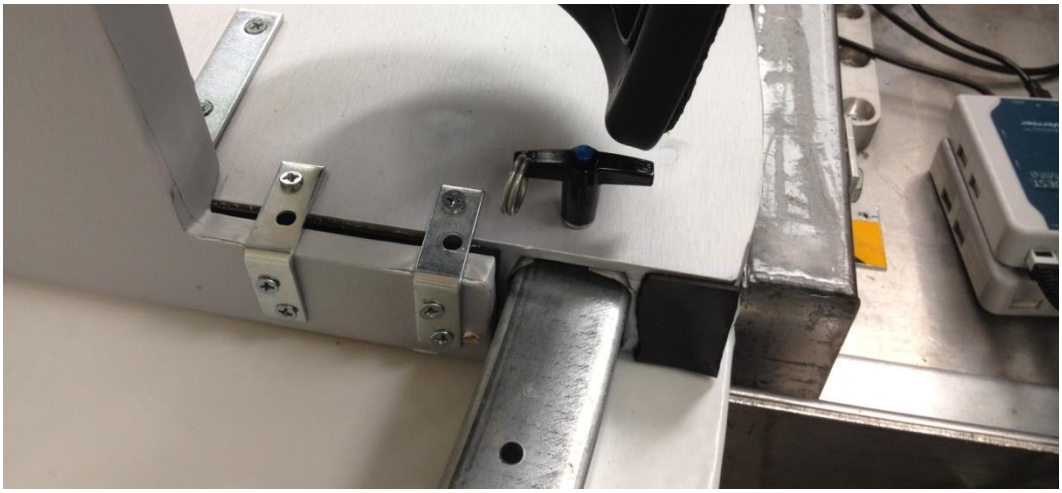

Figure 28- Side/back rest adjustment pin

When the trunk angle is adjusted, the material stretched across the back rest can be adjusted on the seat's base via Velcro strips on both sides of the base, as seen in Figure 29. This ensures the fabric supporting the buttocks remains taught independent of the back rest's angle.

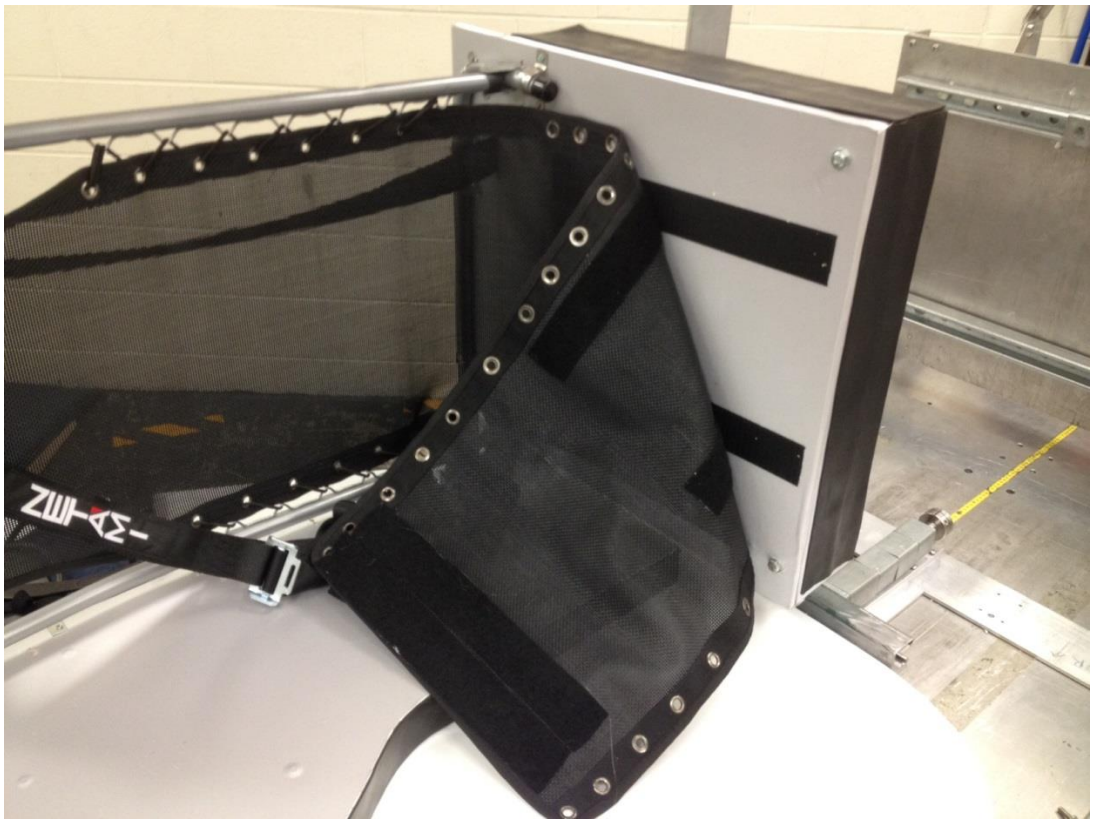

Figure 29- Back rest cloth adjustment

3.5.3 Exerciser Baseplate

The exerciser baseplate mounts the exercise device to the centrifuge arm. It is primarily the same hardware as the mockup, with two modifications. First, the trolleys used previously to secure one end of the cycle's base to the exerciser baseplate struts were replaced with additional telescoping struts. Second, the exerciser baseplate was attached to the centrifuge arm via linear tracks and lockable carriages (McMaster-Carr, Robbinsville, NJ), which were added in order to make adjusting the baseplate easier. The baseplate has an adjustable range of 0.36 cm along the radius (0.25 m within the 1.4 m radius restriction) and 0.44 m perpendicular to the radius. Figure 30 shows the final exerciser baseplate with cycle ergometer attached.

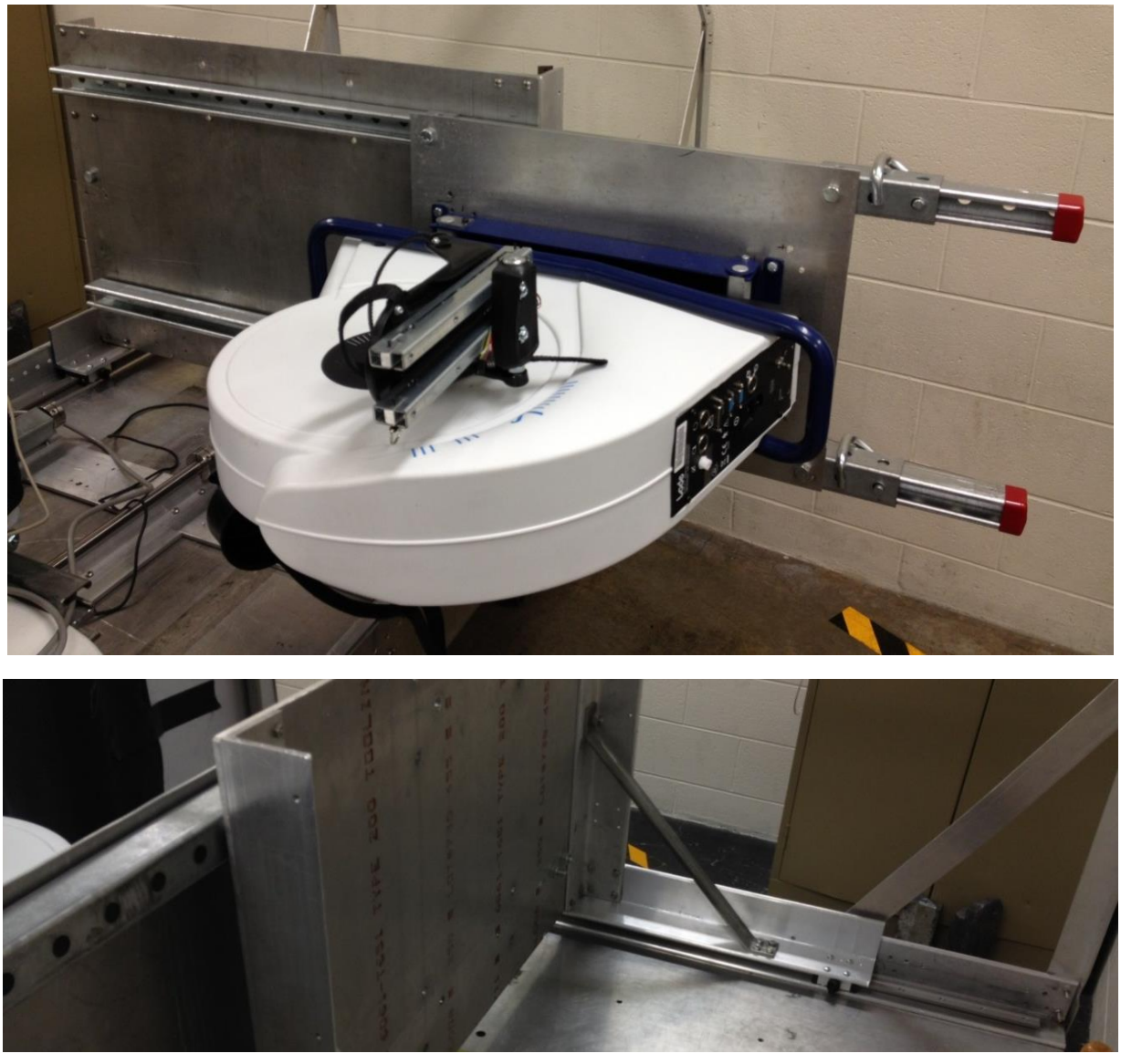

Figure 30- Exerciser baseplate front with attached cycle ergometer (top) and rear showing linear tracks and carriages (bottom)

3.5.4 Leg Cuffs and Frame

The leg cuffs, and frame used to support them, were not changed significantly from those used in the mockup as the original design proved to be highly effective. One modification was made by reducing the number of vertical frame members from 3 to 2 in order to accommodate the sliding base which protrudes over the side of the centrifuge arm. Additional threaded holes were added to the radial frame beams to allow the radial position of the eye bolt to be adjusted depending on the height of the subject. Figure 31 shows the final leg cuffs and frame design.

Figure 31- Leg cuffs and supporting frame

3.5.5 Cycle Ergometer

The primary exercise device for the CRC AG platform is a Lode Angio ergometer, seen in Figure 30 (Lode BV, Groningen, Netherlands). The Angio was selected because it met all requirements specified for the exercise device, and is also being used on SRC's at Russia's Institute for Biomedical Problems (IBMP) and the German Aerospace Center (DLR), thereby creating commonality between centers that will enhance future collaborations. Table 6 lists applicable specifications of the Angio. Additionally, the ergometer includes the Lode Ergometry Manager (LEM) software package allowing the ergometer to be controlled via the onboard computer. The LEM can be used to pre-program custom exercise regimens, enter and save subject data such as age, height, and weight, and save/ export data on workload and rate of cycling.

Table 6- Lode Angio ergometer specifications

Parameter	Specification
Max Workload (continuous)	750 W
Max Workload (peak)	1000 W
Max Rotation	255 RPM
Incremental Control	1 W
Accuracy	± 3 W @ <100 W ± 3% @ 100 - 500 W ± 5% @ >500 W
Dimensions	73 x 41 x 54 cm (l x w x h)
Crank Diameter	34 cm
Power Requirement	4 W @ 120 VAC, 60 Hz

In addition to the Angio ergometer, two other exercise devices are currently available for use on the centrifuge. These include the KETTLER mini-stepper (KETTLER USA, Virginia Beach, VA) as well as a Stamina® In-Motion® E100 Elliptical Trainer (Stamina Products Inc., Springfield, MO). The KETTLER stepper is the same hardware used in previous MIT SRC exercise studies [63] and would need minimal modification other than transfer of the strain gauges from the cycle in order to measure foot force. The elliptical requires additional modifications in order to be mounted to the exerciser baseplate. All exercise devices can also be removed in order to do passive studies on the CRC as well as orthostatic tolerance tests.

3.5.6 Instrumentation Suite

The final component of the CRC platform is the instrumentation suite. Instrumentation includes both physiological and mechanical sensors, selected based off of the requirements specified in AGREE, cost, and interface requirements. Figure 32 shows the location of all instrumentation and Table 7 summarizes sensor specifications to the extent that they are published. All sensors, with the exception of the IR camera, are hardwired to the onboard desktop and managed through one of two programs: Logger Lite 1.6.1 (for Vernier sensors) and Lode Ergometry Manager (for Lode sensors).

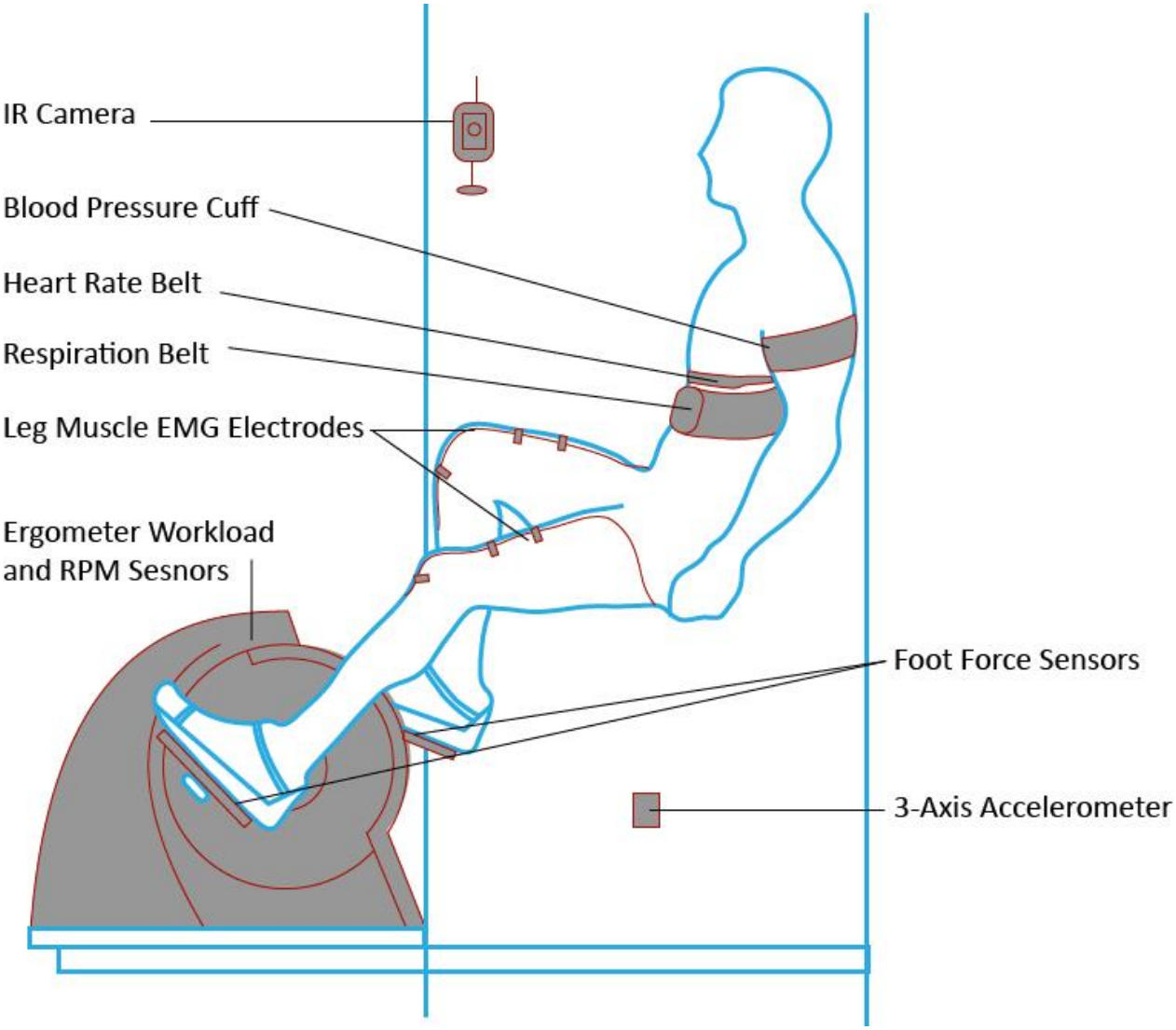

Figure 32- CRC instrumentation suite

Table 7- Instrumentation suite specifications

Instrument	Supplier	Range	Accuracy	Notes
Heart Rate Belt	Vernier	--	--	Max sample freq. = 0.2 Hz
Surface EMG (x2)	Vernier	0-5 mV	--	--
Blood Pressure Cuff	Lode	--	--	--
Respiration Belt	Vernier	--	--	Requires interface with gas pressure sensor
Foot Force Sensors (x2)	Vernier	-850 to +3500 N -200 to +850 N	±1.2 N ± 0.3 N	Two available settings
3-Axis Accelerometer	Vernier	±5 G	±0.05 G	--
IR Camera	Foscam	22 feet	--	--
Ergometer	Lode	--	--	See Table 4

There are currently only 8 ports available for Vernier sensors, and there are 9 required inputs to accommodate all of the sensors. For the pilot run detailed in Chapter 4, only one of the two EMG sensors was used. Finally, though not instrumentation, two-way voice-activated radios (Midland Radio Corporation, Kansas City, MO) were also added to the platform to facilitate communication between the subject and the controller.

Sensor setup requires interfacing with the onboard computer, which can be done either directly or remotely from the control room computer via LogMeIn. An operations checklist includes step-by-step instructions for setup, trial implementation, and account passwords can be found in Appendix D.

4 PLATFORM MECHANICAL CHARACTERIZATION AND VALIDATION

Having fabricated the new CRC, the next step in the development process involved testing operations, characterizing performance, and validating the platform. This chapter begins with a discussion of the Moment Minimization Tool (MMT) that was developed to assist the operator in placing counterweights to minimize bending moments on the centrifuge arm. It next presents the results of motor performance and vibrations tests. The chapter ends with a discussion of the pilot run done to validate the entire system.

4.1 Weight

The total weight of all hardware, not including the subject and only including the permanent counterweights, is 378 kg which is a 6.5% increase in weight from the previous design with exerciser. Table 8 summarizes each component and its mass.

Table 8- Mass of hardware components

Item	Quantity	Mass (kg)
Centrifuge Arm	1	70.9
Exercise Baseplate	1	21.0
Baseplate Struts	2	3.50
Ergometer + Strut Mounts	1	33.0
Seat Base	1	5.00
Back/Side Rest	1	5.00
Slider Board	1	48.0
Leg Cuffs/ Frame	1	5.00
Monitor	1	4.50
Desktop	1	4.50
APC Power Supply	2	12.5
Permanent CW	4	37.3
TOTAL		378

4.2 Bending Moments

Moments about the rotation shaft are calculated before each trial in order to determine the optimal placement of counterweights which minimize the total moment. Total moment is calculated as the sum of both static and dynamic (spinning) moments:

$$M_{total} = M_{static} + M_{spinning}$$

$$M_{total} = \sum_{i=1}^{n} m_i \, \vec{r_i} \, g \quad + \sum_{i=1}^{n} m_i \; z_i \; (\vec{r_i} \, \omega_i^2)$$

$$M_{total} = \sum_{i=1}^{n} m_i \, \vec{r_i} \; (g + z_i \, \omega_i^2)$$

where:

n = number of components = 13

m = item mass (kg)

g = gravitational acceleration = 9.8 m/s^2

z = height above centrifuge bed (m)

ω = angular velocity (rad/s)

$\vec{r}$ = position vector (x,y) (m)

The CRC is divided into 13 components (those listed in Table 8, with the ergometer and strut mounts separated into two components) for moment calculations. For the spinning moment, the forces exerted on the pedals by the subject while cycling are also included, which based on early trials, were determined empirically to be 20% of subject bodyweight. Given that the components of the CRC are not distributed along a single axis, moments are calculated as vectors using the coordinate systems specified in Figure 33. This same coordinate system was used for additional mechanical characterization analyses detailed later in the chapter. While these axes do not align with axes of the subject's body, they were chosen because they are more intuitive to the controller who must perform the calculations.

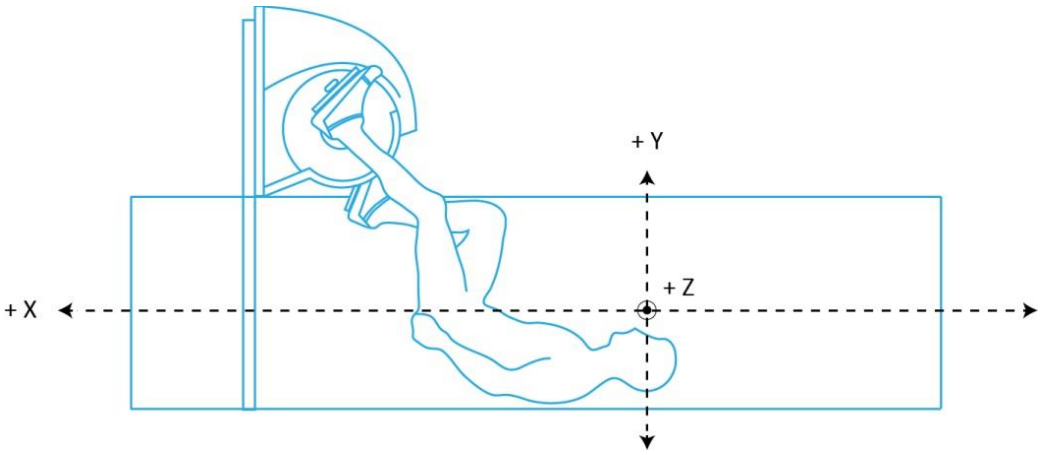

Figure 33- Centrifuge coordinate frame

Minimization of the total moment was previously done on the MIT SRC using a spreadsheet tool that allowed the operator to add in the available counterweights, via trial and error, in order to minimize the total moment along a single axis. For the CRC, a significantly more robust Moment Minimization Tool (MMT) was developed to optimize counterweight placement automatically for the operator. Figure 34 shows a collapsed view of the tool's user interface (UI) (does not show intermediate cells used in moment calculations), which was kept in Microsoft Excel to facilitate its use by multiple operators. In the MMT, moments are calculated along both the x and y axes. The tool requires seven inputs from the controller, entered into the blue boxed region on the MMT UI. These inputs include: subject weight, subject gender, radius at the feet, radius at the base of the slider board, perpendicular offset of the ergometer along the struts, desired G-level at the feet, and trunk angle. These inputs are used to correctly specify the position vector $\vec{r}$ for each element, as well as to properly distribute the mass of the subject's body. The subject's body mass is broken into seven segments, and based on the gender input, the MMT automatically calculates the distribution of mass across each body segment based on NASA anthropomorphic mass distribution data [62]. The inputs are also used to calculate the angular velocity needed to achieve the desired G level at the feet, highlighted in red at the top of the UI, the value of which is the used to derive angular velocity for the spinning moment calculations.

Minimization of the total moment is accomplished using the available counterweights and specifying their placement on the centrifuge arm. Placements were restricted to locations where the counterweights could be properly secured. This included two locations along the x-axis behind the subject's head, each at a different height and each allowing placement along the Y-axis to be specified as centered or on either edge.

- CENTRIFUGE MOMENT MINIMIZATION TOOL -

	Spin rate	27.9 rpm						
		RPM						
Subject Weight (lbs)	155							
Gender	Male							
Foot Radius (m)	1.15							
Slider Radius (m)	1							
Ergometer Offset (m)	0.51							
Desired G Level (@ feet)	1							
Trunk Angle	0							
	Item	Qty	Mass (kg)			Dx (m)	Dy (m)	Dz (m)	TOTAL M (Nm)
Centrifuge	Centrifuge bed itself	1	70.9			0.55	0	0	382.54
	Exercise Baseplate	1	21.0			1.63	0	0.31	426.28
	Baseplate Struts	2	3.5			1.52	0.3	0.35	163.00
	Ergometer + Strut Mounts	1	33.0			1.15	0.51	0.35	700.89
	Seat Base	1	5.0			0.96	-0.27	0.44	46.79
	Back/Side Rest	1	5.0			0.45	-0.30	0.18	8.51
	Slider Frame + Slider Board	1	48.0			0.41	-0.17	0.07	119.89
	Monitor	1	4.5			0.03	0.6	0.3	35.06
	Leg cuffs/ frame	1	5.0			0.41	0	0.75	33.22
	Desktop	1	4.5			-0.7	-0.13	0.19	-42.69
	APC Power Supply	2	12.5			-1	0	0.04	-253.78
Counterweights	Permanent CW	2	37.3			-0.88	0	0.34	-834.34
	Permanent CW	2	37.3			-0.83	0	0.38	-808.06
	CW 1	0	21.8	0	2	-0.96	0.4	0.525	0.00
	CW 2	0	20.7	0	2	-0.96	0.4	0.525	0.00
	CW 3	1	11.6	0	1	-0.96	0	0.525	-159.10
	CW 4	1	11.4	0	0	-0.96	-0.4	0.525	-221.50
	CW 5	1	7.2	0	2	-0.96	0.4	0.525	-57.61
	CW 6	0	6.8	1	0	-1.12	-0.4	0.025	0.00
	CW 7	0	10.7	1	2	-1.12	0.4	0.025	0.00
				2					
Human	Head	1	3.2			0	-0.30	0.35	-12.29
	Torso	1	41.5			0.45	-0.30	0.35	79.58
	Arms	1	6.7			0.45	-0.30	0.35	12.85
	Upper Legs	1	10.8			0.85	0	0.35	117.65
	Lower Legs	1	6.5			1.075	0.255	0.35	110.96
	Feet	1	1.6			1.15	0.51	0.35	34.10
	Cycling Forces	1	21.1			1.15	0.51	0.35	104.50
	TOTAL		499.7						9.94

Figure 34- Collapsed few of Moment Minimization Tool

The MMT uses the Solver add-In to order to minimize the magnitude of the total moment using:

$$\min \left(\sqrt{M_x{}^2 + M_y{}^2} \right)$$

where

$$M_x = M_{static,x} + M_{spinning,x}$$

$$M_y = M_{static,y} + M_{spinning,y}$$

Appendix E includes the entire MMT spreadsheet with the constraints and equations used by the tool detailed. Once optimized, the necessary counterweights and their placement are highlighted in the spreadsheet for the controller to easily identify.

4.3 Motor Characterization

Design requirements for the MIT CRC included four requirements related to motor performance:

> 24. The SRC motor and tachometer shall be able to maintain velocities of 60-200 deg/sec to an accuracy of +/- 2%.
> 25. The SRC motor shall maintain a constant angular velocity within 2-5% of the command velocity.
> 26. The SRC angular velocity shall be reproducible step-to-step, subject-to-subject, or day-to-day within 5-10% of command value.
> 27. The SRC motor shall provide smooth angular acceleration between 5-15 deg/sec^2 with a nominal rate of 10 deg/sec^2

In order to verify that these requirements were met, and to inform the accuracy of future studies, two motor mechanical characterization tests were done. These included three 'spin-up runs' to evaluate angular velocity set point accuracy and consistency, an 'acceleration run' to evaluate the motor's acceleration range and consistency. The three spin-up runs were used to test whether the motor met requirements 24-26. During these trials, which took place across two days, a subject was secured on the CRC and weights were added to simulate the maximum allowable subject weight of 200 pounds. Counterweights were added next as specified by the MMT. The CRC was then accelerated to angular velocities of 10-30 RPM in increments of 5 RPM, and held at each speed in order to check for variability. Figure 35 shows the x axis (centrifugal) accelerations during each of the trials. Once the centrifuge had reached the target speed (acceleration) it was left for three minutes and no additional adjustments were made. At no point was the subject cycling. Note that Trial 3 had to be terminated shortly after the centrifuge reached 30 RPM due to a cable that came loose. Thus, there were only two sets of data for the 30 RPM phase of the trials.

