EXERCISE IN ARTIFICIAL GRAVITY

by

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SUBMITTED TO THE DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS ON MAY 6, 2005 IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS.

ABSTRACT

Artificial gravity provided by short radius centrifugation is considered a promising countermeasure to the deleterious physiological effects of microgravity during long-duration space flight. We investigated the feasibility of dual countermeasures to address space flight deconditioning of the musculoskeletal and cardiovascular systems, by combining centrifugation with lower-body exercise. The exercise device is a small stair-stepper with constant resistance provided by dampers beneath each foot, and is the first such device to be used in centrifuge studies. We modified the existing centrifuge to support the additional stresses due to exercise and added following structural elements: support struts on the rotation shaft, a redesigned footplate to which the exercise device was mounted, and horizontal support beams. We also added a sliding mattress with linear ball bearings on rails, so that the subject's body can move up and down while stepping. Design changes and exercise feasibility were validated by having subjects exercise during centrifugation at 23 rpm. We measured heart rate, blood pressure, forces on the feet, and knee deflection due to Coriolis accelerations, for up to four subjects. As expected, heart rate and blood pressure did increase normally with exercise on the centrifuge, relative to when not exercising. However, both heart rate and systolic blood pressure were higher for exercise on the non-spinning centrifuge than on the spinning centrifuge, attributable to the necessity of pulling against the stair-stepper's dampers in order to exercise while lying supine. Approximately half the subject's weight was exerted on the footplate when not exercising. This was expected: since the subject's head was at zero radius and thus at 0-g radially, the100% artificial gravity gradient along the body's longitudinal axis gave an average effective gravity of about 0.5 g. More pressure (up to 80% body weight) was exerted when the subject was stair-stepping. The measured lateral deflection of the knee during normal stair-stepping and knee bend exercises increased up to three inches compared to deflections in a non-rotating environment. This issue must be further addressed to determine if stair-stepping or knee bend exercises are to be used safely in artificial gravity.

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AUTHOR'S NOTE:

The following brand names, found in the text, are trademarks:

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Unless otherwise noted, all photos were taken by Jessica Edmonds.

Throughout this paper I use the term "we". In this case I am referring to those that I work with. Specifically, Thomas Jarchow assisted me in most of my work, as did Paul Bauer. Additionally, several undergraduate research assistants assisted with this work. Tom Walker and Ben Feinberg worked on the stability elements of the centrifuge. Agnieszka Koscielniak helped with the setup for the Coriolis displacement measurements, and analysis. Heather Samuelson was of great assistance with the foot force measurement sensors.

I use the term "footplate" to refer to the large structure to which the exercise device is mounted – it is not actually in contact with the subject's feet as long as the exercise device is present. I use the term "foothold" to refer to each of the plastic foot grips mounted to the pedals of the stair-stepper. The subject's feet are in contact with the footholds at all times.

1 INTRODUCTION

Artificial gravity is considered for use as a countermeasure to the deleterious physiological effects of long-duration space flight. These deleterious effects include bone loss, muscle atrophy, disorientation due to neurovestibular conflict, and cardiovascular deconditioning. Countermeasures to physiological deconditioning due to weightlessness have been explored since the problem was identified. Solutions range from exercise to specialized suits to pharmaceuticals. In the future, artificial gravity may be implemented as a countermeasure (Young 2003). Because artificial gravity places the whole body into a gravity-like environment, it effectively "kills the problem at its source", rather than pinpointing and addressing the different symptoms of weightlessness. Artificial gravity is achieved through centrifugation; the centripetal acceleration created by a rotating environment creates a radial force vector. The angular velocity and the radius determine the "artificial gravity" vector (a_{AG}), whose magnitude is experienced as:

$$a_{AG} = r\omega^2 \qquad \textbf{Equation 1}$$

where r is the radius of the centrifuge or subject position, and ω is the angular velocity of the centrifuge.

The purpose of this study was to implement an exercise device on a short-radius centrifuge, in order to assess the feasibility of exercise during centrifugation. I believe that exercise will not only be beneficial, but in fact necessary, in conjunction with artificial gravity during space flight. In their deconditioned state, astronauts subjected to the centripetal acceleration of an artificial gravity centrifuge will likely experience orthostatic hypotension, and exercise will prevent the symptoms of pre-syncope that accompany this.

During long-duration space flight, intermittent short-radius centrifugation with exercise could be used as a replacement for the current exercise regimen. The program may be characterized as "a spin in the gym", and each astronaut could have his own workout program, for some time every day, in a gravity environment.

1.1 Physiological Deconditioning during Long-Duration Space Flight

Within hours of entering the microgravity environment of space, astronauts begin to experience negative side effects of weightlessness. Approximately 71% of space shuttle astronauts experience space motion sickness, a result of conflicting signals from their neurovestibular systems, exacerbated by visual signals of other crewmembers in unfamiliar orientations (Jennings, David et al. 1988). Due to the lack of a pressure gradient in the body, there is a net loss of body fluid, and cardiovascular responses are attenuated. As time passes the musculoskeletal system also deteriorates as a result of lack of loading forces.

In the following sections, I will first outline the deconditioning experienced by each major physiological system due to space flight. In Sections 1.2 through 1.4 I will discuss how current and future countermeasures address the deconditioning of each of these systems.

1.1.1 Neurovestibular conflict

When astronauts first experience weightlessness, they may experience a variety of orientation illusions (Oman 2001). Some of these illusions are due to the continual freefall environment of orbiting space flight. This eliminates the gravity vector and removes its stimulation of the otolith organs, which then perceive only linear accelerations, not the absent (but expected) gravity vector. Further, as other crewmembers move about without a common vertical, the frame of the room no longer matches the astronaut's idiotropic vector (the vector along the body axis) and the polarity cues (the expectation that other crewmembers should also have their feet pointed towards the floor). Adaptation usually occurs within a few days, but disorientation due to the altered vestibular system makes navigation difficult in a space station with many corridors and modules.

Aside from disorientation, space motion sickness is a partially debilitating effect of space flight, which may be explained by a sensory-motor conflict (that is, internal conflict between sensory systems, such as the visual and vestibular systems) (Young

2000). Space motion sickness is particularly a concern for first-time astronauts, but usually disappears in the first three days.

1.1.2 Cardiovascular deconditioning

Baroreceptors are sensors located in the walls of some thoracic and neck arteries that send the central nervous system signals about blood pressure levels - particularly the change of pressure levels. With stimulus, the baroreceptors signal the veins and arterioles to dilate or constrict, and also signal either an increase or decrease in heart rate (Guyton and Hall 2000). The baroreceptors are responsible for orthostatic tolerance, the capacity to tolerate an imposed pressure gradient, such as that caused by standing up in Earth's gravity. More specifically, baroreceptors enable us to wake up after sleeping (supine) for eight hours, and then stand up quickly. When we stand up and the blood is suddenly pulled down from the brain and upper body, the heart is notified immediately to increase its output to compensate for the sudden pressure gradient caused by gravity. This increased cardiac output allows the blood to continue pumping up to the brain, and therefore prevents loss of consciousness. Peripheral resistance (constriction of veins and arterioles) also increases and helps maintain blood pressure. In space, the body is in a similar situation as when lying supine in 1-g: without the influence of gravity, there is no pressure gradient towards the feet, and so the baroreceptors allow the heart to deliver a lower output. Astronauts experience orthostatic intolerance (also called "orthostatic hypotension" due to the uncontrolled decrease in blood pressure in the thoracic cavity) upon return to 1-g. Upon landing on a planet, orthostatic hypotension due to prior weightlessness may lead to a decreased response of the baroreceptors. When the astronaut stands up on the planetary surface, the baroreceptors may be so deconditioned that they do not signal the heart to increase cardiac output, and the arterioles and veins to increase peripheral resistance, in enough time to prevent the astronaut from losing consciousness due to lack of blood to the brain.

The plots of Figure 1 (Heldt, Shim et al. 2002) show the heart rate response of an astronaut 120 days before space flight, and on landing day after space flight. Data collection began (time=0) when the astronaut stood up in Earth's gravity. It is apparent that after space flight, the heart rate increases more slowly upon standing, and does not stabilize at the pre-flight level (approximately 100 beats per minute, or bpm, for pre-flight, and approximately 130 bpm for post-flight). These are symptoms of orthostatic intolerance, and a similar trend is seen for blood pressure.

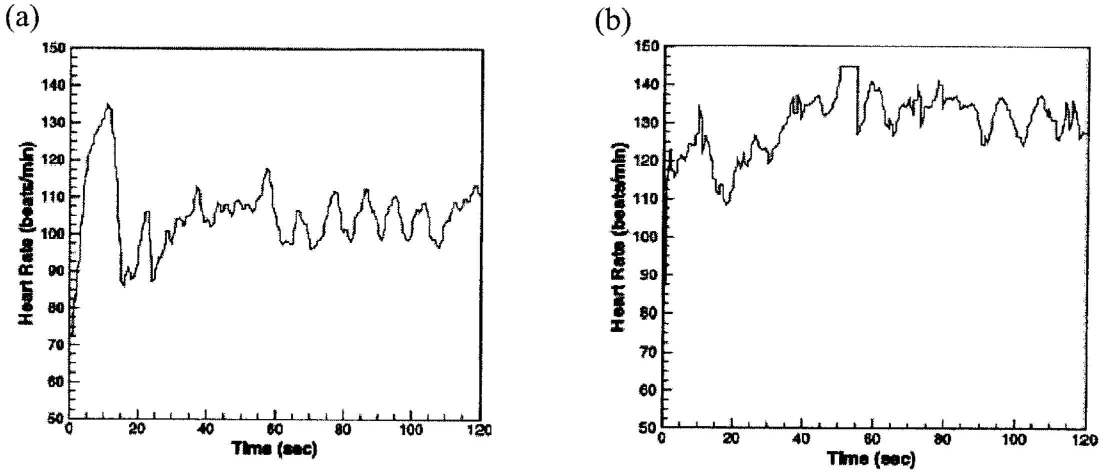


Figure 1. Demonstration of orthostatic intolerance after space flight. Data is (a) pre-flight, and (b) post-flight. This is Figure 11, p. 1249, from Heldt, Shim et al. (2002).

Body fluid volume in general is redistributed in weightlessness. Leg volume decreases in-flight in as little as six hours, and the face becomes puffy because of the fluid volume increase in the upper body (Thornton, Hoffler et al. 1977). In general, the rate of fluid shifts appears to follow an exponential course, with a maximum at 24 hours, and plateaus after 3-5 days. Further, the mechanisms that regulate body fluid volume sense an increase in blood volume near the heart (usually this "extra" blood is pulled down into the legs by gravity). The sense of "too much fluid" results in increased urinary excretion and decreased blood volume (Guyton 2000).

Finally, another aspect of cardiovascular deconditioning is the fact that muscle atrophy and inactivation (Section 1.1.3) reduces the use of the venous pump, which is the contraction of muscles around veins to aid in pumping blood back to the heart.

1.1.3 Musculoskeletal deconditioning

Bone loss

Bone mineral density (BMD) decreases in weightlessness, with recovery periods to pre-flight BMD levels of up to three years (Oganov, Bakulin et al. 2000). The data shown in Figure 2 is from an unknown number of subjects on 14 space flights of five to eleven months duration, and demonstrates the extended recovery time for BMD. Bone loss is greatest in the legs, lumbar spine, and pelvis. It is much less prominent in the upper body. On earth, modeling and remodeling processes build up and resorb bone, respectively. Increased mechanical compressive load on the bones results in reduced remodeling, and therefore a bone under continual load would grow. Decreasing the load does the opposite: remodeling rate increases, and bone loss results. This is exactly the case in weightlessness, as the compressive loads of gravity are absent. BMD is a general indicator of bone strength, so decreased BMD is a concern for planetary missions. If the astronaut has been weightless for many months (and lost bone strength), he or she may fracture a bone upon standing up in the gravitational environment of the planetary surface.

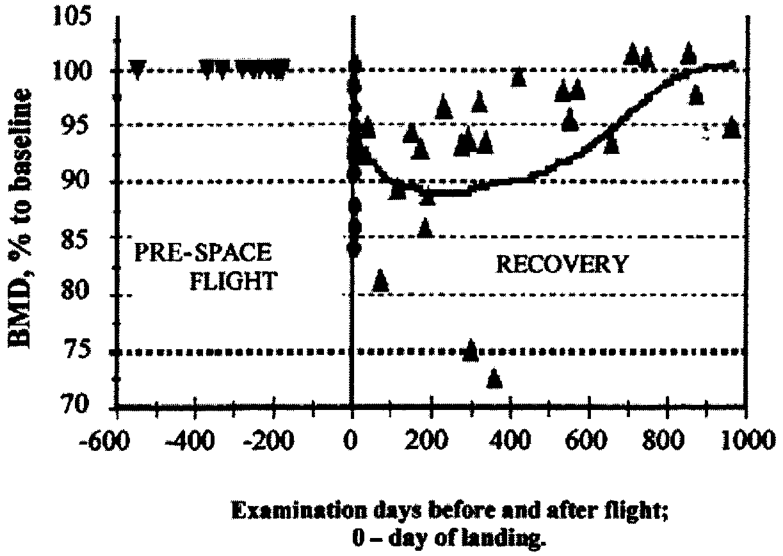


Figure 2. BMD changes before and after space flight (Oganov, Bakulin et al. 2000). The vertical line represents 7-11 months in space; left of the vertical line is before the space flight, and right of the vertical line is after landing. Triangles represent measurements from cosmonauts on 14 space different flights.

Muscle atrophy

Body movements, and in particular muscle group usage, are heavily altered in space. In 0-g, the legs are no longer used to support the body's weight, nor for walking. They are mostly used for stabilization and balance, and ambulation is achieved primarily with the arms. Such decreased load and use of the legs results in muscle atrophy of the lower part of the body. Muscle atrophy can be reversed after landing with exercise and increased usage, but the process takes a long time, and is a potential problem for a planetary landing.

1.2 Current Countermeasures

Exercise countermeasures aboard the International Space Station (ISS) include a treadmill, a cycle ergometer, and a Resistive Exercise Device (RED). Astronauts typically spend 1.5 hours per day, six days per week, exercising using this equipment (Coolahan, Feldman et al. 2004). Specific exercise protocols are designed for each astronaut (Williams 2003), and aside from equipment malfunction or extenuating circumstances (such as equipment malfunction), astronauts usually do as much or more exercise than they are assigned (Thomas 2005, personal communication).

Due to the small sample size and medical privacy considerations, there is no comprehensive study on the effectiveness of these countermeasures during space flight. However, anecdotal evidence supports the use of exercise countermeasures, and extensive ground-based (including bed rest) studies have shown that these devices successfully (although not completely) attenuate deconditioning of the musculoskeletal and cardiovascular systems. Some of these studies are highlighted below.

1.2.1 Treadmills

The treadmill is used frequently by the astronauts. To exercise, they are restrained by a bungee cord and harness to the treadmill and may walk or run in a somewhat normal fashion. Treadmill exercise has been shown to maintain aerobic capacity as measured by $\dot{V}_{O_2}$-max (Figure 3).

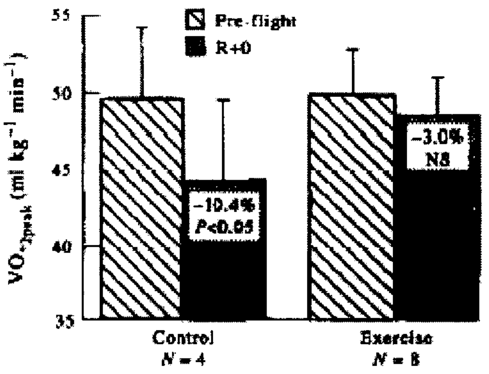


Fig. 9. Treadmill aerobic capacity.

Figure 3. Treadmill exercise during space flight maintains $\dot{V}_{O_2}$ -max, measured on landing day (R+0). Figure from p. 4 of Nicogossian, Pool et al. (1995).

In general, high loads are desired to properly maintain bone mineral density (BMD) and the balance of bone modeling and remodeling, and has been demonstrated to be a useful countermeasure against bone loss for long-duration space flight (LeBlanc and Schneider 1992, Cann 1997). High dynamic loading is particularly effective in promoting bone growth (Bassey and Ramsdale 1994); for example, a study involving female college gymnasts demonstrated that the very high axial loads associated with such activity significantly increase BMD (Taaffe, Robinson et al. 1997). For this reason, the impact loads of the treadmill are desirable.

1.2.2 Ergometers

A 30-day bed rest experiment was performed to assess the effects of exercise during simulated microgravity (Greenleaf, Bernauer et al. 1989, Greenleaf, Wade et al. 1989, Greenleaf, Vernikos et al. 1992, and Greenleaf, Bernauer et al. 1994). The study explored the benefits of isotonic exercise and isokinetic exercise. Isotonic (constant force) exercise required two daily 30-minute continuous exercise periods, with varying levels of the peak $\dot{V}_{O_2}$, and was intended to maintain aerobic capacity. Isokinetic (constant speed) exercise required two daily periods of several repetitions of leg flexion and extension, and was intended to maintain muscular strength and endurance. Isotonic exercise was better than isokinetic exercise (or no exercise) in maintaining $\dot{V}_{O_2}$ -max, plasma volume, and fluid balance (fluid intake minus urinary excretion) (Greenleaf, Bernauer et al. 1989 and Greenleaf, Vernikos et al. 1992). Isokinetic exercise was shown to be better than isotonic exercise (or no exercise) for increasing the total work done by knee extension (pre- vs. post- bed rest). There was a significant decrease in tilt tolerances (indicating orthostatic hypotension) after bed rest for all three groups, and there were no significant differences for the groups that exercised. The authors noted that even though the plasma volume was unchanged in the isotonic group, these subjects still experienced orthostatic hypotension. For this reason, they suggested that hypovolemia is not necessarily the major factor that determines post-bed rest orthostatic intolerance (Greenleaf, Vernikos et al. 1992). This suggests that even if we are able to maintain the astronauts' plasma volume at Earth levels through exercise, they may still have problems with orthostatic intolerance upon return to a planetary environment. Is it possible that combining exercise with artificial gravity increases orthostatic tolerance and maintains plasma volume at the same time?

A daily regimen of isotonic cycle ergometer and isokinetic ergometer training (legs and arms) are suggested by Greenleaf, Bulbulian et al. (1989). About 30 minutes per day of 70-100% intensity isotonic exercise plus ten sets of five repetitions of isokinetic exercise at maximal voluntary contraction would maintain aerobic capacity, strength, and endurance at near-Earth levels. The authors also suggest that when it is allowable for the astronauts to lose about 10% of their aerobic capacity, strength, and endurance, then only the isokinetic exercise regimen for the legs must be followed (this exercise prescription calls for less than 30 minutes per day).

1.2.3 Resistance devices

Experiments with various exercise countermeasures to muscle atrophy have shown that fast-twitch muscles atrophy more than slow-twitch muscles (Convertino 1991). An effective countermeasure to fast-twitch muscle atrophy may be resistive exercise (as opposed to aerobic, cardiovascular endurance exercise, such as the treadmill or the ergometer alone). The author also described the importance of eccentric instead of only concentric exercises. (Concentric exercise requires tension during muscle contraction, as when you are pulling a dumbbell up towards your shoulder. Eccentric exercise is tension during muscle lengthening, as when you slowly lower the dumbbell.)

I suggest that artificial gravity inherently requires eccentric action; that is, in order to press against the footplate, one must extend his or her legs away from the body, lengthening the muscles in the legs while pushing.

Treadmills and ergometers aide in ensuring aerobic capacity and endurance, but they do not efficiently combat muscle atrophy (for review, see Tesch and Berg 1997). Resistance training in space, particularly training that utilizes both eccentric and concentric motions, addresses this problem. The RED was shown in ground-based studies to increase muscle mass and strength just as well as free-weight exercise (seven subjects per group), but there was no increase in BMD, as there was with the free-weight exercise group (Schneider, Amonette et al. 2003). Additionally, the RED provided significantly smaller foot-ground reaction forces in weightlessness than in an Earth 1-G environment, when tested in parabolic flight (Lee, Cobb et al. 2004).

Not all evidence from exercise programs as a countermeasure has been positive. 12 men were tested before and after 14 days of bed rest (Bamman and Caruso 2000). Half of the men exercised every other day during the bed rest (squats while supine), half did not. There was no significant difference in isokinetic strength measures. Isokinetic strength loss was observed in both groups after the bed rest period.

1.2.4 Other countermeasures

Russian countermeasures are similar to those used by U.S. astronauts, but additionally they have used special suits (Figure 4) in space to counteract physiological symptoms of weightlessness (Kozlovskaya and Grigoriev 2004). The Penguin suit provides axial loading through a system of elastic straps along the long axis of the body (Figure 4a). It is rarely used anymore since the dynamic loading of the treadmill and harness are a preferable, but is kept onboard the ISS as a reserve if the cosmonauts do not use the treadmill for some reason (Oman 2005, personal communication).

The Tchibis suit is a lower body negative pressure (LBNP) suit, which is a encasement of the torso and legs (Figure 4b). Decreased pressure in the encasement leads to a shift of fluids into the legs, similar to the effect of gravity on Earth. A LBNP suit similar to the Russian suit, was tested on Skylab 4 (Johnson, Hoffler et al. 1977). For all three subjects, heart rate during -50 mmHg LBNP was significantly greater than without the LBNP for nearly all in-flight tests (22-23 tests each over 84-day mission), with a declining trend towards the end of the mission. Systolic blood pressure decreased upon application of LBNP, but as the mission progressed, the systolic blood pressure decreased less significantly. The decreasing trend for both heart rate and systolic tolerance indicated that repeated treatment with LBNP gradually lessened the symptoms of orthostatic intolerance, encouraging the cardiovascular system to return to its pre-flight condition.

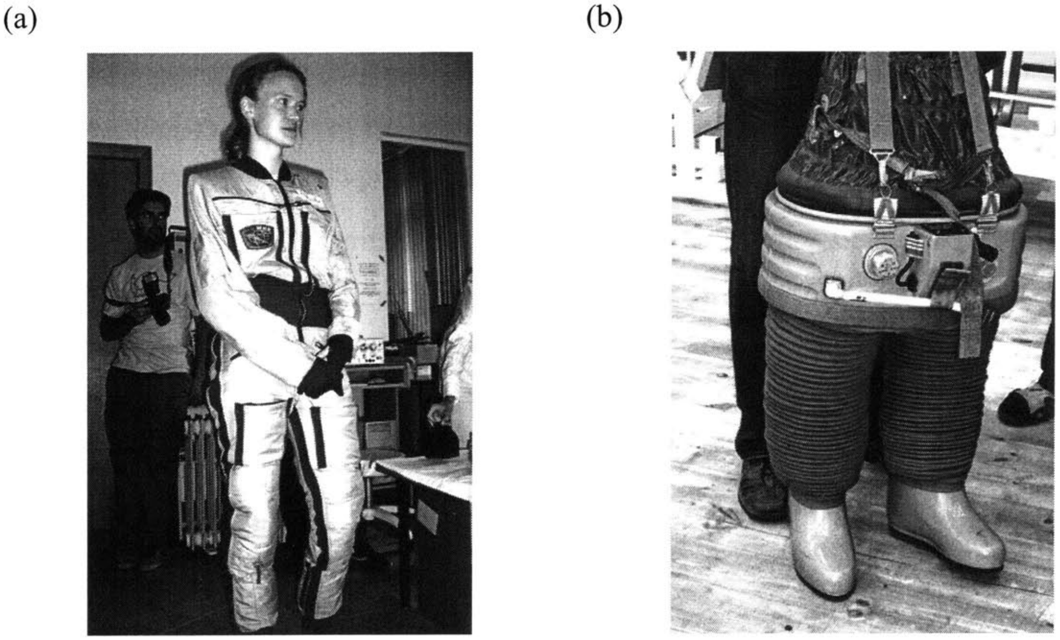


Figure 4. (a) Penguin suit and (b) Tchibis suit (lower body negative pressure), in its inactivated state (atmospheric pressure).

1.3 Centrifugation

1.3.1 Neurovestibular effects

Artificial gravity exacerbates the neurovestibular conflict, rather than stabilizing it as Earth's gravity does. The problem centers around the Coriolis forces associated with a rotating centrifuge, and their effects on head movements (Young 2000, Sienko 2000, and Lyne 2000). The sensory organs of the neurovestibular system are the otoliths and the semi-circular canals. The otoliths are linear accelerometers. With the head at the center of rotation, the otoliths are about 1.5 inches off center, so they only get a small stimulation by the centripetal acceleration. They do signal to the subject a supine position. The semicircular canals do not sense gravity but are activated by the rotation of the centrifuge. Inside each canal (shaped like a partial torus) is a fluid called endolymph, and each torus is blocked by a membranous wedge called the cupula. When the head turns, the movement of the endolymph displaces the cupula, sending the signal of "head rotation". The semi-circular canals are orientated in an approximately orthogonal manner, in order to sense every direction of rotation. The canals are referred to as the lateral, posterior, and anterior canals. I will discuss head movements in the roll (axial), pitch (sagittal), and yaw (coronal) planes, which activate the components of the semi-circular canals in those directions, although the semicircular canals are not themselves in the roll, pitch, and yaw planes.

With the head on center, lying supine, horizontal centrifugation will activate the component of the semi-circular canals in the yaw plane. The subject will sense the acceleration of the bed, but after rotation levels off to constant velocity, the cupulas of the canals return to their resting positions, and the sensation of rotation will gradually die away. When the bed decelerates, the yaw component of the semicircular canals will again be activated, but in the opposite direction, as the deflection of the cupulas will be opposite to the direction of acceleration. The subject has the sensation of rotating in the opposite direction.

For clockwise rotation (from the point of view of an observer standing above the centrifuge), the subject will feel clockwise rotation during acceleration, and then will stop sensing that rotation after several seconds of constant velocity rotation. If a subject undergoing constant velocity clockwise rotation (as viewed from above) pitches his head up while still rotating, the roll components of the semi-circular canals are taken out of the plane of rotation. This is analogous to a sudden deceleration (as described above), and the subject will feel that his body is rotating in the counterclockwise direction (the sensation will be cart-wheeling with right ear down first). Furthermore, with the head-up pitch movement, the yaw components of the semi-circular canals are suddenly brought into the plane of rotation. Now, the yaw components of the semicircular canals are activated and sense rotation in the clockwise direction (the sensation will be spinning, like an ice skater, to the right). The pitch components of the semi-circular canals give the correct signal, which is that the person has pitched his head forward. Therefore, the subject feels the illusory sensation that he is pitching forward, cartwheeling to the right, and spinning to the right. Clearly, such sensations will be undesirable to the astronauts.

Illusory sensations can be predicted using this explanation (Hecht, Kavelaars et al. 2001); additionally, head movements out of the plane of rotation cause a transient increase in heart rate and an increase in motion sickness. Much work has been done to determine if adaptation will be possible for astronauts, so that short radius centrifugation is an acceptable countermeasure. Current studies show that adaptation will be possible (Brown 2002, Brown, Hecht et al. 2003, Bruni 2004, Adenot 2004, and Adenot, Jarchow et al. 2005).

1.3.2 Cardiovascular conditioning

Artificial gravity allows the astronaut to, in essence, "stand up" for a period of time. The problem with this treatment is the same as when the astronaut stands up after a long space flight: in the deconditioned state, orthostatic hypotension is a real threat. A solution to this problem is discussed in Section 1.4.

Baroreceptors sense a change in pressure in the neck and thorax (see Section 1.1.2). Experiments with short- and long-arm centrifuges led to the hypothesis that the hydrostatic gradient in the body (the feet at the rim of centrifugation) results in baroreceptor stimulation (Burton and Meeker 1992). When spinning horizontally about the naso-occipital axis, blood is pulled from the upper half of the body towards the lower half. As a result, there is less fluid in the thorax and head than when the person was lying supine without centrifugation. This relative decreased thoracic pressure leads to increased cardiac output, since the stimulus is similar to going from supine to standing. Such stimulation due to artificial gravity could help to slow down the cardiovascular deconditioning and could encourage greater orthostatic tolerance. It is possible that artificial gravity exposure at regular intervals will also reduce or even prevent the decreased blood volume. Burton and Meeker (1992) found that their subjects were able to tolerate higher g-levels (measured at the heart) during short-arm centrifugation than during long-arm centrifugation. This indicates that the 100% pressure gradient across the longitudinal axis of the body may be favorable to stimulation of the baroreceptors in the thorax.

Tolerance of subjects to a very high pressure gradient was tested on a 4’ 9” centrifuge (Piemme, Hyde et al. 1966). This short length forced the subjects to recline with their knees bent. Subjects were centrifuged in increments of 1-g, up to 7-g’s at the rim (so the maximum pressure gradient was 0-g at head, 1 to 7-g’s at feet in the body-axis direction). All subjects easily tolerated 1- and 2-g’s, and six of seven subjects were able to tolerate 3-g’s for a full two-hour exposure. Their pulse rates did not increase significantly after the first ten minutes of spinning on the centrifuge. At 3-g’s, however, the subjects complained of musculoskeletal pain, particularly in the legs and in the lower back. For cardiovascular reasons most subjects had to terminate the experiment at 5-g’s after 25 minutes: they experienced gray-outs, blackouts, or lightheadedness. All but one subject had to terminate the experiment after several minutes at 7-g’s or less for this reason. The exceptional subject, a physician, performed continuous leg exercise (of a type not specified). This anecdote supports the idea of combining exercise with centrifugation to increase tolerance to artificial gravity.

For nine subjects (not in bed rest), the effects of seven consecutive days of one-hour exposure to 2-g centrifugation were studied (Iwasaki, Hirayanagi et al. 1998). Baroreceptor sensitivity increased significantly after a week of centrifuge treatment, relative to the same subjects’ baroreceptor sensitivities before the seven days of treatment (Figure 5). (Baroreceptor sensitivity is explained by the author as increased parasympathetic activity with a non-significant decrease in sympathetic activity, as measured by high and low frequency analysis of heart rate spectra.)

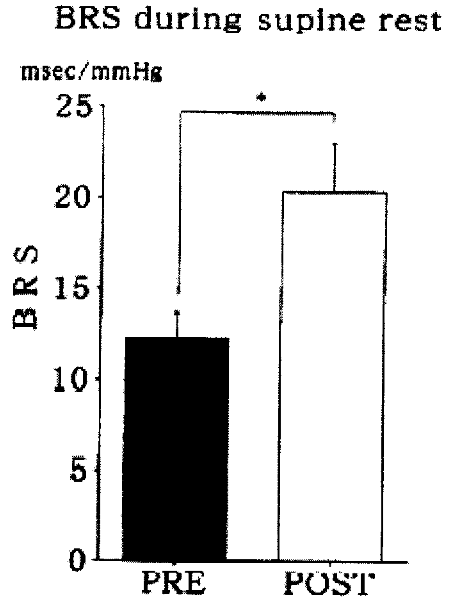


Figure 5. Baroreceptor sensitivity pre- and post-treatment (subjects were tested before and after seven days of one hour daily exposure to 2-g centrifugation). From p. 180 of Iwasaki et al. (1998).

Past research in our lab has shown a slight increase of heart rate during centrifugation when head-turns are performed, which is possibly due to increased motion sickness (Hecht, Kavelaars et al. 2001). In general, heart rate does not change significantly for 1-g centrifugation (measured at the feet) relative to lying supine, but does increase significantly for 1.5-g centrifugation (Hastreiter 1997, Hastreiter and Young 1997).

1.4 Exercise during Centrifugation

1.4.1 Cardiovascular effects

When placed in an artificial gravity environment after some amount of time in space, the astronauts may experience orthostatic hypotension. Baroreceptor deconditioning and the inactivation of the venous pump could result in the astronaut's inability to withstand the centripetal acceleration of the centrifuge without detrimental effects (lightheadedness or fainting). Rhythmic exercise may be a solution to the problem of orthostatic hypotension on the centrifuge. Early studies by Pollack and Wood (1949) showed that while walking, average venous pressure in the veins of the ankle was less than during quiet standing, showing that such movement combats the pooling of blood in the lower half of the body (Figure 6).

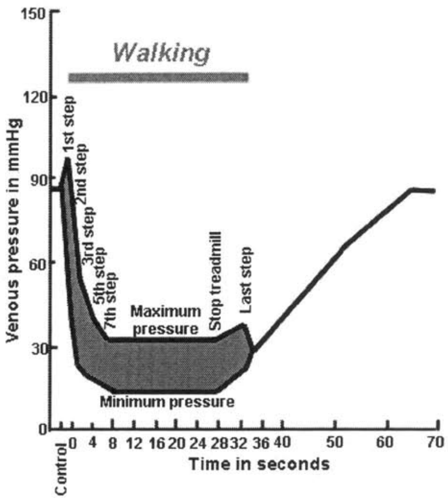


Figure 6. Venous pressure in the ankle is less during walking than during quiet standing (Figure 7 from Pollack and Wood (1949)).

During exercise, blood flow to the hard-working muscles increases through vasodilation of the intramuscular vessels (Guyton and Hall 2000). Rhythmic exercise compresses the intramuscular blood vessels during contraction, but blood flow increases to the muscles in between contractions (Figure 7). Additionally, this pumping motion aids in venous return and helps to force blood opposite the gravity vector and towards the heart and brain.

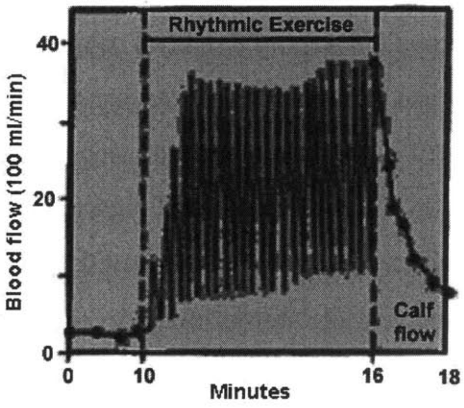


Figure 7. Blood flow during rhythmic exercise (Figure 84-8, p. 975, from Guyton and Hall (2000)).

The result of exercise - increased heart rate (and thus cardiac output) and increased mean arterial blood pressure – mimics the proper response of the baroreceptors. Pumping of the legs and increased venous return make it less likely that the centrifuged astronaut will experience lightheadedness or other presyncopal symptoms. Exercising on the centrifuge, it seems, would recondition the venous return mechanism and possibly reduce the venous distensibility occurring in weightlessness (Vil'-Vil'yams and Shul'zhenko 1980), and therefore increase orthostatic tolerance.

A team at the University of California, Irvine built a "Space Cycle" prototype to demonstrate the technical feasibility of a human-powered centrifuge (Kreitenberg, Witmer et al. 2000). They cited an example of Velodrome bicycle racers, who reach speeds in excess of 40 mph on a 110 ft. radius track, creating greater than a 1.4-g force on their bodies. These racers are unable to train for Velodrome races in other facilities, because of the increased gravity vector they experience when exercising on the incline of the track. Kreitenberg et al. suggest that this paradigm may be applied to a centrifuge; their centrifuge is two bicycle apparatuses suspended from a 1 ft. radius arm. The subjects pedal, facing forward, and as their speed increases, the bicycles passively pivot to remain nearly parallel to the resultant artificial gravity vector. The center of gravity of the riding subject is between two and three feet from the rotation axis, depending on the angle of pivot of the bicycle. The investigators demonstrated the feasibility and subject comfort of this design, and noted that motion sickness was not a problem for most people, and heart rate and blood pressure remained within the normal range for moderate exercise.

An experiment at Nagoya University explored subject tolerance on a centrifuge, with and without exercise (Iwase, Fu et al. 2003). Subjects spun with and without bicycle ergometer exercise (maximum 150W) on a short radius centrifuge to a maximum of 2-g at heart level. Subjects' heart rate and mean arterial pressure increased with increasing g-loads, and increased more with exercise. The authors of this study defined a metric called the "anti-g score", defined as (the sum of the g-levels) × (the time at those levels, until the subject must stop due to orthostatic intolerance). Orthostatic intolerance was defined as one or more of the following:

"1) onset of presyncopal symptoms e.g. nausea, sweating, gray-out or dizziness, including a drop in systolic BP >15 mmHg and/or sudden bradycardia (heart rate drop >15 bpm);

"2) progressive reduction in systolic blood pressure to <80 mmHg,

"3) the subject requested termination" (p. P-102).

So, a subject able to tolerate ten minutes of 1-g, then three minutes of 2-g (10×1 + 3×2 = 16) has a lower anti-g score than a subject able to tolerate six minutes at 2-g, then two minutes at 3-g (6×2 + 2×3 = 18). The authors found that while the subjects were exercising, they were able to achieve higher anti-g scores, and suggested that this may be because leg pumping due to exercising aids in venous return.

Other studies have also supported exercise during centrifugation: Greenleaf, Gundo et al. (1997) used a 1.9-meter radius and two bicycles to show that heart rate increased with increasing acceleration during centrifugation, and increased more when exercise was combined with centrifugation. Vil'-Vil'yams and Shul'zhenko (1980) found that the decrease in heart rate and increase in venous compliance that occurred as a result of 28-day dry immersion was best attenuated with cycle ergometry during short-radius centrifugation (the attenuation was better than either of these countermeasures alone). Caiozzo, Rose-Gottron et al. (2004) found that exercising during centrifugation caused a smaller increase in heart rate per unit of artificial gravity level than passive centrifugation, indicating that exercise aided in venous return and cardiac output.

Exercise during artificial gravity may potentially cause more neurovestibular conflict and subsequent motion sickness, due to the "up and down" motion of the body inherent to many types of exercises (see Figure 8). The acceleration of artificial gravity that is felt by the subject and sensed by the otoliths depends on the subject's position along the radius, as dictated by Equation 1. In the up position, the head is on-center, and the otoliths do not sense the acceleration of artificial gravity. However, as they are moved off-center in the down position, the otoliths not only sense Earth's gravity, but also artificial gravity from the rotating environment. There is some potential for motion sickness due to the up and down motion necessary for normal exercise, which produces Coriolis stimulation. Exercise on a centrifuge itself, without the up-down motion, does not stimulate motion sickness in most subjects as mentioned above (Kreitenberg, Witmer et al. 2000).

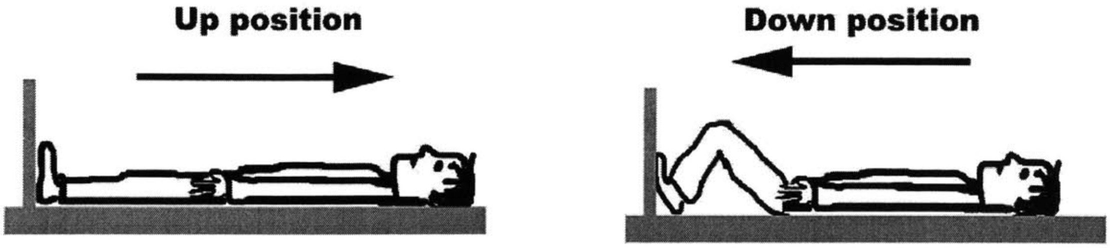


Figure 8. Positions of a subject when exercising.

1.4.2 *Musculoskeletal conditioning*

Bone growth

We do not know if exercise on a centrifuge offers a clear benefit to the skeletal system as compared to exercise on a treadmill restrained by bungee cords, but it would ameliorate the discomfort of the treadmill harness (Convertino and Sandler 1995). Both a treadmill with a bungee harness and exercise on a centrifuge offer the footward force and the impacts necessary to assist in maintaining bone mineral density and bone mass. Comparative studies of exercise with a bungee versus exercise on a centrifuge have not been done.

Muscle building

Just as it is important to condition the bones, artificial gravity offers the benefits of exercising against the resistance of one's own body. The general benefit is prevention of muscle atrophy. As with all countermeasures, however, all factors must be examined. D'Aunno, Robinson et al. (1992) performed experiments with rats in hindlimb suspension (the rat is suspended by the tail to simulate weightlessness on the rear of its body; the analysis is done only on its hind legs). One group of rats experienced four 15-minute bouts of 1.2-g centrifugation per day, and the other group experienced four 15-minute bouts of Earth's gravity per day, for one week. The Earth's gravity group maintained muscle mass, but the centrifugation group did not, indicating that centrifugation at 1.2 g's for a total time of 1 hour per day did not prevent muscle atrophy as well as standing in Earth's gravity did. The experimenters noted that the centrifugation group also voluntarily decreased their food intake, and suggested that the muscle atrophy may be partially due to the stress the centrifuge group animals were under.

2 CONSTRUCTION AND IMPLEMENTATION

In order to implement an exercise system on our existing centrifuge, we identified three major elements to be designed and constructed: the exercise device, an improved footplate, and a sliding mattress. The design and construction are outlined below.

2.1 Exercise Device

2.1.1 Requirements

We chose the requirements of the exercise device as follows:

1) Exercise involves only the legs.
2) Device is as compact and as simple as possible.
3) Low impact exercise; that is, the subject should not lift his foot from the device for each motion of the exercise.
4) The device has the potential to be held in the static position for non-exercise experiments.

The fact that the subject is lying down allows movement of the legs, but not the upper part of the body. To minimize weight added to the centrifuge, the size of the exercise device had to be small enough to fit on a reasonably sized footplate. We also excluded exercise devices requiring external power or feedback from an external control source. We harbored some concern over the subject making forceful impacts in the radial direction during exercise, which could induce rocking, and an undesirable moment on the centrifuge's support shaft. Additionally, rocking would alter the speed of the centrifuge, such that the motor could not accurately control the centrifuge to a constant angular velocity. For this reason we a sought a low-impact exercise device.

2.1.2 Device chosen

Given these requirements, the two apparent choices were an ergometer or a stair-stepper device. Their motions are somewhat similar; the stair-stepper was chosen in part because the motion of the lower half of the body is minimized, and because this exercise device (a stair-stepper) has not yet been used in centrifuge studies. The Kettler mini-stepper was purchased for use on the centrifuge (Figure 9).

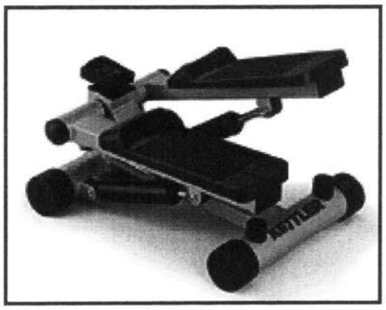


Figure 9. The Kettler mini-stepper (photo from www.stepper-superstore.com, accessed May 15, 2005).

The stair-stepper measures 13" x 18" x 12.25", and weighs 25 lbs. Resistance to exercise is provided by a non-variable damper beneath each foot. A small computer on the stepper shows number of steps, stepping rate, time of exercise, and calories burned (the method for obtaining calories burned is unknown). Plastic rings on the base provided traction for the device's use on the ground; these rings were removed for use on the centrifuge. We modified the stair-stepper slightly to secure the subject's feet by replacing the plastic footholds with footholds from the Concept II rower machines (Figure 10).

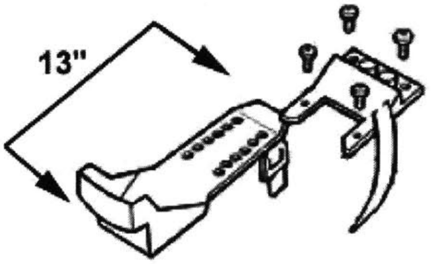


Figure 10. Exploded diagram of the Concept II rower footholds (modified from http://www.concept2.co.uk/shop/parts_diagrams.php, accessed May 15, 2005)

There is a triangle of space in the exercise device enclosed by the dampers, the footholds, and the metal stem beneath the computer, which fits a 2" x 4" wooden block when the footholds are in the neutral position, securing the device from moving. In this way, the stepper can be used as a footrest in non-exercise experiments.

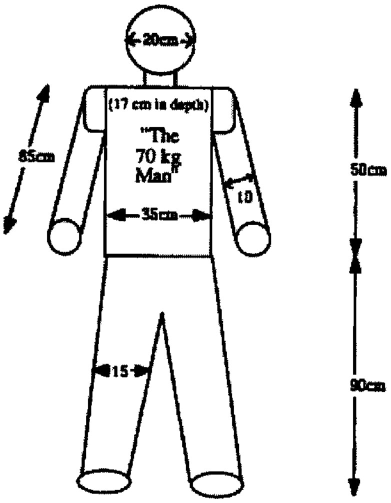
2.2 Footplate

2.2.1 Requirements

A new footplate was required to accommodate the increased forces expected from exercising. We chose the requirements for the footplate as follows:

1) Supports loads up to 300 lbs.
2) Securely mounts the stair-stepper device.
3) Easily adjustable along the radius of the centrifuge for different subject heights.

We calculated expected forces in the "worst-case scenario", spinning at the highest velocity of 30 rpm. Weights and moment arms for the body segments of a 200-lb, 6-foot tall person were calculated using the anthropometric dimension assumptions that were used in the original construction of the centrifuge (Diamandis 1988), see Figure 11.



Estimate Volume and Weight of Body Segment

Head:	$4/3 \cdot \pi \cdot r^3$	$= 4/3 \cdot \pi \cdot (.1)^3$	Vol = .0042 m^3	W=3.65 kg
Thorax:	$L \cdot W \cdot D$	$= .50 \cdot .35 \cdot .17$	Vol = .0298 m^3	W=25.9 kg
Arms:	$2(\pi \cdot r^2 \cdot L)$	$= 2(\pi \cdot (.05)^2 \cdot .65)$	Vol = .0102 m^3	W=8.88 kg
Legs:	$2(\pi \cdot r^2 \cdot L)$	$= 2(\pi \cdot (.08)^2 \cdot .90)$	Vol = .0362 m^3	W=31.5 kg
Totals:			Vol = .0804	W=70.0kg

Figure 11. Figure 7.1 and Table 7.1 from pp. 40-41 of Diamandis (1988). These are for a 70-kg (155-lb.), 1.67-m (5' 6") tall person.

We can use these assumptions to extrapolate expected weights and moment arms for a 200-lb, 6-foot tall person. Equation 1 was used for each body segment, and the resulting forces were added together (Table 1). The top portion of the slider mattress (see Section 2.3) was also included in this calculation. A more detailed explanation of the calculations in Table 1 is found in Appendix A.

Table 1. Weights, moment arms, and expected radial force (at 30 rpm) for a 200-lb., 6-foot tall subject.

	Percent Weight (use Diamandis's table)	Centerpoint is what percent of body length? (use Diamandis's table)	Actual weight of body segment (lbs.)	Mass of segment (slugs)	Arm of centerpoint of segment (ft.)	Radial force of segment, spinning at 30 rpm (lbs.)
Head	5.21	5.99	10.42	0.32	0.36	1.13
Thorax	37.00	31.14	74.00	2.30	1.87	42.44
Arms	12.77	35.62	25.54	0.79	2.14	16.68
Legs	45.00	73.05	90.00	2.80	4.38	121.04
Total body	100		200	6.21		181.29
+slider				0.62	1	1.95
TOTAL						**183.24**

Given this upper limit, the weight of the top half of the slider, and a 1.5 factor of safety, and allowing for no friction in the support, we designed for expected loads of up to 300 lbs. For the height of the footplate, it was necessary to fit the Kettler Mini-Stepper on the footplate. For the comfort of the subject, the device was to be placed four inches above the surface of the centrifuge, securely mounted with as little vibration as possible. The width of the device was dictated by the width of the centrifuge bed surface.

Finally, we wanted this footplate to be easily adjustable for subject height along the radius of the centrifuge, and for the footplate to be safely secured at that height. Therefore, we desired a smooth sliding surface for adjustability, and high-load capacity pins at small intervals.

2.2.2 Design

The general design is shown in Figure 12, and explanations for the components follow.

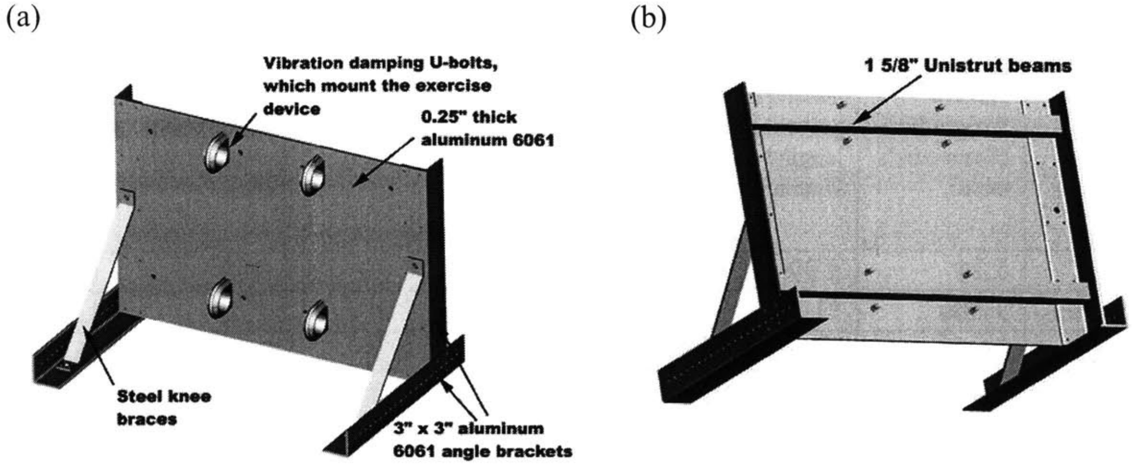


Figure 12. ProEngineer (2001 Education Version) shadow drawing of final footplate design, as viewed from the (a) front and (b) back. Elements are labeled; see Appendix B for detailed description of components.

The previous footplate deflected in the center during centrifugation with high loads, and was 1/8" thick aluminum. We chose, therefore, to use ¼" aluminum to minimize this bending. Additionally, the loads we expected prompted us to use two 1 5/8" x 1 5/8" Unistrut beams on the back side of the footplate, spanning the width of the bed, placed opposite the four contact points of the exercise device. One 36-inch long beam of this Unistrut will withstand 1130 lbs. uniform load, with a deflection of 0.13 inch (www.unistrut.com, accessed May 15, 2005). Vibration was minimized by mounting the exercise device to the footplate using vibration-damping U-bolts.

In order to meet sizing design requirements, the footplate was generally dimensioned as follows in Figure 13 (all dimensions in inches). Detailed engineering drawings are available in Appendix B.

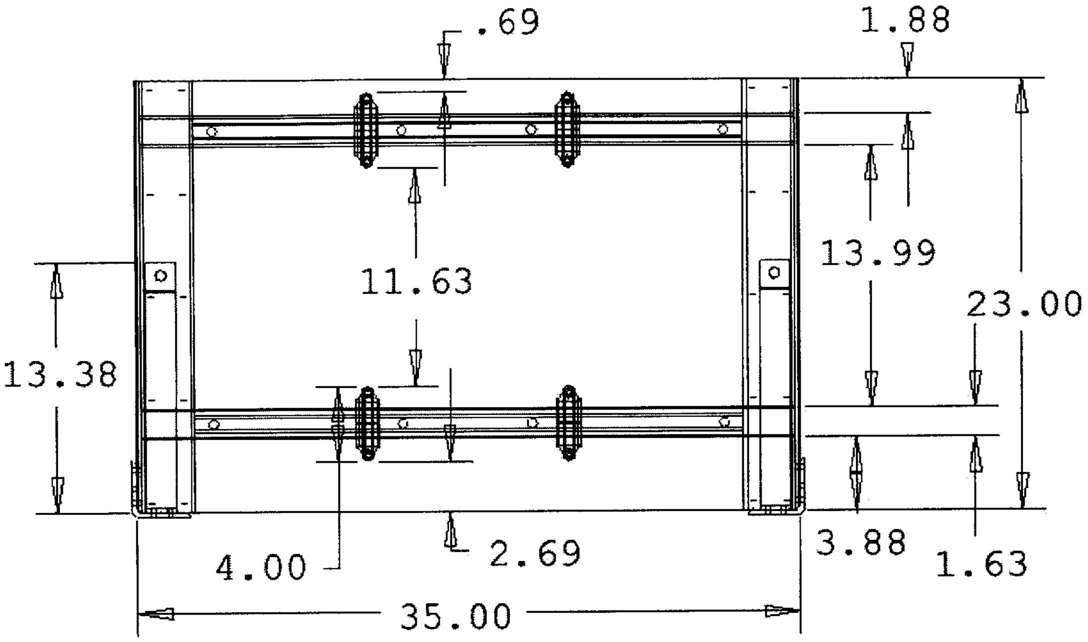


Figure 13. Dimensions of footplate.