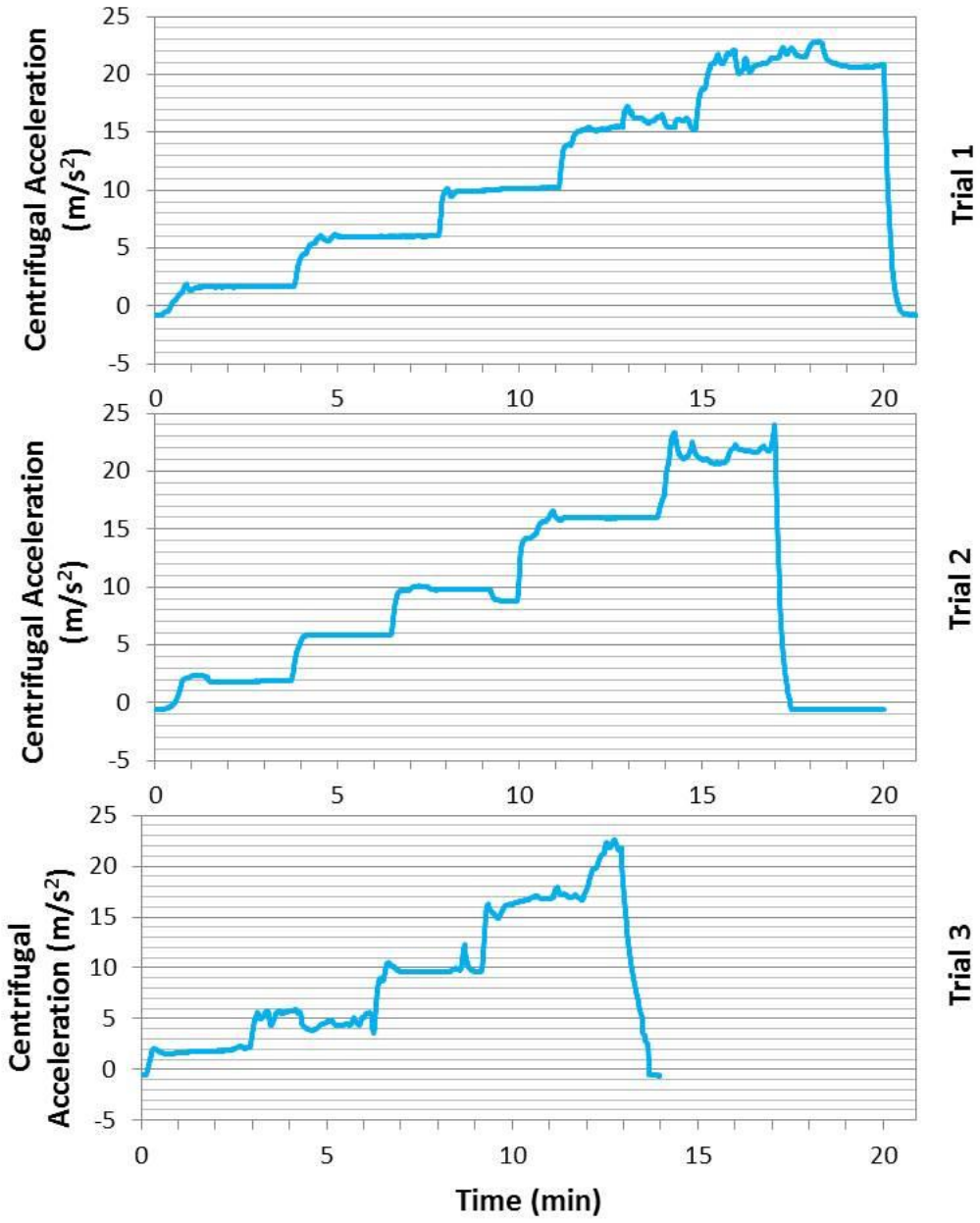

Figure 35- Results of motor accuracy and consistency spin-up runs

The data was first analyzed to test for Requirements 24 and 25, which pertain to the angular velocities and accuracies of the motor. Given that the existing MIT SRC motor was considered a constraint not to be changed, the range of achievable angular velocities was not something that could be altered. However the motor is rated for a max speed of 35 RPM which corresponds to 210 deg/s, an angular velocity above the 200 deg/s maximum specified in the requirements. The motor is therefore considered to meet the portion of the requirements relating to angular velocity range. The spin-up runs only went up to 30 RPM as this was above the speed necessary to achieve 1 G at the subject's feet on the CRC.

The prescribed accuracies of angular velocity specified in Requirements 24 and 25 are in conflict in that the specified percent accuracies do not match. For the purposes of this analysis, the least conservative value was selected given the age of the existing motor used on the CRC. Thus, angular velocity had to be within 5% of the command value in order to meet the requirements. Automatic control of the CRC was not available, so the controller had to set the speed manually with a dial interface. Because the granularity of control was compromised by this, data was compared to the average speed achieved during each phase of each trial as opposed to absolute set point. Thus, the motor was tested to see whether the minimum and maximum speeds reached during each phase were within 5% of the average speed. Table 9 summarizes the results of each trial, and for each of the five tested angular velocities indicates whether the min and max recorded speeds were within the required 5% range. As seen in the table, the specified accuracy was achieved at rotational velocities of 10-25 RPM in at least one trial, though never was the accuracy achieved at a given angular velocity in all three trials. This indicates that the controller must actively monitor angular velocity even after initially setting it, and make adjustments as needed. Thus, the motor only partially met Requirements 24 and 25.

Table 9- Speed set point accuracy results summary (all angular velocities in RPM)

	10 RPM		15 RPM		20 RPM		25 RPM		30 RPM	
Trial 1										
Average	8.36		16.04		20.77		26.00		30.17	
Min	8.30	-0.71%	15.99	-0.31%	20.59	-0.87%	25.46	-2.08%	29.31	-2.88%
Max	8.43	0.82%	16.11	0.44%	20.96	0.91%	27.18	4.52%	31.28	3.66%
Trial 2										
Average	9.05		15.84		20.16		26.15		30.40	
Min	8.63	-4.67%	15.77	-0.40%	19.37	-3.96%	25.98	-0.64%	29.57	-2.75%
Max	10.05	11.03%	15.88	0.28%	20.51	1.74%	26.21	0.24%	32.04	5.38%
Trial 3										
Average	8.66		14.34		20.49		26.78		--	
Min	8.12	-6.22%	12.38	-13.65%	20.26	-1.09%	25.29	-5.56%	--	--
Max	9.25	6.87%	15.85	10.58%	22.92	11.88%	27.70	3.44%	--	--

The next requirement evaluated was Requirement 26 which specifies that the command angular velocity of the centrifuge must be accomplished step-to-step, day-to-day, and subject-to-subject within 10% of the command value. The three spin-up trials were run with the same subject across two days

and evaluated at the same five steps (rotational velocities). With the exception of 10 RPM, the average speeds achieved in all trials were within the specified 10% of the command speed. At 10 RPM, there was one instance in which the speed was 17% less than the command value, however it did achieve the 10% necessary during trial 2. This discrepancy is thought to not be related to the motor, but a result of the controller who set the motor to a lower speed than specified. Thus, it was determined that the motor did meet Requirement 26.

Finally, a series of acceleration runs were done to check whether angular accelerations provided by the motor met Requirement 27. As before, a subject was weighted to 200 pounds and counterweights were added as specified by the MMT. The centrifuge was accelerated at its maximum rate up past 9.8 m/s^2 at the feet of the subject (16.3 m/s^2 at the end of the centrifuge bed where the accelerometer was located). The subject was not pedaling, and this was repeated five times. Once the target acceleration was exceeded, the centrifuge motor was turned off and the arm was allowed to come to a complete standstill. The entire motor control unit was shut off between each trial. Results of the acceleration trials are shown in Figure 36, with the centrifugal acceleration at the tip of the centrifuge bed shown in red, and the angular acceleration shown in blue.

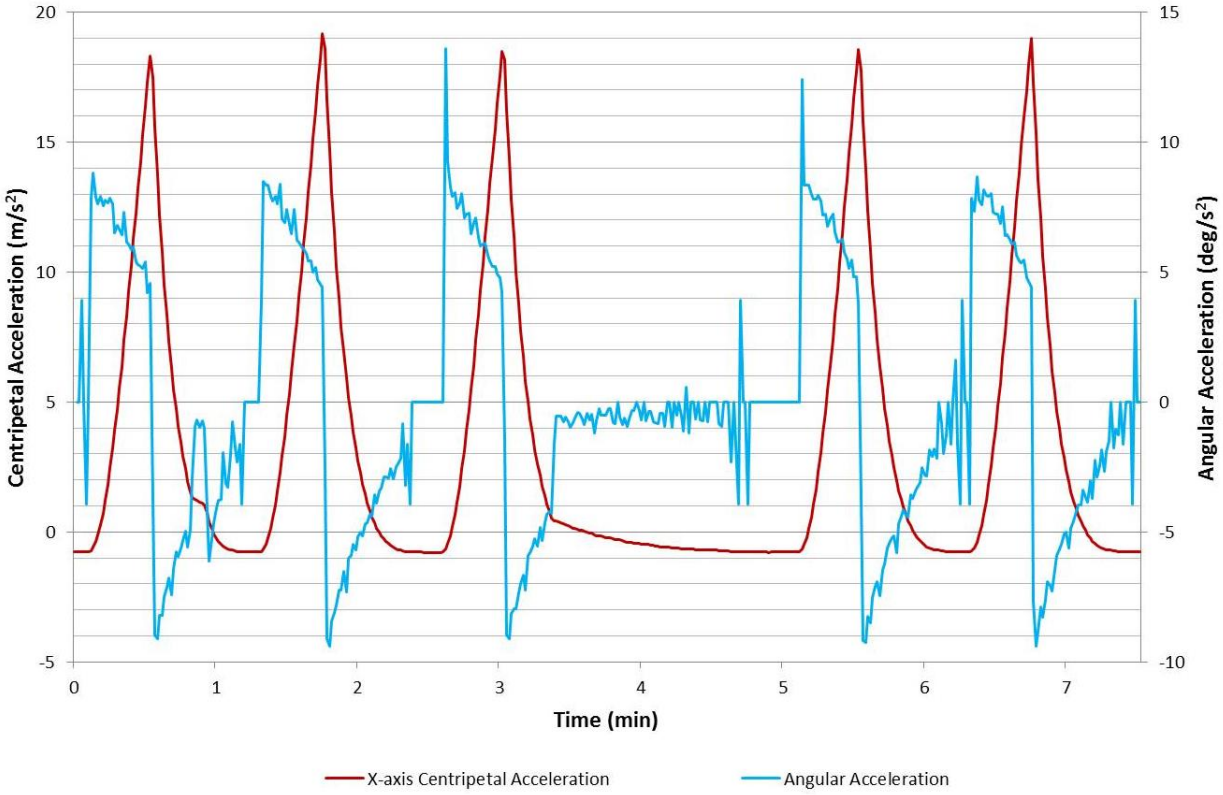

Figure 36- Acceleration runs results, centrifugal acceleration at the CRC arm tip (blue) and angular acceleration (red)

Given that there is no active braking on the centrifuge, only the periods of active positive acceleration were analyzed. Based on the observed centrifugal accelerations, angular acceleration of the centrifuge arm was calculated. The maximum angular acceleration measured was 13.6 deg/s^2 and the minimum was 3.79 deg/s^2, thus the maximum angular acceleration did not exceed the 15.0 m/s^2 maximum requirement though the minimum did fall slightly below the minimum requirement of 5.0 m/s^2.

A one-way repeated measure ANOVA was used to find that there was no significant difference in mean angular acceleration between the five trials (P=0.53). Further, a linear regression was done across measured angular accelerations for each trial. In all cases the Pearson coefficient was greater than 0.90. Thus, it was determined that the motor provided consistent and smooth acceleration within the angular acceleration limits specified by the Requirement 27.

Finally, theoretical power calculations for the motor were done as part of a comprehensive power analysis of the CRC, which can be found in Appendix F.

4.4 Vibrations

In order to test vibrations of the CRC, a vibration run was done. As during the spin-up and acceleration runs, a subject was weighted to the maximum 200 pounds and counterweights were added as specified by the MMT. The centrifuge was accelerated to 10, 20, and 30 RPM. At each interval, the subject rode passively for 1.5 minutes, and then cycled for an additional 1.5 minutes. The cycle was loaded to 50 W and the subject was instructed to cycle at a comfortable rate and to try as best as possible to maintain the same rate of cycling across phases. Data was collected at a sampling frequency of 100 Hz. Figure 37 shows the accelerations in all three axes as well as the average RPM of cycling for each phase of the vibration run.

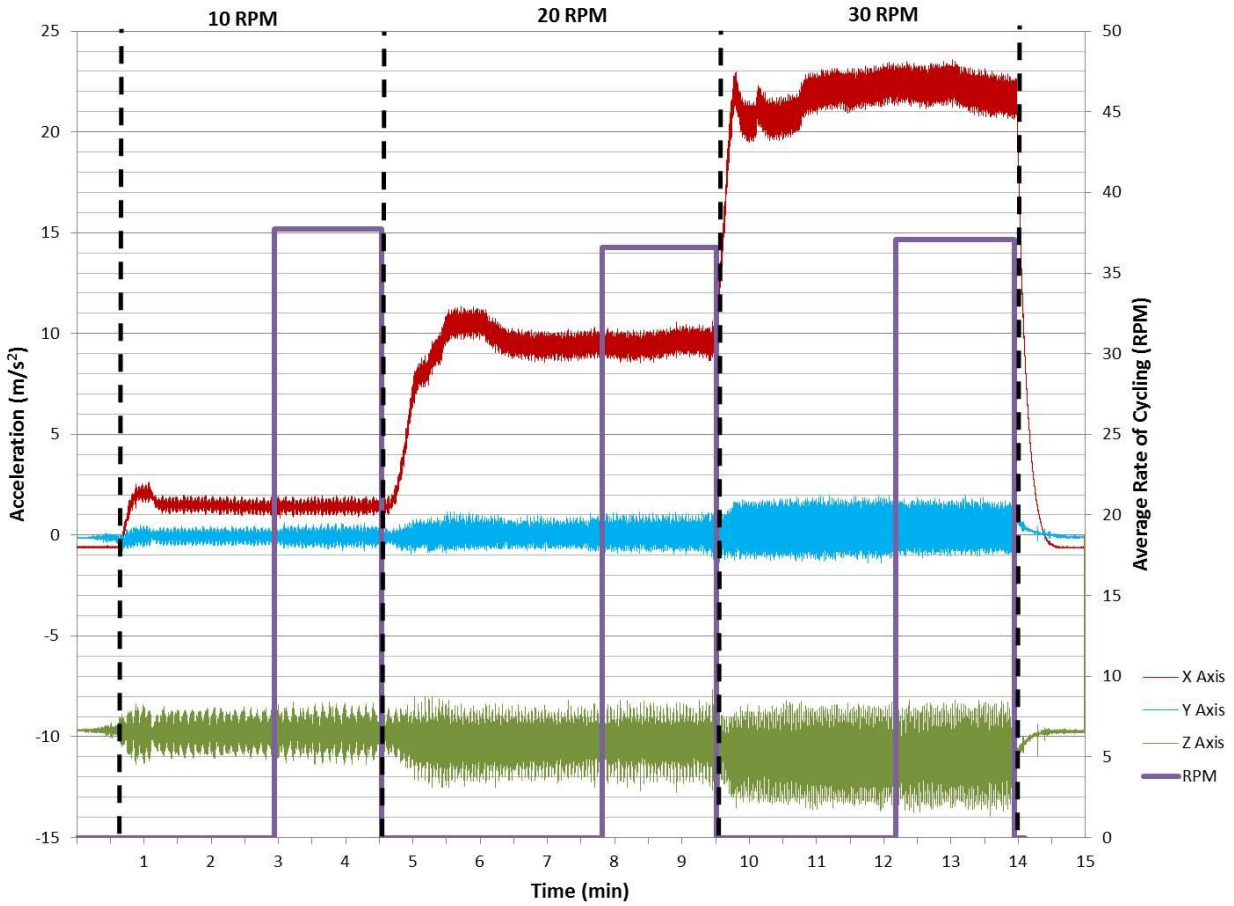

Figure 37- Vibration study accelerations (red, blue, green) and cycling rate (purple)

The data from each phase was then separated into the passive and active portions, and was then converted to the frequency domain via a fast Fourier transform (FFT). The primary direction of concern for vibrations was along the z axis (normal to the ground) as this is the direction in which the centrifuge arm has the largest amount of freedom to move, and is also the direction where the largest amplitude of vibrations were observed during each phase of the trial as seen in Figure 37. Table 10 summarizes the results of the peak frequency analysis for the z axis, and Appendix G includes the frequency domain plots for all axes.

Table 10- Z axis frequency analysis results

Trial Phase		Peak Frequency (Hz)	Magnitude (AU)
10 RPM	Passive	19.92	1108
	Active	19.87	853.6
20 RPM	Passive	19.68	1796
	Active	19.7	1130
30 RPM	Passive	19.53	2288
	Active	19.51	1993

As can be seen in Table 10, there is a peak in the frequency distribution at around 20 Hz across all phases and conditions. A two-way ANOVA of the z axis amplitudes revealed that there is a significant effect of angular velocity (P=0.037) but no significant effect of cycling (P=0.091). It was observed that cycling did add new local peaks at approximately 2 and 37 Hz which were not observed in the passive phases. However, the amplitudes of the peaks were two to three orders of magnitude lower than the peaks at 20 Hz. Thus, it was determined that cycling did not impact vibrations.

There were large vibrations at a frequency of ~20 Hz on the CRC, the amplitude of which changed significantly with a change in angular velocity. It is possible that these vibrations are from the motor given that they change in amplitude with increasing speed. However, the fact that frequency does not change with increasing speed might imply that it is not the motor. Instead, the cause could be structural bending moments. The counterweights added for the trial were determined using the MMT for a case of 28 RPM (1 G at the feet) with cycling. The tool had been set to use cycling forces of 30% body weight, which was 200 lbs. Using this counterweight configuration as a constant, the MMT was used to calculate the total moment for each other case used in the vibration trial. The actual forces from pedaling were adjusted to reflect the measured peak foot forces during the trials, which were near 150 N during each phase (16.5% of the 200 lb. bodyweight). The results, seen in Figure 38, show that the same general trends in total moment are seen as in the peak frequency amplitude. That is, for a given phase (RPM) total moment is greater when not cycling than it is when cycling, just as peak frequency amplitude is greater when not cycling. Also, the total moment for both cycling conditions decreases as angular velocity decreases, just as peak frequency amplitude decreases as angular velocity decrease. A more thorough investigation of the CRC's vibrations is suggested, but this preliminary analysis indicates that the oscillating bending moment, and not the motor or cycling, is the cause of vibrations.

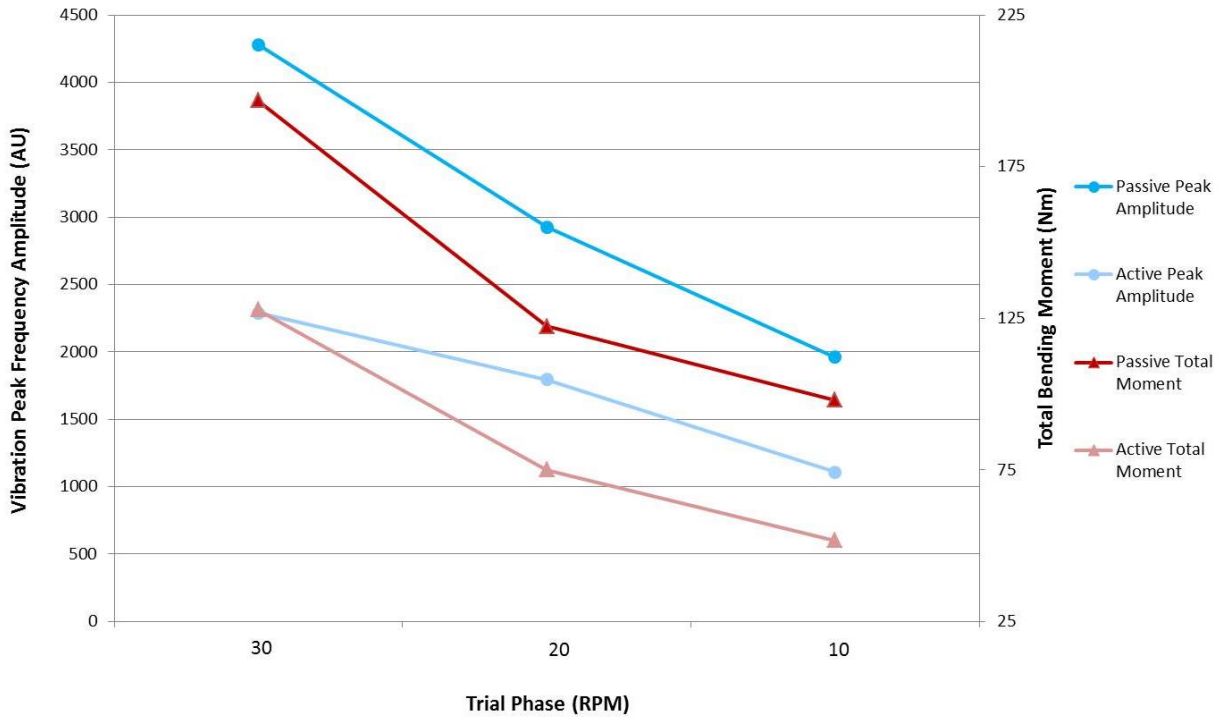

Figure 38- Vibration peak frequency amplitude (blue) and total moment (red) trends

4.5 Pilot Run

As a final validation off all components of the CRC, including the fabricated hardware, sensor suite, control software, MMT, and motor, a pilot run was done. The pilot run was done following a COUHES approved protocol. The approved COUHES application including consent and eligibility forms can be found in Appendix H. The entire protocol lasted 15.5 minutes and used an exercise regimen that was based on several short trials prior to the full pilot run. The protocol consisted of: a three minute warm-up at 25 W, a 30 second transition to 50 W, five minutes at 50 W, a 30 second transition to 100 W, five minutes at 100 W, a thirty second transition down to 25 W, and a one minute cool-down at 25W after which the exercise load was reduced to 0 W while the centrifuge decelerated. Trials prior to the pilot run showed that ramped transitions between workloads were helpful for making the change easier for the subject. The workload levels were also selected based on these trials; subjects noted that loads above 100 W were difficult thus that was selected as the maximum workload. Figure 39 shows the pilot run protocol as it appears set-up in the LEM ergometer management software.

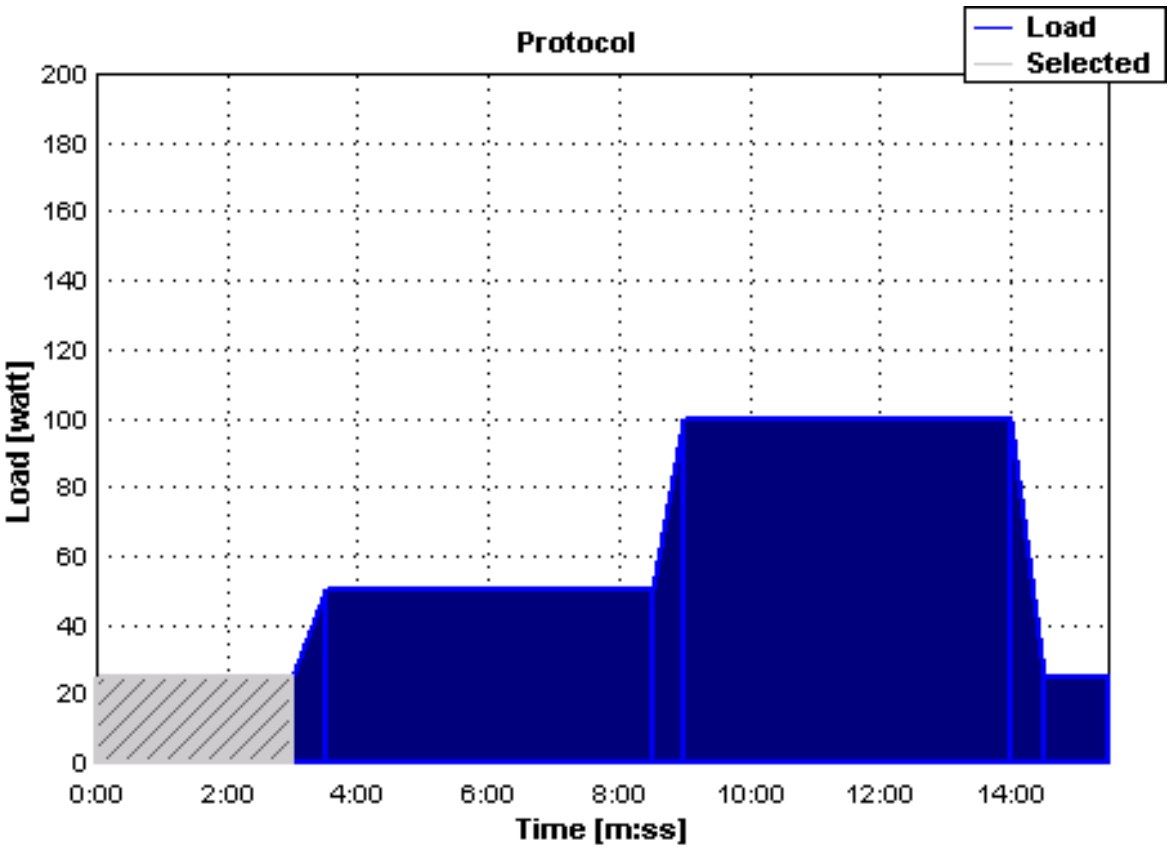

Figure 39- LEM screenshot of pilot run ergometer protocol

The pilot study was also used to validate a checklist developed for running trials on the CRC. This checklist can be found in Appendix D. As part of the checklist, a practice spin-up is done prior to the actual trial to allow the subject to better get situated in the chair and identify any adjustments needed before the longer run. Also, at the time of the trial the Lode Blood Pressure unit and custom cushions had not yet arrived, thus a wrist blood pressure cuff (CVS Pharmacy, Woonsocket, RI) and mockup cushions were used in place. Figure 40 shows the subject strapped in and hooked up to all sensors.

The following subsections detail the results for each of the measured systems which include: accelerations, ergometer workload, heart rate, respiration rate, blood pressure, foot forces, rate of cycling, and the wireless video feed.