In order to make the footplate easily adjustable along the long axis of the centrifuge bed for different subject heights, we mounted the footplate to two 1/4-inch thick, 10-foot long angle brackets, 35 inches apart (see Figure 12) such that these two footplate angle brackets fit inside the angle brackets mounted to the centrifuge, which run the whole length of the bed (these are the stabilization elements described in Section 3.1.2). In this way, the footplate runs along a "track" when it is adjusted.

To secure the footplate along this track at variable positions for different subject heights, we drilled holes at 1-inch intervals along the centrifuge angle brackets and along the footplate angle brackets. Two ¼-inch diameter high load capacity pins per side are inserted into these holes once the footplate is positioned for each subject. Two pins per side are desirable to secure the footplate against the forces and moments induced by exercise (see Figure 14).

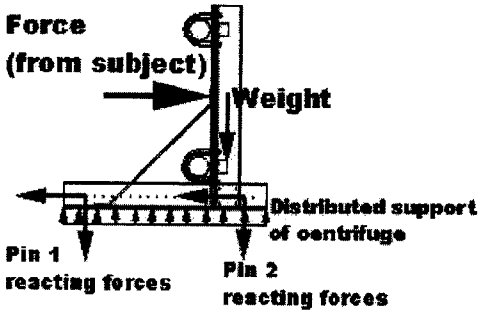


Figure 14. Simplified diagram of force on footplate and moment. It is apparent that two pins are necessary to counteract the moment.

2.3 Slider

Exercise on a stepper device would be difficult while lying on a mattress. On Earth, the weight of the subject's body against the mattress creates friction that acts opposite the force due to artificial gravity. We partially eliminated this problem by using a 1-inch thick foam mattress on a platform that slides with the subject. In this way, the subject still feels pressure on her back, but must no longer work against friction during exercise. This allows her to benefit more from the artificial gravity force alone.

2.3.1 Requirements

The requirements for the slider device were as follows:

1) 3.7 feet in length.
2) Linear low-friction movement.
3) Distributed load on the centrifuge.
4) Able to be statically secured.

The slider mattress had to be sized to accommodate a 6-foot tall person from head to hips (it is not required that the legs are placed on the mattress, since they are moving). Given our anthropometric calculations (Table 1), we needed the mattress to be 3.7 feet in length.

The attachment of the slider device to the centrifuge bed needed to distribute the forces, so as not to stress the light aluminum honeycomb structure of the centrifuge bed surface (Diamandis 1988). The sliding mechanism needed to be nearly frictionless and only allow movement in the radial direction. Additionally, we required the option that the slider could be statically secured for non-exercise experiments.

2.3.2 Design

Diamandis (1988) built a slider device for the original centrifuge in this lab. That slider device was modified to accommodate our needs.

We fitted a wooden platform 37" x 23" with foam covering, and covered the foam with fabric. This serves as the mattress. (The length, 37 inches, does not quite satisfy the 3.7-foot requirement. However, the whole length of the thorax and hips does not need to be on mattress to comfortably exercise, so we decided to use Diamandis's pre-existing platform.) At the bottom of this mattress there is a rectangular aluminum bracket 19" x 12.75", and each corner of the bracket has cylindrical linear ball bearings. This combination makes up the top part of the slider. Separately, we attached four brackets to a second wooden platform 40" x 24". The brackets mount two steel rails 3 feet long. This wooden platform sits on the bed of the centrifuge, secured to its surface by self-lock mushroom-head fastener (a very strong type of Velcro). The top portion (mattress) can then slide freely along the bottom portion (wooden platform with rails) in the radial direction, with a range of motion of 15 inches (Figure 15).

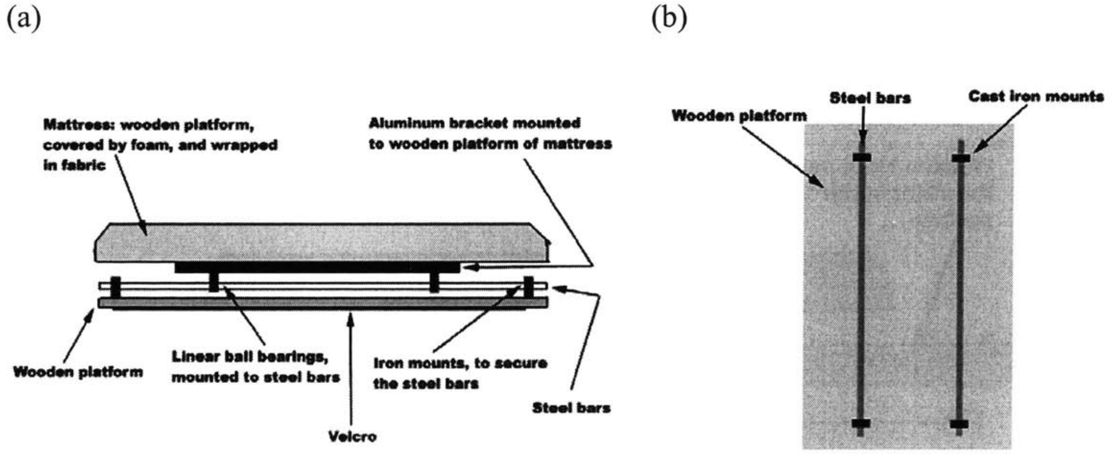


Figure 15. Slider mattress. (a) Side view of device, top (mattress) and bottom (platform) portions. (b) Top view of bottom part only. This wooden platform is the portion that attaches to the bed.

Originally we had planned to simply mount the rail mounts directly to the centrifuge bed. However, each of the four 2 5/8" x 3/4" mounts would exert nearly a point load of one quarter of the subject's body weight. Because the strength of the honeycomb paneling is in *distributed* forces, we instead attached these rail mounts to a wooden platform, which is secured to the bed. The Velcro on the bottom of the wooden platform allows the whole slider mattress combination to be moved up or down along the radius of the bed. There are two configurations under which experiments are performed. The first configuration places the subject's head and body (hips and above) on the mattress, such that when the feet are strapped into the stair-stepper and the subject is stretched out, the slider is in the up position. This allows for comfortable exercise, using either the stepper, or doing knee bends. The second configuration is for experiments not relevant to this thesis. It requires that the slider be secured in the up position, the subject's feet are secured, and the subject's head is placed in the helmet, which is attached to the center of rotation of the bed. The second configuration requires, first, that the bottom portion of the slider (wooden platform) be moved four inches towards the center of the bed, and second, that the slider be statically secured. The first requirement was simple to address, since the Velcro allowed the wooden platform to easily be moved up and down. The second requirement prompted us to cut wood stoppers to go beneath each rail, between the rail mount and the aluminum ball bearing frame, to keep the mattress in the up position (see Figure 16).

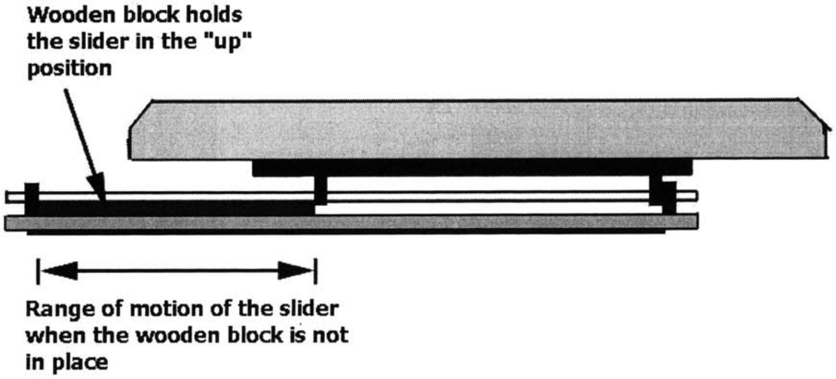


Figure 16. Slider can be secured in the up position using two wooden blocks beneath the steel rails.

We tested bronze bushings as a replacement for the linear ball bearings. The bushings provided negligible vibration, but the friction was substantially greater and the subject then had to provide much force to slide up and down. We decided to use the ball bearings instead, despite the audible noise and the slight vibration, because it allowed for the subject to feel the greatest effect of artificial gravity.

This slider allows the centrifuge to be used for a second type of exercise, knee bends. Hereafter the type of exercise will be specified.

The final exercise system on the centrifuge is shown in Figure 17.

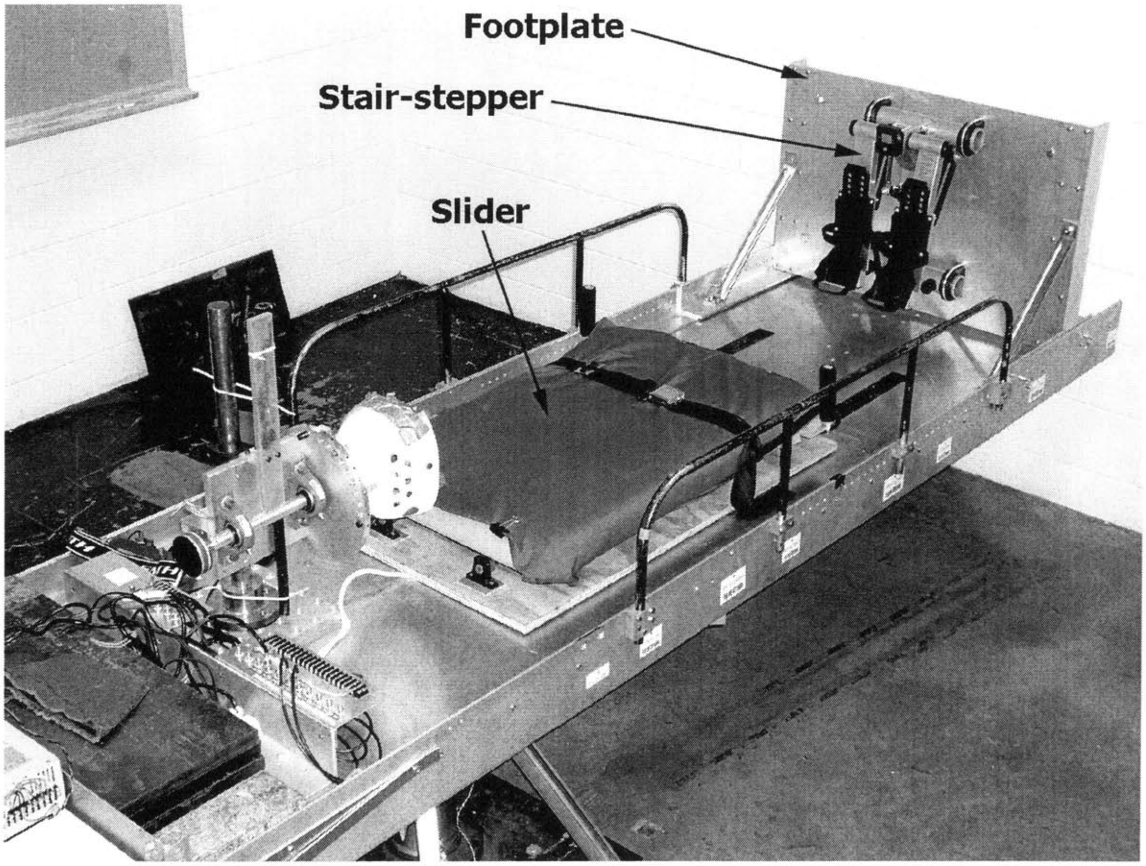


Figure 17. Exercise system on the Man-Vehicle Laboratory centrifuge. The helmet is not in place for exercise experiments.

3 VALIDATION

Validation of the exercise system design included mechanical validation and preliminary physiological validation. Mechanical validation was necessary so that this system may be used safely; preliminary physiological validation may help give direction to future research.

3.1 Mechanical Validation

3.1.1 Expected Moment Calculations

There will be some added moment to the centrifuge due to stair-stepping or knee bends. For the following calculations, we will assume the largest subject size of 200 lbs., 6 feet. If the subject steps with his full body weight on one foothold of the stepper, the force will be opposed by the damper beneath the foot for the period of time that it takes him to step to the bottom of the device. Once his foot hits the bottom, he imposes a force on the footplate equal to his body weight in artificial gravity (approximately half his body weight on Earth, in this case 100 lbs.) Thus, at the bottom of each step, there will be a moment imposed at the base of the footplate, the magnitude of which is calculated by Equation 2.

$$M_{stepper} = F_{step} \times d_{stepper} = 79 \text{ ft.} \cdot \text{lbs.}$$

Equation 2

$M_{stepper}$ is the moment about a point at the base of the footplate, F_{step} is the artificial gravity weight of the subject when he steps with one foot, and $d_{stepper}$ is the moment arm. In this case, F_{step} is 100 lbs., since total artificial gravity weight is ½ Earth weight when spinning at 1-g at the feet. $d_{stepper}$ is the distance from the bed to a point halfway up one foothold of the stepper device, and is equal to 9.5 inches (Figure 18). Note that the base of the footplate is approximately horizontally collinear with the top of the support shaft (neglecting the thickness of the bed), which means $M_{stepper}$ also acts about the top of the support shaft.

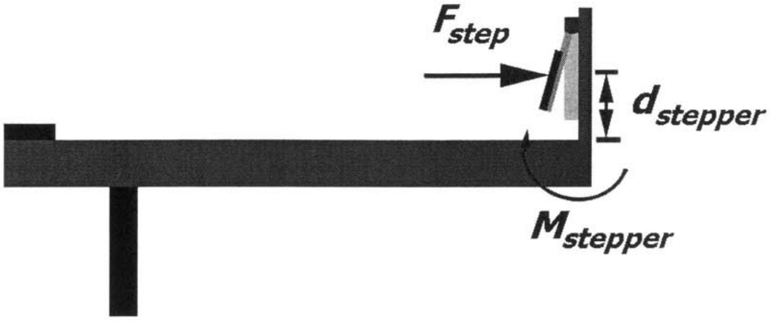


Figure 18. A moment is applied about the base of the footplate.

A second moment is due to imbalance of weight on the centrifuge; rocking due to this imbalance is discussed in 3.1.3. This moment is about the top of the centrifuge support strut:

$$M_{bed} = F_{fp} \times d_{fp} + F_{slid} \times d_{slid} + F_{subj} \times d_{subj} - F_{cw} \times d_{cw} = 107 \text{ ft.} \cdot \text{lbs.} \qquad \textbf{Equation 3}$$

The variables are defined as follows.

M_{bed} : moment about the top of the centrifuge support strut
F_{fp}: weight of footplate plus slider (75 lbs.)
d_{fp}: moment arm of footplate (6 ft.)
F_{slid}: weight of the slider (45 lbs.)
d_{slid}: moment arm of slider (2 ft.)
F_{subj}: weight of subject (200 lbs.)
d_{subj}: moment arm of subject (3 ft. for a 6-ft. person)
F_{cw}: weight of counterweights on other side of centrifuge (400 lbs.)
d_{cw}: moment arm of counterweights (31 in.)

See Figure 19.

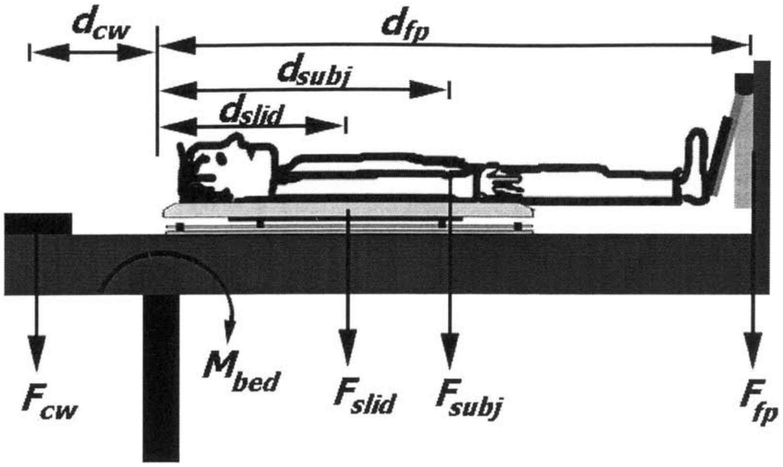


Figure 19. A moment is applied about the top of the support shaft.

The magnitude of the total moment about the top of the support strut, then, is

$$M_{total} = M_{stepper} + M_{bed} = 186\,\text{ft.}\cdot\text{lbs.} \qquad \textbf{Equation 4}$$

To find the moment about the base of the centrifuge when it is spinning, we would also take into account the radial force due to centrifugation, and multiply that by the moment arm that is the distance from the base to the top of the support shaft. This moment varies with centrifuge speed, and stability is outlined below in Section 3.1.3.

3.1.2 Added stability elements

Diamandis (1988) designed the centrifuge to be used for exercise with an ergometer or by knee bends (using the slider he built), but primarily the centrifuge was to be used for sleep studies. For his experiments, he placed a waterbed on the centrifuge, for the subject to comfortably sleep.

Original centrifuge design is shown in Figure 20. Diamandis calculated the inertia of the centrifuge to require 0.49 horsepower, taking into account the elements shown in Figure 20.

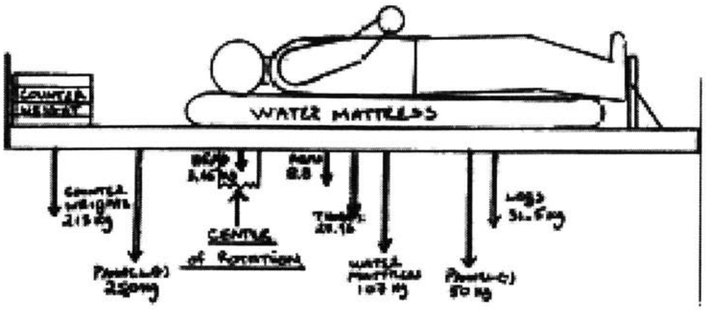


Figure 20. Weight balance of the centrifuge as it was originally designed (Figure from p. 43, Diamandis (1988)).

The design required a 5.12-inch diameter support shaft, with an inner tube, separated by radial ball bearings.

Diamandis did not describe any problems with wobbling or rocking of the centrifuge during spinning. We did, however, notice some rocking of the bed; particularly, precession of the support shaft. For this reason, we chose to overhaul the centrifuge structure, adding stability elements where deemed necessary.

Support struts

We added Unistrut beams to the support shaft to counteract the rocking of the support shaft on its metal plate. The support shaft is attached by a steel flange to a steel plate, which is mounted to the concrete. We added another flange around the top of the support shaft, and four supporting struts, which are attached at the other side by the same bolts that hold the metal plate into the concrete (Figure 21). An engineering sketch of the support struts can be found in Appendix C.

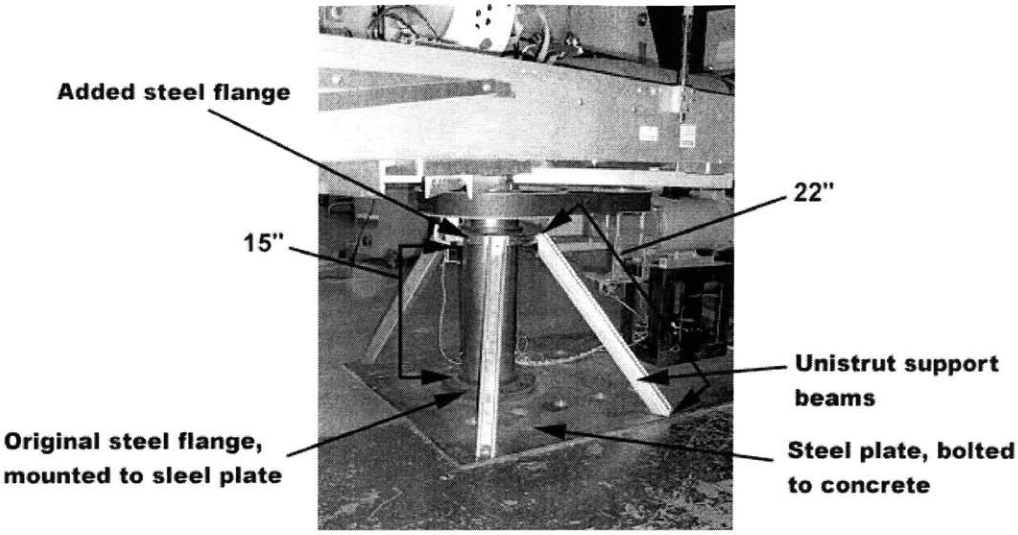


Figure 21. Unistrut support struts added to centrifuge support shaft.

This stability element diminished the rocking of the bed. We believe that some of the motion sickness subjects felt on the bed may have been attributable to this rocking; in addition to the centrifuge being more stable, motion sickness experiments should be more consistent with the added support struts.

Angle brackets along the bed

To counteract potential twisting of the centrifuge due to exercising, we chose to strengthen the bed lengthwise by adding ¼" thick, 3" x 3" leg aluminum angle brackets (Figure 22). Additionally, these angle brackets would act as a track along which the footplate could slide (Section 2.2.1). Aside from a stopper, the inner surface of the angle brackets was intentionally maintained as a smooth surface. Holes were drilled at 1-inch intervals along the side of the bed, through the angle bracket, for positioning of the footplate.

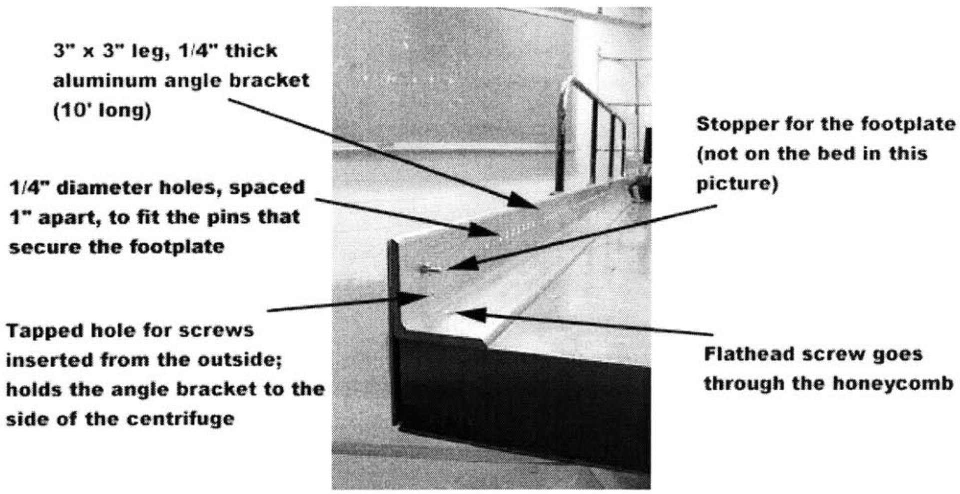


Figure 22. Angle bracket supports; view is from the foot of the bed, without the footplate on the bed.

3.1.3 Centrifuge stability as a function of spin rate

Before these stability modifications, and to a small extent, even after adding them, we noticed that centrifuge stability was largely determined by the spin rate of the centrifuge. That is, when the centrifuge was spinning slowly, we tended to see more rocking about the support shaft than when the centrifuge was spinning at higher speeds.

The reason for this is analogous to a proper of a spinning gyroscope: when the angular velocity of the gyroscope is higher, the precession of its axis is slower. When the angular velocity is lower, the precession is faster.

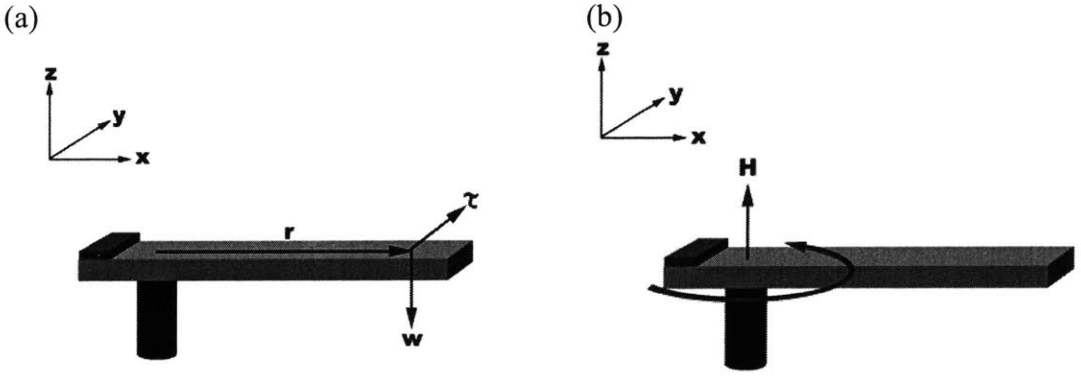


Figure 23. The (a) torque and (b) angular momentum experienced by the centrifuge.

We can understand this using the theory of a precessing gyroscope, assuming precession occurs about the top of the support shaft. The equation that governs gyroscopic precession is:

$$\vec{\Omega} = \frac{\vec{\tau}}{\vec{H}}$$

Equation 5

The torque, $\vec{\tau}$, is found by:

$$\vec{\tau} = \vec{r} \times \vec{w}$$

Equation 6

where $\vec{r}$ (the radius of the net moment arm) is in the positive x-direction and $\vec{w}$ (the net weight on one side of the centrifuge, creating a moment arm) is in the negative z-direction, such that $\vec{\tau}$ is in the positive y-direction (Figure 23a).