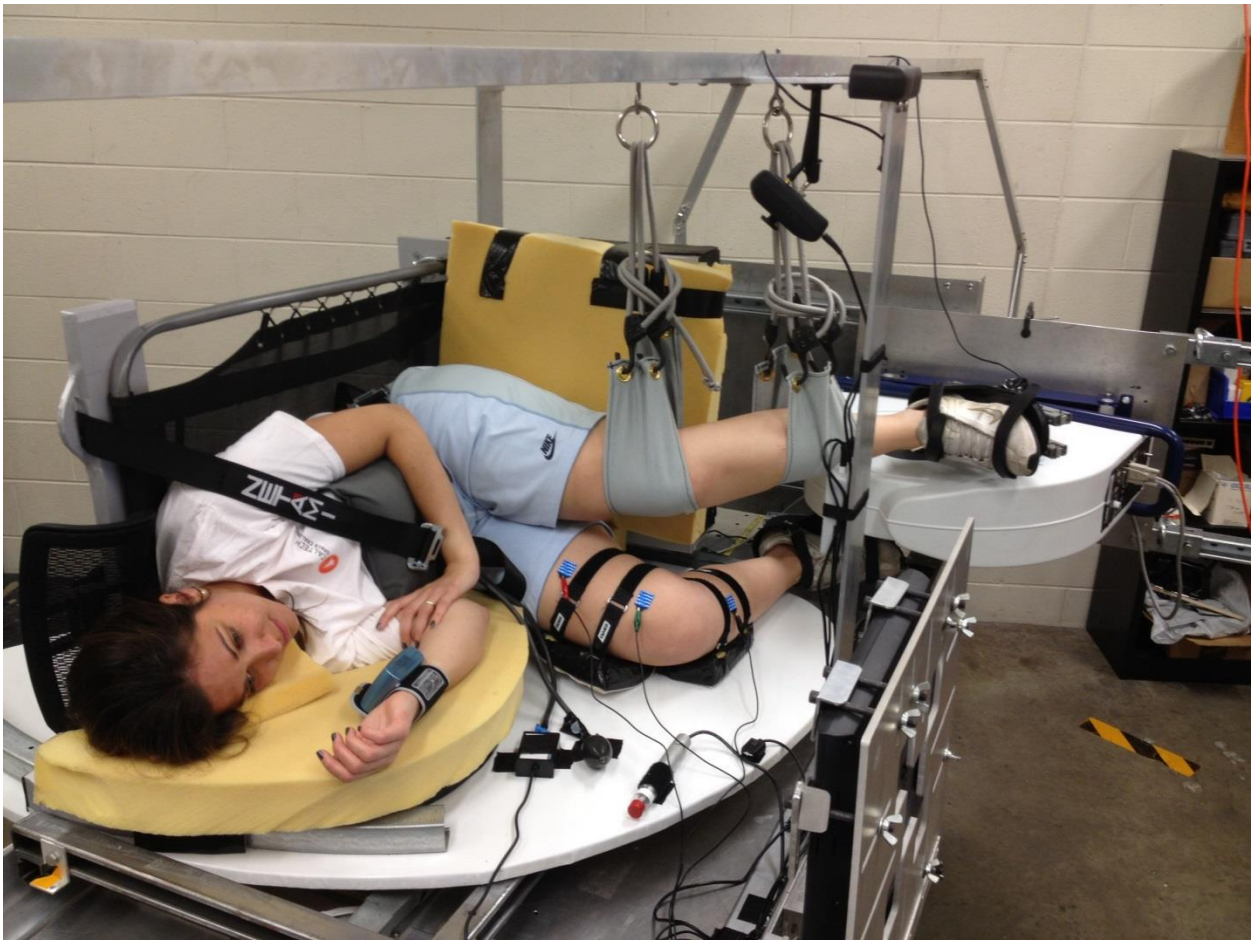

Figure 40- Pilot run subject strapped in with all components (face shown with permission)

4.5.1 Accelerations

The accelerations measured in all three axes by the onboard accelerometer, placed at the feet of the subject, are plotted in Figure 41. Based on the results of mechanical characterization runs the operator was actively controlling the X axis accelerations targeting 9.8 m/s^2. As seen in the figure, there was a sudden deceleration at approximately eight minutes into the pilot run which seemed to correspond with the increase in workload on the bike. This was subsequently adjusted for by the controller. All other measurements were nominal, the accelerometer worked with no data gaps, and the centrifuge provided smooth angular acceleration and deceleration at the beginning and end of the run.

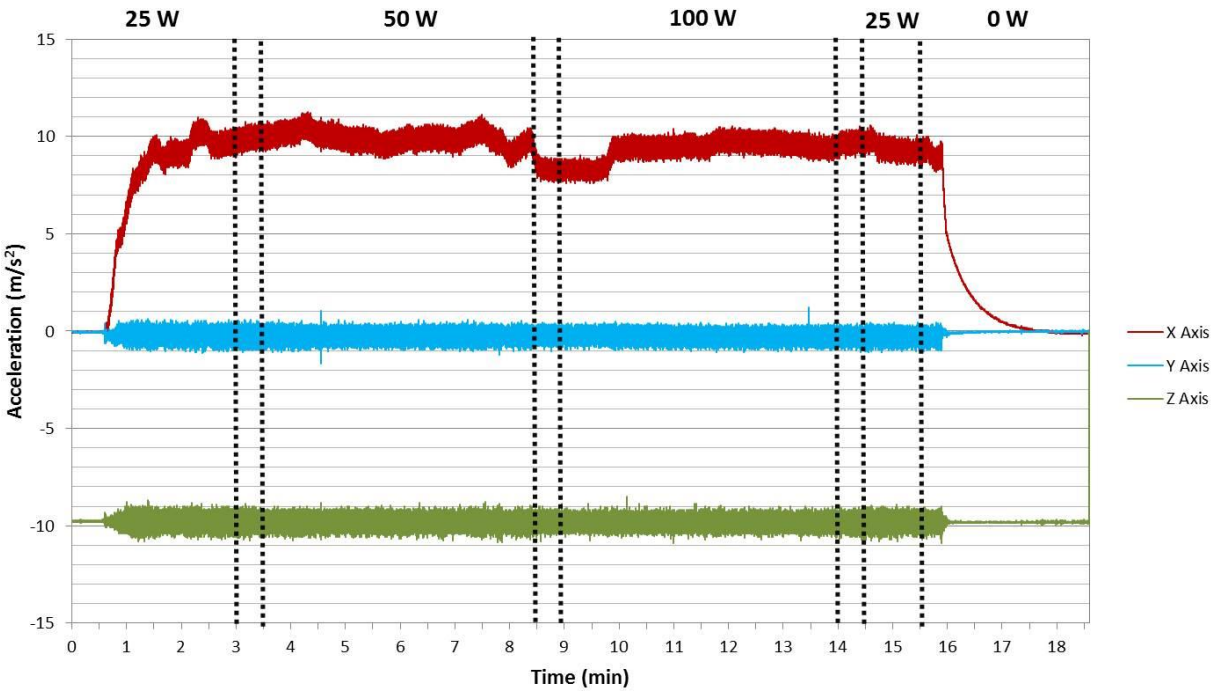

Figure 41- Pilot run accelerometer data

4.5.2 Ergometer Workload

The cycle ergometer consistently provided the specified load throughout the entire pilot run, thereby validating this capability of the exercise device.

4.5.3 Heart Rate

The heart rate data collected during the pilot run can be seen in Figure 42. There were no data drop outs from the wireless sensor. The observed trend across each phase of the pilot run matched what was expected. There was a rapid increase in heart rate during the 25 W warm-up, followed by an elevated but stable heart rate during the 50 W workload. Heart rate again increased after the transition to 100 W followed by a continued gradual increase during the five minutes at 100 W. Immediately after the transition back to 25 W, heart rate decreased rapidly, and then decreased to within 10 BPM of the starting heart rate once the workload was reduced further to 0 W. The 32 year old subject was within their exercise target heart rate range during both periods of exercise (50 and 100 W).

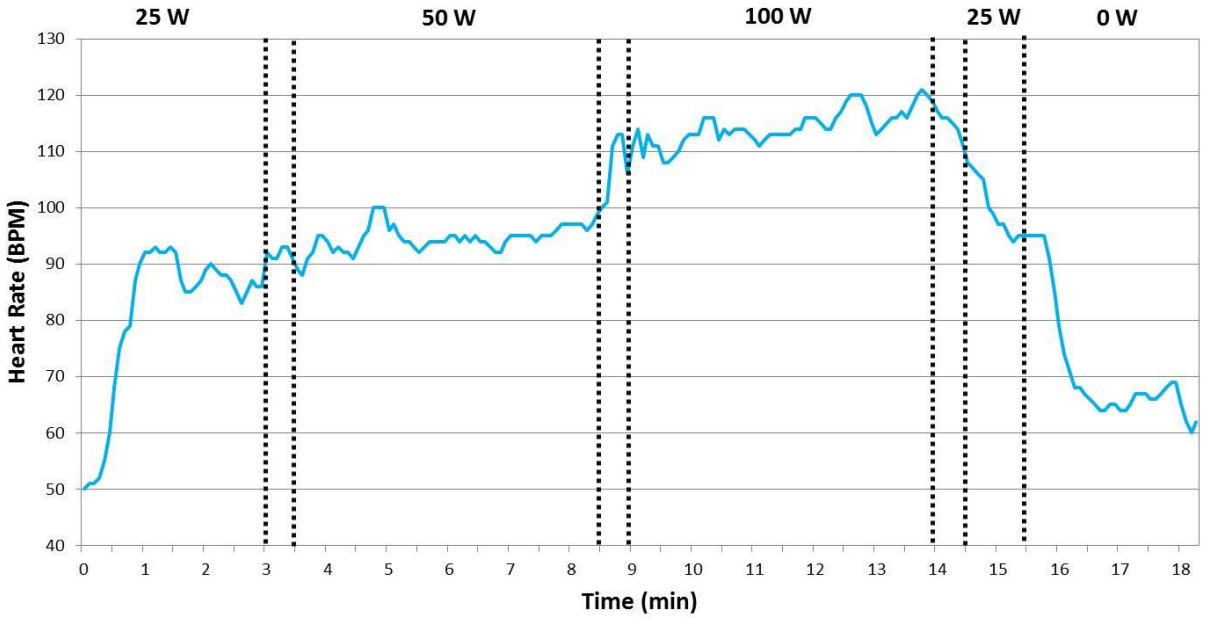

Figure 42- Pilot run heart rate data

4.5.4 Respiration Rate

The respiration rate monitor is comprised of an air pouch which sits on the subject's chest. As the subject breaths in and out, the pressure changes within the pouch are sampled by the sensor. Figure 43 shows the results from the respiration rate belt during the pilot run, with the various phases indicated. As can be seen in the figure, there is a downward trend in the minimum belt pressure throughout the course of the trial. This indicates that air may be leaking from the sensor, in turn affecting the accuracy of respiration magnitude. Also, there are a number of pressure spikes throughout the trial, which given their magnitude, suggest they were not caused by the subject's breathing but rather an external force on the belt either from the safety harness, the subject's arm, or movement of the upper torso while cycling or shifting.

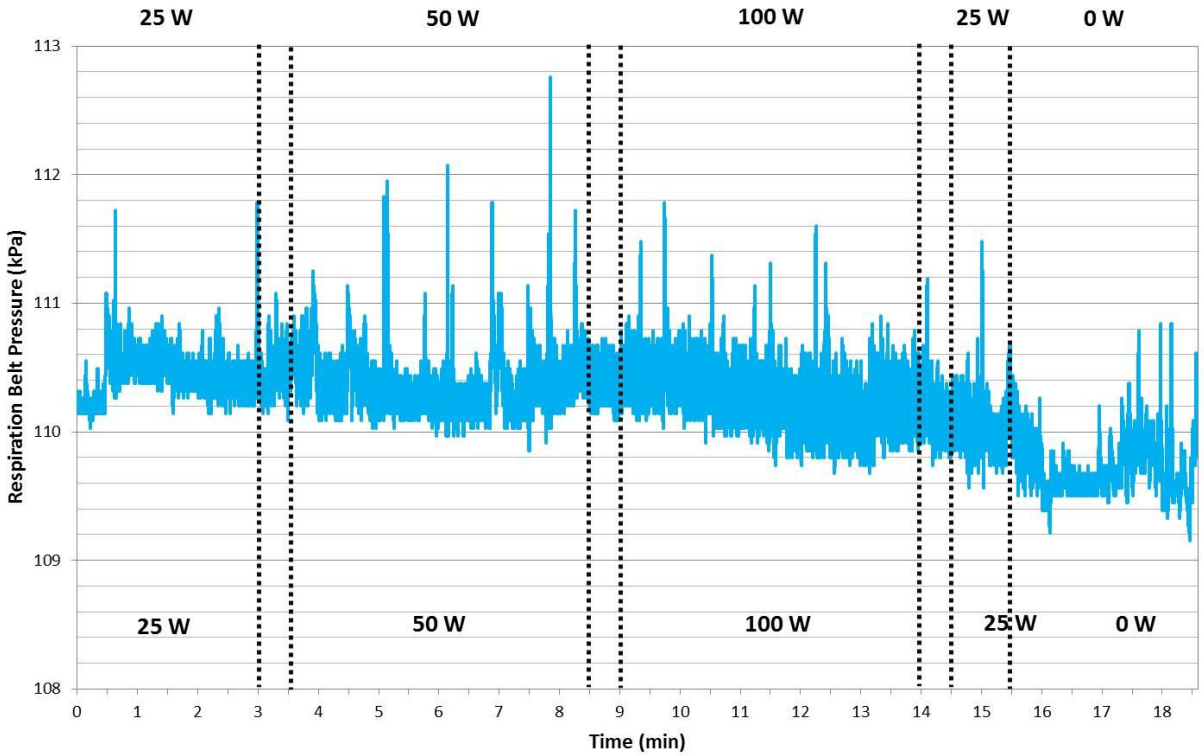

Figure 43- Pilot run respiration rate data

Frequency analysis was done on the respiration belt data using the FFT in order to quantify the rate of respiration. Figure 44 shows the frequency distribution for each of the four phases of exercise. While the data indicates that respiration occurs in the range of 0-1 Hz for all phases, there is a lack of clear peaks. Furthermore, there is little change in magnitude across each phase, despite the indication in the raw data of an increase in magnitude during the 100 W phases. Previous studies using the same respiration belt on subjects cycling in the supine position on the same cycle ergometer showed clear results in respiration frequency and relative magnitude [66]. While the data from the pilot run represents only one trial, the noise encountered in both the raw data and frequency analysis indicates that the respiration belt may not be working as intended. This could be easily explained by the sideways positioning of the subject, the movement of the subject during cycling, and the position of the safety harness and arm relative to the belt. It is therefore recommended that the respiration belt be swapped for a VO2max sensor or thermistor to more accurately monitor respiration during centrifugation.

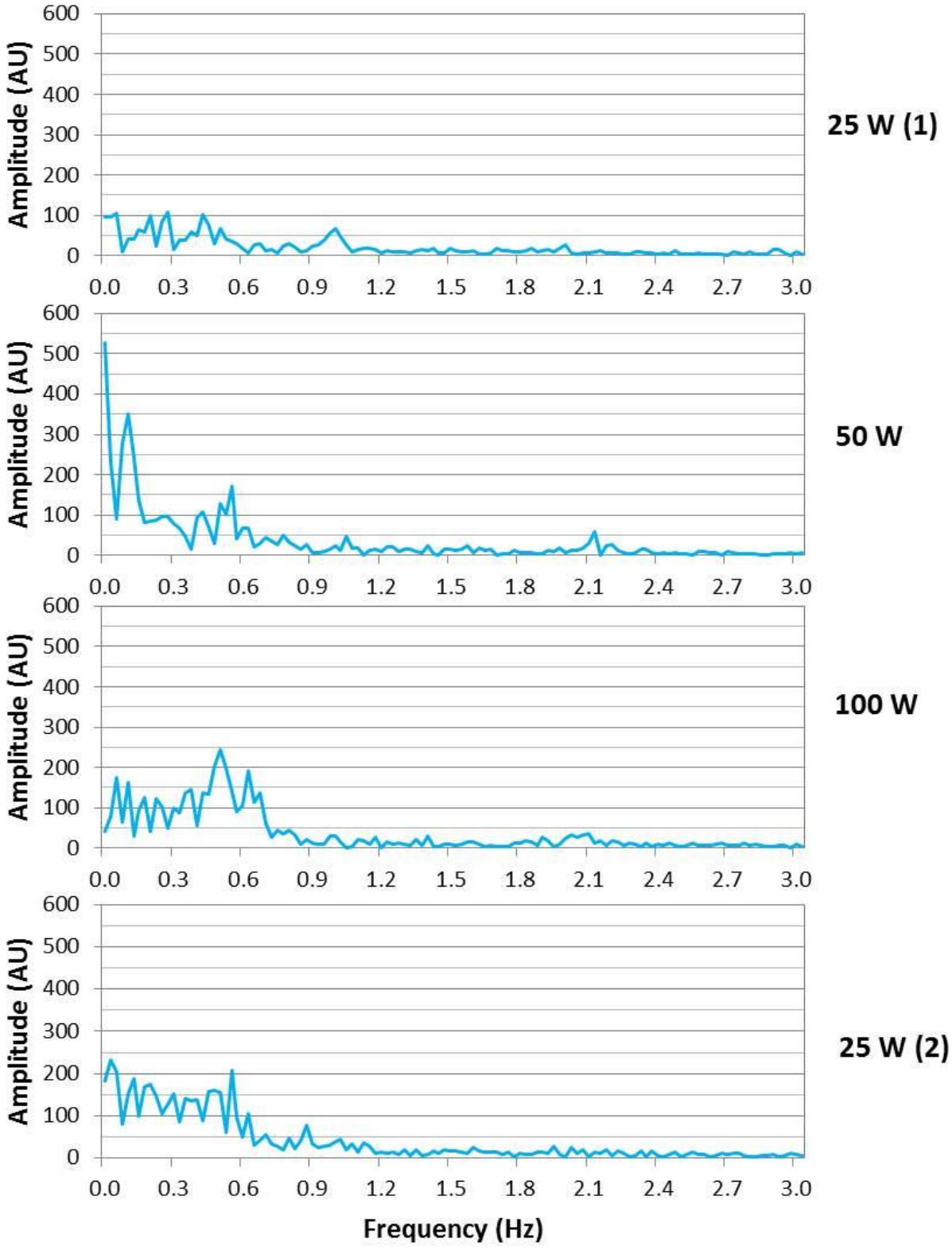

Figure 44- Pilot run respiration frequency analysis

4.5.5 Blood Pressure

Blood pressure was measured four times during the pilot run, once in the middle of each of the four phases. The blood pressure cuff was located on the subject's write which was at heart level. Systolic and diastolic pressures were manually recorded by the controller after being called out by the subject. Mean arterial pressure (MAP) was then calculated using:

$$MAP = P_{dia} + \frac{1}{3}(P_{sys} - P_{dia})$$

Figure 45 shows the results from the pilot run. Blood pressure would be expected to rise both from centrifugation as well as from cycling [67,68]. During the pilot run, the MAP showed a trend that matched the workload phases of the trial. Whether or not this trend was significant would require more data points and trials.

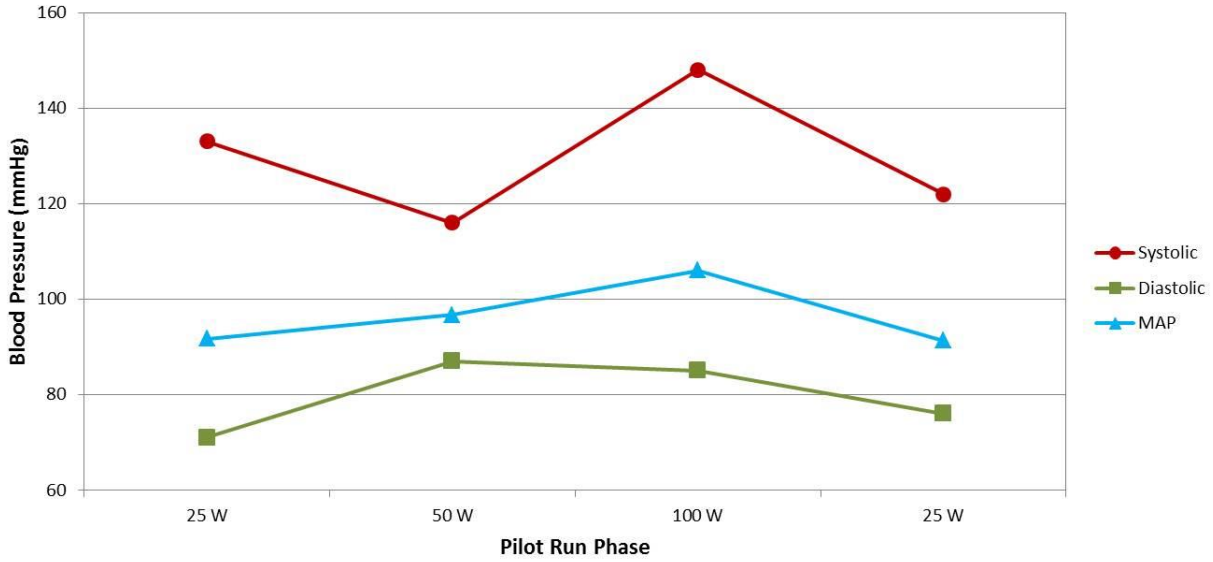

Figure 45- Pilot run blood pressure data

A more robust blood pressure sensor which integrates with the cycle and LEM is planned for implementation prior to the start of formal trials. This blood pressure cuff will be capable of getting pre-programmed to inflate and collect blood pressure data at specified intervals. Because this device is designed to be used in tandem with the cycle ergometer, its data collection and storage will be streamlined with existing software. Furthermore, the cuff is designed to be used during activity by limiting the movement artifacts.

4.5.6 Leg Muscle Activation

Surface electromyography (EMG) electrodes were place on the rectus femoris of the subject's lower leg. Figure 46 shows the raw data from the pilot run.

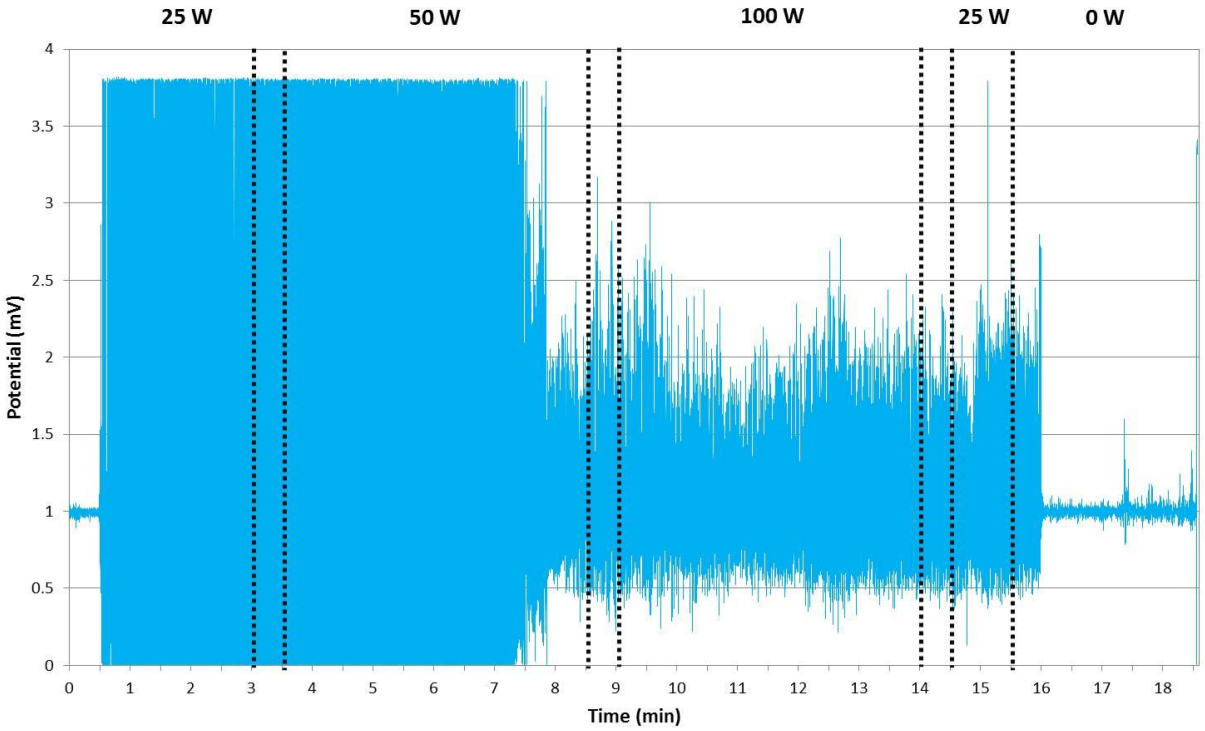

Figure 46- Pilot run rectus femoris surface EMG data

Though a thorough EMG signal analysis is beyond the scope of the pilot run, the figure shows that signals were detected which started and ended when the subject started and stopped cycling. However the amplitude and waveform homogeneity during the first portion of the run are significantly different from those in the latter, and this change does not occur during any transition period.

There are a number of issues which could have caused the observed discrepancy and also caused inaccuracies in the recorded data. First, the electrodes were adhered to the subject's skin but were likely being tugged slightly during cycling. Movement artifacts are a known issue in EMG signals and must be filtered. A more robust method of adhesion beyond what is currently on the electrodes should be used. Second, the subject's skin was not prepped prior to attaching the electrodes. If surface EMG's are to be done in the future, the site of the electrodes should be cleared of any hair, then lightly abraded and cleaned with alcohol in order to minimize skin impedance. Even if these issues are addressed, there are further limitations to the use of the current surface EMG equipment; the typical peak frequencies observed in a frequency analysis of the EMG signal fall in the range of 20-90 Hz for slow twitch muscles

and 90-500 Hz for fast twitch muscles [69]. In order to analyze this entire frequency range through a Fourier transform of the signal data, the sampling frequency would have to be 1000 Hz. However, given that the current surface EMG equipment interfaces with the Logger Lite software, such a sampling frequency would likely cause performance issues especially if data was to be collected over extended periods of time. A more robust validation should be done of the EMG equipment before it is used in additional trials, and alternatives to the brand of sensor should be investigated.

4.5.7 Cycling Rate

The subject was instructed to cycle at a rate that was comfortable and to then try and maintain that rate throughout the trial. The subject was able to see their RPM in real time via the monitor onboard the centrifuge which showed the LEM interface. The results of cycling rate can be seen in Figure 47. The average cycling rate during the trial, after the initial acceleration and before deceleration, was 62.4 RPM with a standard deviation of 2.41 RPM indicating that the subject was successful in maintaining a consistent rate of cycling.

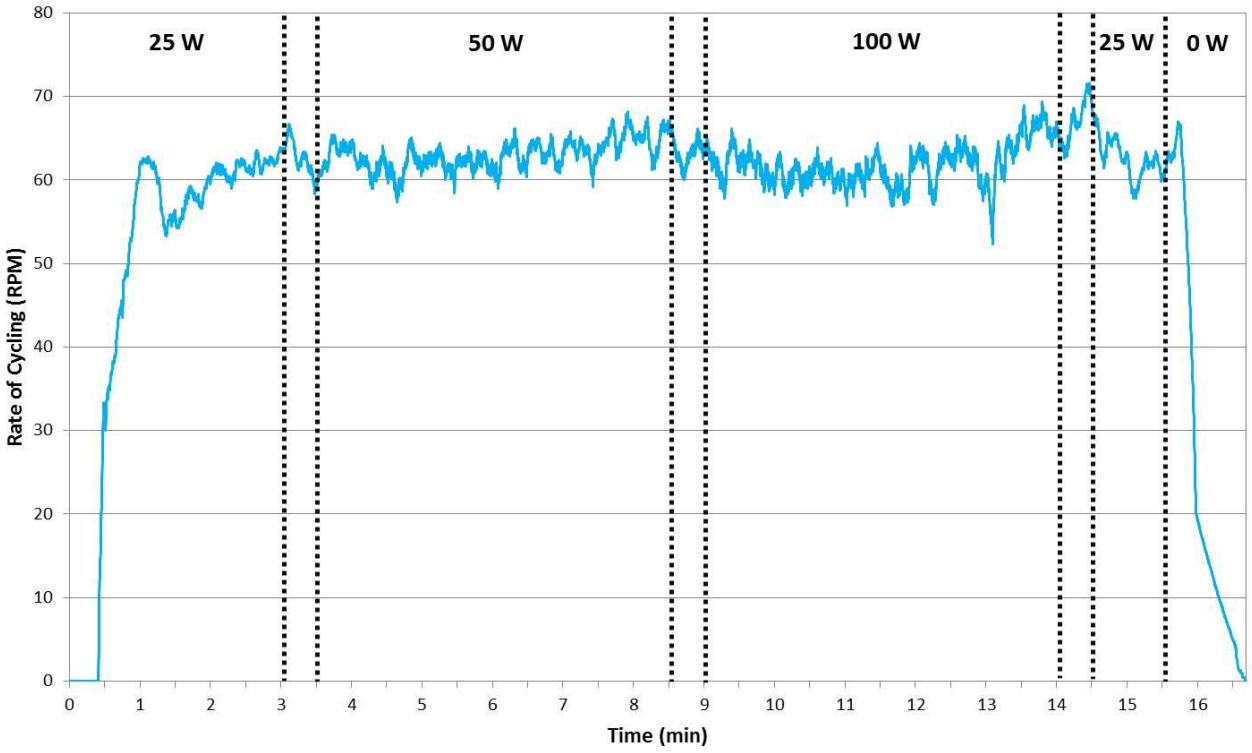

Figure 47- Pilot run cycling rate data

In the future, the subject should not be instructed to maintain a consistent rate of cycling and instead should be instructed to simply do what is most comfortable. Ideally the subject would maintain a constant peak foot force and adjust their RPM to meet the changing workload demands, as this consistent foot force would help to reduce any oscillations in the spinning moment of the CRC.

4.5.8 Foot Force

The foot force sensors are modified from the original Vernier force plate to include only the two strain gauges, which are then screwed between the pedals and the crank shaft of the cycle ergometer. As such, the measurements must be calibrated by noting the '0' force when the pedals are parallel to the exercise baseplate and no one is pushing on them. Figure 48 shows the calibrated results of measured foot force from both feet during the pilot run. Peak forces fell between 100-250 N across the different workload phases, which correspond to 12.9-32.1 % of bodyweight. Of particular interest is the qualitative asymmetry between the two feet, with the left foot producing noticeably greater peak forces especially as the workload increased.

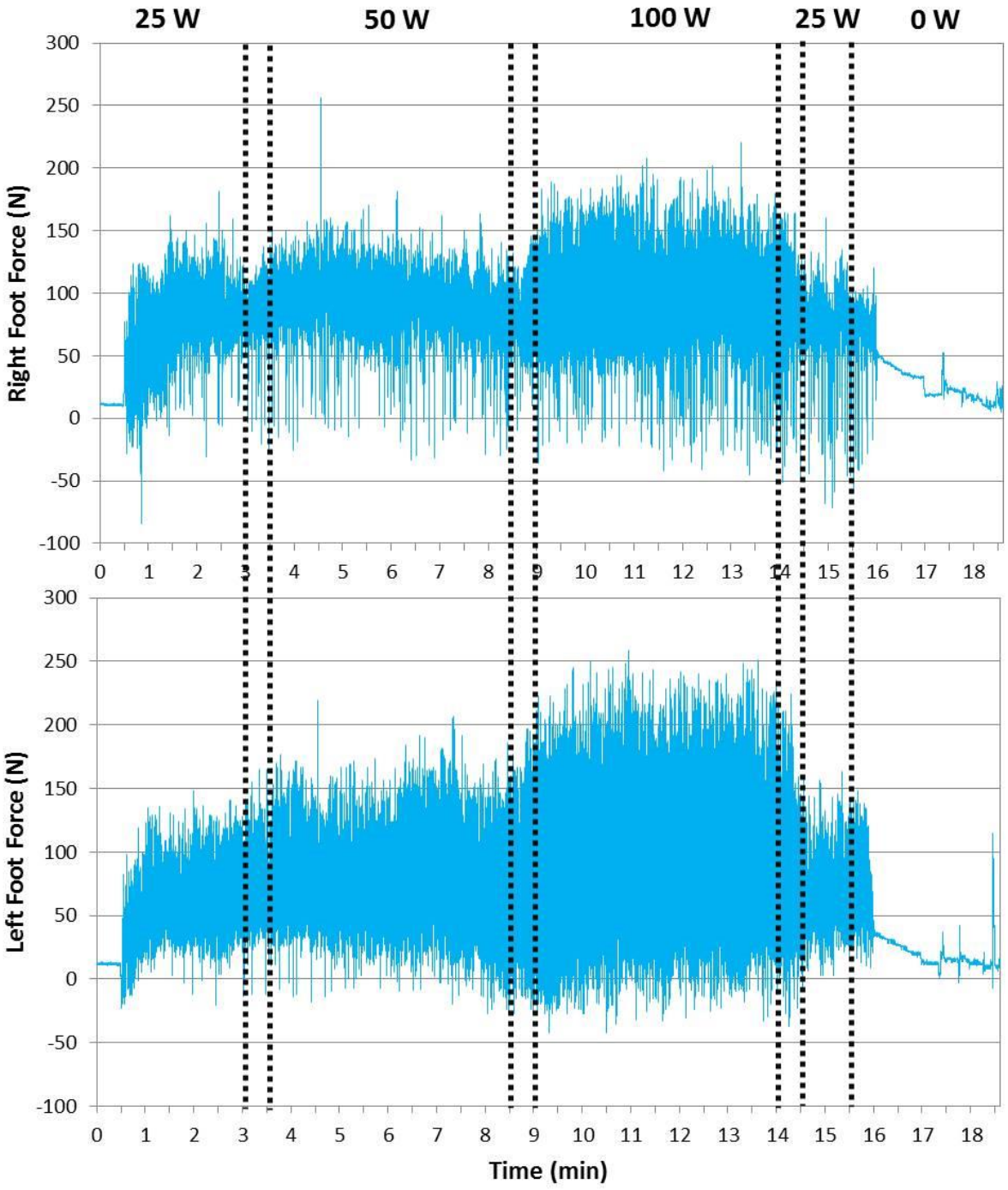

Figure 48- Pilot run foot force data

A frequency analysis was done of the foot forces to compare differences between the two feet, the results of which can be found in Figure 49. In all cases, the peak cycling frequency was at approximately 1 Hz, which validates the RPM data that showed a consistent cycling rate of 60 RPM. At workloads of 50 and 100 W, the magnitude at 1 Hz was higher in the left foot than the right foot by 9.38% and 36.7% respectively. The subject commented that during the trial, the heel of the right foot would rub on the

sliding base frame depending on how hard the subject was pushing on that foot. To avoid this, the subject was consciously altering the amount of force of the bottom (right) foot, which would at least partially explain the difference in peak force between the two feet. Whether there is an additional effect on applied force from the two different ways in which each leg is being supported should also be investigated. Despite this, the noted discrepancy by the subject which was found evidenced in the data provides validation for the foot force sensors.

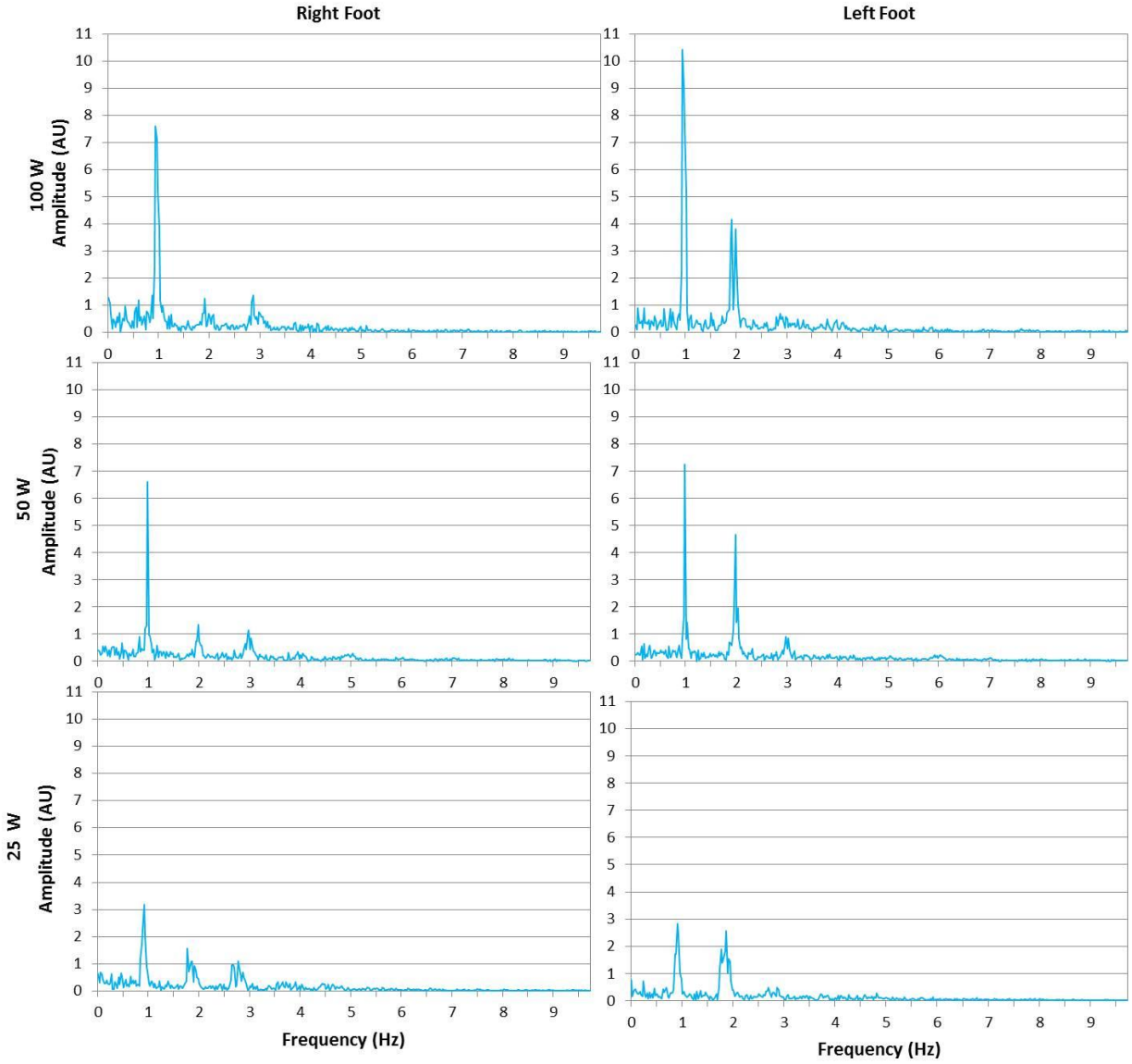

Figure 49- Foot force frequency distribution

4.5.9 Wireless Camera

The wireless camera successfully captured video for the entire duration of the test. Due to the spinning of the camera the refresh rate was reduced to approximate 0.5-1 Hz. This did not impact the effectiveness of the camera's ability to allow the controller to monitor the facial expression of the subject for any signs of discomfort or presyncope.

4.5.10 Comfort

Finally, the subject completed the exit survey after finishing the pilot run. They indicated that the CRC was a 3 out of 5 with regards to comfort (5 being most comfortable), and out of a 5 point scale on the exercise regimen (5 being most strenuous) indicated that the 25 W load was a 1, the 50 W load was a 3, and the 100 W load was a 4. The subject did not have any muscle soreness, did not experience motion sickness, and did not notice any Coriolis forces while cycling.

Taken together, the various elements of the pilot run validated the CRC's ability to perform an extended trial and to collect and manage data from a number of physiological and mechanical sensors. There are select sensors which will need additional validation or replacement: the planned new blood pressure equipment is expected to solve the current issues of blood pressure data collection, a VO2max mask or thermistor in place of the current respiration belt is recommended, and different EMG equipment should be investigated.

5 CONCLUSIONS AND FUTURE WORK

This project aimed to design, build, and validate a new compact radius centrifuge (CRC) artificial gravity test platform on the existing MIT short radius centrifuge. Motivated by a recent proposal to put a human centrifuge onboard the ISS, the CRC represents a new class of centrifuge designed to meet spatial requirements which do not permit all users to fit along the radial position. The MIT CRC that was designed and built accommodates the entire range of heights specified for the astronaut corps by the NASA Human Integration and Design Handbook, while constraining all hardware to a maximum radius of 1.4 meters. Further, the MIT CRC includes a cycle ergometer for exercise during centrifugation, and also positions subjects in such a way that aligns the direction of the legs while exercising with the direction of Coriolis forces, thereby reducing the risk of hip or knee injuries cause by deflection.

The final design of the CRC is the result of a process that included concept design, prototyping with human-in-the-loop evaluation, and iterative fabrication. The final deliverable also includes an updated Moment Minimization Tool (MMT) for use by the operator to find the optimal placement of counterweights for each subject. The performance of the existing motor was evaluated, as were vibrations of the centrifuge. Finally, a pilot run was done to validate that all systems worked and could run concurrently. Future work falls generally into two categories, design improvements and research studies, each of which is detailed below.

5.1 Adjustments and Design Improvements

Although all effort was made to design and deliver a robust and versatile test platform, there remain additions and refinements can still be made to further improve the design. These include:

i. Pilot Run Adjustments: A number of small improvements were identified during the pilot run. These are detailed in Appendix A, and should be implemented prior to starting full tests.
ii. Motor Repair or Replacement: Motor characterization tests indicated that the motor was unable to consistently maintain set point velocities. Options for a new motor should be investigated, the communication dropout error should be resolved on the automatic controls so that they can be used again, and the control system should be revalidated. While the controls were originally designed as a closed loop system, it is possible that the manual controls are open loop, or that the control system is not functioning as intended.

iii. Continued vibration analysis: A preliminary analysis from a vibration run done as part of the CRC's validation indicates that oscillating bending moments may be the primary cause of vibrations of the platform. This hypothesis should be tested further, and the vibrations should be studied to insure they do not pose a threat to the centrifuge's safety.

iv. Updated Sensors: The pilot run found that the current respiration belt needs to be replaced by a different type of respiration sensor, potentially a VO2max mask or thermistor at the nose. The surface EMG electrodes, while showing changes in potential that corresponded to muscle activation while cycling, need further validation and more robust sensors should continue to be investigated. The Delsys EMG's, for example, have previously been used successfully in MVL. Finally, the new blood pressure cuff, which at the time of writing has not arrived, must also be installed and validated.

v. New Leg Pads: The current leg pads are the same as those used during prototyping, and should be rebuilt to be more robust, thicker for the upper leg, and include longer straps. The leg pads may also be redesigned to use air pouches instead of foam. This would allow for fine adjustment of the lower leg position in the same way that the bungees allow it for the upper leg.

vi. Onboard Biking Video: The AGREE proposal included a virtual reality headset to be worn by the user. The onboard monitor on the MIT CRC sits directly in front of the subject, so incorporating a video of cycling through various terrains could help to further reduce motion sickness as well as make the exercise experience more enjoyable.

vii. New Centrifuge Control User Interface (UI): A new control UI was originally planned for the current project, but had to be stopped shortly after concept design due to time constraints. Suggested features to include in a future UI design include:

    a. Primary speed control column, similar in design to the existing centrifuge control UI which shows the speed set point, actual speed, and the start/stop button.
    b. Large display area for virtual control of the onboard computer, as is currently done through LogMeIn.
    c. IR camera video feed display
    d. An integrated digital checklist which must be clicked by the operator before the centrifuge can be started. The checklist items would include the most important aspects for safety including: consent form signing, safety harness check, centrifuge walk-around check, counterweight placement, and slider board/ergometer/exercise baseplate lock check.

e. A timer to aid in syncing the LEM and Logger Lite data. Such a timer could be used by the controller to note points at which each program was started and stopped.
f. Inspection indicator that illuminates after every 20-30 hours of cumulative operation. While disassembling elements of the MIT SRC in order to clear the centrifuge arm for the new CRC, a number of loose bolts were found. To avoid this on the CRC, the UI should use an embedded time tracker that illuminates an 'Inspect' icon after a set period of operation, prompting the controller to check the fit of all nuts onboard as well as look for any other visible signs of needed maintenance.

5.2 Future Studies

The MIT CRC was designed to be a versatile platform that allows for a range of future studies. Based on the literature and discussions with both MIT and externally interested researchers, two primary areas of interest for future research include:

Cardiovascular Responses: The unique positioning of the subject on the CRC results in centrifugal accelerations on the head as well as a gravity gradient that does not align with the body's z axis. Given the recent problem of papilledema identified in astronauts and its possible link to increased intracranial pressure during spaceflight, the cardiovascular effects of the centrifugal accelerations on the head are of particular interest. The blood pressure gradient across the body might also be explored, both as it relates to the position of the subject as well as the effects of cycling. Using the adjustable trunk angle feature of the chair, the subject could be leaned forward to approximately align the trunk of the body with the radius of the CRC for control runs, with trunk angle and G-level then manipulated between trials.

Exercise Regimens: The range of workloads that can be provided by the ergometer, the various trunk angles at which the subject can be positioned, and the ability to interchange exercise devices allows the CRC to be used as a platform on which the optimal exercise regimens can be identified. Bed rest studies with partner institutions like IBMP might allow the effectiveness of these protocols at preventing deconditioning to be tested.

The robust CRC test platform which has been constructed accommodates the full range of the astronaut corps anthropometry while containing all hardware, including a cycle ergometer, within a radius that is more realistic of what might be available on future spacecraft. At the same time, the unique way on which the subject is positioned on the CRC addresses the lateral deflection of the knees from Coriolis forces which has previously been a problem in centrifuges with exercise. The MIT CRC has met a majority of the requirements specified in the AGREE proposal. This includes a suite of physiological and mechanical sensors, whose operations have been validated through a pilot run.

Further improvements of the CRC over the previous SRC also include the enhancement of accuracy, ease of operations, and safety of the test platform. Motor characterization has provided important information regarding its performance, which in previous MIT SRC studies was simply assumed to be correct. This information, combined with the ability to now observe actual accelerations at the point of interest as opposed to only assuming the set RPM was correct, will result in tests that are of much higher accuracy in their G-level than has previously been accomplished at MIT. Finally, the MMT and operations checklist that have been developed make operations easier for the controller, while simultaneously reducing wear on the hardware and improving safety.

Given the compact design, subject positioning, available sensors, tested accuracies, and validated operations, the MIT CRC represents one of the most unique yet realistic centrifuges currently in available for artificial gravity research. It is hoped that through these future studies the MIT CRC will provide a better understanding of the effects and capabilities of an inflight-centrifuge, and perhaps contribute in some small way to progressing towards the inevitable trip to Mars.

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APPENDICES

Onboard Mockup User Testing
December 11, 2012 – January 23, 2013

Leg Pads

- Upper leg pad desired (over only lower leg)
- Lower leg pad came off of leg plate and got caught, causing the subject to stop cycling and adjust
- Subject 5 used only the upper leg pad and commented that it was fine. Lower leg touched the plate but subject did not notice until it was pointed out.
- Pads tend to come loose

Leg Cuffs

- Most commented that the leg cuffs were comfortable.
- Subject 4 did not mention it as a problem, but it was noticed that the lower leg cuff was extended down (away from the center of rotation) and should have been adjusted. Subject 5 specifically mentioned that this was a problem and that it inhibited leg movement. Position was moved for subsequent subjects.
- Color coding of some kind would be helpful for quickly identifying which cuff is which, and the direction in which it should be laced through the eyes.

AG Settling

- Some subjects mentioned they adjusted themselves during spin-up. Subsequent subjects were instructed to do so.
- Subject 3 did not adjust even after at 1 G
- Subject 5 was able to get into near settled position from beginning
- Subject 4 and 5 commented that settling caused the placement of the bike to be sub-optimal, suggest doing a 'settling spin-up' to make fine tune adjustments before starting trials

Upper Body

- All subjects commented that they felt comfortable, even relaxed. Pillow was fine, and seatbelt was not uncomfortable
- Subject 1 commented that her hip on the chair was slightly uncomfortable. Subsequent subjects were specifically asked about this and no one else had a problem.
- Subjects were instructed to do whatever was most comfortable with their arms. Many naturally assumed a position like sleeping their side, with one arm under their head and the other folded over their body. Subject 3 commented that this was awkward. Subject 5 commented that the uncertainty before starting is what made it awkward, but that once spinning it was comfortable. All other subjects said it was comfortable.

- Subject 2 commented on hygiene of pillow- need for case/vinyl/maintenance protocol in final design

Operations

- Leg plate is unsupported beyond the chair frame, but bears a majority of the subject's weight as they enter. Should be reinforced.
- Subject 5 expressed concern that the strap would fall onto someone's face if the user was not careful. Shoulder strap is started in the upright position.
- Onboard battery power was a problem and limitation to data collection. Should investigate decreased capacity and consider replacement.
- Automatic control application was not functioning properly, all trials were done manually.
- Subjects' view of kill switch was hindered by the Teflon plate, placement should receive more careful consideration, glow in the dark tape or indicator also suggested for riding in the dark.
- While moving the baseplate along the z-axis, it would tip over once all pins had been removed. .

Appendix A: Prototyping and Pilot Run Notes

Pilot Run
May 10, 2013

Leg Pads

- Upper leg pad not touching slider board, even with additional foam, though subject did not comment on this being a problem.
- Leg pad straps causing discomfit behind knees.

Leg Cuffs

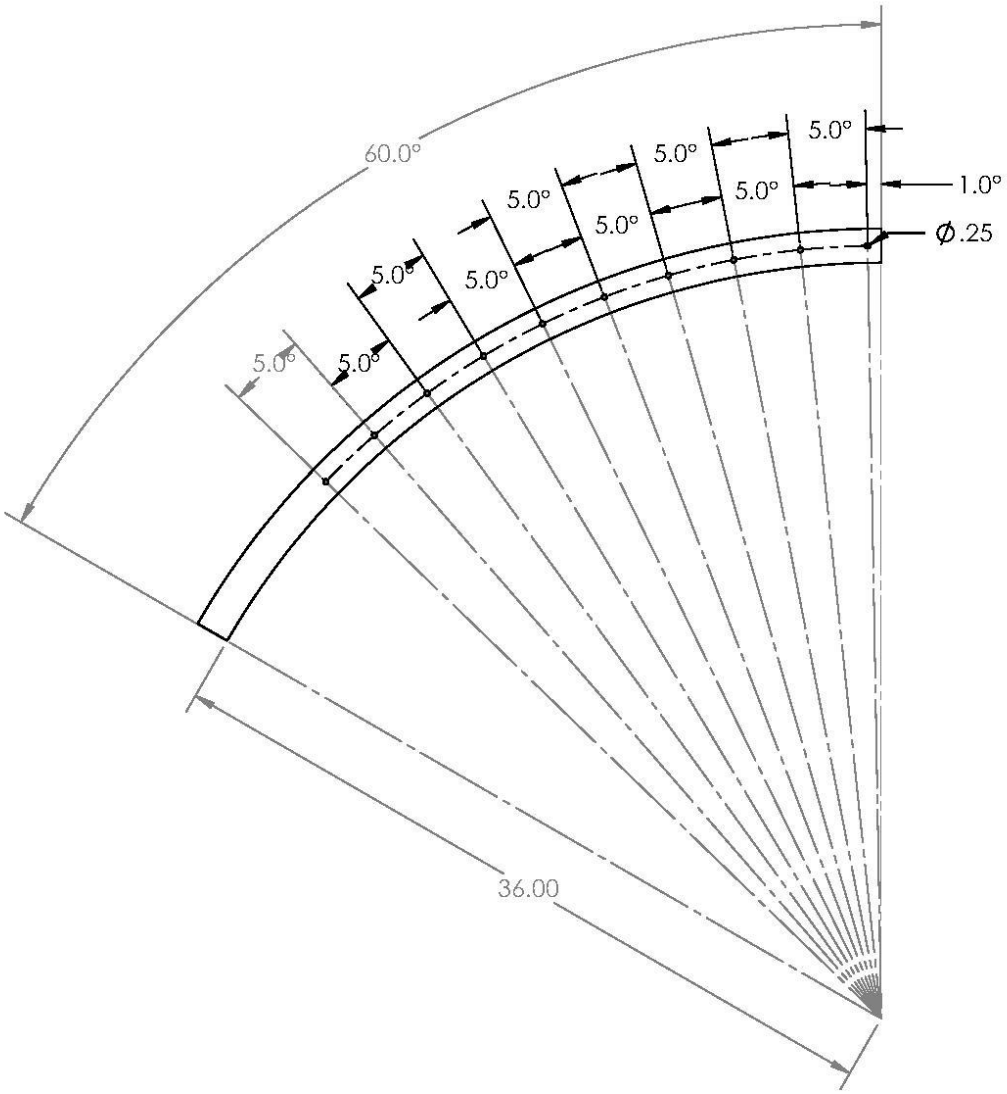
- Subject indicated these worked.
- Some slippage caused the subject to make adjustments while spinning; suggested higher friction surface should be added to interior of strap.

Cycle Ergometer

- Subject commented that lower pedal was hitting slider board frame depending on the force applied, resulting in the subject intentionally pedaling unnaturally to avoid hits.
- Subject commented that they felt they were pedaling with their heels as opposed to the more natural balls of their feet. Pivot point between the pedals and the crankshaft should be moved further towards the front of the foot.

Operations

- Two controllers were present. This aided the process significantly, as both were able to help expedite the boarding/unboarding process, and during the trials one could monitor the data and video feed while the other communicated with the subject to alert them of changing workloads.
- The wireless headsets were not working, and should be implemented before final trials.
- There were still slight oscillations of the slider board along the rails, even with all strut segments in. Subject did not notice nor was affected, but additional methods of securing slider board should be implemented.