$\vec{H}$, the angular momentum created by the spinning centrifuge, is in the positive z-direction, and is the product of the moment of inertia about the z-axis ($\vec{I}$) and the angular velocity ($\vec{\omega}$) (Figure 23b).

$$\vec{H} = \vec{I} \cdot \vec{\omega}$$

Equation 7

Thus, the direction of precession (Equation 5) is in the negative x-direction.

Note that if we increase the angular velocity $\vec{\omega}$, the precession velocity decreases; likewise if we decrease $\vec{w}$ or $\vec{r}$. In practice, $\vec{r}$ is the distance from the rotation axis to the center of gravity of the centrifuge; this is why we want to keep the centrifuge balanced as much as possible (the center of gravity should be right over the center of rotation).

3.2 Physiological Validation

All experiments with subjects were carried out under approval from MIT's Committee for the Use of Humans as Experimental Test Subjects, protocol number 0405000759. The informed consent form is found in Appendix D.

3.2.1 Heart rate, blood pressure and physiological response

At high enough g-levels, centrifugation without exercise increases heart rate and blood pressure (Hastreiter 1997, Hastreiter and Young 1997, see also Section 1.3.2). We also expected to see both heart rate and mean arterial blood pressure increase due to the increased work output of exercise, just as they would in a normal 1-g environment (Guyton and Hall 2000).

Protocol

Three subjects (two male, one female) exercised for 45 minutes, alternating spinning and not spinning every five minutes, to assess the effects of exercising in simulated weightlessness (supine, not spinning), versus artificial gravity (spinning). Heart rate was recorded over every one-minute period using an Acumen heart rate monitor. The Acumen heart rate monitor is a single lead electrocardiogram attached to an elastic chest strap, which transmits a low frequency radio signal to a receiver, worn as a wristwatch. Saved heart rate data can be downloaded to a spreadsheet after the exercise session. Blood pressure was obtained every five minutes using an Omron digital blood pressure monitor, model HEM-711 (standard automatic cuff). The protocol is shown in Figure 24.

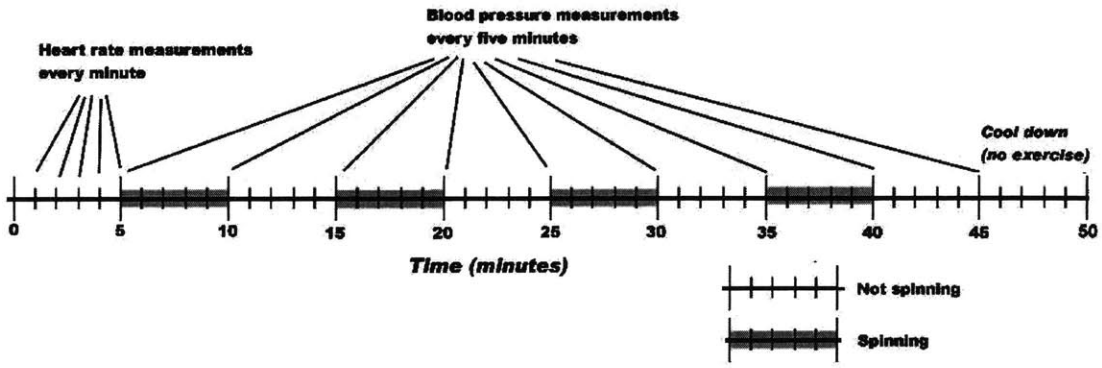


Figure 24. Experiment protocol for heart rate and blood pressure measurements.

The heart rate monitor averaged the subject's heart rate over the one-minute period, so each heart rate data point was an average over one minute. The blood pressure cuff was only capable of measuring while the subject was lying still, so the subject stopped exercising every five minutes and began the blood pressure reading immediately thereafter, to obtain a measurement as close as possible to the blood pressure during exercise (the measurement took about one minute; the subject resumed exercise immediately thereafter). Two subjects exercised using the stair-stepper and one subject exercised by doing knee bends.

Results

Subjects' resting heart rates were measured on the still and the spinning centrifuge (Table 2). As found by Hastreiter (1997), resting heart rate was about the same for subjects when supine and when centrifuged to 1-g at the feet.

Table 2. Subjects' supine resting heart rates.

Subject	Resting HR, not spinning (bpm)	Resting HR, spinning (bpm)
1	69	70
2	54	53
3	73	74

Exercise results for the same subjects are summarized in Table 3. The resting heart rates (lying on the still centrifuge) are slightly different because this experiment was performed on a different day.

Table 3. Average heart rates for subjects exercising with and without centrifugation.

Subject	Resting HR, not spinning (bpm)	HR, exercising while not spinning (bpm)	HR, exercising while spinning (bpm)
1 (stepping)	67	115	98
2 (stepping)	57	98	82
3 (knee bends)	62	79	77

Contrary to what we expected, all three subjects exhibited higher heart rate and systolic blood pressure when exercising without spinning, than when exercising with spinning (Figure 25). This was particularly true for the subjects who were stepping. Increasing heart rate and mean arterial blood pressure are indicators of increased work output during exercise (Guyton and Hall 2000); these two parameters increase in order to increase cardiac output and venous return. Here we see an increase in systolic blood pressure and basically no change in diastolic blood pressure. This indicates an increase in mean arterial pressure, following Equation 8 (where *MAP* is mean arterial blood pressure, P_{dias} is diastolic blood pressure, and P_{syst} is systolic blood pressure). See the Discussion (Section 1) for an analysis of the results.

$$MAP = P_{dias} + \tfrac{1}{3}(P_{syst} - P_{dias}) \qquad \textbf{Equation 8}$$

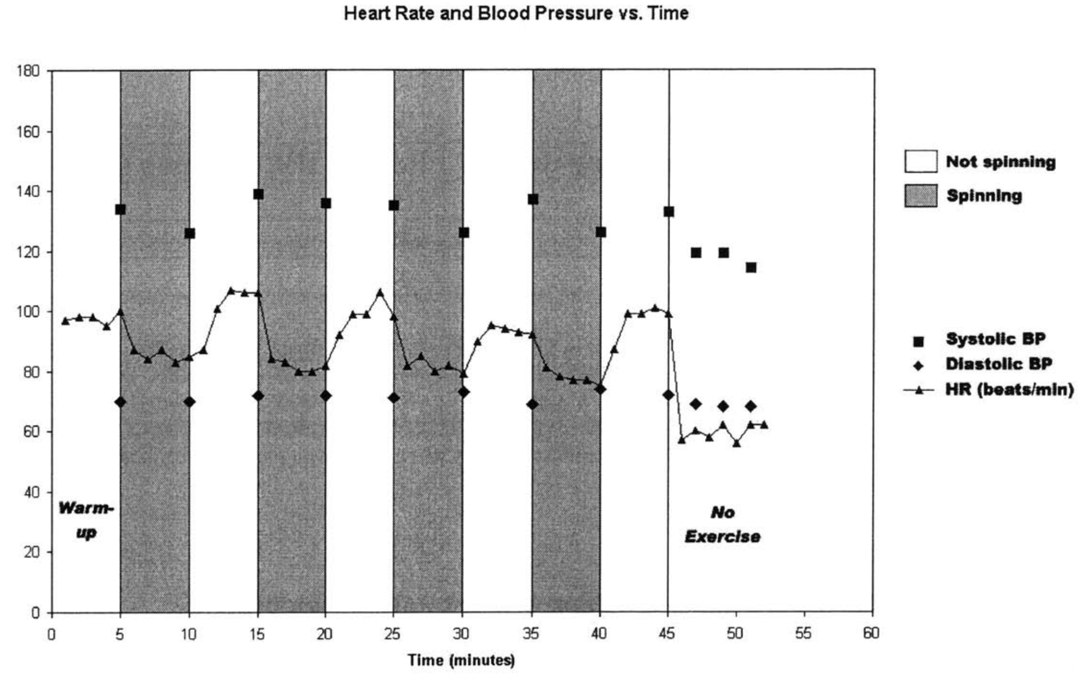


Figure 25. Subject 2, stair-stepping. Both heart rate and blood pressure were generally lower during the non-spinning periods. This subject's resting heart rate was 57 bpm.

3.2.2 Forces On the Feet

According to the anthropometric model outlined in Section 2.2.1 and Appendix A, we expect approximately half of the subject's body weight to be exerted on the footholds during 23 rpm centrifugation. This is assuming no friction between the subject's back and the surface of the centrifuge; the slider mattress should account for this (there should be no friction vector opposing the vector of centripetal acceleration). However the top half of the slider, which weights 20 lbs., is effectively attached to the subject's back and contributes to the artificial gravity weight/sensed by the strain gauges.

Taking into account the weight of the slider mattress, expected values for reaction forces on the feet for subjects of different weights are listed in Table 4 and shown graphically in Figure 26; the information for obtaining these values is in Appendix A.

Four subjects lay still, then stair-stepped, on the centrifuge while spinning at 23 rpm, and in two cases 30 rpm as well. Reaction forces on the feet were recorded.

Table 4. Total weight exerted on both footholds (static position) for subjects of different weights and heights, taking into account the 20-lb. slider mattress. An explanation and full table of values can be found in Appendix A.

Actual Body Weight (lbs)	AG weight at 23 rpm		AG weight at 30 rpm	
	lbs.	percent actual weight	lbs.	percent actual weight
110	50	45	85	77
120	57	47	97	80
130	64	49	109	84
140	72	51	122	87
150	79	53	135	90
160	88	55	149	94
170	97	57	165	97
180	106	59	180	100

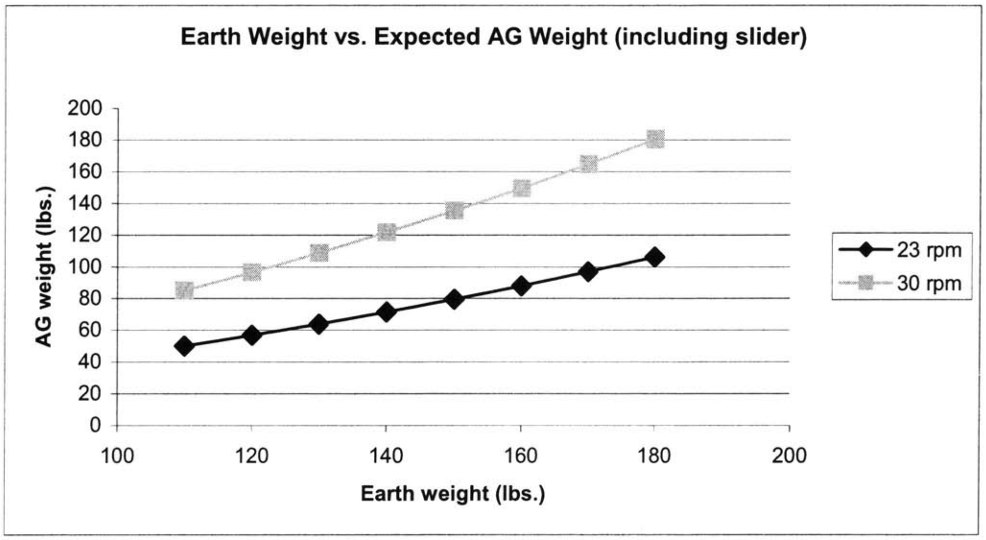


Figure 26. Graph of information in Table 4.

Instrumentation

We modified two Contek digital bathroom scales for these measurements. Each scale consisted of four strain gauges positioned beneath each of the rubber feet of the scale; the voltages from the strain gauges sum to give one value. We disassembled the scale and repositioned the strain gauges between two 12" x 6" aluminum plates, to fit beneath the footholds of stepper device (see Figure 27). The circuit board layout for the strain gauges and the circuit diagram of the operational amplifier are in Appendix E.

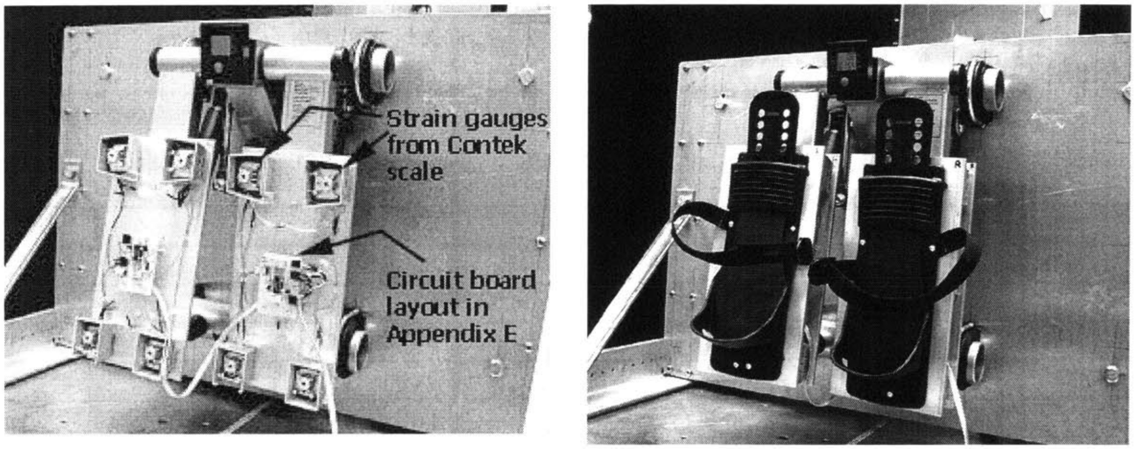


Figure 27. Foot reaction force sensors, mounted to the exercise device. Here they are shown (a) without the top aluminum plate and exercise foothold, and (b) with the aluminum plate and foothold in place.

Results

As predicted, when not exercising and spinning at 23 rpm, subjects exerted approximately 50% of their body weight on the foot sensors. This indicates that the slider mattress effectively eliminates friction between the subject's back and the surface of the centrifuge.

Table 5. Measured forces (resolution of approximately 5 lbs.) for four subjects on the centrifuge.

Subject actual weight	Artificial gravity weight at 23 rpm	Artificial gravity weight at 30 rpm	Maximum force exerted when stepping
150	80 **(53%)**	-	120 **(80%)**
155	75 **(48%)**	110 **(71%)**	75 **(48%)**
175	95 **(54%)**	125 **(71%)**	120 **(69%)**
230	110 **(48%)**	-	195 **(85%)**

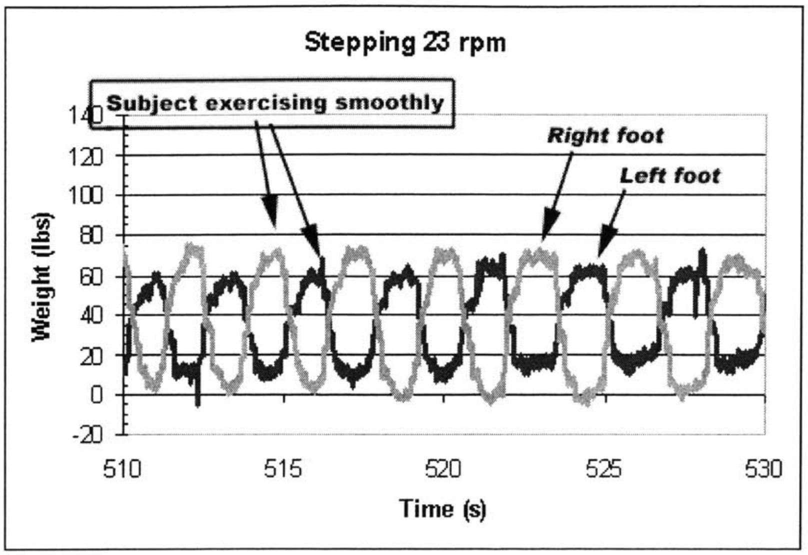
Depending on how the subjects exercised, they experienced very different forces. Both the 150 lb. and the 175 lb. subject attained forces of 120 lbs. while stepping forcefully and reaching the bottom limit of each step. It is apparent (Figure 28) that forceful exercise added up to 40 lbs. to each step, reaching up to 80% body weight. The 155 lb. subject, however, exercised smoothly, and only attained forces of 75 lbs.

The top half of the slider, when in Earth's gravity, weighs 20 lbs., but its center of gravity is only 12 inches off-center in the up position. That means that the slider increases a subject's artificial gravity weight by 3.6 lbs. for 23 rpm and by 6.1 lbs. for 30 rpm.

All subjects supported more of their weights on the footplate with their right foot, with the exception of the 155 lb. subject, who put more weight on his left foot during 30 rpm centrifugation only. Two subjects stepped more strongly with their right feet; two subjects stepped more strongly with their left feet.

We noticed changes of up to 20 lbs. in the weight of a subject lying still after he did one knee bend (Figure 29). This is a hysteresis-like effect: I suspect that the strain gauges may stick slightly in the deflected position after being depressed forcefully, giving a higher reading than is accurate. The opposite effect was seen when the subject lifted his feet off of the foot scales by holding onto the centrifuge's side rails (when he replaced his feet, the scales sensed that he was 20 lbs. lighter). A possible reason for this hysteresis effect is that when the strain gauge mechanisms from the Contek bathroom scales were positioned between aluminum plates, they were necessarily connected in a rigid parallel configuration. It is possible that this configuration resulted in some internal tension acting like a stiff spring, affecting the strain gauge readings after this stiff spring was deflected. However, the mechanism is still under investigation. Calibration data from the sensors is given in Appendix F, and all subjects' data is given in Appendix G.

(a)



(b)

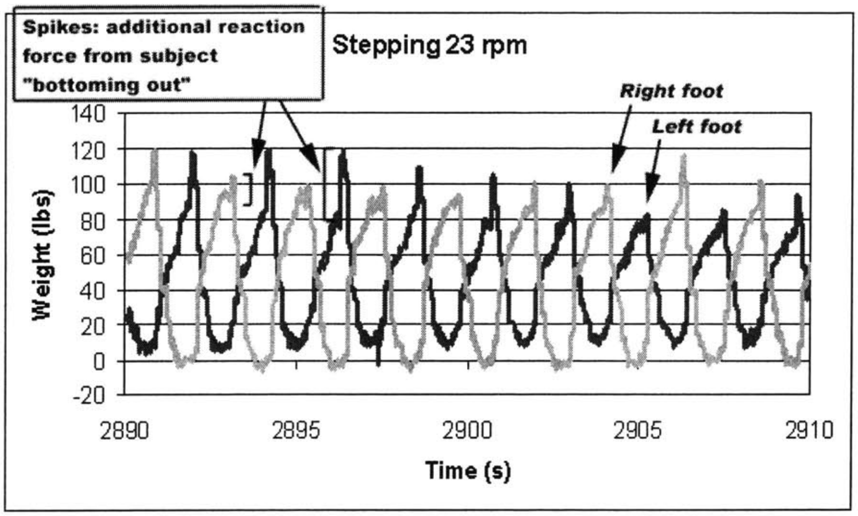


Figure 28. Force exerted on stepper footholds (left and right feet). (a) Subject exercising smoothly on the stair-stepper. (b) Subject exercising forcefully on stair-stepper, reaching the bottom limit of each step.

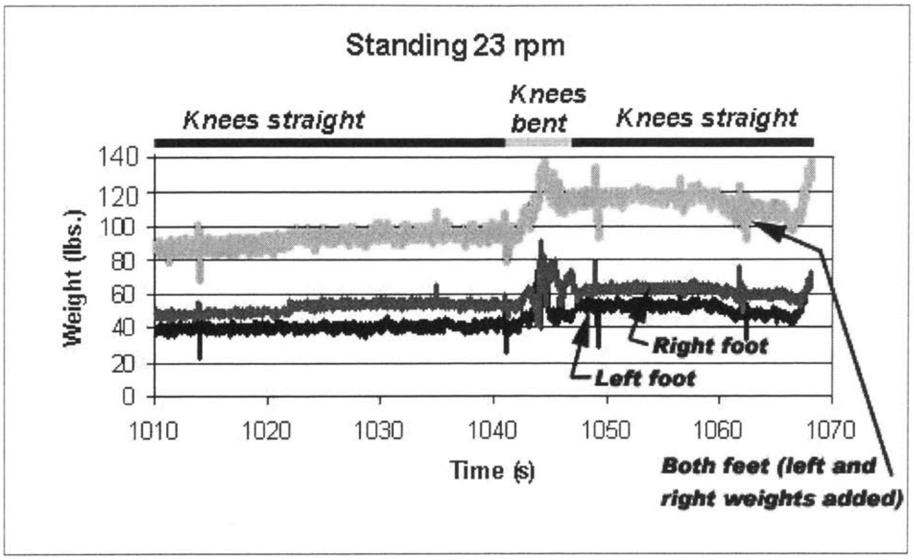


Figure 29. The strain gauges from the Contek scales stick after an extra force is applied. After bending his knees, the subject attains a total weight increase of 20 lbs. This is the 230 lb. subject.

3.2.3 Coriolis accelerations on knees

We investigated the possibility that subjects exercising on the centrifuge would experience Coriolis accelerations, described by the equation:

$$\vec{a}_{Coriolis} = 2\vec{\omega} \times \vec{v} \qquad \textbf{Equation 9}$$

where $\vec{a}_{Coriolis}$ is the Coriolis acceleration, $\vec{\omega}$ is the angular velocity of the centrifuge, and $\vec{v}$ is the radial velocity. Therefore, when viewed from above, if the subject moves his knee towards the rim of the centrifuge while the centrifuge is rotating clockwise, he will experience a lateral acceleration pushing his leg and knee to the right side (Figure 30).

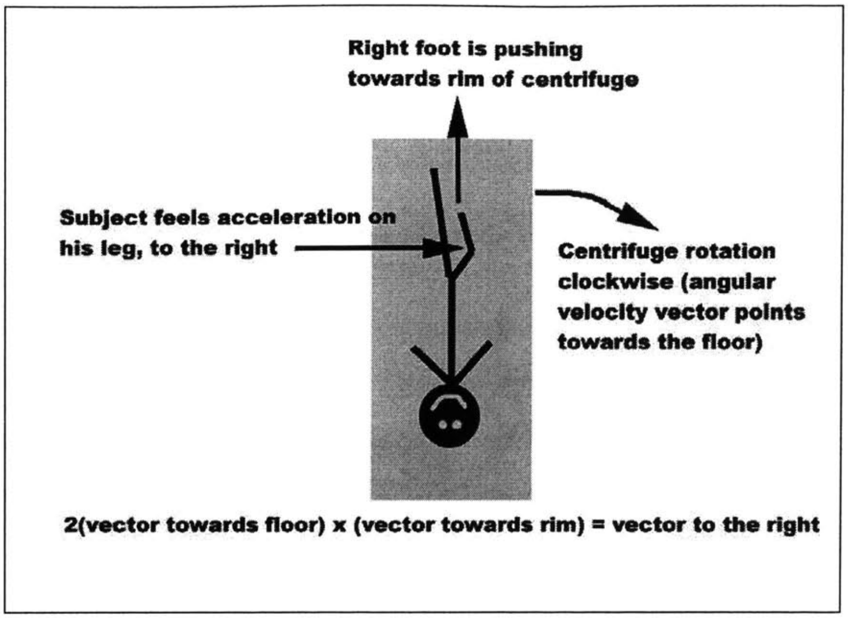


Figure 30. Diagram of Coriolis acceleration felt by a subject moving his leg towards centrifuge rim.

I performed a validation study with three subjects (two female, one male) to gain some information on this potential concern.

Protocol and analysis

The centrifuge was set up with a video camera mounted above the subject's head, pointed at his knees, to which we strapped yellow markers (Figure 31). The subject was asked to exercise while the centrifuge was stationary, when the centrifuge was spinning at 23 rpm, and after the centrifuge was stopped. The post-spinning exercise was performed to check for after-effects of the Coriolis accelerations on the knees (overcompensation in the opposite direction). All three phases were run for both stair-stepping and knee bends.