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		ANGULAR: MACH ± BEND ±	MFG APPR.			
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		THREE PLACE DECIMAL ±	COMMENTS:			
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Sliding Base Curved Strut

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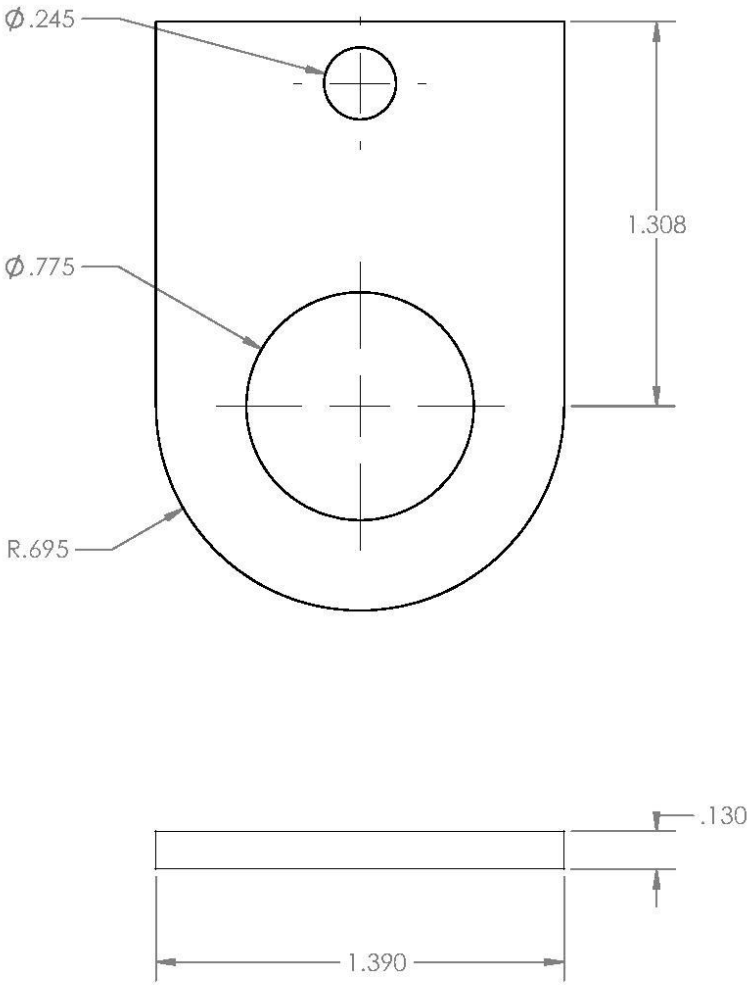

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Top/Side

Angio Mount Clip

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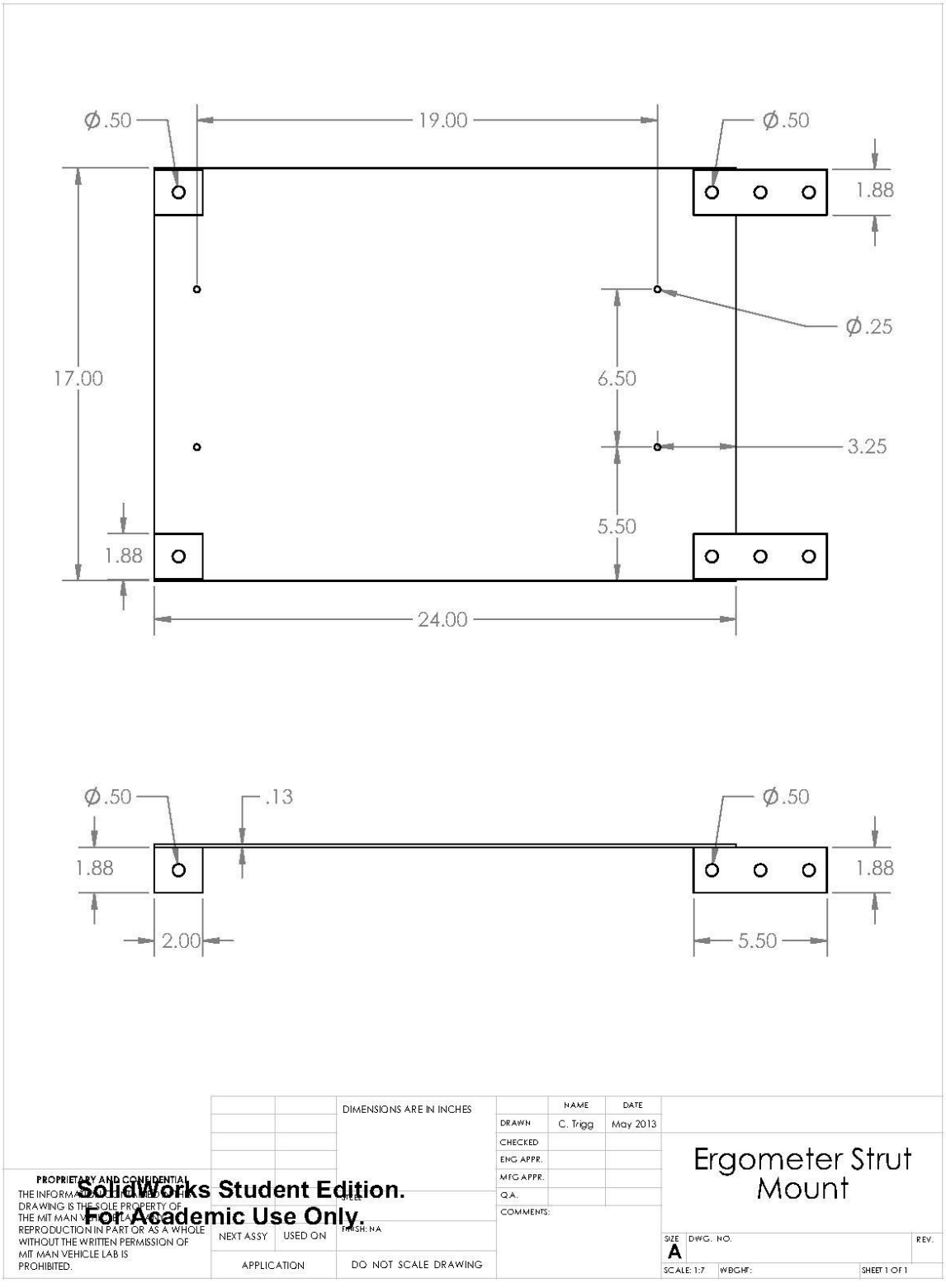

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Ergometer Strut Mount

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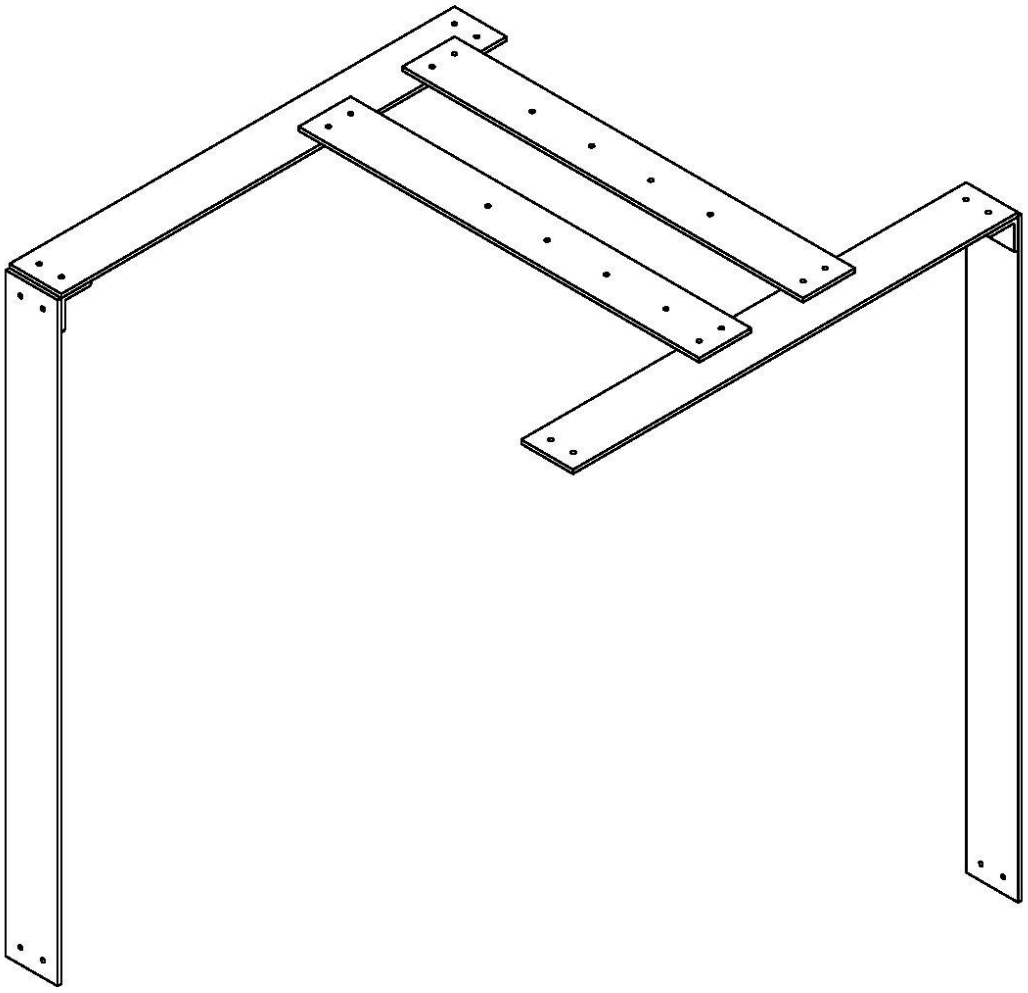

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Isometric

Leg Cuff Frame

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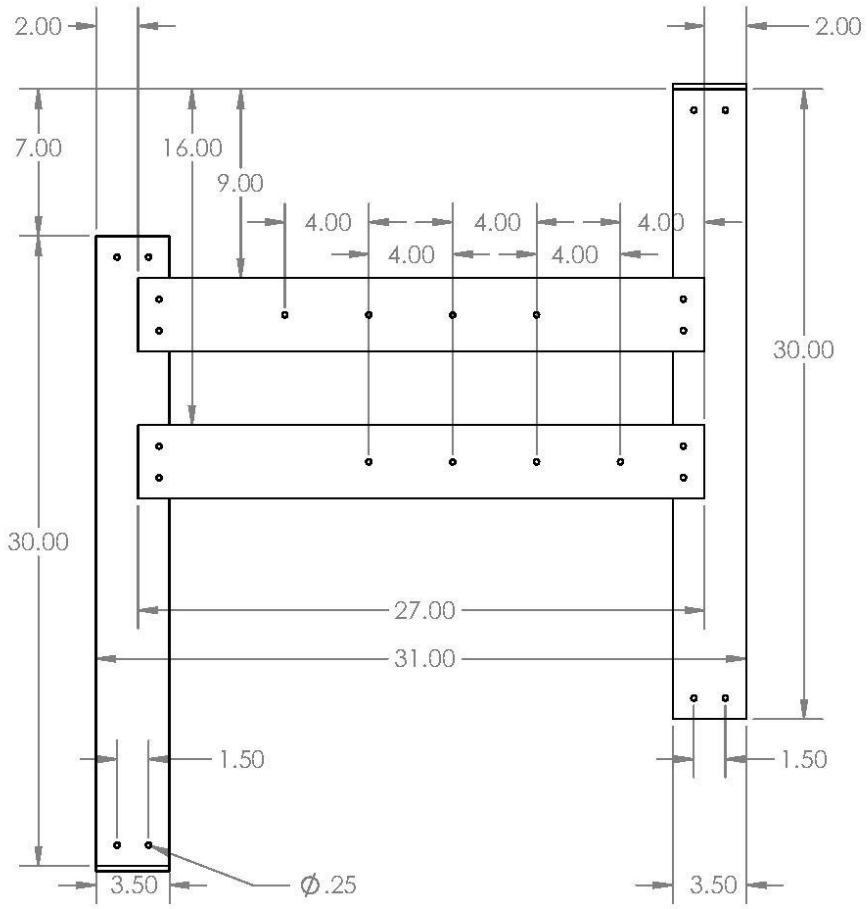

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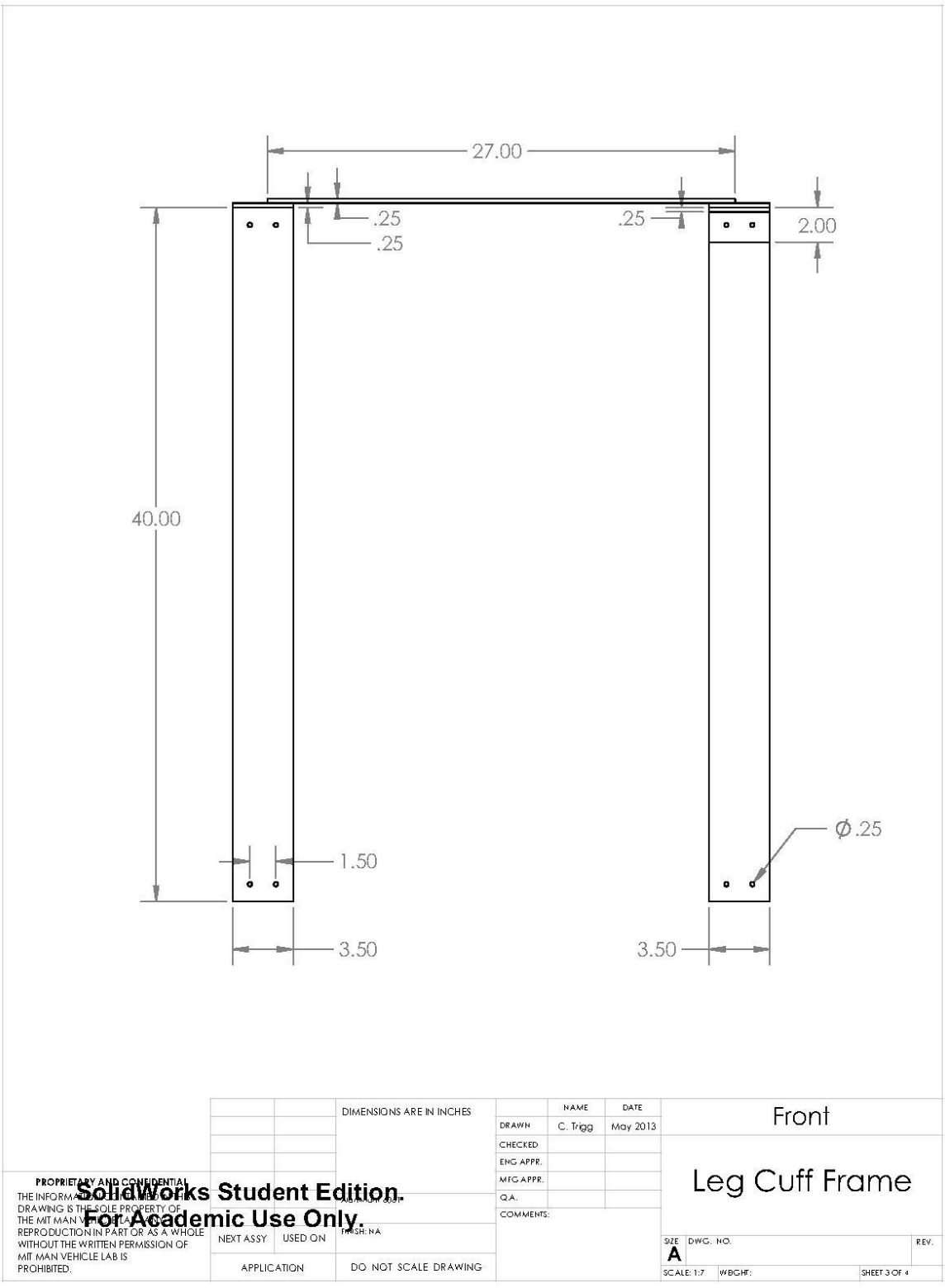
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:7 / WEIGHT: / SHEET 2 OF 4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Front
Leg Cuff Frame
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NEXT ASSY
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APPLICATION
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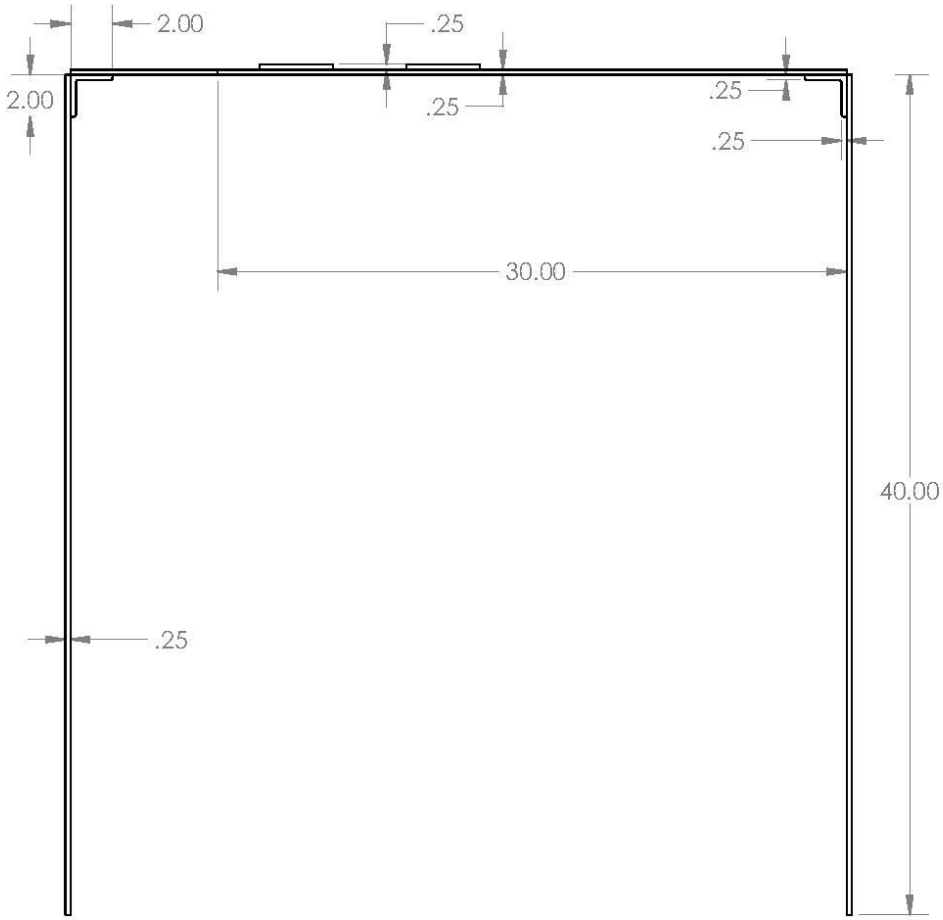
WEIGHT:
SHEET 3 OF 4

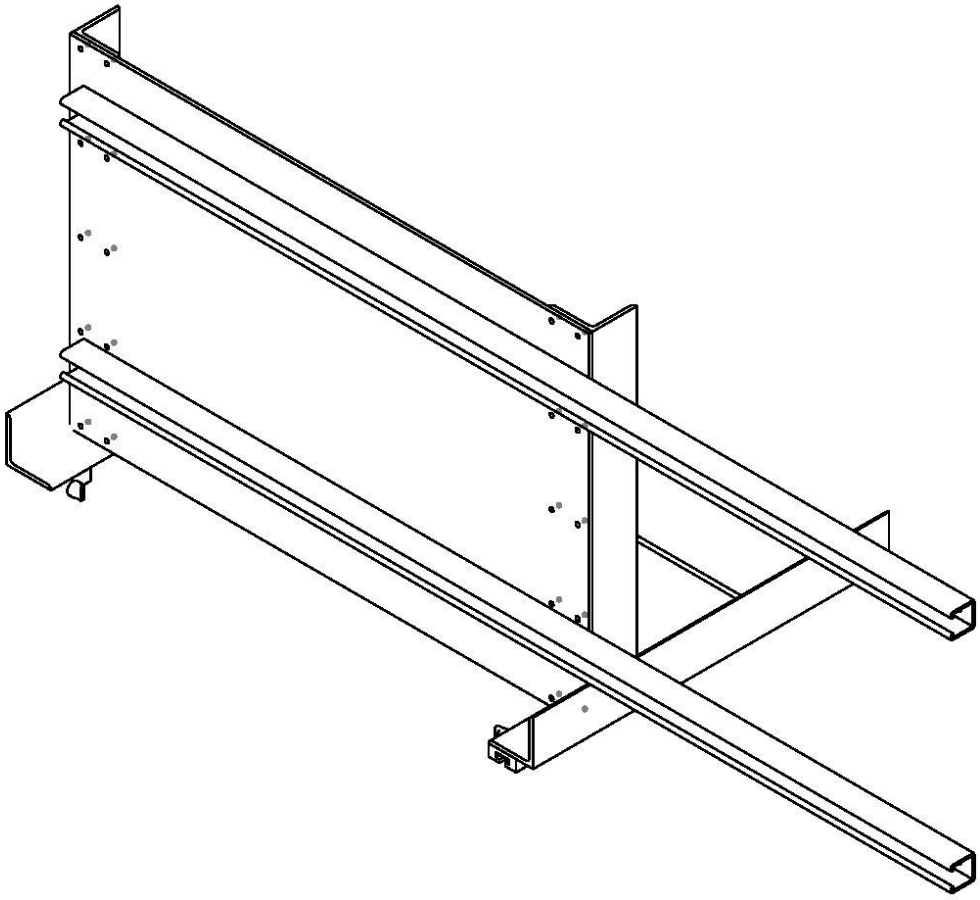


		DIMENSIONS ARE IN INCHES		NAME	DATE
			DRAWN	C. Trigg	May 2013
			CHECKED		
			ENG APPR.		
			MFG APPR.		
			Q.A.		
			COMMENTS:		
		FINISH: N/A			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

Side

Leg Cuff Frame

SIZE	DWG. NO.	REV.
A		
SCALE: 1:7	WEIGHT:	SHEET 4 OF 4



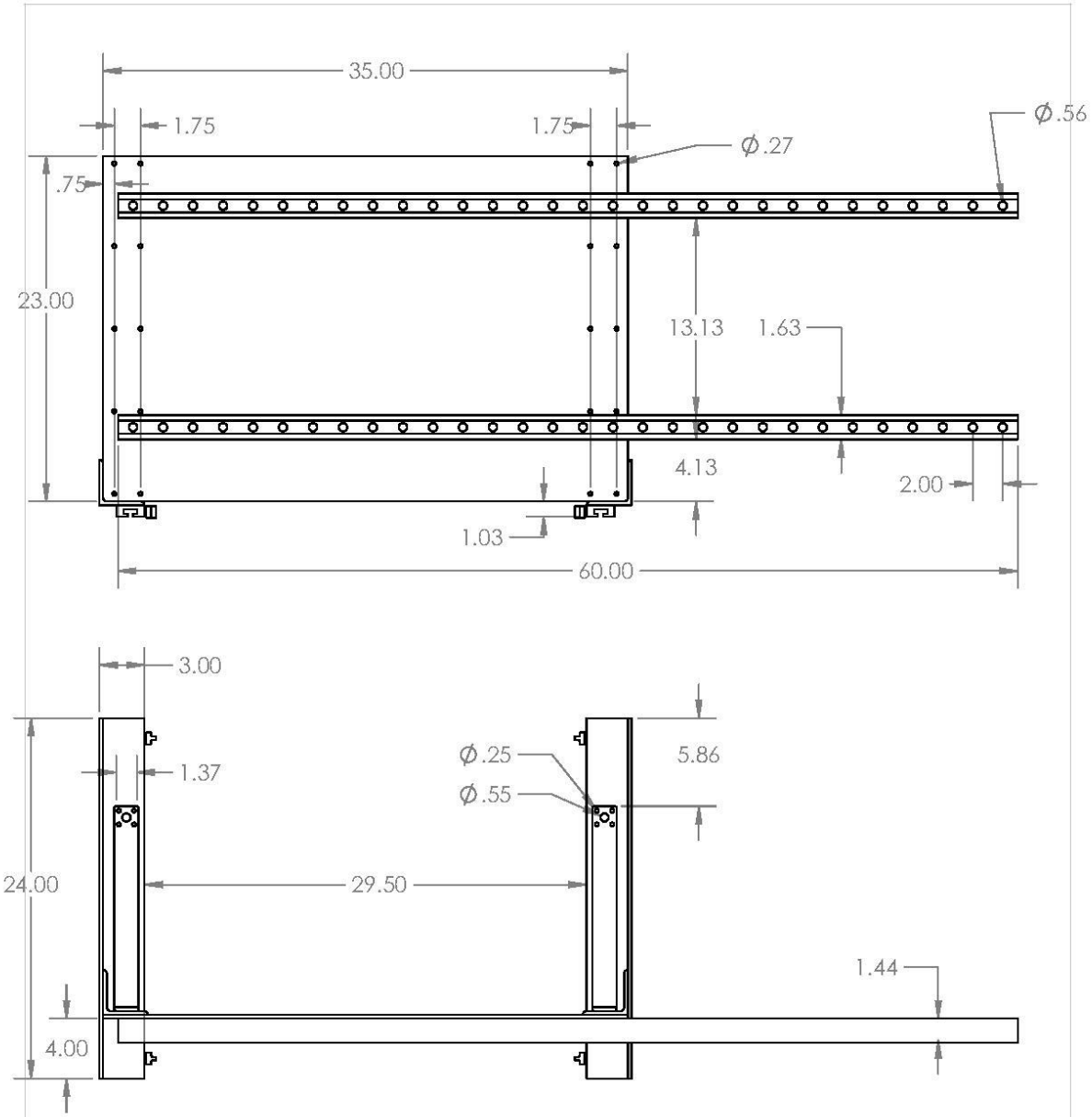
		DIMENSIONS ARE IN INCHES		NAME	DATE
			DRAWN	C. Trigg	May 2013
			CHECKED		
			ENG APPR.		
			MFG APPR.		
			Q.A.		
			COMMENTS:		
		Material: Alum. 6061			
NEXT ASSY	USED ON	FINISH: NA			
APPLICATION		DO NOT SCALE DRAWING			

Isometric

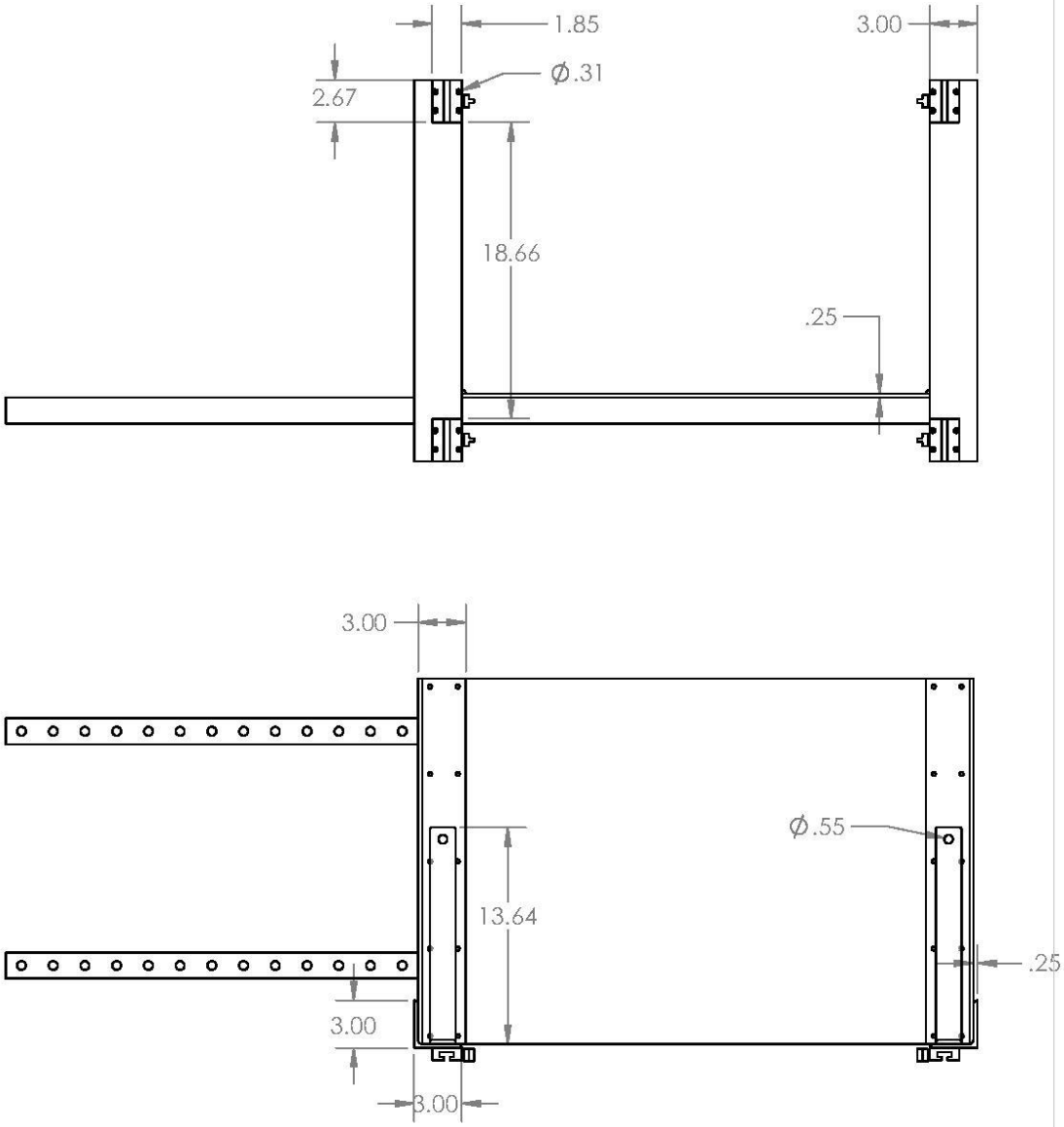
Exercise Baseplate

SIZE A | DWG. NO. | REV.