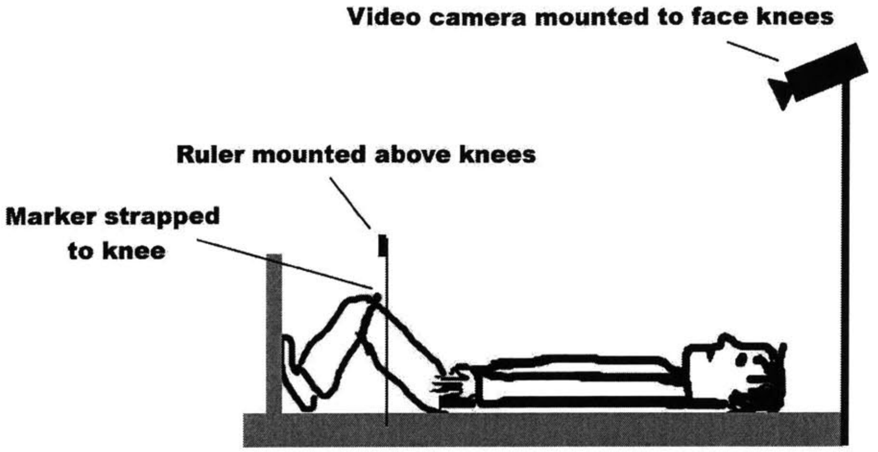
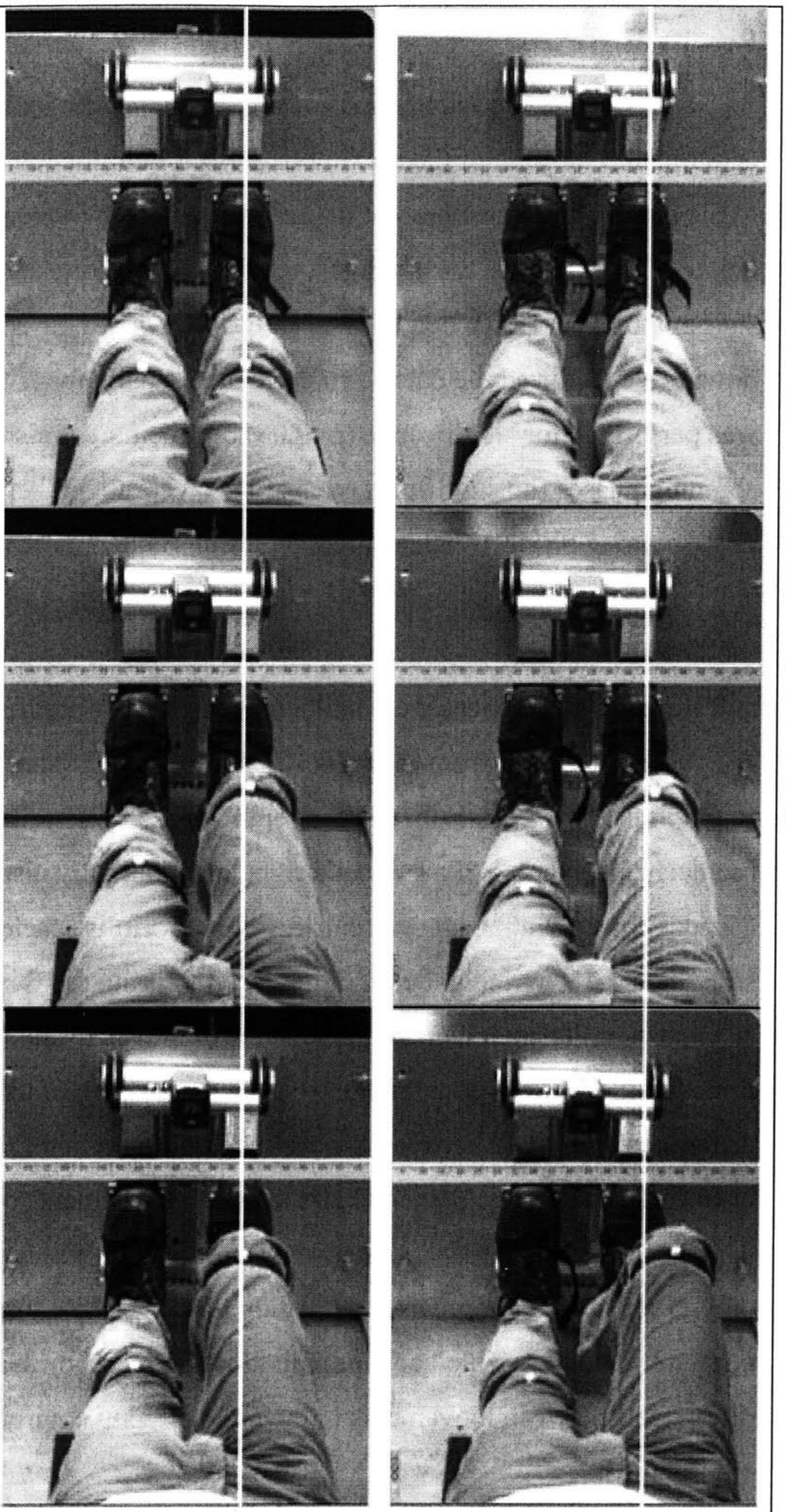


Figure 31. Setup for measurements of Coriolis forces on knees.

Video data was analyzed frame by frame on a computer screen, and the yellow markers were matched with the inch marks on the ruler. The maximum deflection to the left and right was recorded for each movement (up and down, ten cycles). Figure 32 shows still frames from the video data, and the right hand column, showing a movement in the spinning environment, shows the knee deflecting due to the Coriolis acceleration.



Right knee extended

Right knee partially flexed

Right knee flexed

Figure 32. Still images from video data of knee deflection. The left hand column (top, middle, then bottom) shows a knee being flexed in the non-spinning environment, and the right hand column shows a knee movement in the spinning environment. The white lines show the starting position of the knee movement.

Results

We found total deflections of up to three inches during spinning. Total deflection is defined as the sum of the maximum deflection to the left and the maximum deflection to the right of the starting point of the knee, for each movement of the exercise (up or down). Table 6 gives the average knee deflections for each knee of each subject, for stair-stepping and knee bends. The values shown are for 20 movements, ten up and ten down. We analyzed the data from each knee separately using SYSTAT. A paired t-test was performed for significance ($p<0.05$) between the pre-spinning and the during-spinning phases (no significant after-effects were found between the pre-spinning and post-spinning phases). The starred values in Table 6 indicate instances in which the pre-spinning and during-spinning knee deflections were significantly different. When looking at each knee separately, and when looking at the difference between knee bends and stepping, differences were neither consistent nor predictable.

It is apparent from the values in Table 6 that greater deflections were sometimes found in the "pre" phase than in the "spin" phase. A possible reason for this is individual biomechanics: that is, if a subject's right knee normally displaces medially when flexed ("knock-kneed"), then on our centrifuge, the Coriolis accelerations could effectively straighten the longitudinal path of movement during the flexing motion. Looking separately at the up and down movements of the knee, and taking into account which direction the Coriolis acceleration was acting for each of those movements, no clear difference was found between the pre- and during-spinning phases. There was also no clear difference between medial and lateral displacements due to Coriolis accelerations. A probable reason for lack of statistical significance was the small number of measurements, and imprecise acquisition of data (visual inspection of video data). Future analysis should take into account individual biomechanics, and look only for the absolute differences between movements in the non-spinning environment and the spinning environment.

Interestingly, for most trials, subjects 2 and 3 had significantly different knee deflections during centrifugation than before centrifugation, but the third subject (subject 1) did not show as much difference. The two affected subjects had little or no prior experience exercising on the centrifuge, but the third subject had exercised while spinning on the centrifuge many times prior to this study. Adaptation to Coriolis accelerations during arm reaching movements has been demonstrated in large-radius rotating rooms (Lackner and Dizio 2003); it is possible that subjects may adapt to Coriolis accelerations acting on the knees. Further studies are needed to establish if there is an adaptive training effect.

Table 6. Average knee deflections in inches for each subject. Starred values indicate a significant difference between the Pre and Spin phases.

	Subject 1				Subject 2				Subject 3			
Knee	**Left**		**Right**		**Left**		**Right**		**Left**		**Right**	
Phase	**Pre**	**Spin**	**Pre**	**Spin**	**Pre**	**Spin**	**Pre**	**Spin**	**Pre**	**Spin**	**Pre**	**Spin**
Steps	0.5	0.8	0.8	1.0	2.8*	1.0*	2.7	0.7	0.2*	1.1*	1.1*	0.9*
Bends	0.4	0.6	0.8*	1.4*	1.3*	1.0*	0.4*	1.0*	2.0*	1.1*	1.0*	2.5*

4 DISCUSSION

Implementation of the exercise device on the centrifuge posed few mechanical problems. Validation required some stability elements to be added, but it is apparent that on this particular centrifuge, low impact (stair-stepping) exercise does not cause problematic rocking or instability. We did see changing angular velocity of the centrifuge caused by sliding along the centrifuge platform on the slider mattress. The magnitude of the moment of inertia (I_z) of a point mass (m) about the axis of rotation (z) is proportional to its distance from that axis (r), squared (Equation 10).

$$I_z = mr^2 \qquad \textbf{Equation 10}$$

As the center of mass of the subject moves away from the axis of rotation of the centrifuge, the moment of inertia increases. In the absence of any change in motor torque, the magnitude of the angular momentum (H) remains the same due to conservation of momentum; thus, the angular velocity (ω) must decrease, as described by Equation 11.

$$H = I_z\omega \qquad \textbf{Equation 11}$$

It will be necessary to implement a closed loop controller for the centrifuge motor to address the changing angular velocity during centrifugation.

The pilot studies outlined in Section 3.2 demonstrate the feasibility of exercise in artificial gravity from a physiological standpoint. Several findings are worth a detailed discussion. One point of interest was that the heart rate and systolic blood pressure increased more when the subject exercised while not spinning, than while spinning. I am confident that this does not imply that exercise during centrifugation is not a "good workout". Previous authors (Greenleaf, Bernauer et al. 1989), have shown that exercise during centrifugation effectively maintained work capacity and aerobic endurance, and also maintained certain aspects other of cardiovascular function, including baroreceptor sensitivity (Caiozzo, Rose-Gottron et al. 2004), venous return, and cardiac output (Vil'-Vil'yams and Shul'zhenko 1980). Additionally, exercise during centrifugation increased tolerance to high g-levels (Iwase, Fu et al. 2003). For this study, we determined that our heart rate and blood pressure results were due to the nature of the exercise device. Standing in Earth's gravity, the stair-stepper resists the weight of the user using a damper under each foothold. When a subject is supine on the slider mechanism (simulating 0-g), and pushes against the foothold, she simply pushes off the foothold. In order to push one foothold down, she must pull the other foot up towards her body, pulling against the damper of the other foot. This is a much more difficult, unnatural, and tiring motion than pushing the damper down. The knee bends were also more difficult when not spinning, since it was also necessary to pull with both legs, rather than to push and then relax for the remaining part of the cycle. This unexpected outcome brought up an interesting characteristic of concentric and eccentric exercise, and the importance of eccentric exercise in space (Convertino 1991). On Earth, eccentric exercise is quite natural; the foot pushes against the ground with every step, or upon standing up from a chair. Without gravity, such eccentric motions are harder to produce. This is exactly what happened here: the stair-stepper device, without the assistance of gravity, was generally a concentric (pulling) exercise machine. With increasing artificial gravity, it became more and more an eccentric exercise machine, as it would be on Earth. Our findings also indicate that the stair-stepper may function as a resistive exercise device in addition to functioning as an aerobic conditioning device. In practice, combining cardiovascular and resistive exercise would save time, launch weight, and room in the spacecraft.

We also found another unexpected result, involving the reaction forces on the stair-stepper footholds. This presents an advantage of the stair-stepper over cycle ergometry: the possibility that it allows for "impact" exercise. While exercising energetically (so that the stair-stepper footholds bottom out), subjects experience impulsive forces in a manner similar to walking (Figure 28). This has promising implications as a countermeasure, as dynamic impact exercise is extremely useful in space (see Section 1.2), since astronauts don't experience the high longitudinal loads and impacts necessary to build and maintain bone density. I suggest that the stair-stepper mounted to a short-radius centrifuge offers an alternative option for impact exercise in space (aside from the treadmill and harness with a bungee cord), with the added benefit to the cardiovascular system of the artificial gravity environment. As expected, subjects experienced higher forces on their feet in the 30 rpm environment (up to 71% body weight when not exercising) than in the 23 rpm environment. Future work should attempt to identify the ideal angular velocity for this short-radius centrifuge, to maximize forces on the feet without exceeding the venous return capability of the cardiovascular system, or provoking motion sickness too rapidly. Other centrifuge studies have identified g-level tolerances with respect to the cardiovascular system (Piemme, Hyde et al. 1966, Iwase, Fu et al. 2003), but the tolerances must also take into consideration motion sickness susceptibility.

Coriolis accelerations caused significant deflections of the knees for some trials of the three subjects (Section 3.2.3). Future studies to study the effects of Coriolis accelerations should address the following questions: Is there a difference between medial and lateral displacements of the knee? Is there a difference in the effect of Coriolis accelerations when the leg muscles are activated (such as pushing up from a knee bend) versus when the muscles are less activated (flexing the knees)? Is there an adaptive training affect as subjects gain experience exercising on the centrifuge? Subjects also reported feeling a side-to-side rocking in their hips; this was not measured. It is possible that repeated exercise motions of the legs, affected by Coriolis accelerations, will cause pain or damage to the knees. If rocking of the hips is involved, lower back problems could also occur. It would be possible to avoid these Coriolis accelerations by positioning the subject on his or her side (such as Kreitenberg, Witmer et al. 2000). In this way, $\vec{\omega}$ and $\vec{v}$ would still be in the same direction as on our centrifuge, but the motion out of the plane of rotation would be in the direction that the knee bends as on a bicycle. This side-positioning introduces a new set of problems with respect to motion sickness and disorientation that has not been studied on our centrifuge; adaptation studies have until now been limited to head turns from the nose-up position (e.g. Brown 2002, Adenot 2004, Bruni 2004).

To summarize the "lessons learned" from the construction and validation of the exercise system:

- Radial movements of a subject's center of mass on the centrifuge change its moment of inertia, which changes the angular velocity. This requires a controller for the motor, or at the very least a satisfactorily stable support shaft.
- Rather than testing exercise while spinning versus exercise while not spinning, it may be more relevant to test exercise while spinning versus exercise while not spinning but *using bungee cords*, as the astronauts do. In this way, we could better compare our artificial gravity exercise system with the current exercise systems in space, using the subject's supine position as a simulation of 0-g.
- Impact exercise is important and should be exploited! If a cycle ergometer is used instead of a stair-stepper, impact may be possible through some type of catch mechanism installed in the cycle gear.
- It may be wise to tailor the construction of the system such that the subject is on his side, to avoid the effect of Coriolis accelerations.

For use in space, a short radius centrifuge could be modified to have spaces for two or even four people. It would require less structural reinforcement, since there is no bending moment due to the weight of the astronaut and the equipment on it. The exercise system we used is simple and requires no external power, which would be desirable for space flight, but it may be necessary to size down this exercise system to comply with launch weight requirements.

This project has demonstrated the feasibility of a stair-stepper on a centrifuge; other researchers (Iwase, Fu et al. 2003, Kreitenberg, Witmer et al. 2000, Greenleaf, Gundo et al. 1997) have demonstrated the feasibility of a bicycle ergometer on a short radius centrifuge. Are other exercise devices even better suited to artificial gravity? The stair-stepper allows for some impact loading; would it be possible to mount a small treadmill to a centrifuge? Another possibility for exercise in artificial gravity is a resistive exercise device mounted to the centrifuge. Such a device might include a squatting capability, and possibly arm exercisers. It is difficult to say if this would have musculoskeletal advantages over the Resistive Exercise Device used aboard the ISS.

This study did not address the effectiveness of exercise in artificial gravity, which is clearly an important next step if this is to be considered as a space flight countermeasure. We have shown that it is possible to exercise on the centrifuge; now we must show whether or not it is desirable. Then, if it is desirable, what protocol is the most efficient for astronauts during a long-duration space flight?

Effectiveness should be studied as a somewhat long-term project, and eventually in conjunction with bed rest. The major limitation for an experiment without bed rest would be that both the control and experimental groups would be living in 1-g, so their bodies would not be deconditioned as astronauts' bodies would be. One solution is to use subjects who do not exercise regularly. I recommend the following three groups (amount of exercise and duration of the experiment are estimates):

1) **Exercise in artificial gravity.** Subjects exercise for four hours per week while spinning on the centrifuge.
2) **Earth-based exercise.** Subjects exercise for four hours per week on the same device (stair-stepper), upright in Earth's gravity.
3) **Exercise in 0-g.** Subjects exercise for four hours per week on the same device mounted to the non-spinning centrifuge, using bungee cords and a harness, as the astronauts currently use.

Each week, resting heart rate, blood pressure, and $\dot{V}_{O_2}$-max would be recorded as indicators of the subject's aerobic progress. It may be desirable to take strength measurements as well. Aerobic progress would be compared for each group; we would hope to find similar results for the Earth exercise group and the AG exercise group.

The efficiency of exercise must then be studied, to design an exercise protocol for astronauts. How much must the subjects exercise, and with what frequency? These studies must be done to make this countermeasure feasible for space flight.

5 CONCLUSION

This study demonstrates the feasibility of exercise in artificial gravity in the context of the short-radius centrifuge at MIT. The study demonstrated the successful implementation of a stair-stepper device on a short radius centrifuge, to allow research in the area of dual countermeasures: artificial gravity and exercise. This is the first study of its kind to use a stair-stepper as the exercise device aboard an artificial gravity centrifuge. Structural modification of the centrifuge with additional support elements included support struts on the rotation shaft, a new, redesigned footplate, and horizontal support beams. A slider mattress facilitated the radial movement of the subject's body during exercise. Preliminary physiological validation of such a countermeasure required several pilot studies.

Heart rate and blood pressure increase normally with exercise in artificial gravity. Interestingly, it was more difficult (higher heart rate and systolic blood pressure) for the subject to exercise without artificial gravity than it was to exercise with it. This was due to the necessity of "pulling" in addition to "pushing" off of the exercise device; it is possible that the human body is more attuned to eccentric motion (common in Earth's gravity) than concentric motion (exercise more easily utilized in space). Foot reaction force sensors indicated that approximately half of the subject's weight was exerted on the footplate when lying still in a 23 rpm rotating environment (head on-center). Subjects were able to increase the reaction forces on their feet by up to 40 lbs. by exercising forcefully, and spinning the centrifuge at 30 rpm increased artificial gravity body weight up to 71% of the subject's actual weight. Lateral and medial deflection of the knees due to Coriolis accelerations when stair-stepping and when doing knee bends was also measured. Deflections of up to three inches were found, and in some cases were significantly greater ($p<0.05$) than the deflections in a non-rotating environment. These deflections must be further characterized in future studies. Future studies should also address effectiveness of exercise in artificial gravity, and outline recommended protocols for this dual countermeasure to be used in space flight.

REFERENCES

Unistrut Metal Framing General Engineering Catalog. Wayne, MI, Unistrut Corporation. **2005**.

Adenot, S. (2004). "Artificial Gravity: Changing the Intensity of Coriolis Cross-Coupled Stimulus with Head-Angle." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Adenot, S., T. Jarchow, et al. (2005). Adaptation of VOR to Coriolis Stimulation. Clinical and Basic Oculomotor Research. S. Ramat and D. Straumann. New York, The New York Academy of Sciences. **1039:** 88-96.

Bamman, M. M. and J. F. Caruso (2000). "Resistance exercise countermeasures for space flight: implications of training specificity." J Streng & Con Res **14**(1): 45-49.

Bassey, E. J. and S. J. Ramsdale (1994). "Increase in femoral bone density in young women following high-impact exercise." Osteoporos Int **4**(2): 72-75.

Brown, E. (2002). "Artificial Gravity: The Role of Visual Inputs in Adaptation to Short-Radius Centrifugation." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Brown, E. (2002). "Artificial Gravity: The Role of Visual Inputs in Adaptation to Short-Radius Centrifugation." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Bruni, S. (2004). "Artificial Gravity: Neurovestibular Adaptation to Incremental Exposure to Centrifugation." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Burton, R. R. and L. J. Meeker (1992). "Physiologic validation of a short-arm centrifuge for space application." Aviat Space Environ Med **63**: 476-481.

Caiozzo, V. J., C. Rose-Gottron, et al. (2004). "Hemodynamic and metabolic responses to hypergravity on a human-powered centrifuge." Aviat Space Environ Med **75**: 101-108.

Cann, C. E. (1997). Response of the Skeletal System to Spaceflight. Fundamentals of Space Life Sciences. S. E. Churchill. Malabar, Krieger. **1:** 83-103.

Convertino, V. A. (1991). "Neuromuscular aspects in development of exercise countermeasures." Physiologist **34**(1, Suppl.): S-125 - S-128.

Convertino, V. A. and H. Sandler (1995). "Exercise countermeasures for spaceflight." Acta Astronaut **35**(4/5): 258-270.

Coolahan, J. E., A. B. Feldman, et al. (2004). Integrated physiological stimulation of an astronaut exercise protocol. 55th International Astronautical Congress, Vancouver, Canada.

D'Aunno, D. S., R. R. Robinson, et al. (1992). "Intermittent acceleration as a countermeasure to soleus muscle atrophy." J Appl Physiol **72**(2): 428-433.

Diamandis (1988). "Artificial Gravity Sleeper." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Greenleaf, J. E., E. M. Bernauer, et al. (1994). "Isokinetic strength and endurance during 30-day 6 degree head-down bed rest with isotonic and isokinetic exercise training." Aviat Space Environ Med **65**: 45-50.

Greenleaf, J. E., E. M. Bernauer, et al. (1989). "Work capacity during 30 days of bed rest with isotonic and isokinetic exercise training." J Appl Physiol **67**(5): 1820-1826.

Greenleaf, J. E., R. Bulbulian, et al. (1989). "Exercise-training protocols for astronauts in microgravity." J Appl Physiol **67**(6): 2191-2204.

Greenleaf, J. E., D. P. Gundo, et al. (1997). Cycle-powered short radius (1.9 m) centrifuge: effect of exercise versus passive acceleration on heart rate in humans. NASA Technical Memorandum 110433.

Greenleaf, J. E., J. Vernikos, et al. (1992). "Effect of leg exercise training on vascular volumes during 30 days of 6 degree head-down bed rest." J Appl Physiol **72**(5): 1887-1894.

Greenleaf, J. E., C. E. Wade, et al. (1989). "Orthostatic responses following 30-day bed rest deconditioning with isotonic and isokinetic exercise training." Aviat Space Environ Med **60**: 537-542.

Guyton, A. C. and J. E. Hall (2000). Textbook of Medical Physiology, Tenth Edition, W.B. Saunders Company.

Hastreiter, D. (1997). "Artificial Gravity as a Countermeasure to Spaceflight Deconditioning: The Cardiovascular Response to a Force Gradient." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Hastreiter, D. and L. R. Young (1997). "Effects of gravity gradient on human cardiovascular responses." J Gravit Physiol **4**(2): 23-26.

Hecht, H., J. Kavelaars, et al. (2001). "Orientation illusions and heart-rate changes during short-radius centrifugation." J Vestib Res **11**: 115-127.

Heldt, T., E. B. Shim, et al. (2002). "Computational modeling of cardiovascular response to orthostatic stress." J Appl Physiol **92**: 1239-1243.

Iwasaki, K., K. Hirayanagi, et al. (1998). "Effects of repeated long duration +2Gz load on man's cardiovascular function." Acta Astronaut **42**(1-8): 175-183.

Iwase, S., Q. Fu, et al. (2003). "Effects of simultaneous load of centrifuge-induced artificial gravity and ergometer exercise as the countermeasures for space deconditioning on human cardiovascular function." J Gravit Physiol **10**(1): P-101 - P-105.

Jennings, R. T., J. R. David, et al. (1988). "Comparison of aerobic fitness and space motion sickness during the shuttle program." Aviat Space Environ Med **59**: 448-451.

Johnson, R. L., G. W. Hoffler, et al. (1977). Lower Body Negative Pressure: Third Manned Skylab Mission. Biomedical Results from Skylab. R. S. Johnston and L. F. Dietlein. Washington, D.C., National Aeronautics and Space Administration, SP-377.

Kozlovskaya, I. B. and A. I. Grigoriev (2004). "Russian system of countermeasures on board of the International Space Station (ISS): the first results." Acta Astronaut **55**: 233-237.

Kreitenberg, A., J. B. Witmer, et al. (2000). Space Cycle - ground-based prototype development. American Institute of Aeronautics and Astronautics, AIAA 2000-5207.

Lackner, J. R. and P. A. Dizio (2003). "Adaptation to rotating artificial gravity environments." J Vestib Res **13**: 321-330.

LeBlanc, A. and V. Schneider (1992). "Countermeasures against space flight related bone loss." Acta Astronaut **27**: 89-92.

Lee, S. M. C., K. Cobb, et al. (2004). "Foot-ground reaction force during resistive exercise in parabolic flight." Aviat Space Environ Med **75**(5): 405-412.

Lyne, L. E. (2000). "Artificial Gravity: Evaluation of Adaptation to Head Using Subjective Measures." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Nicogossian, A., S. Pool, et al. (1995). "Status and efficacy of countermeasures for physiological deconditioning from space flight." Acta Astronaut **36**(7): 393-398.

Oganov, V. S., A. Bakulin, et al. (2000). "Results of studies of the effects of space flight factors on human physiological systems and psychological status, and between the NSBRI and IBMP." BONE **Section 4**.

Oman, C. (2001). Human Visual Orientation in Weightlessness, Springer Verlag.

Oman, C. (2005). Personal communication.

Piemme, T. E., A. Hyde, S, et al. (1966). "Human tolerance to Gz 100 percent gradient spin." Aerospace Medicine: 16-21.

Pollack, A. A. and E. H. Wood (1949). "Venous pressure in the saphenous vein at the ankle in man during exercise and changes in posture." J Appl Physiol **1**(9): 649-662.

Schneider, S. M., W. E. Amonette, et al. (2003). "Training with the International Space Station Interim Resistive Exercise Device." Med Sci Sports Exerc **35**(11): 1935-1945.

Sienko, K. H. (2000). "Artificial Gravity: Adaptation of the Vestibulo-Ocular Response to Head Movements during Short-Radius Centrifugation." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Taaffe, D. R., T. L. Robinson, et al. (1997). "High-Impact Exercise Promotes Bone Gain in Well-Trained Female Athletes." J Bone Miner Res **12**(2): 255.

Tesch, P. A. and H. E. Berg (1997). "Resistance training in space." Int J Sports Med **18**(Suppl. 4): S322-S324.

Thomas, D. (2005). Personal communication.

Thornton, W. E., G. W. Hoffler, et al. (1977). Anthropometric changes and fluid shifts. Biomedical Results from Skylab. R. S. Johnston and L. F. Dietlein. Washington, D.C., NASA SP-377.

Vil'-Vil'yams, I. F. and Y. B. Shul'zhenko (1980). "Functional state of the cardiovascular system under the combined effect of 28-day immersion, rotation of a short-arm centrifuge, and exercise on a bicycle ergometer." Kosmicheskaya Biologiya I Aviakosmicheskaya Meditsina **2**: 42-45.

Williams, D. R. (2003). "The biomedical challenges of space flight." Annu Rev Med **54**: 245-258.

Young, L. R. (2000). "Vestibular reactions to spaceflight: human factors issues." Aviat Space Environ Med **71**(9, Suppl.): A100-104.

Young, L. R. (2003). Artificial Gravity. Encyclopedia of Space Science and Technology. New York, John Wiley & Sons. **1:** 138-151.

APPENDIX A. CALCULATIONS: BODY WEIGHT IN ARTIFICIAL GRAVITY

Section 2.2.1 describes briefly the process of calculating a subject's body weight in artificial gravity; this section describes that process in more detail.

The force of artificial gravity due to centrifugation is:

$$F_{AG} = mr\omega^2$$ **Equation 12**

where F_{AG} is the force in pounds, m is the mass of the object in slugs, r is the distance from the center of rotation to the point of measurement in feet, ω is the angular velocity of the bed in radians per second.

To get a good estimate of the subject's weight in artificial gravity, I divide the subject's body into several major segments, which have different masses and lie at different radii from the center of rotation. I will also factor in the mass and radius of the top half of the slider, which, since it moves along with the subject when she is exercising, adds to the force of artificial gravity. Then, I must add up each of these segments to obtain the expected force for the subject to experience on her feet (Figure 33).

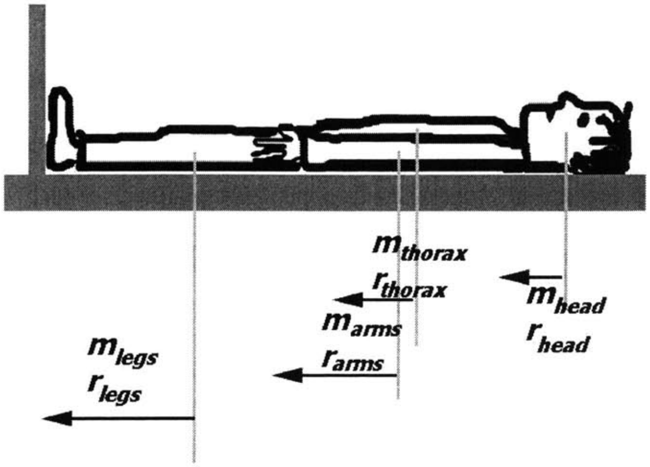


Figure 33. The body is divided into segments, each with some mass (*m*), at some distance (*r*) from the center of rotation.

The equation becomes:

$$F_{AG} = \left(m_{head}r_{head} + m_{thorax}r_{thorax} + m_{arms}r_{arms} + m_{legs}r_{legs} + m_{slider}r_{slider}\right)\omega^2 \qquad \textbf{Equation 13}$$

I take the radius of each segment to be the center of the segment; that is, if the arms range from 10 inches to 40 inches from the center of rotation, we take the radius to be 25 inches.

Using Diamandis's (1988) anthropometric assumptions, I have estimated percentages of total body weight for each of the body segments, and also estimated percentages of total body length. However, rather than attempting to calculate artificial gravity weight for every combination of weight and height, I will here assume "ideal" weight and height combinations. To do this I need typical body heights per unit body weight. I used general body weight ranges (medium frame), obtained from the Metropolitan Life Insurance Company tables (1983). I took the average of the minimum and maximum body weights per inch of height, and averaged men and women, in order to find one average weight for each height (Table 7). I then graphed weight versus height and found the regression equation (Figure 34). It is important to note that by taking the average, and then by flipping the axes (weight versus height instead of height versus weight), I am making gross assumptions about the anthropometry of humans. However, the purpose for obtaining height data was simply to get a more accurate number for to total artificial gravity weight of the subject.

Using Equation 13, I estimated the artificial gravity weight per 10 pounds of Earth weight. The values assume that there is no friction between the subject's back and the centrifuge surface; in other words, the only force acting along his body axis is his artificial gravity weight. As mentioned above, they take into account the mass and radius of the center of gravity of the top half of the slider. Mass and radii are given in slugs and feet, for final values in pounds. These calculations and the final values can be found in Table 8 (note that the table wraps around the page).

Table 7. Weights (ranges) for a given height of men and women. From: Metropolitan Life Insurance Company Tables (1983).

Inches	MenMin	MenMax	WomMin	WomMax	AVG WT.
58			109	121	115
59			111	123	117
60			113	126	119.5
61			115	129	122
62	131	141	118	132	130.5
63	133	143	121	135	133
64	135	145	124	138	135.5
65	137	148	127	141	138.25
66	139	151	130	144	141
72	157	170	148	162	159.25
73	160	174			167
74	164	178			171
75	167	182			174.5
76	171	187			179

From regression equation:	
Weight	Typical height
110	57.073
120	59.918
130	62.763
140	65.608
150	68.453
160	71.298
170	74.143
180	76.988

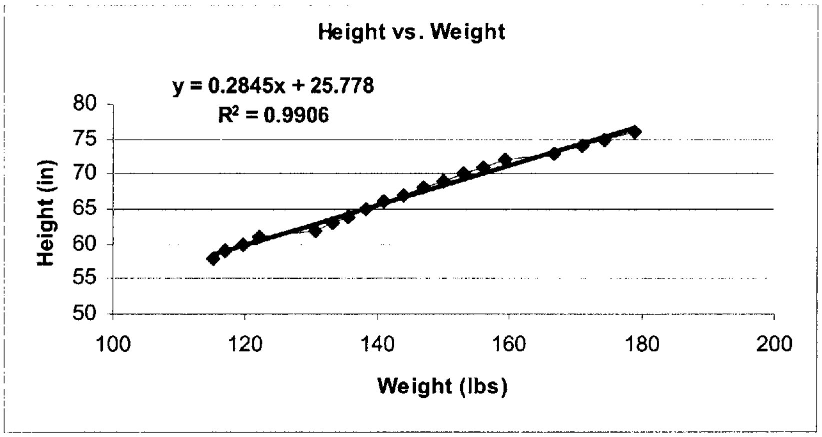


Figure 34. Height vs. Weight, given the data from Table 7.

Table 8. Calculations for total AG weight at 23 rpm and 30 rpm.

23 rpm	2.409 rad/s	Equation (ht and wt)
30 rpm	3.142 rad/s	ht=0.2845*wt+25.778

	Body part divisions		**110-lb. person**		**120-lb. person**	
	% weight	**% length**	**mass (slugs)**	**radius (ft.)**	**mass (slugs)**	**radius (ft.)**
Head	**5**	**6**	0.18	0.29	0.19	0.30
Thorax	**37**	**31**	1.26	1.48	1.38	1.55
Arms	**13**	**36**	0.43	1.69	0.47	1.78
Legs	**45**	**73**	1.54	3.48	1.68	3.65
Total body mass	**100**	**100**	3.41		3.72	
Slider			0.621	1.00	0.621	1.00
			Expected AG weight (lbs.)		**Expected AG weight (lbs.)**	
	23rpmWT		50.03		56.77	
	%normal		0.45		0.47	
	30rpmWT		85.10		96.58	
	%normal		0.77		0.80	

	130-lb. person		**140-lb. person**		**150-lb. person**	
	mass (slugs)	**radius (ft.)**	**mass (slugs)**	**radius (ft.)**	**mass (slugs)**	**radius (ft.)**
Head	0.21	0.31	0.23	0.33	0.24	0.34
Thorax	1.49	1.63	1.61	1.70	1.72	1.77
Arms	0.51	1.86	0.55	1.95	0.59	2.03
Legs	1.82	3.82	1.96	4.00	2.10	4.17
Total body mass	4.03		4.34		4.65	
Slider	0.621	1.00	0.621	1.00	0.621	1.00
	Expected AG weight (lbs.)		**Expected AG weight (lbs.)**		**Expected AG weight (lbs.)**	
23 rpm wt.	63.94		71.52		79.53	
% normal	0.49		0.51		0.53	
30 rpm wt.	108.77		121.67		135.29	
% normal	0.84		0.87		0.90	

	160-lb. person		170-lb. person		180-lb. person	
	mass (slugs)	radius (ft.)	mass (slugs)	radius (ft.)	mass (slugs)	radius (ft.)
Head	0.26	0.36	0.27	0.37	0.29	0.38
Thorax	1.84	1.85	1.95	1.92	2.07	2.00
Arms	0.63	2.12	0.67	2.20	0.71	2.28
Legs	2.24	4.34	2.38	4.52	2.52	4.69
Total body mass	4.96		5.27		5.58	
Slider	0.621	1.00	0.621	1.00	0.621	1.00
	Expected AG weight (lbs.)		Expected AG weight (lbs.)		Expected AG weight (lbs.)	
23 rpm wt.	87.96		96.81		106.08	
% normal	0.55		0.57		0.59	
30 rpm wt.	149.63		164.68		180.45	
% normal	0.94		0.97		1.00	

APPENDIX B. TECHNICAL DRAWINGS FOR THE FOOTPLATE

Technical drawings of the footplate are shown below. All dimensions are in inches. The majority of the footplate was constructed from aluminum 6061, except for the crossbars seen in View 2, which are steel Unistrut beams, and the knee braces (diagonal cross-pieces) seen in View 3, which are steel knee braces.

All drawings were made using ProEngineer, 2001 Educational Version.

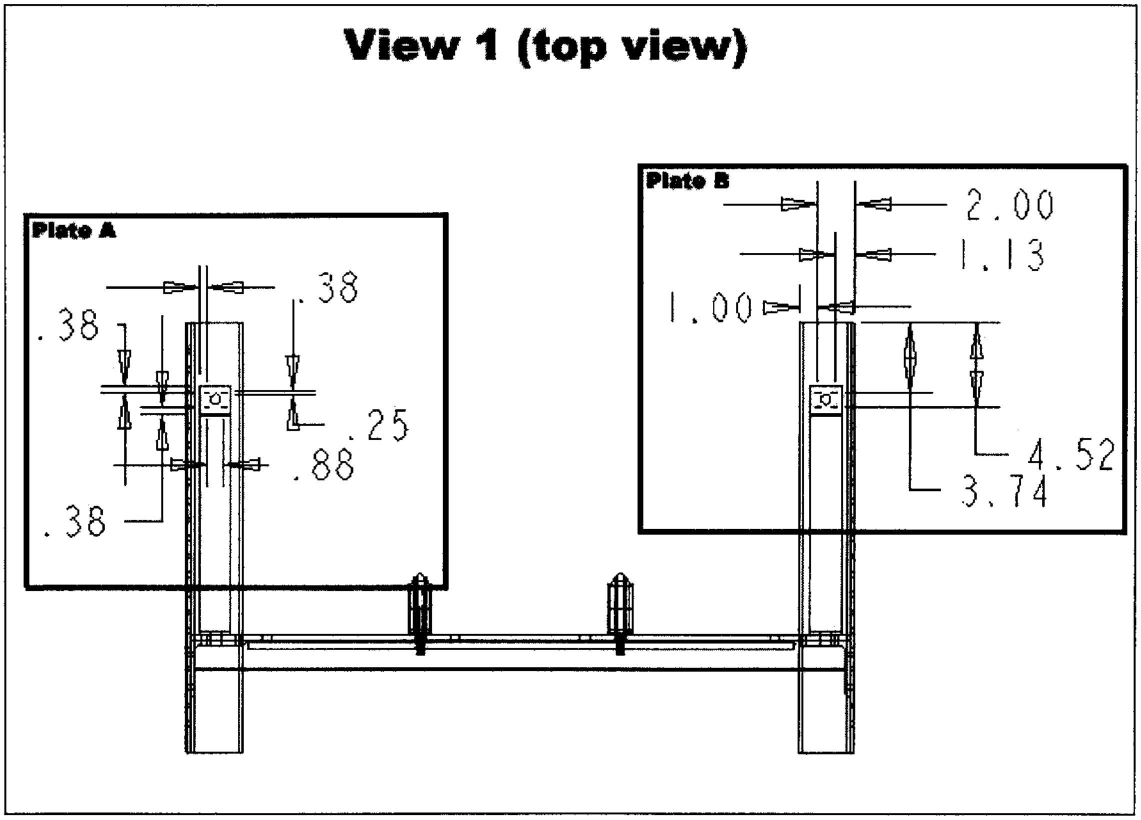


Figure 35. Technical drawing of footplate, top view.

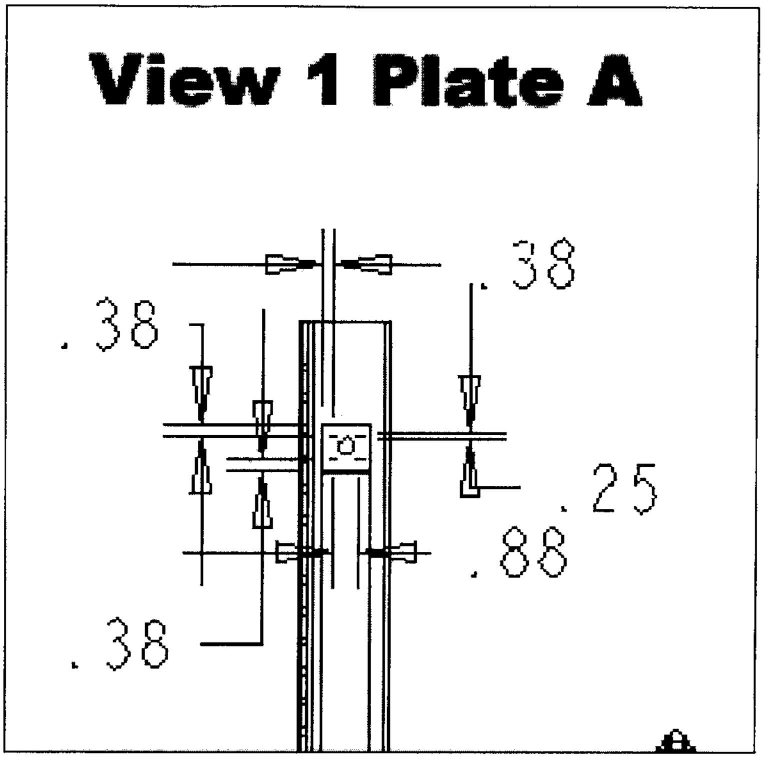


Figure 36. Zoom image of top view.

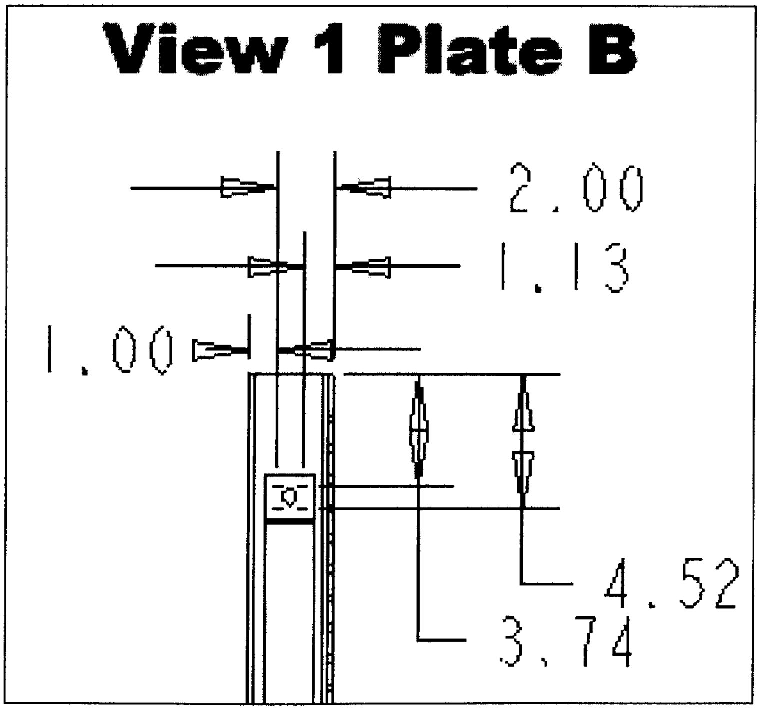


Figure 37. Zoom image of top view.

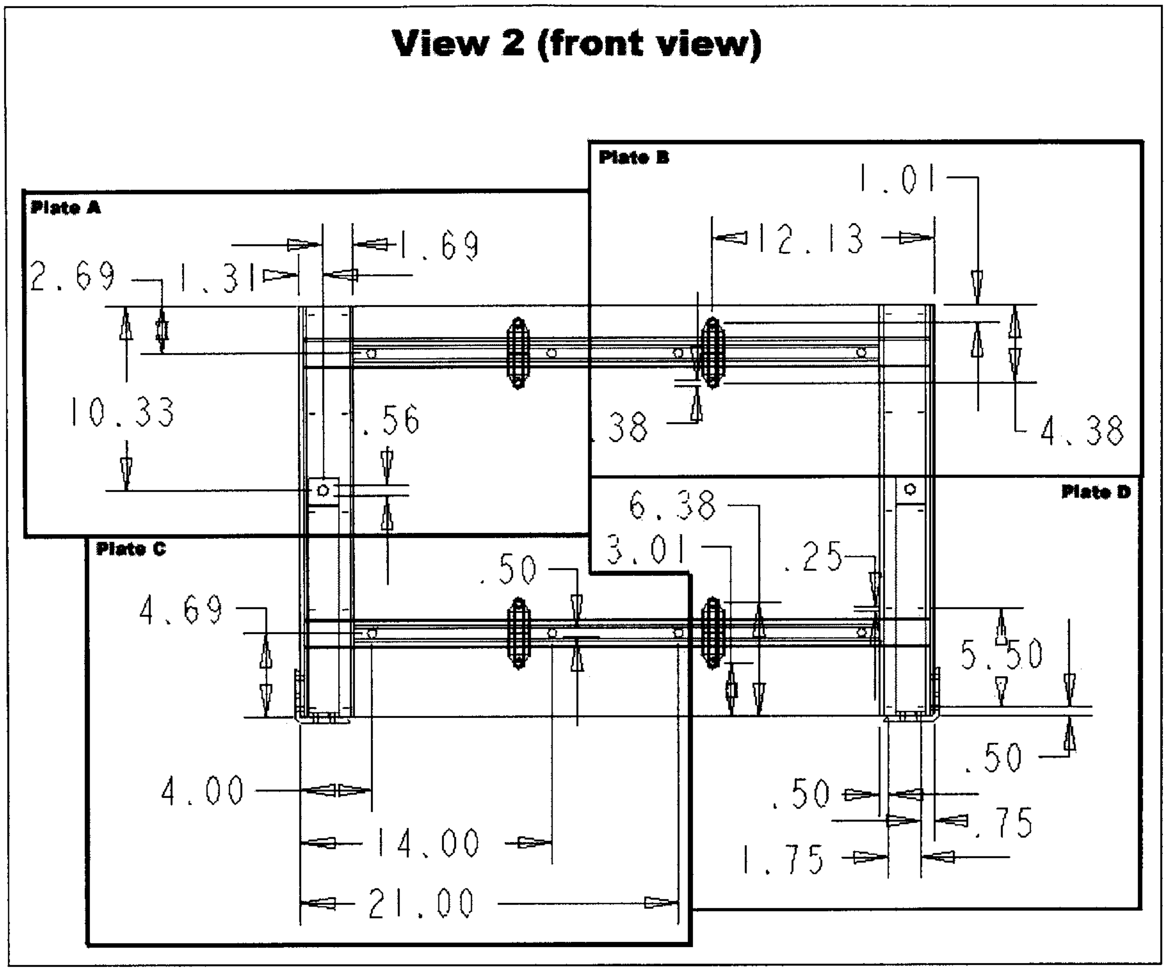


Figure 38. Technical drawing of footplate, front view.

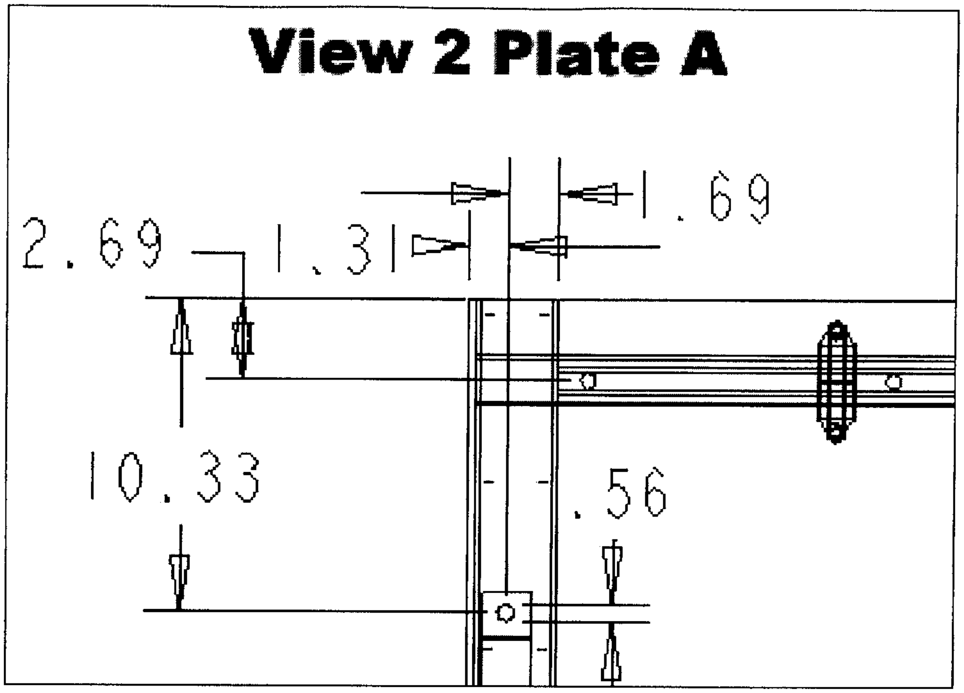


Figure 39. Zoom image of front view.

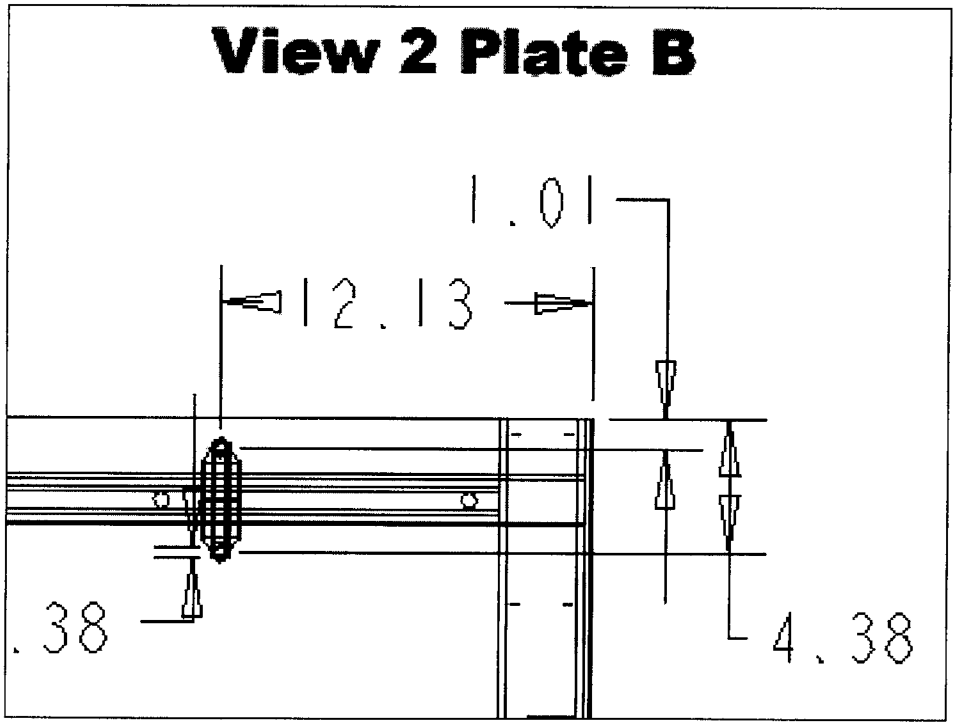


Figure 40. Zoom image of front view.

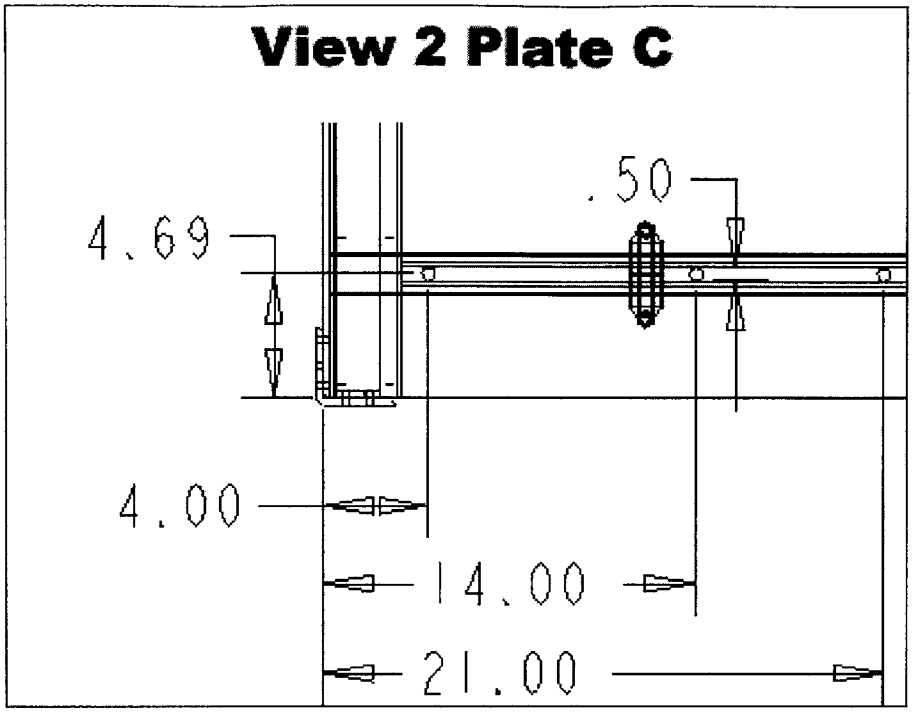


Figure 41. Zoom image of front view.