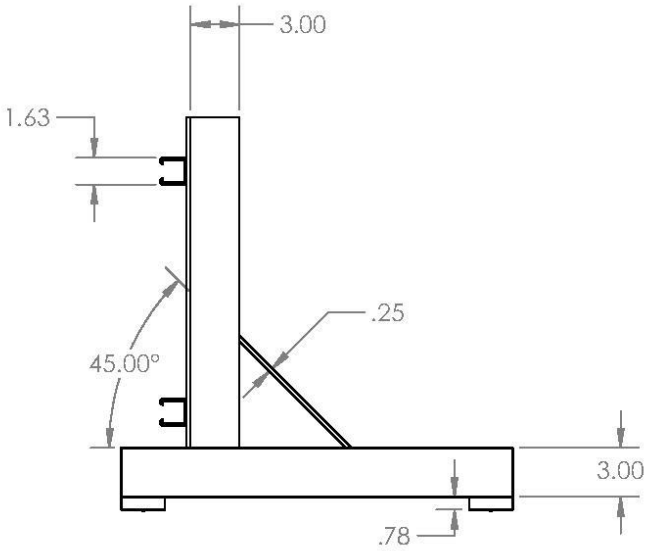
SCALE: 1:7 | WEIGHT: | SHEET 1 OF 4



		DIMENSIONS ARE IN INCHES		NAME	DATE	Front/Top
			DRAWN	C. Trigg	May 2013	
			CHECKED			Exercise Baseplate
			ENG APPR.			
			MFG APPR.			
			Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH: N.A				SIZE A · DWG. NO. · REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:9 · WEIGHT: · SHEET 2 OF 4



		DIMENSIONS ARE IN INCHES		NAME	DATE	Bottom/Rear
			DRAWN	C. Trigg	May 2013	
			CHECKED			Exercise Baseplate
			ENG APPR.			
			MFG APPR.			
			Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH: N.A				SIZE A / DWG. NO. / REV.
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:9 / WEIGHT: / SHEET 3 OF 4



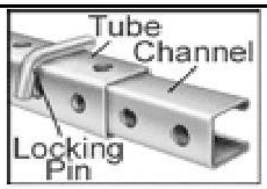
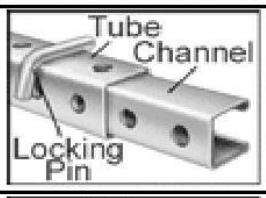
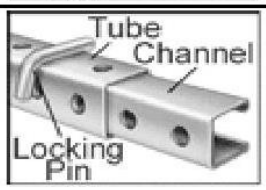
		DIMENSIONS ARE IN INCHES		NAME	DATE
			DRAWN	C. Trigg	May 2013
			CHECKED		
			ENG APPR.		
			MFG APPR.		
			Q.A.		
			COMMENTS:		
		MATERIAL: Aluminum 6061			
		FINISH: N/A			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			

Side

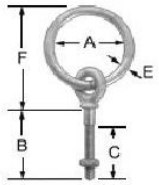
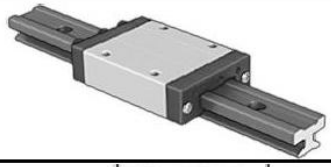
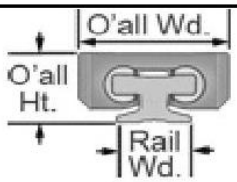
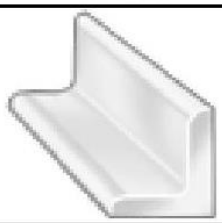
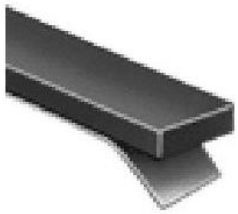
Exercise Baseplate

SIZE	DWG. NO.	REV.
A		
SCALE: 1:9	WEIGHT:	SHEET 4 OF 4

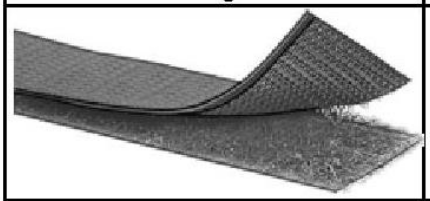
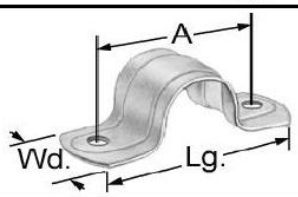
Appendix C: Bill of Materials

Image	P/N and Description
	Plastic end cover and end caps for strut channel P/N: 3312T63/3312T82 Price: $1.12/0.82 each
	Curved strut channel (1 5/8" x 1 5/8"), 0.105" thick, 36" inner radius, 115 degree trace P/N: 3147T1 Price: $95.05 each
	High Profile Push-Button Quick-Release Pin 1/4" Diameter, 1-1/2" Usable Length P/N : 90985A113 Price: $19.09 each
	Locking Pin for Telescoping Round-Hole Strut Channel P/N: 3138T71 Price: $12.96 each
	5' Zinc-Plated Tube, 1-7/8" X 1-7/8", for Telescoping Round-Hole Strut Channel P/N: 3138T31 Price: 47.65 each
	Telescoping Round-Hole Strut Channel 1-5/8" X 1-5/8", Zinc-Plated, 5' Length P/N: 3138T61 Price: $19.20 each

Appendix C: Bill of Materials

Image	P/N and Description
	Ringbolt 300 Series SS, 400#WII, 2-1/4" L Bolt, 5/16"-18 Thrd P/N: 3025T79 Price: $10.78 each
	Guide Rail, 15 mm Width, for 47 mm Width PTFE-Lined Sleeve Bearing Carriage P/N: 9867K12 Price: $0.07 per mm
	Lockable PTFE-Lined Sleeve Brng Carriage Threaded Through-Hole, for 15 mm Rail Width P/N: 3249K2 Price: $56.25 each
	Multipurpose Aluminum (Alloy 6061) 90 Deg Angle, 1/4" Thick, 3" X 3" Legs, 4' Length P/N: 8982K62 Price: $52.99 each
	Adhesive-Back Medium-Strength Neoprene Rubber 3/32" Thick, 2"/4" Wide, 36" Long, Black P/N: 8461K13/8461K43 Price: $9.20 each/$15.84 each
	Multipurpose Aluminum (Alloy 6061) Tube 7/8" OD, .745" ID, .065" Wall Thickness, 3' Length P/N: 9056K732 Price: $24.98 each

Appendix C: Bill of Materials

Image	P/N and Description
	General Purpose Nylon Hook and Loop 2" Width X 10' Length, Adhesive Back P/N: 9273K23 Price: $25.41 for 10 foot length
	Type 304 Stainless Steel Two-Hole Clamp for 13/16" OD, 1/2" Pipe/Rigid Conduit Size P/N: 8874T16 Price: $1.36 per pkg (packs of 1)
	Extreme-Temperature Slippery PTFE Film Adhesive-Backed .01" Thick, 36" Width P/N: 2208T82 Price: $45.76 per ft.
	Brass Tapping Insert for Wood Slotted Drive, 5/16"-18 Internal Thrd, 5/8" Length P/N: 90016A030 Price: $6.97 per pkg (packs of 10)
	Push-on Round Cap Fits 7/8"-15/16" OD, 3/4" Inside Height P/N: 9753K57 Price: $6.84 per pkg (packs of 100)
	Velcro Reusable Self-Gripping Cable Ties, 0.5 Inches x 8 Inches Long, Black, 100 Ties per Pack (91140) P/N: Amazon.com
	Ostart 8 Black Baby Furniture Corner Safety Bumper Security Table Desk Corner Edge Protector Guard Cushion Softener P/N: Amazon.com Price: $6.99 (Prime)

Appendix C: Bill of Materials

Image	P/N and Description
	6061 Aluminum Rectangular Bar, Unpolished (Mill) Finish, T6511 Temper, Standard Tolerance, Inch, Meets AMS QQ-A-200/8/ASTM B221 Specifications, 1/4" Thickness, 3-1/2" Width, 72" Length P/N: Amazon.com Price: $37.06 (Prime)
	Optional Breathable Mesh Headrest. Fits 818 Series Only. P/N: Amazon.com Price: $45.54
	Strathwood Basics Anti-Gravity Adjustable Recliners P/N: Amazon.com Price: &64.99 (Prime)
	Netami 25-0045 Black 4 Point Cam Lock Seat Belt Harness P/N: Amazon.com Price: $54.99 (Prime)
	6061 Aluminum Angle, Unpolished (Mill) Finish, Extruded, T6 Temper, Standard Tolerance, Inch, Meets ASTM B308/AMS-QQ-A 200/8 Specifications, Equal Leg Length, Rounded Corners, 2" Leg Lengths, 1/4" Wall Thickness, 12" Length P/N: Amazon.com Price: $15.14 (Prime)
	Camco 42503 RV 12" Awning Straps P/N: Amazon.com Price: $6.59 (Prime)
	3 Inch Thick, 4 Pound Density Visco Elastic Memory Foam Mattress Pad Bed Topper. Made in the USA P/N: Amazon.com Price: $168.59 (Prime)
	Master Lock 3038DAT SteelCor 6"- 24" Adjustable Bungee Cord P/N: Amazon.com Price: $5.19 (Prime)

Appendix D: Operations Checklist

A. Setup

1. Control room computer ..... ON
    a. Username: Chris
    b. Password: spinaround
2. 'Experiment in Progress' Sign……..……..ON
3. Onboard Battery……..……ON
4. Onboard Computer ..... ON
    a. Password: spinaround
5. Ergometer…… ……..ON
6. Open LEM:
    a. Login (upper right corner)
        i. Username: lode
        ii. Password: service
    b. Add subject name
    c. Select 'Warm-Up' protocol
7. Open Logger Lite 1.6.1
    a. Check for all sensor inputs
    b. Check collection frequency and time interval of frequency (Experiment -> Data Collection)
8. Record room temperature and humidity.
9. Record value of 0 forces for left and right pedals.
10. Disinfect HR belt.
11. Centrifuge anchor clamp……..……..……LOCKED
12. Ergometer baseplate……..……LOCKED
13. Ergometer on struts……LOCKED
14. Chair……..……..LOCKED
15. Prepare consent, eligibility, and post-test survey documentation.
16. From control room computer log in remotely to onboard computer via www.logmein.com:
    a. Username: ctrigg@mit.edu
    b. Password: hal9OOO (*letter O not zero*)
17. Check onboard camera feed: 192.168.0.13
    a. Username: admin
    b. Password: spinaround
    c. Use lower Login button (server push mode)

B. Subject Orientation

1. Review all sections of Consent Form with subject, ask about any questions/concerns.
2. Sign Consent Form.
3. Administer Eligibility and Pre-Procedure Questionnaire.
4. Check results to Questionnaire Clarification document to ensure eligibility.
5. Check subject clothing (no loose articles, nothing in pocket, proper shoes with toe covering).
6. Weigh subject on scale.
7. Enter weight in MMT and LEM profile.
8. Enter height and DOB in LEM profile.

Appendix D: Operations Checklist

C. Boarding

1. Don leg pads (2).
2. Add saline solution to HR belt.
3. Allow subject to don HR belt.
4. Don respiration belt.
5. Check Logger Lite for HR belt signal.
6. Climb in and attach safety harness in all 3 positions.
7. Adjust slider board so eyes are at COR. Lock in place with strut sections and enter radial distance at the end of the slider board into the MMT.
8. Adjust position of eye bolts as needed to align with upper and lower leg.
9. Strap feet into ergometer.
10. Don upper leg cuffs (2).
11. Adjust exerciser baseplate radially. Lock in place with pins (1-2) and carriage locks. Enter position into the MMT.
12. Adjust ergometer along struts. Lock in place with pins (2). Enter distance into the MMT.
13. Tighten upper leg cuffs.
14. Don blood pressure cuff.
15. Adhere EMG electrodes .
    a. Red/Green across target muscle
    b. Black (ground) on separate area
16. Adjust headrest as needed.
17. Secure accelerometer at radial foot location.
18. Complete inputs, run MMT.
19. Add counterweights as specified.
20. Disconnect batteries from power strip. Store extension cord.
21. Flip on the kill switch circuit box (check for light).
22. Check that subject can reach kill switch.
23. Unclamp centrifuge arm, stow clamp.
24. Push centrifuge arm 360° to check for clearances.

D. Warm-Up Spin

1. Check camera feed to confirm live display.
2. Begin LEM 'Warm-Up' protocol.
3. Start Logger Lite data collection.
4. Manual control box ……..……ON
5. Control type……..……..MANUAL
6. Run type……..……..RUN
7. Direction……..……..FORWARD
8. RPM Dial……0
9. Engage (click up once to 'Start').
10. Alert subject to begin cycling.
11. Accelerate centrifuge gradually to ~15 RPM.
12. Alert subject to adjust body position as needed.
    Ask about comfort and positioning of:
    a. Safety harness
    b. Lower leg pads
    c. Upper leg cuffs
    d. Position of ergometer
    e. Sensors
13. Check Logger Lite for active sensor readings.
14. Alert subject to deceleration.
15. Push centrifuge arm 360° to check for clearances.

Appendix D: Operations Checklist

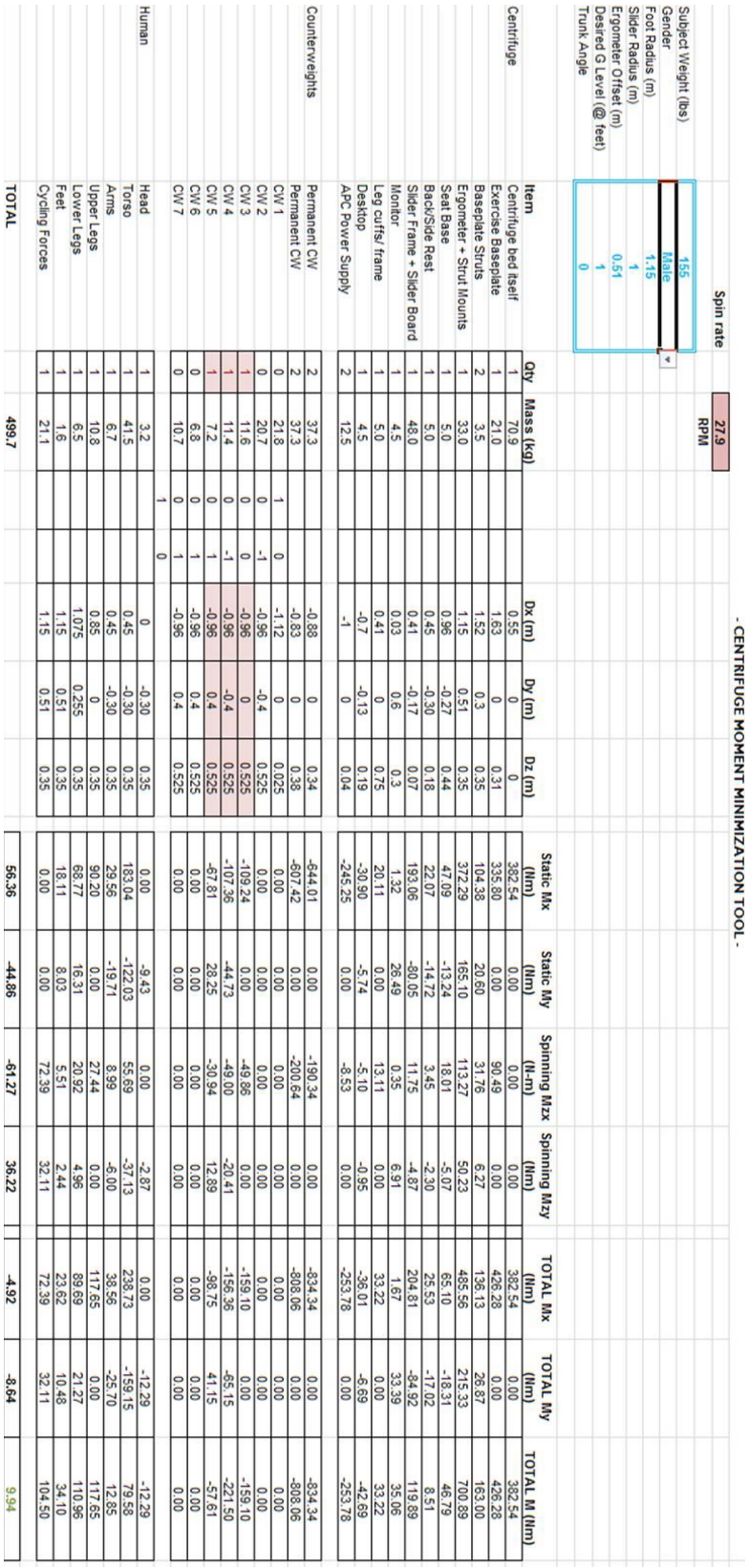
E. Trial

1. Begin LEM protocol.
2. Start Logger Lite data collection.
3. Manual control box ……OFF
4. Manual control box ……ON
5. Control type……MANUAL
6. Run type……RUN
7. Direction……FORWARD
8. RPM Dial……0
9. Engage (click up once to 'Start').
10. Alert subject to begin cycling.
11. Accelerate centrifuge gradually to specified acceleration.
12. During trial, alert subject to upcoming changes in workload.
13. During trial, monitor:
    a. Subject via video and oral communication
    b. Sensor readouts
    c. Acceleration (speed). Adjust as necessary.
14. Alert subject to deceleration (suggest closing eyes).
15. Decelerate centrifuge to 0 RPM.
16. Stop/save LEM protocol.
17. Stop/save Logger Lite data collection.

F. Post-Trial

1. Manual control box ……OFF
2. Centrifuge anchor clamp..... ……ON
3. Unstrap subject:
    a. Safety harness
    b. EMG electrodes
    c. Blood pressure cuff
    d. Respiration belt
    e. Ergometer foot straps
    f. Upper leg cuffs
    g. Lower leg pads
4. Allow subject to doff HR belt.
5. Plug batteries into power cord.
6. Administer exit survey.
7. Export LEM and Logger Lite data. Exit software.
8. Onboard Computer ..... ……OFF
9. Onboard Battery..... ……..OFF
10. Ergometer..... ……..OFF
11. Kill switch circuit box..... ……..OFF
12. 'Experiment in Progress' sign ..... ……..OFF
13. Control room computer ..... ……..OFF

Appendix E: Moment Minimization Tool (MMT)



- CENTRIFUGE MOMENT MINIMIZATION TOOL -

Subject Weight (lbs)	155
Gender	Male
Foot Radius (m)	1.15
Slider Radius (m)	1
Ergometer Offset (m)	0.51
Desired G Level (@ feet)	1
Trunk Angle	0

Spin rate: 27.9 RPM

	Item	Qty	Mass (kg)	Dx (m)	Dy (m)	Dz (m)	Static Mx (Nm)	Static My (Nm)	Spinning Mzx (N-m)	Spinning Mzy (Nm)	TOTAL Mx (Nm)	TOTAL My (Nm)	TOTAL M (Nm)
Centrifuge	Centrifuge bed itself	1	70.9	0.55	0	0	382.54	0.00	0.00	0.00	382.54	0.00	382.54
	Exercise Baseplate	1	21.0	1.63	0	0.31	335.80	0.00	90.49	0.00	426.28	0.00	426.28
	Baseplate Struts	2	3.5	1.52	0.3	0.35	104.38	20.60	31.76	6.27	136.13	26.87	163.00
	Ergometer + Strut Mounts	1	33.0	1.15	0.51	0.35	372.29	185.10	113.27	50.23	485.56	215.33	700.89
	Seat Base	1	5.0	0.96	-0.27	0.44	47.09	-13.24	18.01	-5.07	65.10	-18.31	46.79
	Back/Side Rest	1	5.0	0.45	-0.30	0.18	22.07	-14.72	3.45	-2.30	25.53	-17.02	8.51
	Slider Frame + Slider Board	1	48.0	0.41	-0.17	0.07	193.06	-80.05	11.75	-4.87	204.81	-84.92	119.89
	Monitor	1	4.5	0.03	0.6	0.3	1.32	26.49	0.35	6.91	1.67	33.39	35.06
	Leg cuffs/ frame	1	5.0	0.41	0	0.75	20.11	0.00	13.11	0.00	33.22	0.00	33.22
	Desktop	1	4.5	-0.7	-0.13	0.19	-30.90	-5.74	-5.10	-0.95	-36.01	-6.69	-42.69
	APC Power Supply	2	12.5	-1	0	0.04	-245.25	0.00	-8.53	0.00	-253.78	0.00	-253.78
Counterweights	Permanent CW	2	37.3	-0.88	0	0.34	-644.01	0.00	-190.34	0.00	-834.34	0.00	-834.34
	Permanent CW	2	37.3	-0.83	0	0.38	-607.42	0.00	-200.64	0.00	-808.06	0.00	-808.06
	CW 1	0	21.8	-1.12	0	0.025	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CW 2	0	20.7	-0.96	-0.4	0.525	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CW 3	1	11.6	-0.96	0	0.525	-109.24	0.00	-49.86	0.00	-159.10	0.00	-159.10
	CW 4	1	11.4	-0.96	-0.4	0.525	-107.36	-44.73	-49.00	-20.41	-156.36	-65.15	-221.50
	CW 5	1	7.2	-0.96	0.4	0.525	-67.81	28.25	-30.94	12.89	-98.75	41.15	-57.61
	CW 6	0	6.8	-0.96	0.4	0.525	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CW 7	0	10.7	-0.96	0.4	0.525	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		1	0										
Human	Head	1	3.2	0	-0.30	0.35	0.00	-9.43	0.00	-2.87	0.00	-12.29	-12.29
	Torso	1	41.5	0.45	-0.30	0.35	183.04	-122.03	55.69	-37.13	238.73	-159.15	79.58
	Arms	1	6.7	0.45	-0.30	0.35	29.56	-19.71	8.99	-6.00	38.56	-25.70	12.85
	Upper Legs	1	10.8	0.85	0	0.35	90.20	0.00	27.44	0.00	117.65	0.00	117.65
	Lower Legs	1	6.5	1.075	0.255	0.35	68.77	16.31	20.92	4.96	89.69	21.27	110.96
	Feet	1	1.6	1.15	0.51	0.35	18.11	8.03	5.51	2.44	23.62	10.48	34.10
	Cycling Forces	1	21.1	1.15	0.51	0.35	0.00	0.00	72.39	32.11	72.39	32.11	104.50
TOTAL			499.7				56.36	-44.86	-61.27	36.22	-4.92	-8.64	9.94

Figure A: Full MMT

Appendix E: Moment Minimization Tool (MMT)

The Moment Minimization Tool (MMT) is an Excel-based optimizer for identifying the location of counterweights in order to minimize the magnitude of the total moment during each trial. The necessary in puts are boxed in blue, as seen in Figure . All data must be added manually with the exception of gender which is selected from a dropdown menu. Note that units of length are in **meters**, as this corresponds to the tape measures on the centrifuge, while weight is entered in **pounds**. Weight is automatically converted to kg for calculations. Trunk angle is entered in **degrees.** Trunk angle inputs can range from -15° (subject leaning forward) to -30° (subject leaning back). A subject aligned parallel to the centrifuge sides is at 0°, and each pin hole corresponds to a 5° adjustment.

	Spin rate
Subject Weight (lbs)	155
Gender	Male
Foot Radius (m)	1.15
Slider Radius (m)	1
Ergometer Offset (m)	0.51
Desired G Level (@ feet)	1
Trunk Angle	0

Figure B: MMT Inputs

The MMT uses the Solver add-in, which comes with Excel but must be enabled if it has not previously been used. Solver works by optimizing (in this case, minimizing) a target cell by manipulating specified variable cells while also applying constraints to those cells. The variable cells used in the tool are those highlighted in Figure .

		A		B	C			
Counterweights	Permanent CW	2	37.3			-0.88	0	0.34
	Permanent CW	2	37.3			-0.83	0	0.38
	CW 1	0	21.8	1	0	-1.12	0	0.025
	CW 2	0	20.7	0	-1	-0.96	-0.4	0.525
	CW 3	1	11.6	0	0	-0.96	0	0.525
	CW 4	1	11.4	0	-1	-0.96	-0.4	0.525
	CW 5	1	7.2	0	1	-0.96	0.4	0.525
	CW 6	0	6.8	0	1	-0.96	0.4	0.525
	CW 7	0	10.7	0	1	-0.96	0.4	0.525
				1	0			
Human	Head	1	3.2			0	-0.30	0.35
	Torso	1	41.5	D	E	0.45	-0.30	0.35

Figure C: MMT Solver variable inputs

Column A is a binary column that switches counterweights on and off. Counterweights that should be used will appear with a 1 in column A and will automatically highlight in red. Note that the top two rows of the counterweight section refer to the two sets of permanent counterweights and are therefore not manipulated.

Columns B and C are used to determine the placement of the selected counterweights. Column B determines where counterweights are located along the x and z axes. These cells are also binary, with 0 corresponding to the upper available location (x= -0.960 m, z=0.525 m) while 1 corresponds to the lower location (x=-1.12 m, z=0.025 m). Values in column C are selected to be -1, 0, or +1 by the optimizer which determines whether the counterweight is placed along the -y axis edge (opposite side from ergometer), the center of the arm, or the +y edge (same side as ergometer) respectively. This corresponds to distances of -0.4, 0.0, and +0.4 m. Figure shows the upper and lower locations for counterweights, and Figure shows the location outputs highlighted. Cells D and E in Figure are further constraints for the optimizer which limit the number of counterweights that can be placed in the upper location (cell D) to 3 because of the limited available volume and limit the number of blocks that can go on either extreme of the y axis (cell E).

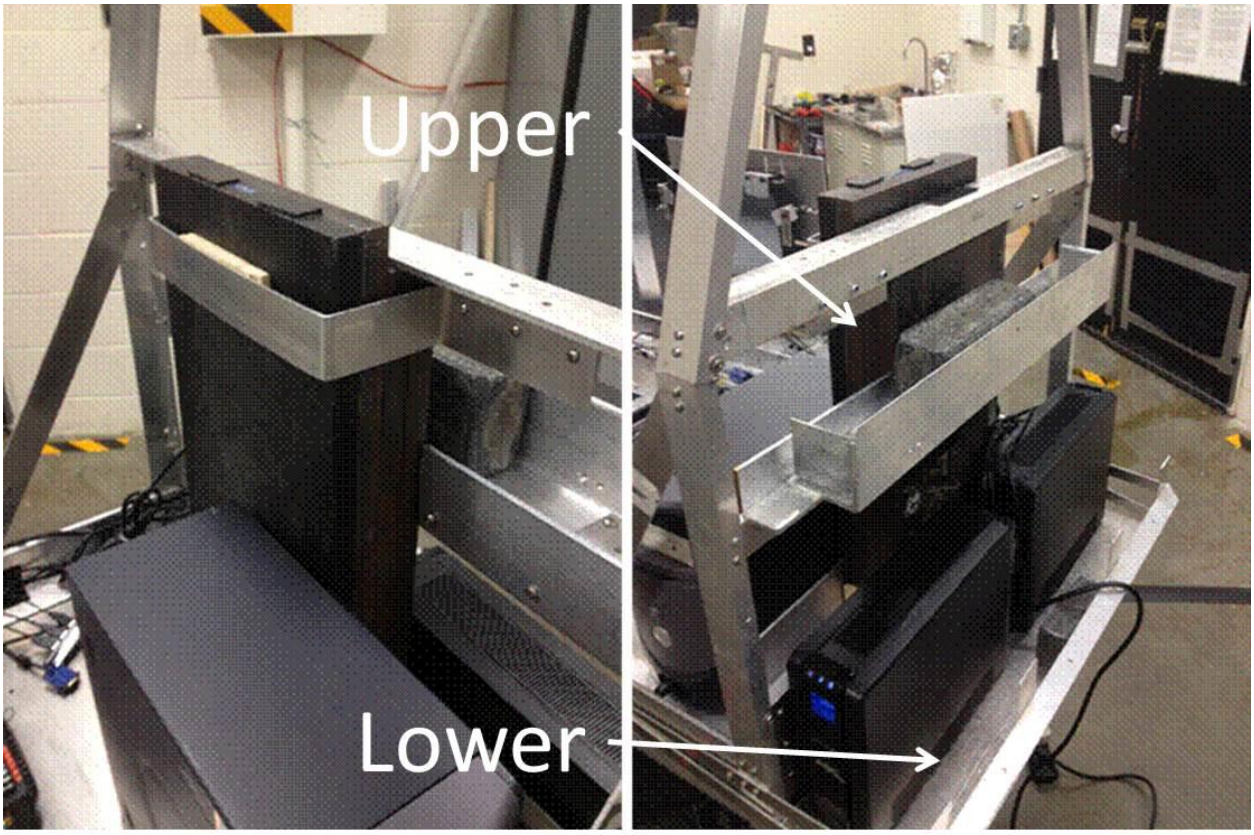


Figure D: Rear permanent counterweights (left), and locations for variable counterweights (right)

Counterweights	Permanent CW	2	37.3			-0.88	0	0.34
	Permanent CW	2	37.3			-0.83	0	0.38
	CW 1	0	21.8	1	0	-1.12	0	0.025
	CW 2	0	20.7	0	-1	-0.96	-0.4	0.525
	CW 3	1	11.6	0	0	-0.96	0	0.525
	CW 4	1	11.4	0	-1	-0.96	-0.4	0.525
	CW 5	1	7.2	0	1	-0.96	0.4	0.525
	CW 6	0	6.8	0	1	-0.96	0.4	0.525
	CW 7	0	10.7	0	1	-0.96	0.4	0.525
				1	0			
Human	Head	1	3.2			0	-0.30	0.35
	Torso	1	41.5			0.45	-0.30	0.35

Figure E: MMT counterweight placement outputs

The Solver uses the Evolutionary solving method, and is programmed to automatically stop after two minutes if an optimal solution has not been converged upon. However, the controller can elect to continue solving after this time period, and should if the incumbent solution is not less than ~20 Nm.

Appendix F: Power Requirements

The theoretical power demands of the CRC were calculated in order to inform future implementation of such a design. Total power required is defined as:

$$P_{total} = P_{motor} + P_{electronics}$$

where

$$P_{motor} = P_{acceleration} + P_{wind\ resistance} + P_{friction}$$

$$P_{electronics} = P_{computer} + P_{monitor} + P_{ergometer} + P_{camera}$$

In order to calculate each of the power requirements, the following were used:

$$P_{acceleration} = (\frac{1}{2} I\ \omega(t)^2\ )\ dt$$

$$P_{wind\ resistance} = (\ \frac{1}{2}\ \rho\ C_d \sum_{i=1}^{n} A_i\ v(t)_i^2\ \ )\ dt$$

$$P_{friction} = \left(\mu\ (g\ m_{total}\ )\ v(t)\right)\ dt$$

Where

$I =$ centrifuge moment of inertia $= 451\ \text{kg} * m^2$

$\omega =$ angular velocity (rad/s)

$\rho =$ density of air $= 1.225\ \text{kg/m}^3$

$C_d =$ coefficient of drag = 1

$A_i =$ forward facing surface area of element i

$v_i =$ tangential linear velocity of element i

$\mu =$ bearing coefficient of friction = 0.1

$m_{total} =$ mass of centrifuge + subject + counterweights $= 539\ \text{kg}$

g = gravitational acceleration = 9.8 m/s^2

Because the angular velocity vector is in the z direction, only the z component of the moment of inertia needed to be considered. In order to calculate the moment of inertia, the centrifuge was broken into 7 components, and each was treated as a flat plate. Thus the total moment of inertia was calculated as:

Appendix F: Power Requirements

$$I_{zz} = \sum_{i=1}^{7} m_i \left(d_i^2 + \frac{1}{12}\left(a_i^2 + b_i^2 \right)\right)$$

where:

m_i = mass of element i (kg)

d_i = radial distance to center of element i (m)

a_i = length of element i (m)

b_i = width of element i (m)

The total moment of inertia is 451 kg*m^2. Table summarizes the components and values used in the moment of inertia calculation.

Table A: Moment of inertia calculation parameters

Item	m (kg)	d (m)	a (m)	b (m)	I (kg*m^2)
Batteries	25	1	0.1	0.8	26.4
Counterweights	192.2	0.88	0.12	0.3	150.5
Computer	9	0.7	0.18	0.4	4.6
Slider Board/Seat/Subject	176	0.45	0.8	1.1	62.8
Ergometer	33	1.15	0.65	0.52	45.5
Exercise Baseplate	28	1.63	0.9	0.1	76.3
Centrifuge Bed	70.9	0.49	3.28	0.9	85.4
				TOTAL	451

In order to calculate the power required to overcome wind resistance, the surface area facing into the wind was calculated using hand measurements of the profile geometries. The simplifying assumption was made that the area was equally distributed from the rear of the centrifuge (-1.15 m) to the end of the CRC hardware (1.4 m). The total area was 1.54 m^2, which was broken into two plates one measuring 1.15 m x 0.47 m and the other 1.40 m x 0.469 m. The total mass of the centrifuge was found using the MMT with a subject weighing 200 lbs. (maximum capacity) and counterweights masses specified by the optimization. This same mass was used for the bearing calculations, and the coefficient of drag based on previous MIT SRC power calculations (Edmonds PhD Dissertation, 2008). Finally, the acceleration profile that was used in all cases was data taken from the first acceleration run done as part of the motor characterization trials (see Chapter 4) up to 1 G at the feet, at which point the angular velocity was held constant.

Appendix F: Power Requirements

The power required for the electronics was also determined using the Kill-A-Watt power meter (P3 International, New York, NY) to be:

$$P_{computer} = 75\ W$$

$$P_{monitor} = 35\ W$$

$$P_{camera} = 4\ W$$

$$P_{ergometer} = 5\ W$$

Figure shows the power requirements over time, as the centrifuge is spun up from 0 to 1 G at the feet (1.15 m which is the approximate location of feet with large subject and with all hardware constrained to the 1.4 m radius).

Figure shows a number of expected trends. First, the power required to actually spin the centrifuge goes to 0 W after 27 seconds, which is when the centrifuge reaches its target speed. Because of the conservation of angular momentum, no additional energy is needed to keep the centrifuge spinning at that point (aside from the power required to overcome friction and wind resistance forces, which are shown separately). The power required to overcome friction and wind resistance increase during acceleration as both resistive forces increase with speed. Once the centrifuge reaches its target acceleration at 27 seconds, they stabilize. The power requirement for electronics is constant during the entire period of acceleration. The magnitude of the electronic power demands relative to the motor power demands is of interest in that they are similar, indicating that electronics could serve as a significant component of the power required for a future inflight centrifuge.

Appendix F: Power Requirements

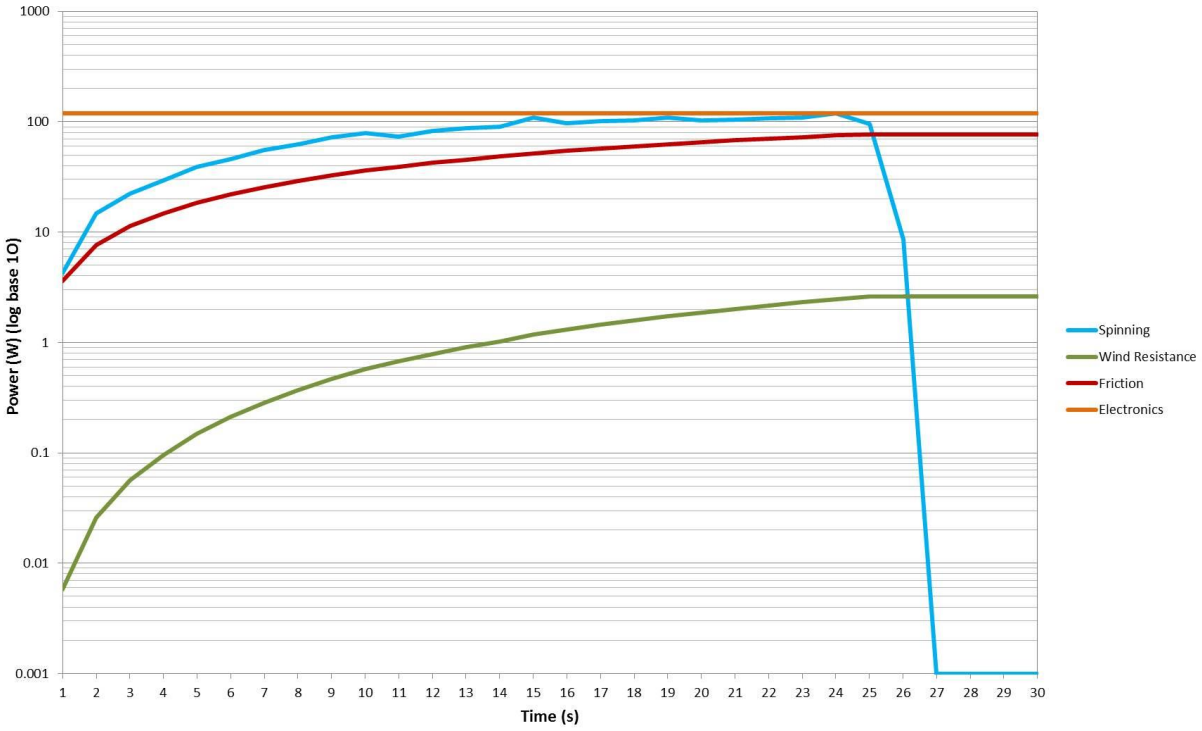


Figure F: CRC power requirements

Appendix G: Vibration Frequency Plots

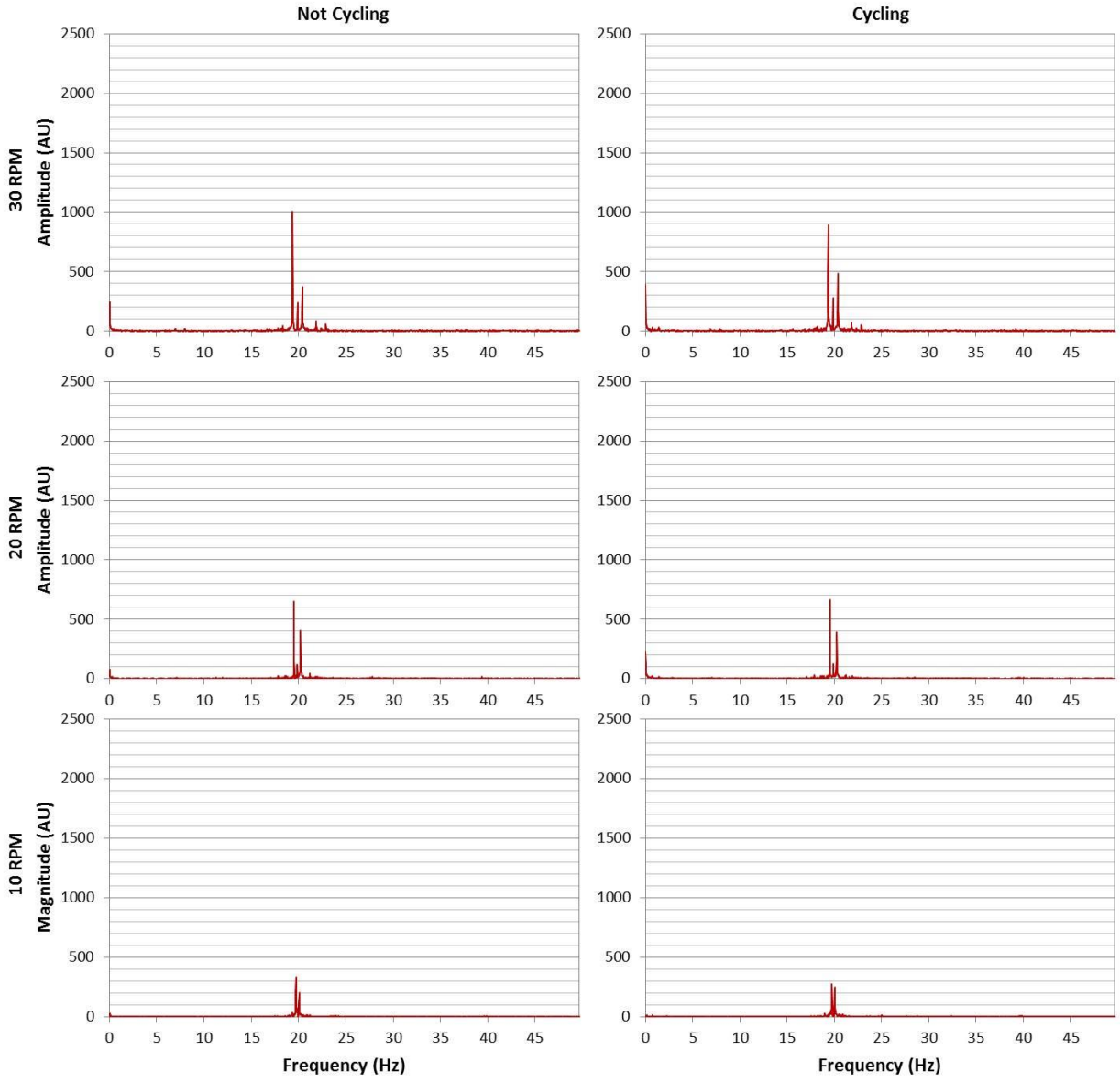


Figure G- X axis vibration frequency distributions

Appendix G: Vibration Frequency Plots

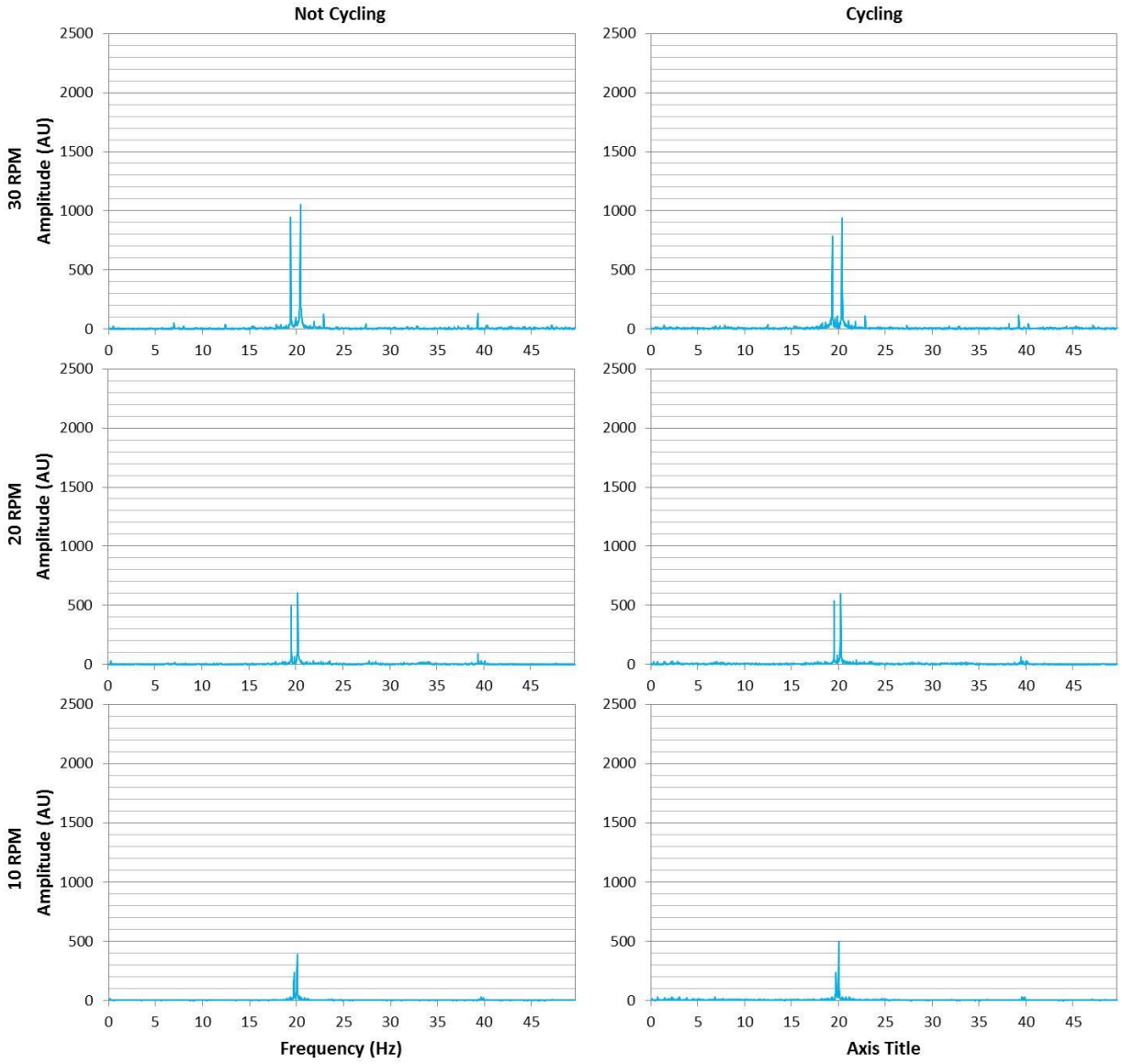


Figure H- Y axis vibration frequency distributions

Appendix G: Vibration Frequency Plots

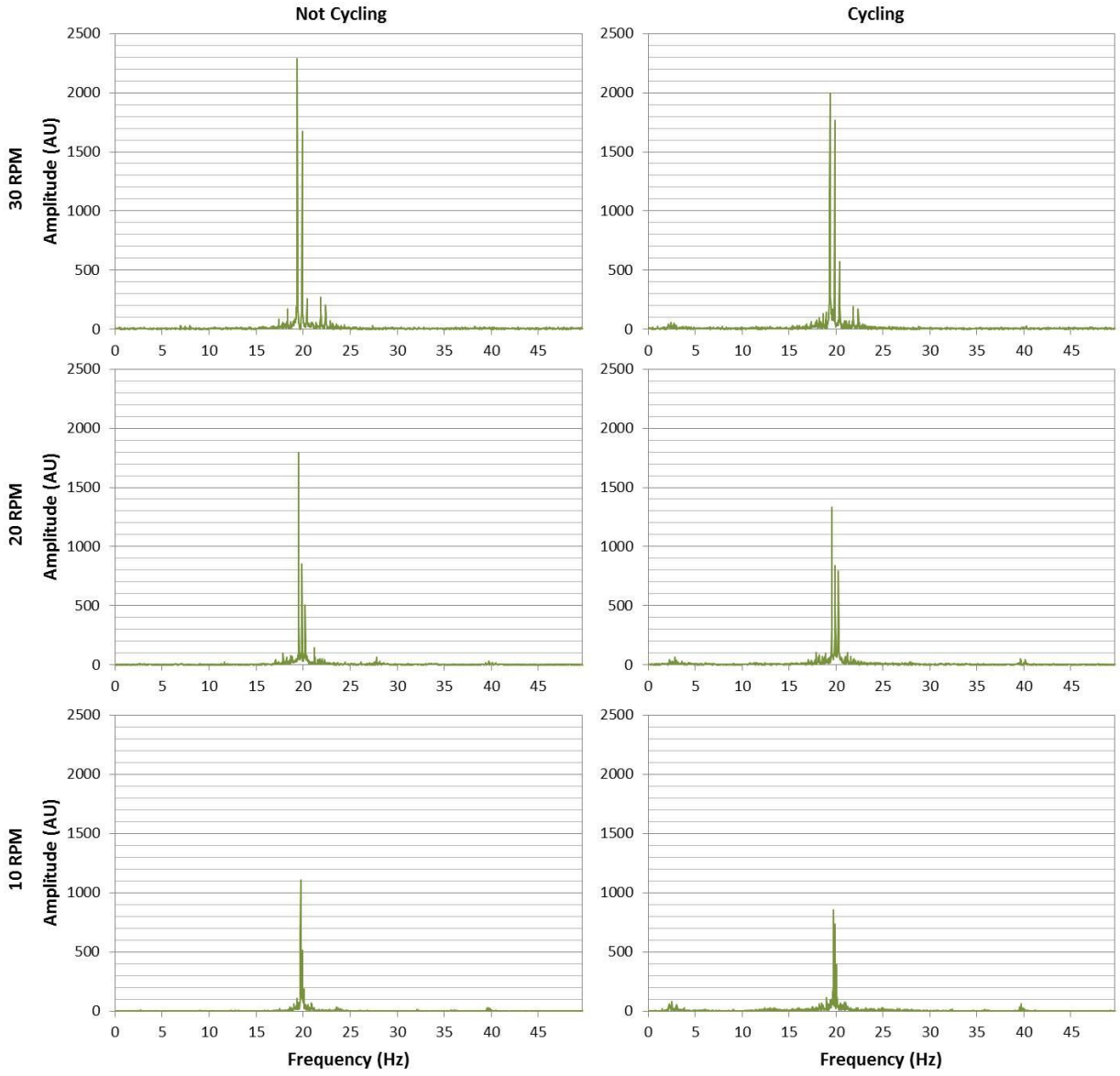


Figure I- Z axis vibration frequency distributions

	Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects	**Application #** (assigned by COUHES)	
		Date	**1/17/2013**

APPLICATION FOR APPROVAL TO USE HUMANS AS EXPERIMENTAL SUBJECTS (STANDARD FORM)

Please answer every question. Positive answers should be amplified with details. You must mark N/A where the question does not pertain to your application. Any incomplete application will be rejected and returned for completion. ***A completed CHECKLIST FOR STANDARD APPLICATION FORM must accompany this application.***

☐

I. BASIC INFORMATION

1. Title of Study	
Artificial Gravity with Ergonomic Exercise: Development and Characterization of a Test Platform Meeting Requirements for Future Inflight Studies	
2. Principal Investigator	
Name: Larry Young	Building and Room #: 37-219
Title: Apollo Professor of Astronautics and Professor of HST	Email: lry@mit.edu
Department: Aeronautics and Astronautics	Phone: 617-253-7759
3. Study Personnel	
All key personnel[1] **including the PI** *must be listed below, with a brief statement of qualifications and study role(s).* ***Important Note:*** *all key personnel are required to complete Human Subject training before work begins on the project.*	

Investigators and other personnel [and institution(s)] include email address:	*Qualifications: Describe briefly*	*Study role(s): (Check box to the right if person will be obtaining consent.)*	
Prof. Larry Young-lry@mit.edu	**Apollo Professor of Astronautics and Professor of HST**	**Primary Investigator**	☐
Chris Trigg-ctrigg@mit.edu	**Graduate student in the AeroAstro Man Vehicle Lab, working on artificial gravity research with advisor, Prof. Young**	**Research Assistant**	☒
			☐

[1] MIT key personnel all individuals who contribute in a substantive way to the execution and monitoring of the study at or on behalf of MIT or affiliated institutions. Typically, these individuals have doctoral or other professional degrees, although other individuals may be included. In particular, investigators and staff involved in obtaining informed consent are considered key personnel.

4. Collaborating Institutions. *If you are collaborating with another institution(s) then you must obtain approval from that institution's institutional review board, and forward copies of the approval to COUHES)*

NA

5. Location of Research. *If at MIT please indicate where on campus. If you plan to use the facilities of the Clinical Research Center you will need to obtain approval of the MIT Catalyst Clinical Research Center.*

Short Radius Centrifuge in 37-127

6. **Funding**. *If the research is funded by an outside sponsor, please enclose one copy of the research proposal with your application. A draft of the research proposal is acceptable.* ***Do not leave this section blank. If your project is not funded check No Funding.***

A. Sponsored Project Funding:

Current Proposal Proposal # _____

Sponsor _____

Title _____

Current Award Account # **6925911**

Sponsor **Skolkovo Foundation**

Title **Space Exploration Research Collaborative**

B. Institutional Funding:

Gift

Departmental Resources

Other (explain) __

No Funding

7. Statement of Financial Interest

Does the principal investigator or any key personnel involved in the study have any financial interest in the research?

Yes No

If yes then attach a **Supplement for Disclosure of Financial Interest** for each individual with an interest. *This supplement, together with detailed guidance on this subject and definitions of the highlighted terms, is available on the COUHES web.*

8. Human Subjects Training. *All study* personnel **MUST** *take and pass a training course on human subjects research. MIT has a web-based course that can be accessed from the main menu of the COUHES web site. COUHES may accept proof of training from some other institutions. List the names of all study personnel and indicate if they have taken a human subjects training course.*

Prof. Larry Young- Completed/passed training Chris Trigg- Completed/passed training	

9. Anticipated Dates of Research	
Start Date: February 1, 2013	Completion Date: **June 1, 2014**

II. STUDY INFORMATION

1. Purpose of Study. *Please provide a concise statement of the background, nature and reasons for the proposed study. Use non-technical language that can be understood by non-scientist members of COUHES.*

Exposure to artificial gravity on a short radius centrifuge (SRC) provides a promising countermeasure to the physiological deconditioning that occurs in microgravity. Recently, an SRC was proposed for onboard the International Space Station to study artificial gravity in the microgravity environment. In order to fit within the existing structure, the proposed SRC was restricted to a maximum radius of 1.4 meters, necessitating that astronauts be positioned in a seated position with the head approximately 30 cm from the center of rotation. The proposed ISS SRC also included a cycle ergometer for exercise during artificial gravity exposure. While the effectiveness of artificial gravity, both with and without exercise, has been studied extensively on the ground, the SRCs that have been used range from approximately 2-3 meters in radius and accommodate subjects in a supine position along the radius. As such, the physiological responses of the position necessitated by the proposed project, the optimum
centrifugation regimen for astronauts, and the mechanical dynamics of such a centrifuge are unknown. The purpose of this study is to characterize the physiology and mechanics of a new test platform aboard MIT's SRC that meets the design requirements of the proposed ISS SRC. The study will also begin developing optimum centrifugation regimens (time and level of artificial gravity exposure, as well as exercise protocol while being centrifuged) to maximize the effectiveness of artificial gravity as a countermeasure to spaceflight deconditioning.