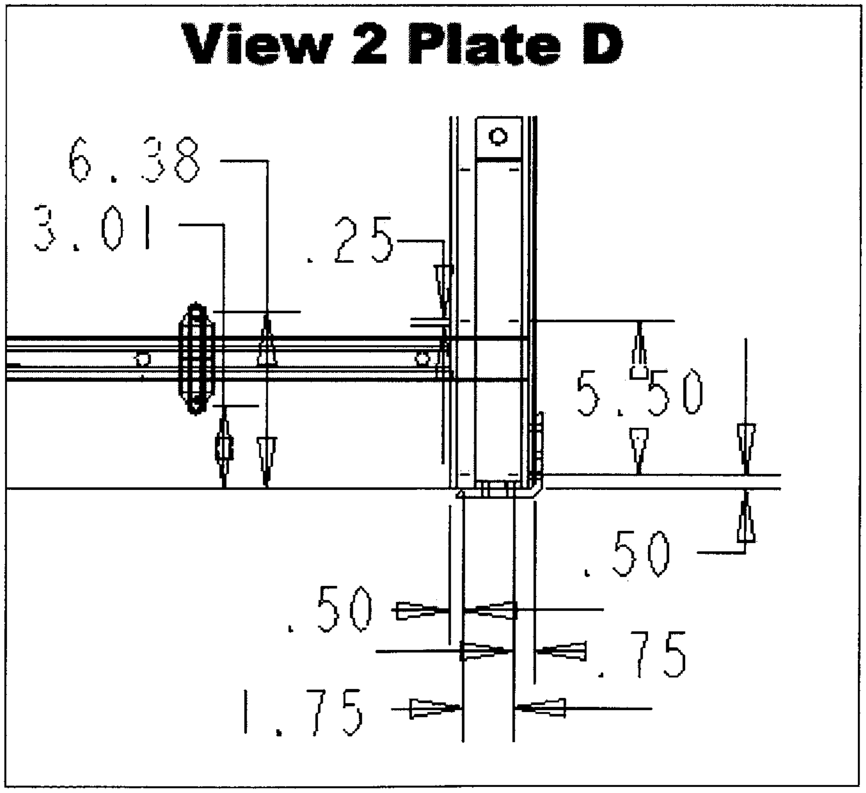


Figure 42. Zoom image of front view.

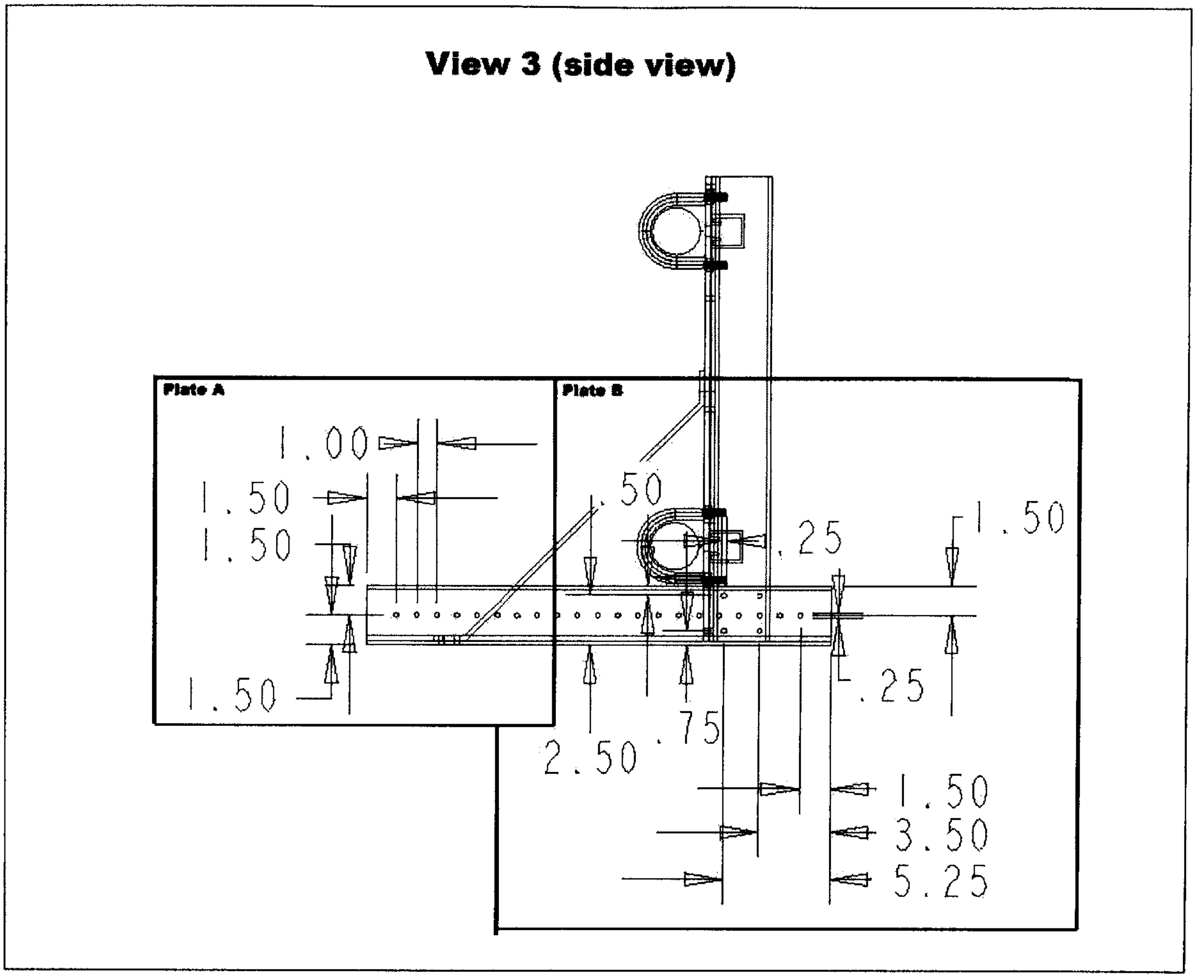


Figure 43. Technical drawing of footplate, side view.

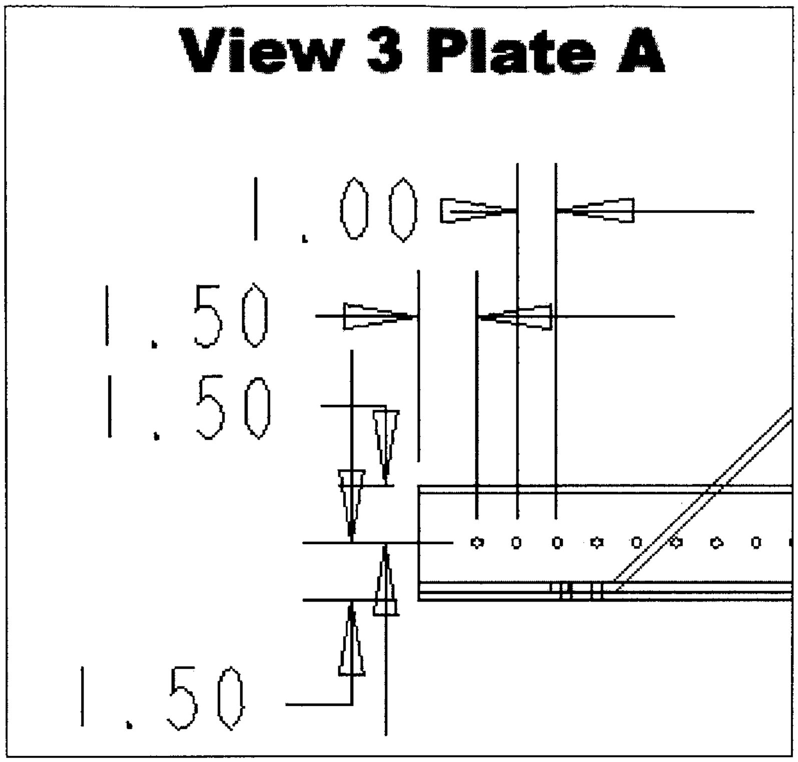


Figure 44. Zoom image of side view.

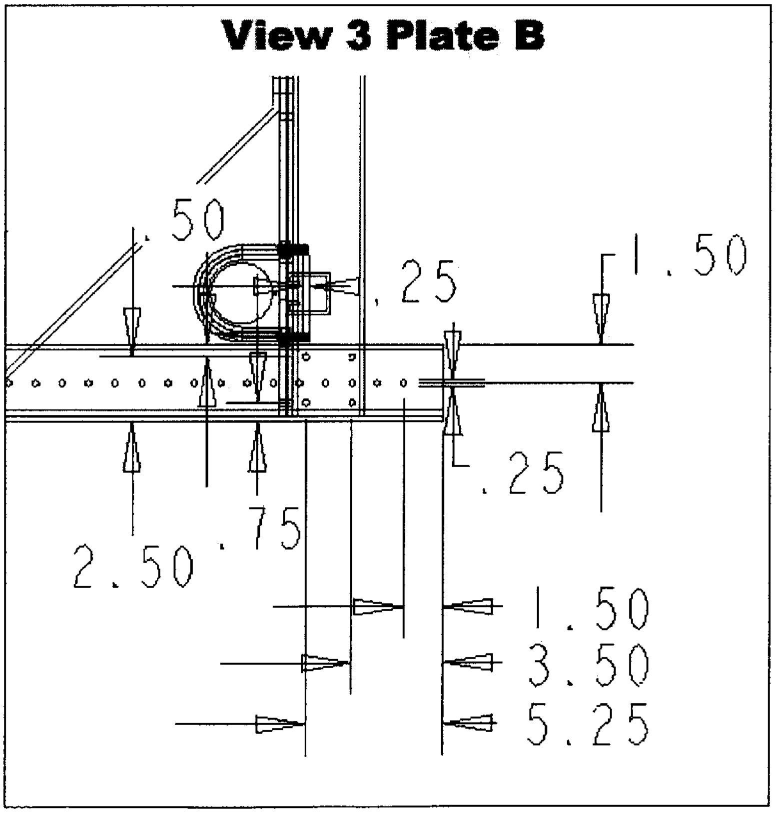


Figure 45. Zoom image of side view.

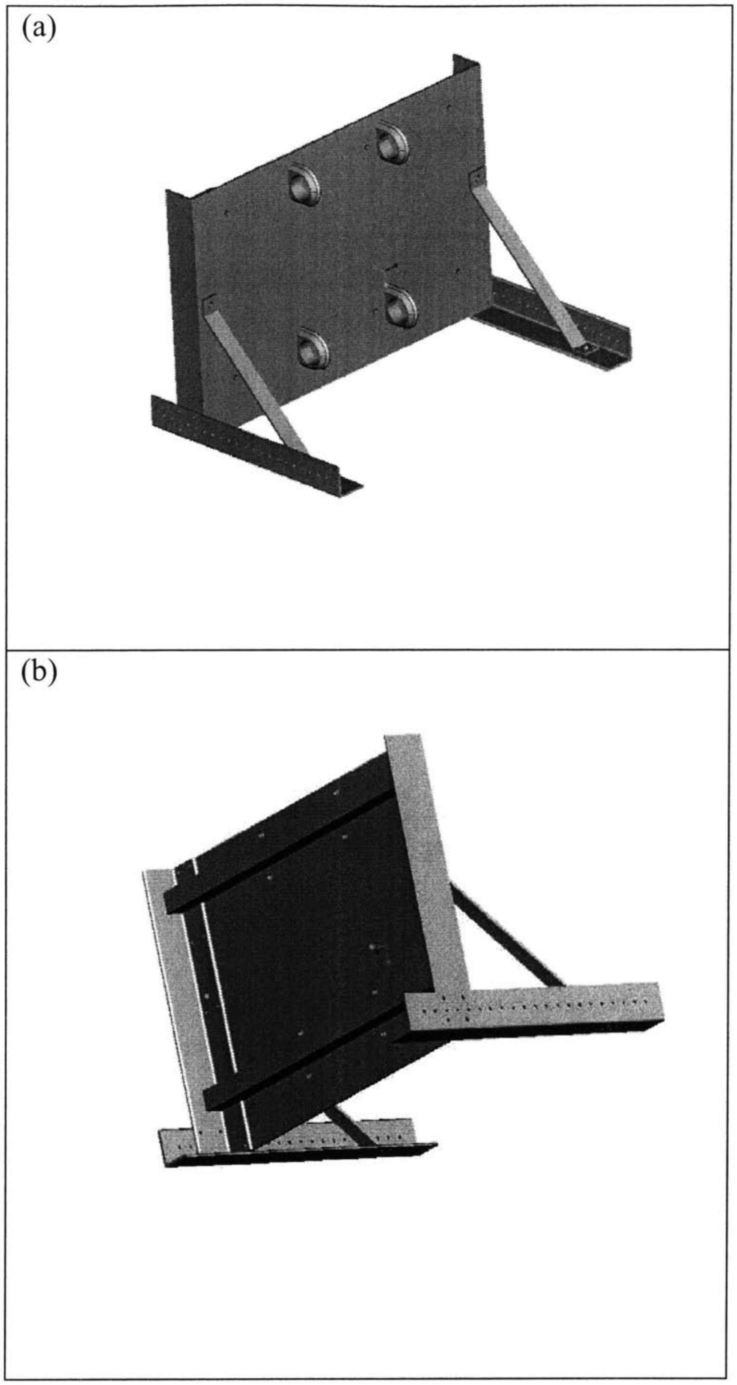


Figure 46. Shadow view of footplate, (a) front and (b) back.

APPENDIX C. UNISTRUT SUPPORT BEAMS: ENGINEERING SKETCH

Figure 47 was created by Ben Feinberg. He and Tom Walker were responsible for manufacturing the Unistrut support assembly for the centrifuge support shaft.

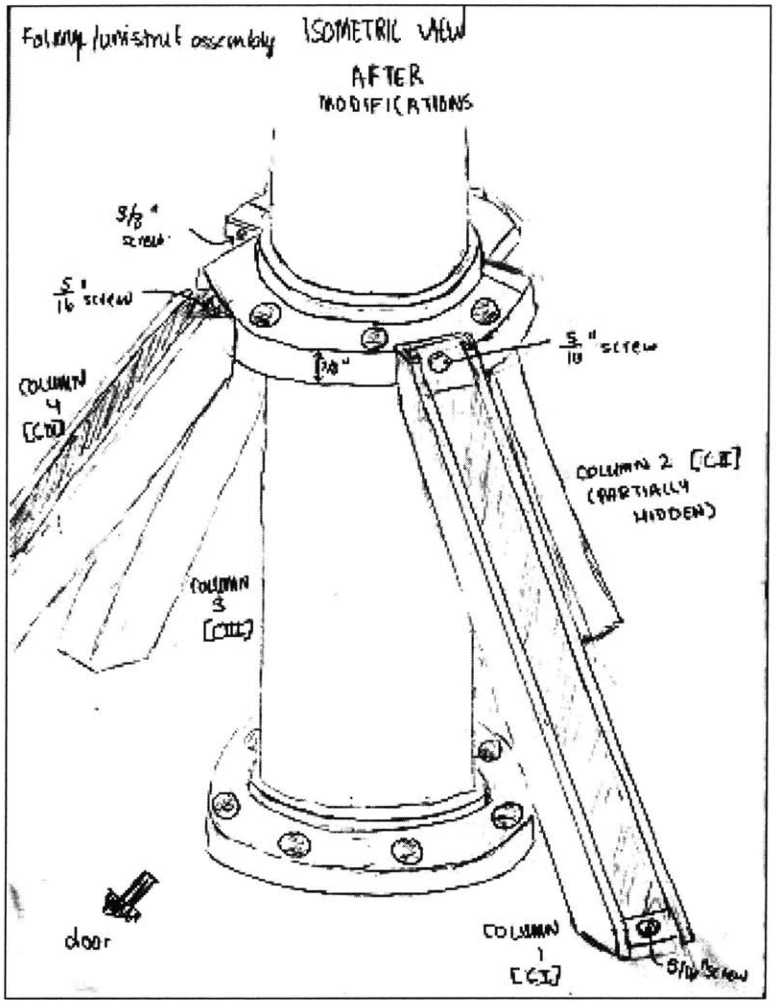


Figure 47. Sketch of the support strut assembly.

APPENDIX D. INFORMED CONSENT FORM

Protocol number 0405000759.

CONSENT TO PARTICIPATE IN BIOMEDICAL RESEARCH

Exercise During Artificial Gravity Through Centrifugation

You are asked to participate in a research study conducted by Laurence Young, Sc.D., Thomas Jarchow, Ph.D., and Jessica Edmonds, graduate student from the Department of Aeronautics and Astronautics Man-Vehicle Laboratory 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 have been asked to participate in this study because you have volunteered and meet the minimum health and physical requirements for our study. 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 research is completely VOLUNTARY. If you choose to participate you may subsequently withdraw from the study 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. If you choose not to participate, it will not affect your relationship with M.I.T. or your right to health care or other services to which you are otherwise entitled.

You should not participate in this study if you have any medical heart conditions, respiratory 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. In addition, you should not participate if you have any musculoskeletal, spinal, or other injury that prevents you from participating in low-impact exercise, such as exercise on a stair-stepper machine. The experimenter will check to see if you meet these requirements.

- **PURPOSE OF THE STUDY**

The purpose of this study is to implement an exercise device on the short-radius Artificial Gravity (AG) centrifuge. We aim to understand the physiological effects of exercise combined with centrifugation. Short radius centrifugation is currently being investigated as a countermeasure to the deleterious effects of weightlessness experienced during long duration spaceflight, and we are investigating the potential additional benefits of lower body exercise during centrifugation to increase the effectiveness of AG as a countermeasure.

- **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, exercise device, and data collection devices. Data collection devices include heart rate sensors (the over-the-counter chest strap, commonly used by athletes) and force sensors on the footplates. After your briefing, the experimenter will record your answers to basic questions about your health, and take your height, weight, blood pressure, and heart rate.

Before lying on the centrifuge, you will be asked to perform some type of exercise upright in the lab, which may be knee bends, use of a stair-stepper device, or other common exercise. Data will be collected during this time, and you will exercise for approximately ten minutes.

During the experiment you will lie on the centrifuge in the supine position. You will be asked to either place your head on a pillow or into a cushioned helmet at the center of the centrifuge that helps you not to turn your head. After lying down, the experimenter will collect data while the centrifuge is stationary, and allow you to rest for approximately ten minutes. After this rest period, you may perform exercise while the centrifuge is stationary. Data will be collected, and you will exercise in the supine position for approximately ten minutes.

The experimenter will ask you if you are ready before starting rotation. Your rotation on the AG centrifuge will not exceed the following parameters:

- Acceleration no greater than 1 revolution per minute, per second
- G-level at your heart no greater than 1g, AND PROPORTIONALLY GREATER G'S AT THE FEET (a "g-level" is defined as the acceleration or force that you would experience normally standing on earth)
- Time of rotation not exceeding 1 hour

Exercising may be in the dark and/or in the light. Your level of exercise (speed at which you pedal, perform knee bends, etc.) will be at your discretion. During this time and after the experiment you will be asked to report your subjective experience (how you feel, how you perceive exercise to be different from exercising in a static upright orientation, etc.). During and after the experiment you will be asked to report your motion sickness rating. These data will be recorded anonymously.

When the experiment is complete, the centrifuge will be stopped, and the experimenter may collect some additional data.

As a participant in experimental trials, you tentatively agree to return for additional trials (at most 5) 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 (which is estimated to last approximately 45 minutes), the time commitment is 20 minutes for the first briefing, 10 minutes for the upright exercise condition, and 10-60 minutes for other procedures before and after rotation. The total time for participation in one day will be approximately 2 hours.

- **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 also experience nausea or motion sickness, but this should be minimized due to you holding your head stationary. The experimenter will frequently ask you about your motion sickness to ensure your comfort. You may also feel sleepy during the experiment, and the experimenter will monitor your alertness through communication and through a video camera.

When you use the stair-stepper device during centrifugation, you may experience lateral forces on your knees. You will exercise at your own pace, and if you experience any discomfort, you are free to discontinue exercise at any time.

Your heart rate may increase due to the rotation speed, and it may increase more due to exercise on the centrifuge. Your heart rate will be measured before and after the experiment. For experiments with accelerations of more than 1.0g at the feet, your heart rate will be continuously monitored. The experiment will be terminated if your heart rate goes above the value: (220 – your age) or a maximum of 200 bpm.

Serious injury could result from falling off the centrifuge while it is rotating. You will be restrained by a safety belt, which is to be worn around the waist/chest at all times while the centrifuge is rotating. The centrifuge is equipped with strong side railings similar to those on a hospital bed, which you may use these to stabilize yourself while you exercise if that is more comfortable for you.

You will be continuously monitored by at least one experimenter in the same room. The investigator can also see you through a video camera mounted on the centrifuge, and in this way determine your well-being and the nature of any problems that arise.

You can also terminate rotation at any time for any reason by pressing the emergency stop button.

The procedure may involve risks that are currently unforeseeable.

- **ANTICIPATED BENEFITS TO SUBJECTS**

You will receive no benefits from this research.

- **ANTICIPATED BENEFITS TO SOCIETY**

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

- **PAYMENT FOR PARTICIPATION**

Eligible subjects will receive payment of $10/hr for their participation. Checks will be mailed within 4-6 weeks of participation. Subjects not eligible for compensation include international students who work more than 20 hours per week, or volunteers from the MIT Man-Vehicle Lab.

- **PRIVACY AND CONFIDENTIALITY**

The only people who will know that you are a research subject are members of the research team. No information about you, or provided by you during the research will be disclosed to others without your written permission, except if necessary to protect your rights or welfare, or if required by law.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity. The data may consist of measures of your foot pressure and heart rate, information from the computer on an exercise device, subjective ratings of motion sickness and illusions experienced during centrifugation, subjective descriptions of your experience during centrifugation, and subjective descriptions of your orientation in space.

During the experiment, the experimenter will monitor you through a video camera 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 VHS tapes. You have the right to review and edit the tape. Any recorded videotapes will be accessible only by members of the current Artificial Gravity research team. Videotapes will be erased in 5 years, at most.

Research data collected during the experiment will be stored in coded files that contain no personal information. The coding of the data will prevent linking your personal data to research data when it is analyzed or archived. Research data is stored in a database and/or ASCII files, and there is no certain date for destruction. The data is stored in the 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.

- **WITHDRAWAL OF PARTICIPATION BY THE INVESTIGATOR**

The investigator may withdraw you from participating in this research if circumstances arise which warrant doing so. If you experience abnormally high heart rate, very high motion sickness levels, or extreme drowsiness or dizziness, you may have to drop out, even if you would like to continue. The investigators, Dr. Laurence Young, Dr. Thomas Jarchow, and Jessica Edmonds, will make the decision and let you know if it is not possible for you to continue. The decision may be made either to protect your health and safety, or because it is part of the research plan that people who develop certain conditions may not continue to participate.

If you must drop out because the investigator asks you to (rather than because you have decided on your own to withdraw), you will be paid the hourly amount stated ($10/hr) for the amount of time that you spent as a subject.

- **NEW FINDINGS**

During the course of the study, you will be informed of any significant new findings (either good or bad), such as changes in the risks or benefits resulting from participation in the research or new alternatives to participation, which might cause you to change your mind about continuing in the study. If new information is provided to you, your consent to continue participating in this study will be re-obtained.

- **EMERGENCY CARE AND COMPENSATION FOR INJURY**

"In the unlikely event of physical injury resulting from participation in this research you may receive medical treatment from the M.I.T. Medical Department, including emergency treatment and follow-up care as needed. Your insurance carrier may be billed for the cost of such treatment. M.I.T. does not provide any other form of compensation for injury. Moreover, in either providing or making such medical care available it does not imply the injury is the fault of the investigator. Further information may be obtained by calling the MIT Insurance and Legal Affairs Office at 1-617-253 2822."

- **IDENTIFICATION OF INVESTIGATORS**

In the event of a research related injury or if you experience an adverse reaction, please immediately contact one of the investigators listed below. If you have any questions about the research, please feel free to contact:

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

Co-Investigators:
Thomas Jarchow
77 Massachusetts Avenue
37-219

Cambridge, MA 02139
(617) 253-0017

Jessica Edmonds
77 Massachusetts Avenue
37-219
Cambridge, MA 02139
(617) 258-9730

- **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 Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T., Room E32-335, 77 Massachusetts Ave, Cambridge, MA 02139, phone 1-617-253 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

____ ______________________________

APPENDIX E. STRAIN GAUGE CIRCUIT DIAGRAMS

Paul Bauer was primarily responsible for reconfiguring the Contek digital bathroom scales to read forces on the stepper; the circuit board layout and circuit diagram for the operational amplifier are shown in Figure 48 and Figure 49.

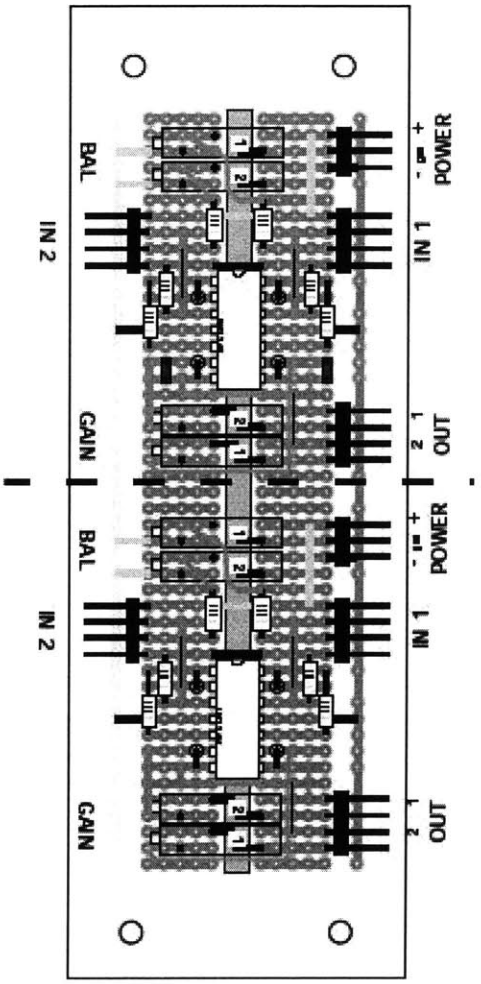


Figure 48. Circuit board layout for the foot reaction force sensors. The input is from four strain gauges from the Contek bathroom scales.

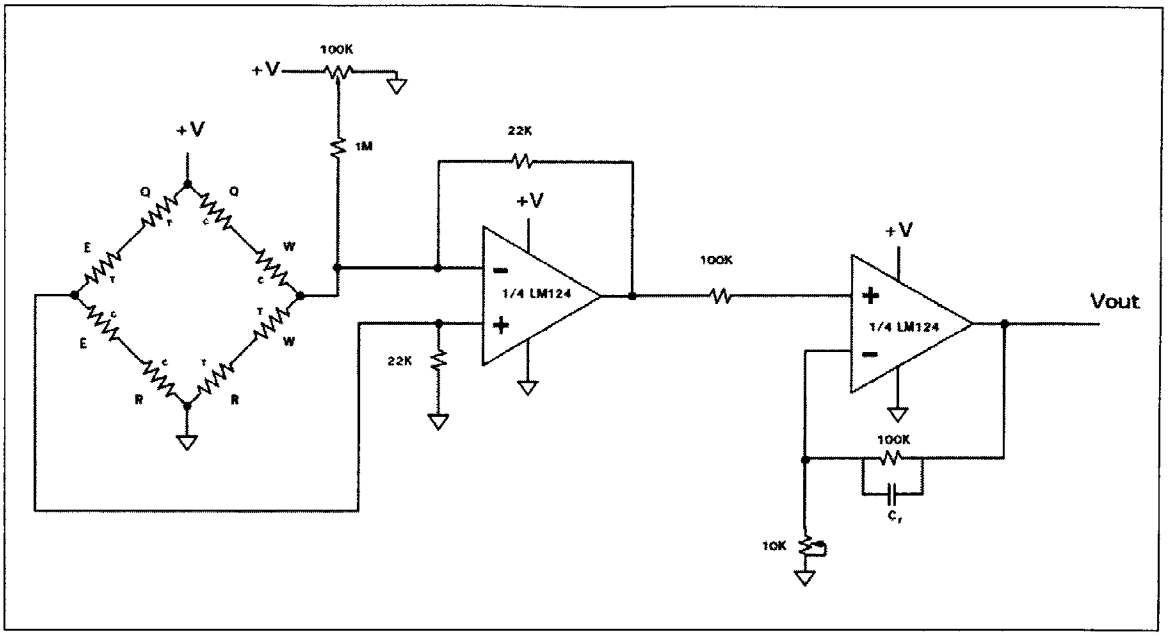


Figure 49. Circuit diagram for the operational amplifier.

APPENDIX F. CALIBRATION FOR SENSORS FOR REACTION FORCES ON THE FEET

Calibration is shown in Table 9. I did the calibration procedure for each group of four force sensors (four sensors were used for each foot's force plate), which I had already assembled using the circuit board, and sandwiched between two ¼", 6"x12" aluminum plates.

I placed each force plate on a concrete floor, and loaded it with two 50-lb. weights. A voltmeter was attached to output leads. With this 200-lb. load, the gain on the circuit board was adjusted so that it was roughly 7V. Since the range was 0 to 12V, I wanted the highest expected *static* load to indicate about half of the range, so that dynamic loads of nearly twice that number could be sensed.

I removed the two 50-lb. weights to begin the calibration process. Four 5-lb. weights were added one at a time, and the voltage reading was recorded at each 5-lb. increment. Instead of adding a fifth 5-lb. weight, all of the weights were removed and a 25-lb. weight was placed on the force plate for the 25-lb. reading. Four 5-lb. weights were added to the 25-lb. weight, one at a time, and the voltage was recorded each time. Instead of adding a fifth 5-lb. weight, all weights were removed and a 50-lb. weight was placed on the force plate. This process was continued up to a total of 200 lbs. (two 50-lb. weights).

Once the footplate was loaded to 200 lbs. and all reading were recorded, I began to take off the weights, 5 lbs. at a time. To do this I first replaced the two 50-lb. weights with one 50-lb. weight, one 25-lb. weight, and five 5-lb. weights. I removed each 5-lb. weight at a time, taking readings for each increment. After taking off the first five 5-lb. weights, I removed the 25-lb. weight and replaced it with five 5-lb. weights. I continued this process until there were no weights left on the force plate. All data for this process is shown in Table 9.

The reason for this "one" and "off" procedure was to check for hysteresis of the sensors. Figure 50 and Figure 51 show the data above, graphically. If the force sensors exhibited a great amount of hysteresis, then the two data sets ("on" and "off") would be very different from each other. It is apparent that every time I replaced five 5-lb. weights with one 25-lb. weight (or vice versa), there is a small jump in the plot. Somehow, the strain gauges sensed one 25-lb. weight as "heavier" than five 5-lb. weights. The mechanism for this is under investigation.

However, if the data was fit with a best-fit line, the pounds-to-volts ratio for both feet was 29.24 (the reciprocal of the slopes shown in Figure 50 and Figure 51). This value was used to calculate each subject's weight in artificial gravity.

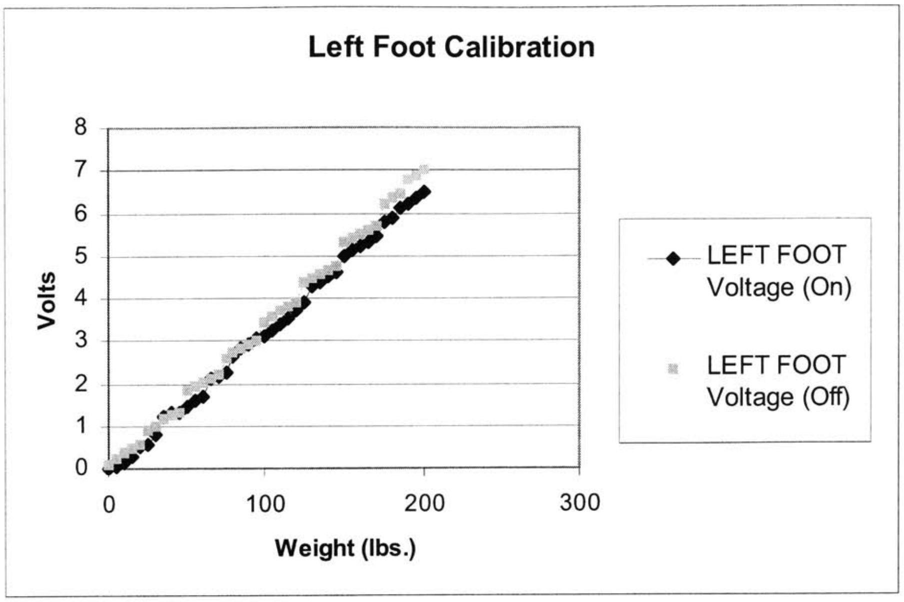
Table 9. Calibration of the sensors.

LEFT FOOT

Weight	Voltage (On)	Voltage (Off)
0	0.01	0.11
5	0.03	0.24
10	0.16	0.4
15	0.3	0.48
20	0.5	0.56
25	0.55	0.88
30	0.82	1.01
35	1.21	1.16
40	1.3	1.25
45	1.31	1.34
50	1.45	1.83
55	1.61	1.93
60	1.71	2.02
65	2.1	2.12
70	2.18	2.2
75	2.24	2.6
80	2.63	2.75
85	2.81	2.82
90	2.9	2.91
95	3.05	3.02
100	3.11	3.44
105	3.27	3.57
110	3.4	3.72
115	3.51	3.82
120	3.71	3.91
125	3.91	4.37
130	4.28	4.47
135	4.39	4.57
140	4.51	4.68
145	4.63	4.77
150	5	5.31
155	5.11	5.41
160	5.22	5.51
165	5.33	5.61
170	5.47	5.69
175	5.79	6.2
180	5.88	6.34
185	6.13	6.44
190	6.22	6.76
195	6.37	6.85
200	6.51	6.99

RIGHT FOOT

Weight	Voltage (On)	Voltage (Off)
0	0.01	0.13
5	0.17	0.27
10	0.3	0.44
15	0.5	0.6
20	0.71	0.72
25	0.84	0.96
30	1.06	1.14
35	1.17	1.3
40	1.34	1.45
45	1.51	1.6
50	1.67	1.74
55	1.89	2.03
60	1.99	2.19
65	2.23	2.32
70	2.41	2.41
75	2.56	2.72
80	2.79	2.87
85	2.92	3.02
90	3.09	3.16
95	3.26	3.29
100	3.36	3.62
105	3.6	3.78
110	3.75	3.88
115	3.93	3.99
120	4.05	4.14
125	4.33	4.47
130	4.45	4.56
135	4.62	4.71
140	4.73	4.83
145	4.94	4.97
150	5.21	5.3
155	5.27	5.45
160	5.43	5.61
165	5.62	5.73
170	5.71	5.87
175	6.01	6.04
180	6.13	6.28
185	6.33	6.46
190	6.51	6.6
195	6.65	6.76
200	6.75	7



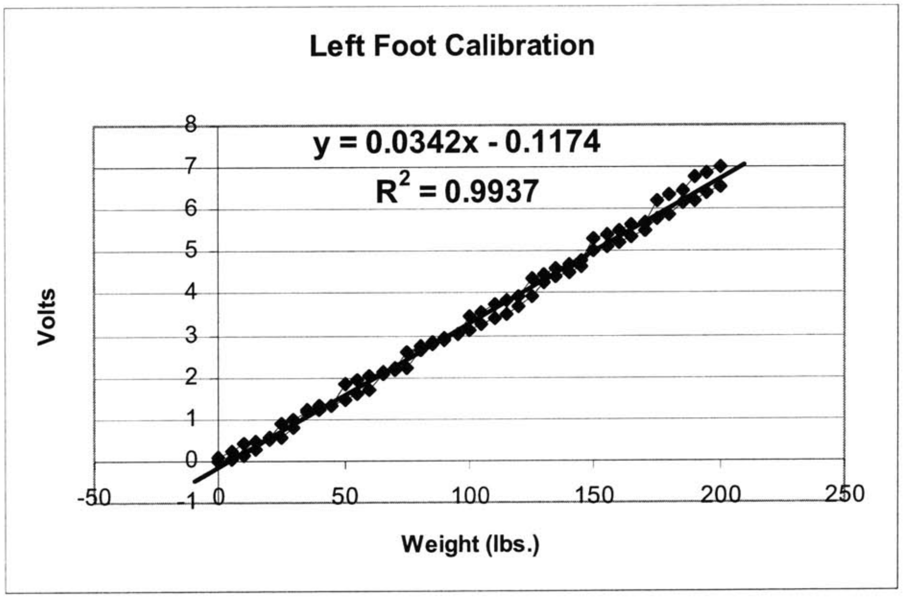
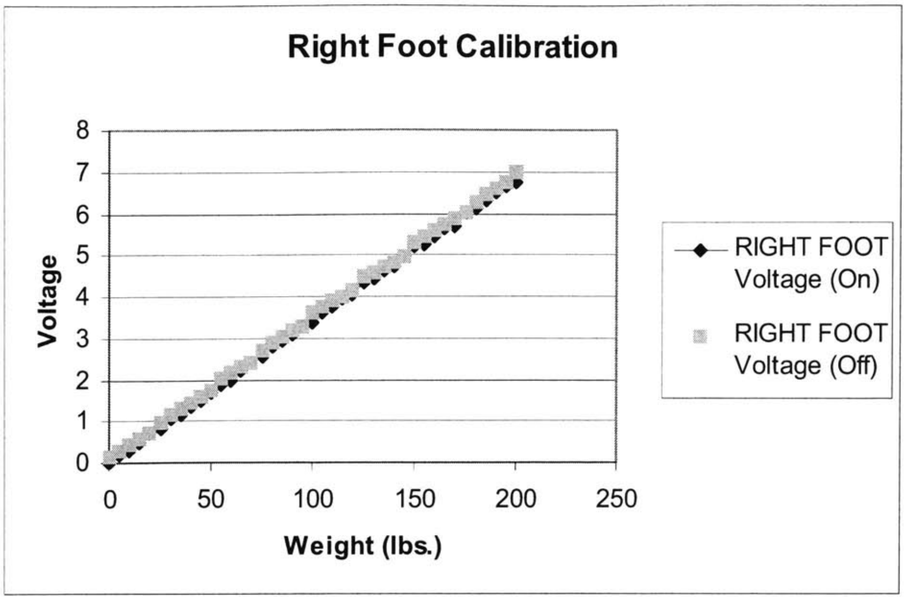


Figure 50. Left foot calibration.



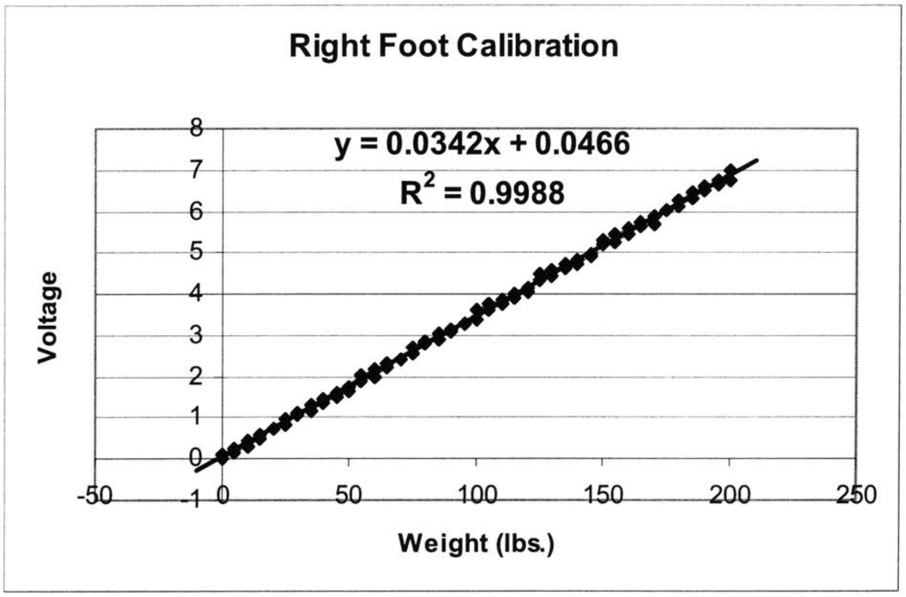


Figure 51. Right foot calibration.

APPENDIX G. FOOT FORCE DATA FOR ALL SUBJECTS.

For all graphs,

Left foot = Dark gray line
Right foot = Medium gray line
Total weight = Light gray line

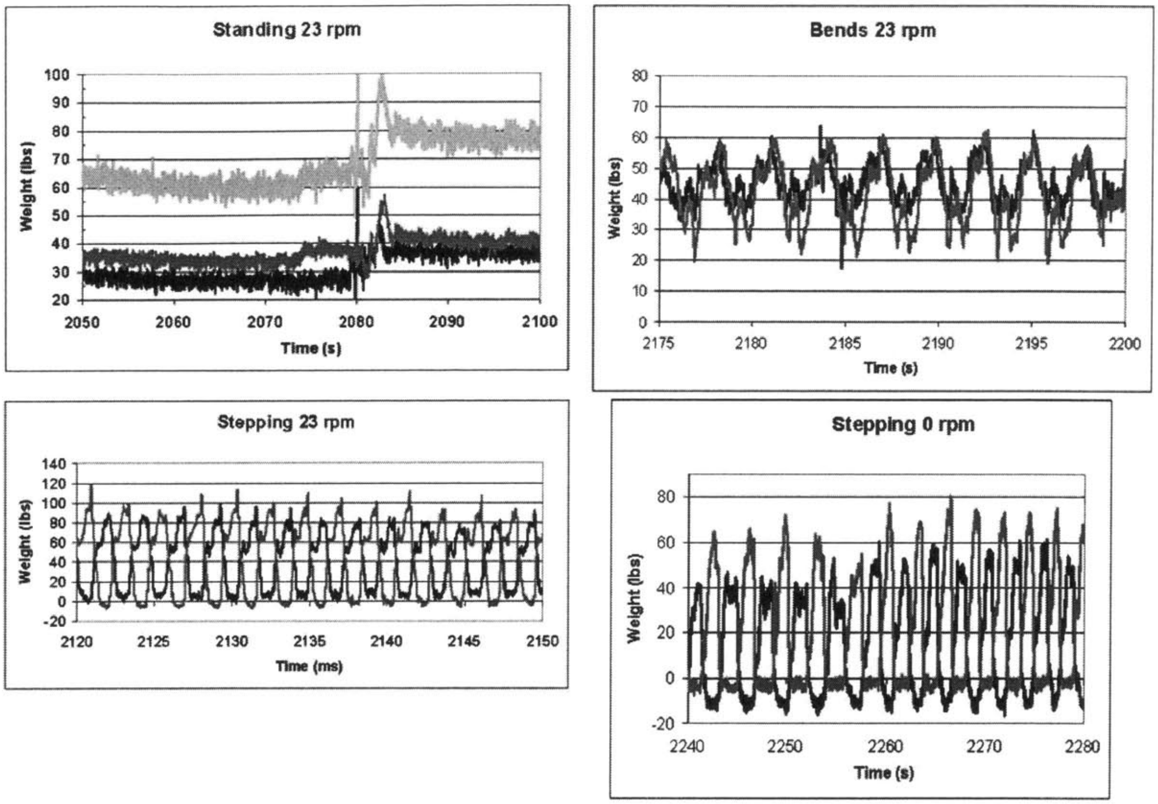


Figure 52. Foot reaction force data for a 150 lb. subject.

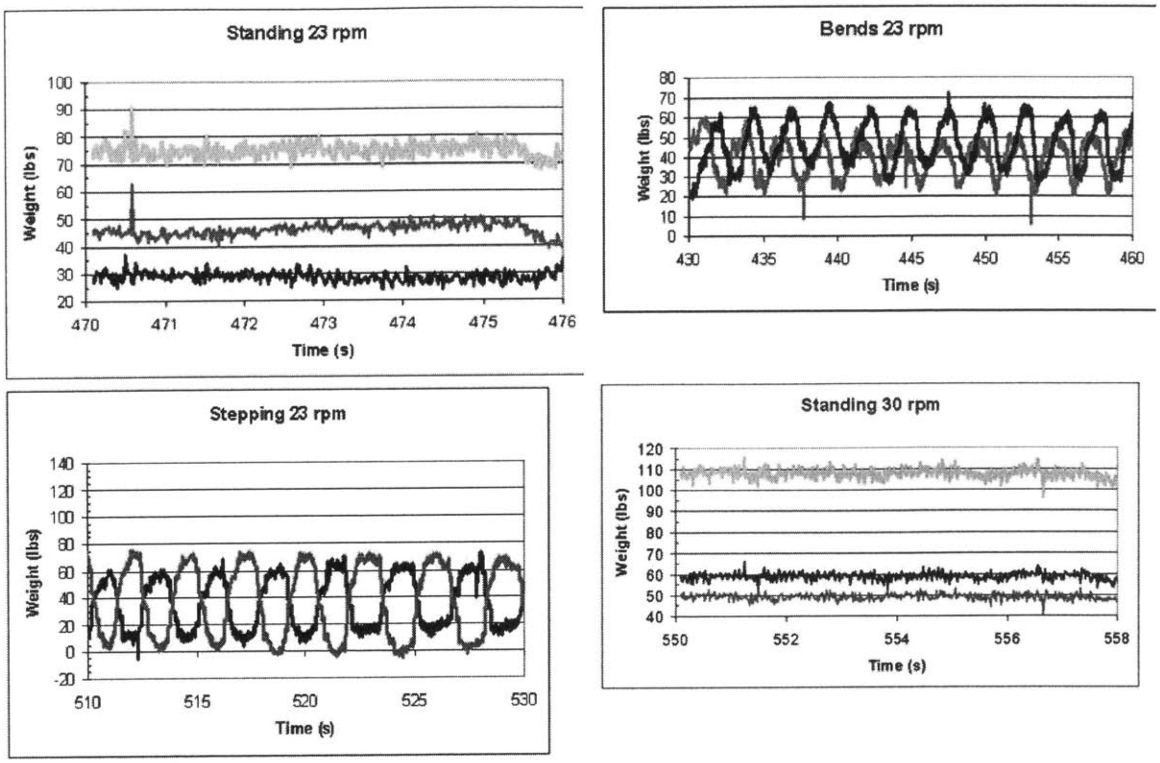


Figure 53. Foot reaction force data for a 155 lb. subject.

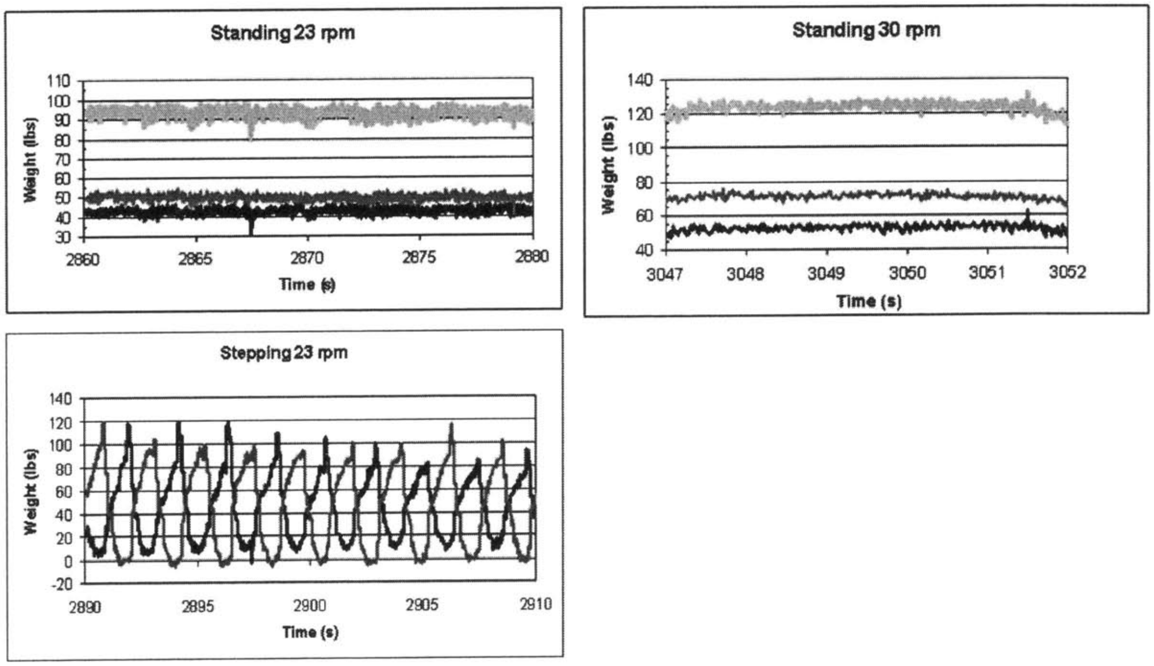


Figure 54. Foot reaction force data for a 175 lb. subject.

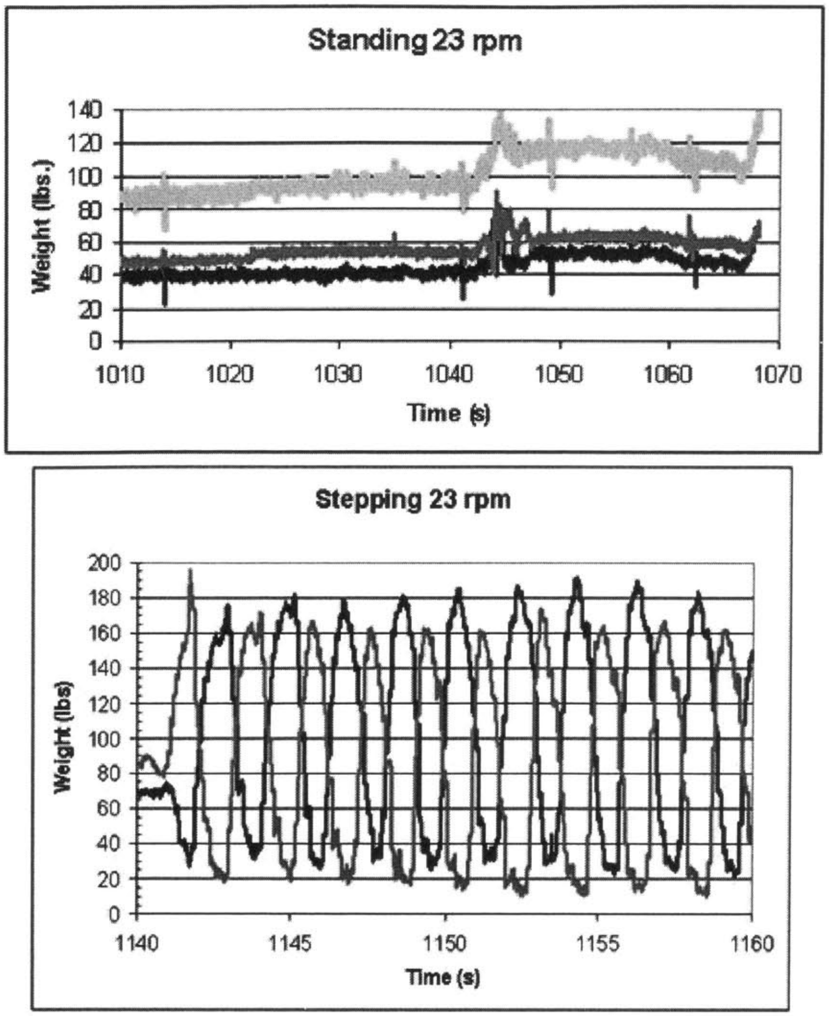


Figure 55. Foot reaction force data for a 230 lb. subject.