2. Study Protocol. *For **biomedical, engineering and related research**, please provide an outline of the actual experiments to be performed. Where applicable, provide a detailed description of the experimental devices or procedures to be used, detailed information on the exact dosages of drugs or chemicals to be used, total quantity of blood samples to be used, and descriptions of special diets.*

*For applications in the **social sciences, management and other non-biomedical disciplines** please provide a detailed description of your proposed study. Where applicable, include copies of any questionnaires or standardized tests you plan to incorporate into your study. If your study involves interviews please submit an outline indicating the types of questions you will include.*

You should provide sufficient information for effective review by non-scientist members of COUHES. Define all abbreviations and use simple words. Unless justification is provided this part of the application must not exceed 5 pages.

Attaching sections of a grant application is not an acceptable substitute.

Subjects will begin by being briefed on the study's purpose and process, and will be given the Informed Consent form during this brief. Subjects will then board the centrifuge, and be fitted with the sensors described below. The subjects will then undergo centrifugation. Given that the development of an optimal centrifugation regimen is part of the study, the exact protocol for artificial gravity exposure is not yet known. However, trials will conform to the following constraints:

-Centrifuge exposure will not exceed 30 minutes
-Acceleration will not exceed 5 rpm/second
-Artificial gravity levels at the feet will not exceed 2 G's ("1G" is defined as the

acceleration or force experienced normally while standing on earth)
-Exercise load will not exceed 300 W

Subjects will be in constant communication with the researcher during the trial and will be able to stop the centrifuge and opt out at any time. The data being collected and the sensors that will be used include:
-Height (tape measure)*
-Weight (EatSmart® Precision digital scale)*
-Heart rate (Vernier Exercise Heart Rate Monitor)
-Blood pressure (commercial, of the shelf blood pressure sensor)
-Limb movements (APDM Opal wireless inertial sensors)
-Force exerted at the feet (Tekscan® Wireless ELF 2 force sensor)
-Leg muscle EMG activity (Vernier EKG sensor)
-Qualitative information on subject comfort and experience (verbal/written survey)

Additional data on the accelerations on the centrifuge arm will also be collected by a 3 axis accelerometer (Vernier 3-Axis Accelerometer) though this sensor will not be attached to, nor affect, the subject. Finally, subjects will be given a survey, similar to those previously given in centrifuge studies, to fill out regarding their perceived comfort and experience

*Measurement taken while standing before boarding the centrifuge

3. Drugs and Devices. *If the study involves the administration of an investigational drug that is not approved by the Food and Drug Administration (FDA) for the use outlined in the protocol, then the principal investigator (or sponsor) must obtain an Investigational New Drug (IND) number from the FDA. If the study involves the use of an approved drug in an unapproved way the investigator (or sponsor) must submit an application for an IND number. Please attach a copy of the IND approval (new drug), or application (new use.).*
If the study involves the use of an investigational medical device and COUHES determines the device poses significant risk to human subjects , the investigator (or sponsor) must obtain an Investigational Device and Equipment (IDE) number from the FDA.

Will drugs or biological agents requiring an IND be used? YES NO
If yes, please provide details:
Will an investigational medical device be used? YES NO
If yes, please provide details:

4. Radiation *If the study uses radiation or radioactive materials it may also have to be approved by the Committee on Radiation Exposure to Human Subjects (COREHS). COUHES will determine if you need COREHS approval.*

Will radiation or radioactive materials be used? YES ☐ NO ☒
If yes, please provide details:

5. Diets

Will special diets be used? YES ☐ NO ☒
If yes, please provide details:

III. HUMAN SUBJECTS

1. Subjects (*that will be consented for this study*)	
A. Maximum number: 15	**B. Age(s): 18-50**

C. Inclusion/exclusion criteria

i. What are the criteria for inclusion or exclusion?

Subjects must be between 18 and 50, be under 200 lbs, and have no known cardiovascular or musculoskeletal medical issues.

ii. Are any inclusion or exclusion criteria based on age, gender, or race/ethnic origin? *If so, please explain and justify*

None

D. Please explain the inclusion of any vulnerable population (e.g. children, cognitively impaired persons, non-English speakers, MIT students), and why that population is being studied.

MIT students will serve as the primary subjects (though the study is not limited to them) because recruitment material will be posted and distributed on the MIT campus. The potential risks and benefits of the study will be no different for this population than any other group of subjects.

2. Subject recruitment *Identification and recruitment of subjects must be ethically and legally acceptable and free of coercion. Describe below what methods will be used to identify and recruit subjects*

Subjects will be recruited through two means:
1. Emails to various MIT lab and student group listservs
2. Flyers posted throughout the MIT campus

Both emails and the flyers will include basic information on the study, criteria for participation, and researcher contact information.

Please attach a copy of any advertisements/ notices and letters to potential subjects

3. Subject compensation *Payment must be reasonable in relation to the time and trouble associated with participating in the study. It cannot constitute an undue inducement to participate*

Describe all plans to pay subjects in cash or other form of payment (i.e. gift certificate)

NA

Will subjects be reimbursed for travel and expenses?

No

4. Potential risks. *A risk is a potential harm that a reasonable person would consider important in deciding whether to participate in research. Risks can be categorized as physical, psychological, sociological, economic and legal, and include pain, stress, invasion of privacy, embarrassment or exposure of sensitive or confidential data. All potential risks and discomforts must be minimized to the greatest extent possible by using e.g. appropriate monitoring, safety devices and withdrawal of a subject if there is evidence of a specific adverse event.*

What are the risks / discomforts associated with each intervention or procedure in the study?

During rotation, subjects may develop a headache or feel pressure in their legs caused by a fluid shift due to centrifugation. Subjects may experience discomfort from the restraint and leg harnesses, and fatigue from exercise. Subjects may also experience nausea or motion sickness, especially as a result of head movements.

What procedures will be in place to prevent / minimize potential risks or discomfort?

Subject comfort has been a primary driver in the design of the centrifuge seat/restaint and cycle hardware. The researcher will work with the subject prior to all trials to fine tune straps and restraints in order to minimize discomfort. The experimenter will frequently ask subjects about their motion sickness to ensure comfort, and subject alertness will be

monitored through communication and through a video during trials. Subjects may stop centrifugation at any time by hitting the onboard kill switch, or by alerting the experimenter. The experimenter also has an emergency stop button in case of a malfunction with the primary controls.

5. Potential benefits

What potential benefits may subjects receive from participating in the study?
There will be no direct benefit to the subject from participation.

What potential benefits can society expect from the study?
The potential benefits to science and society are a better understanding of how short radius centrifugation can enable long duration spaceflight.

6. Data collection, storage, and confidentiality

How will data be collected?
Data will be collected from the sensors listed in Section 2, as well as from subjective suveys completed by participants.

Is there audio or videotaping? YES NO ***Explain the procedures you plan to follow.***
Video of the subject during trials will be taken as a means of safety so that the experimenter can monitor their condition during centrifugation. The videotaping will begi shortly before the centrifuge is started, and will be stopped once the centrifuge has stoppe

Will data be associated with personal identifiers or will it be coded?
Personal identifiers Coded ***Explain the procedures you plan to follow.***
Subjects will be referred to by a number assigned to them as part of the study, and not by any personal information.

Where will the data be stored and how will it be secured?
Data will be stored in Microsoft Excel and ASCII files on Man Vehicle Lab computers. These computers are password protected and only accessible by members of the Artificial Gravity research team.

What will happen to the data when the study is completed?
Data will continue to be stored in the above location following completion of the study.

Can data acquired in the study affect a subject's relationship with other individuals (e.g. employee-supervisor, patient –physician, student-teacher, family relationships)?
No

7. Deception *Investigators must not exclude information from a subject that a reasonable person would want to know in deciding whether to participate in a study.*

Will information about the research purpose and design be withheld from subjects?
YES NO ***If so, explain and justify.***

8. Adverse effects. *Serious or unexpected adverse reactions or injuries must be reported to COUHES within 48 hours. Other adverse events should be reported within 10 working days.*

What follow-up efforts will be made to detect any harm to subjects and how will COUHES be kept informed?
Subjects will be given contact information for the primary investigator as part of the Informed Consent form, which they may then use to contact the PI in the event of adverse effects. COUHES will be notified of any serious adverse reactions or injuries.

9. Informed consent. *Documented informed consent must be obtained from all participants in studies that involve human subjects. You must use the templates available on the COUHES web-site to prepare these forms. Draft informed consent forms must be returned with this application. Under certain circumstances COUHES may waive the requirement for informed consent.*

Attach informed consent forms with this application.

10. The HIPAA Privacy Rule. *If your study involves disclosing identifiable health information about a subject outside of M.I.T., then you must conform to the HIPAA Privacy Rule and complete the questions below. Please refer to the HIPAA section, and to the definitions of protected health information, de-identified data and limited data set on the COUHES web-site.*

Do you plan to use or disclose identifiable health information outside M.I.T.?

YES ☐ **NO** ☒

If YES, then the subject must complete an Authorization for Release of Protected Health Information Form. Please attach a copy of this draft form. You must use the template available on the COUHES web-site.

Alternatively, COUHES may grant a Waiver of Authorization if the disclosure meets criteria outlined on the COUHES web-site.

Are you requesting a Waiver of Authorization?

YES ☐ **NO** ☒

If YES, explain and justify.

Will the health information you plan to use or disclose be de-identified?

YES ☐ **NO** ☒

Will you be using or disclosing a limited data set?

YES ☐ **NO** ☒

If YES, then COUHES will send you a formal data use agreement that you must complete in order for your application to be approved

IV. INVESTIGATOR'S ASSURANCE

I certify the information provided in this application is complete and correct

I understand that I have ultimate responsibility for the conduct of the study, the ethical performance of the project, the protection of the rights and welfare of human subjects, and strict adherence to any stipulations imposed by COUHES

I agree to comply with all MIT policies, as well all federal, state and local laws on the protection of human subjects in research, including:

- **ensuring all study personnel satisfactorily complete human subjects training**
- **performing the study according to the approved protocol**
- **implementing no changes in the approved study without COUHES approval**
- **obtaining informed consent from subjects using only the currently approved consent form**
- **protecting identifiable health information in accord with the HIPAA Privacy Rule**
- **promptly reporting significant or untoward adverse effects**

Signature of Principal Investigator _____ **Date** 1/16/13

Print Full Name and Title LAWRENCE R. YOUNG, APOLLO PROG. of ASTRONOMY

Signature of Department Head B O'M **Date** 1/15/10

Print Full Name and Title BRIAN O'CONNELL, AO

The electronic file should be sent as an attachment to an e-mail: jadams@mit.edu . In addition, two hard copies (one with original signatures) should be sent to the COUHES office: Building E25-Room 143B.

Eligibility and Pre-Participation Questionnaire

Please mark one box for each of the following questions. For any question to which you answered "Yes" please briefly explain. Answering "Yes" does not automatically disqualify you from the study.

Yes ☐ No ☐ 1. Do you currently have any neck, back, chest, hip, knee, ankle, or foot pain/discomfort?

Yes ☐ No ☐ 2. Do you have arthritis in your ankle, knee, or hip?

Yes ☐ No ☐ 3. Are you currently using any cardiac, blood pressure, or muscle relaxation/stimulant medications?

Yes ☐ No ☐ 4. Do you have any history of neck, back, chest, hip, knee, ankle, or foot injuries? When did these occur?

Yes ☐ No ☐ 5. Have you ever had ACL, PCL, MCL, or ACL surgery? If so how long ago?

Yes ☐ No ☐ 6. Have you recently strained a leg muscle (hip, quad, calf, etc.)? If so how long ago?

Yes ☐ No ☐ 7. Have you ever herniated a disk in you back from heavy lifting? If so how long ago?

Yes ☐ No ☐ 8. Have you ever broken a bone in your leg, ankle, or foot? If so, which bone(s) and how long ago?

Yes ☐ No ☐ 9. Are you prone to dizziness or motion sickness?

Yes ☐ No ☐ 10. Do you exercise regularly?

If so, what form (circle)? Cardiovascular, Strength training

How many days per week? _____

How many hours per session?_____

Describe your typical routine (which exercises, weights/reps, etc.)

Yes ☐ No ☐ 11. Do you experience joint or muscle pain when exercising?

Yes ☐ No ☐ 12. Are you, or could you be, pregnant?

To Be Filled Out by Investigator

Subject Number: _____

Weight: _____

Height: _____

Target HR: _____

Exit Survey

1. On a scale of 1-5 how comfortable was cycling on the centrifuge and how natural did it feel (1=very uncomfortable/unnatural, 5=very comfortable/natural),? What, if any, components contributed to discomfort?

2. On a scale of 1-5 how strenuous do you feel the exercise regimen was (1=easy, 5= very strenuous)? If strenuous, was this because of the resistance on the exercise device, the duration of the exercise, or both?

3. Do any muscles or areas of your body feel sore?

4. Did you experience motion sickness? If so, when did this occur?

5. Did you notice the Coriolis forces acting in the lateral direction that you were pedaling (as if pushing or pulling on your knees)?

6. Any other comments you'd like to share?

FOR CLARIFICATION ONLY, THIS PAGE NOT GIVEN TO SUBJECTS

Medical Screening

Subjects will be screened for medical conditions by the Eligibility/Pre-Participation Questionnaire. Of the 12 questions, there are five for which a "yes" answer would result in an automatic disqualification (#1, 2, 3, 11,12) as these indicate the subject has a current medical condition or is on medication that put them at risk.

There are five questions (#4, 5, 6, 7, 8) for which a "yes" answer would result in disqualification depending on the time period since the indicated injury. If subjects indicate the injury has occurred within the last 6 months they will be disqualified, otherwise they will be allowed to participate.

Question 9 pertains to motion sickness; if the subject indicates they are prone to motion sickness this will not disqualify them from the study, however it will alert the investigator to proceed slowly with ramping-up the centrifuge spin rate.

Question 10 pertains to the subject's exercise routine. This question is for data collection purposes and does not affect the subject's eligibility.

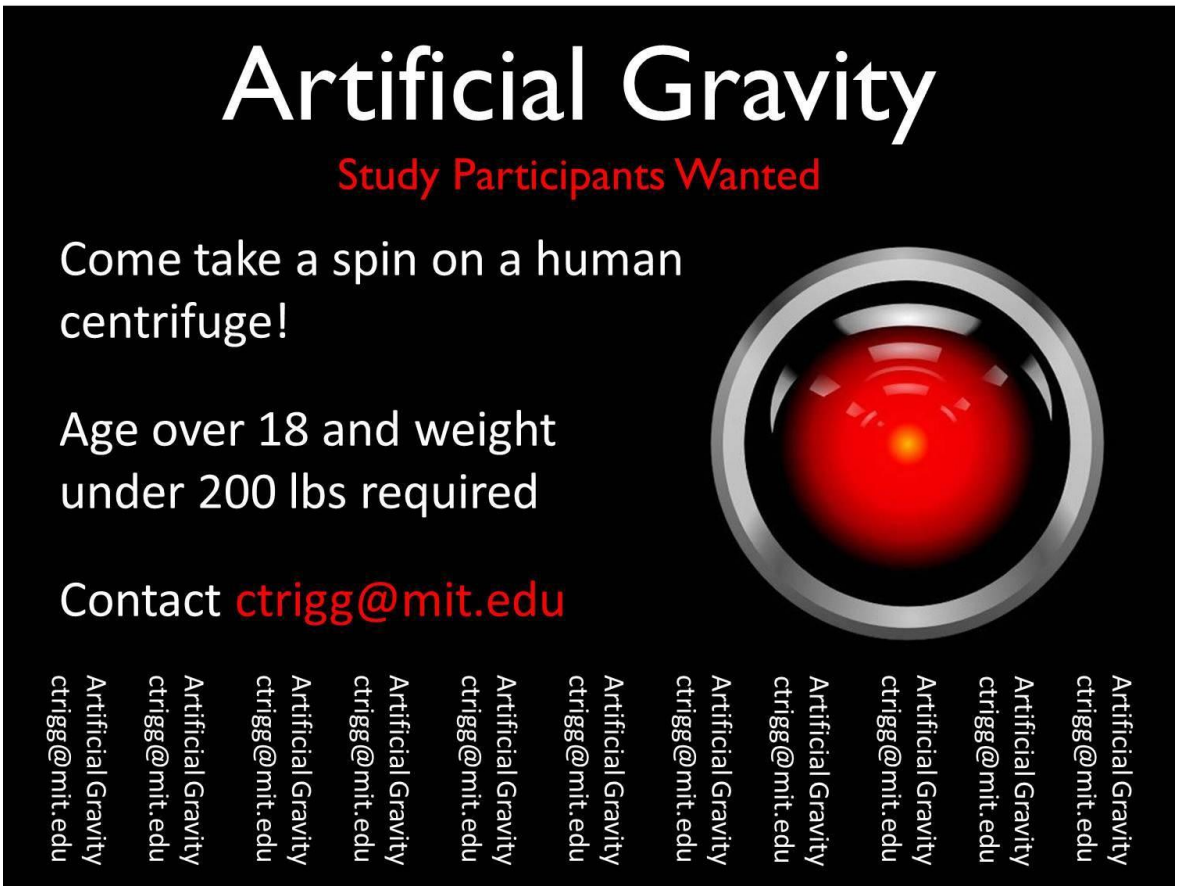
Recruitment Materials

MIT Listserv Email

Dear (group name),

The Man Vehicle Lab (MVL) is looking for participants to help with the artificial gravity study they are currently conducting. Subjects will have the chance to ride the MVL short radius centrifuge. To participate, you must be older than 18 and weigh less than 200 lbs. For more information, contact Chris Trigg at ctrigg@mit.edu.

Campus Flyer



CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

Artificial Gravity with Ergonomic Exercise: Development and Characterization of a Test Platform to Meet Requirements for Future Inflight Studies

You are asked to participate in a research study conducted by Laurence Young, Sc.D., from the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (M.I.T.). The results of this study may be published in a student thesis or scientific journal. You were selected as a possible participant in this study because you volunteered and meet the minimum health and physical requirements. You should read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

PARTICIPATION AND WITHDRAWAL

Your participation in this study is completely voluntary and you are free to choose whether to be in it or not. If you choose to be in this study, you may subsequently withdraw from it at any time without penalty or consequences of any kind. The investigator may withdraw you from this research if circumstances arise which warrant doing so. Such circumstances include evidence that you do not meet the minimum health and physical requirements, or that during the study it becomes clear to the experimenter that you are becoming drowsy, unalert, or uncooperative.

You should not participate in this study if you have any medical heart conditions, respiratory conditions, musculoskeletal conditions, medical conditions which would be triggered if you develop motion sickness, are under the influence of alcohol, caffeine, anti- depressants, or sedatives, have suffered in the past from a serious head injury (concussion), or if there is any possibility that you may be pregnant. The experimenter will check to see if you meet these requirements.

PURPOSE OF THE STUDY

Short radius centrifugation is currently being investigated as a countermeasure to the deleterious effects of weightlessness experienced during long duration spaceflight. The purpose of this study is to characterize, both physiologically and mechanically, a proposed design for a short radius centrifuge that would fit within the confines of a spacecraft, as well as to develop an optimal centrifugation and exercise regimen for this centrifuge.

PROCEDURES

If you volunteer to participate in this study, we would ask you to do the following things: When you arrive at the lab, you will be briefed on the background of centrifugation, disqualifying medical conditions, the experiment protocol, and the various components of the centrifuge, including the emergency stop button, restraining belt, and data collection devices. Data collection devices include a tape measure, scale, heart a rate sensor, blood

pressure sensor, inertial sensors on your legs, EMG electrodes, and force sensors on the pedals of the cycle ergometer. Additional data will be collected from accelerometers on the centrifuge arm, though these sensors will not be attached to your body. After your briefing, the experimenter will record your answers to basic questions about your health, ask you to complete a pre-participation questionnaire, and take your height, weight, blood pressure, and heart rate.

During the experiment you will be on the centrifuge lying on your side with your head slightly to the side of the center of rotation. Two leg pads will be strapped to your lower leg, and two leg cuffs will be strapped around your upper leg. Your feet may be strapped into foot pedals of an exercise device, or left to rest on a platform. A three-point harness will be secured prior to beginning trials. After lying down, the experimenter may collect some data while the centrifuge is stationary. The experimenter will explain the centrifugation regimen, and ask you if you are ready before starting rotation. The regiment will meet the following requirements:

- Acceleration will be no greater than 5 rpm/second
- G-level along your body axis will not exceed 2.0 G at your feet (a "1G" is defined as the acceleration or force that you experience normally while standing on earth).
- Time of rotation will not exceed 1 hour
- Exercise loads will not exceed 300 watts

During rotation the experimenter may direct you to start or stop exercising, and will alert you to changes in speed of rotation and exercise loads. You may opt to perform the trials in the dark to minimize motion sickness. When the experiment is complete, the centrifuge will be stopped, and the experimenter may collect some additional data.

After the experiment you will be asked to report your subjective experience via an exit survey. All data, including the surveys, will be recorded anonymously.

As a participant in experimental trials, you tentatively agree to return for additional trials (at most 10) requested by the experimenter. You may or may not be assigned to a study group that performs similar tasks. Other than the time required for rotation, the time commitment is 20 minutes for the first briefing, and 10-60 minutes for other procedures before and after rotation.

POTENTIAL RISKS AND DISCOMFORTS

During rotation you may develop a headache or feel pressure in your legs caused by a fluid shift due to centrifugation. You may experience discomfort from the restraint and leg harnesses, and fatigue from exercise. You may also experience nausea or motion sickness, especially as a result of head movements. The experimenter will frequently ask you about your motion sickness to ensure your comfort, and your alertness will be monitored through communication and through video cameras. You may stop centrifugation at any time by hitting the onboard kill switch, or by alerting the experimenter.

POTENTIAL BENEFITS TO SUBJECTS

You will receive no benefits from this research.

POTENTIAL BENEFITS TO SOCIETY

The potential benefits to science and society are a better understanding of how short radius centrifugation can enable long duration spaceflight.

PAYMENT FOR PARTICIPATION

Subjects will not be eligible for payment for their participation.

CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law.

Some of the data collected in this study may be published in scientific journals and student theses. The data may consist of height, weight, heart rate, blood pressure, EMG activity, leg motion, forces you apply to the ergometer, subjective ratings of your comfort and motion sickness, and descriptive data on the trials including the artificial gravity loads and exposure time, exercise loads, and accelerations on the centrifuge.

During the experiment, the experimenter will monitor you through video cameras capable of imaging in darkness. You will be monitored to ensure your state of well being and compliance with the experiment protocol. In some cases the video data will be recorded on digitally. You have a right to review and edit the file. Any recorded videos will be accessible only by members of the current Artificial Gravity research team.

Research data collected during the experiment is stored in coded files that contain no personal information. This coding of the data will prevent linking your personal data to research data when it is analyzed or archived. Research data is stored in Microsoft excel files and ASCII files, and there is no certain date for destruction. The data is stored in Man Vehicle Lab computers that remain accessible only by Artificial Gravity team members. The investigator will retain a record of your participation so that you may be contacted in the future should your data be used for purposes other than those described here.

IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact:

Principle Investigator: Laurence Young (37-219) 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-7759	

EMERGENCY CARE AND COMPENSATION FOR INJURY

If you feel you have suffered an injury, which may include emotional trauma, as a result of participating in this study, please contact the person in charge of the study as soon as possible.

In the event you suffer such an injury, M.I.T. may provide itself, or arrange for the provision of, emergency transport or medical treatment, including emergency treatment and follow-up care, as needed, or reimbursement for such medical services. M.I.T. does not provide any other form of compensation for injury. In any case, neither the offer to provide medical assistance, nor the actual provision of medical services shall be considered an admission of fault or acceptance of liability. Questions regarding this policy may be directed to M.I.T.'s Insurance Office, (617) 253-2823. Your insurance carrier may be billed for the cost of emergency transport or medical treatment, if such services are determined not to be directly related to your participation in this study

.RIGHTS OF RESEARCH SUBJECTS

You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you feel you have been treated unfairly, or you have questions regarding your rights as a research subject, you may contact the Chair-man of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E25-143b, 77 Massachusetts Ave, Cambridge, MA 02139. Phone: 617-253-6787.

SIGNATURE OF RESEARCH SUBJECT OR LEGAL REPRESENTATIVE

I have read (or someone has read to me) the information provided above. I have been given an opportunity to ask questions and all of my questions have been answered to my satisfaction. I have been given a copy of this form.

BY SIGNING THIS FORM, I WILLINGLY AGREE TO PARTICIPATE IN THE RESEARCH IT DESCRIBES.

_____

Name of Subject

_____

Name of Legal Representative (if applicable)

_____ _____

Signature of Subject or Legal Representative Date

SIGNATURE OF INVESTIGATOR

I have explained the research to the subject or his/her legal representative, and answered all of his/her questions. I believe that he/she understands the information described in this document and freely consents to participate.

_____

Name of Investigator

_____ _____

Signature of Investigator Date (must be the same as subject's)

SIGNATURE OF WITNESS (If required by COUHES)

My signature as witness certified that the subject or his/her legal representative signed this consent form in my presence as his/her voluntary act and deed.

_____ _____

Name of Witness Date

MIT Committee On the Use of Humans as Experimental Subjects

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 Massachusetts Avenue
Cambridge, Massachusetts 02139
Building E 25-143B
(617) 253-6787

To:	Laurence Young 37-219
From:	Leigh Firn, Chair COUHES
Date:	02/25/2013
Committee Action:	**Approval**
COUHES Protocol #:	1301005479
Study Title:	Artificial Gravity with Ergonomic Exercise: Development and Characterization of a Test Platform Meeting Requirements for Future Inflight Studies
Expiration Date:	02/13/2014

The above-referenced protocol has been APPROVED following Full Board Review by the Committee on the Use of Humans as Experimental Subjects (COUHES).

If the research involves collaboration with another institution then the research cannot commence until COUHES receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. Please allow sufficient time for continued approval. You may not continue any research activity beyond the expiration date without COUHES approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

Adverse Events: Any serious or unexpected adverse event must be reported to COUHES within 48 hours. All other adverse events should be reported in writing within 10 working days.

Amendments: Any changes to the protocol that impact human subjects, including changes in experimental design, equipment, personnel or funding, must be approved by COUHES before they can be initiated.

Prospecitve new study personnel must, where applicable, complete training in human subjects research and in the HIPAA Privacy Rule before participating in the study.

COUHES should be notified when your study is completed. You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with COUHES, original signed consent forms, and study data.