LOW MAGNITUDE HIGH FREQUENCY VIBRATIONS APPLIED TO THE FOOT THROUGH THE PEDAL OF A HUMAN POWERED ARTIFICIAL GRAVITY (HPAG) CYCLE

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Abstract

Astronauts are exposed to hazards unique to space travel. These hazards include radiation exposure and adaptation of the human body to the microgravity environment. For lunar and low earth orbital missions, the exposure period is typically less than six months and return to Earth is less than two weeks away. For travel beyond the Earth's moon, the microgravity exposure time will increase from months to years and return time will increase from weeks to months. Current countermeasures employ impact and high force loading to maintain bone health. An astronaut runs on a treadmill to impact load the weight bearing components of the musculoskeletal system. Elastic bands provide the "down" force for the astronaut while running. For high force loading, the astronaut performs a specified regimen of weight lifting exercises using resistive devices. The resistive devices provide a load in microgravity similar to that of free weights on Earth. These countermeasures have been beneficial in slowing bone adaptation, but have not stopped it.

The imperceptible muscle contractions required for posture maintenance may be the absent load that the skeletal system requires to maintain bone health. Unlike the muscles that are required for impact and high force loading, the postural muscles work continuously to keep humans balanced and upright in a gravity environment. Jumping, running and even sitting require posture maintenance. Studies have shown that low magnitude loads applied at a high frequency to the weight bearing bones have not only maintained the bone mineral density, but also more importantly, maintained the structure of the bones. This thesis demonstrates the design of a vibrating pedal that delivers a perceptible, low magnitude load at a high frequency (~30 Hz) to the foot. This design required no external power and was implemented on a Human Powered Artificial Gravity (HPAG) cycle.

A device similar to the vibrating pedal device created for this research could benefit society by providing an effective therapy against the disease of osteoporosis. A vibrating pedal could easily be mounted on a stationary cycle, possibly even standard bicycle, and provide a beneficial therapy to the user.

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My brother. My protector, your battle now, is a battle many of our people, myself included, have fought. Don your armor Achilles--my brother--though we share the same vulnerability, today we shall share the spoils that belong to the victorious.

I tell you the truth, today you will be with me in paradise. (Luke 23:43)

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FLUFFY...and finally, to all those that know me as Fluff, Fluffy or Fuzzy(?), from Grass Valley to Dayton to Montreal to Sweden: *Wherever I Am, You Are Welcome. If I Eat, You Shall Eat.*

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1 INTRODUCTION

Astronauts are exposed to less than one-Earth-gravity during spaceflight. The human body in its goal to maintain efficiency adapts to the new gravity environment. This adaptation manifests itself in modifications of the neurovestibular, cardiovascular, and the musculoskeletal systems. Each system responds to microgravity with different adaptation rates and stabilization periods, therefore presenting unique risks for the astronaut and the mission.

1.1 Physiological Response to Microgravity

1.1.1 Neurovestibular Response

In the first three days of spaceflight, most astronauts go through a vestibular adaptation period when introduced into the weightless environment of low earth orbit. On Earth, humans orient themselves with the gravity vector by the combined input of the otolith organs, cardiovascular, kidney and other gravireceptor systems (Oman 2001). The concept of "floor" and "ground" no longer applies, as the astronauts are free to float while in low earth orbit aboard the shuttle or the International Space Station (ISS). The Earth gravity-bound cues are replaced by visual orientation cues, such as the astronaut's relation to spacecraft, other astronauts and the position of the Earth relative to the spacecraft. In the early flights of Mercury, Gemini and Apollo, orientation was not an issue. Those early astronauts rarely left their seated positions, since the space for movement in the capsule was limited. Although the disorientation period lasts only a few days, the main danger of this condition lies in the disorientation associated with the lack of a constant gravity vector for reference. The disorientation increases the required time for hazard response and emergency egress. There are no countermeasures for this period. Medication has been prescribed to alleviate the symptoms of space motion sickness, such as nausea.

1.1.2 Cardiovascular Response

Without the pull of gravity, the fluids of the body are no longer drawn to the feet, but are distributed evenly throughout the entire body. This unprecedented, fluid distribution is interpreted as a rush of the fluids to the head. The pressure sensors that are located above the heart signal this perception. These sensors govern fluid volume and in microgravity, they provide the signal that the body interprets as a hyperfluidic condition and decreases the blood volume through the release of water through the kidneys. The fluid volume decrease presents a danger when the crew returns to a gravity environment. The hypofluidic condition, along with the deconditioned cardiovascular control mechanisms leads to orthostatic intolerance. During Earth atmosphere re-entry, the gravity forces are greater than 1G; orthostatic intolerance (inability to stand caused by lightheadedness) could cause an astronaut to lose consciousness during re-entry. The cardiovascular adaptation stabilizes after a few days when exposed to the microgravity environment and also when returned to the gravity environment. The countermeasures for this condition include administered pharmacological pills, fluid supplements added to the system prior to re-entry, and maintenance of the cardiovascular system with exercise during spaceflight.

1.1.3 Musculoskeletal Response

During spaceflight, the weight bearing muscles and bones degenerate. The arms replace the legs as the main instrument for locomotion and the locomotive force required is minimal. The weight bearing bones adapt by reducing their density and the less used muscles atrophy to a weaker condition. The bone mineral density (BMD) of the weight bearing bones decreases at a rate of up to 1.6% per month throughout the microgravity exposure period (LeBlanc 1998). This persistent, cumulative loss in bone structure presents a significant risk for a mission ending injury upon return to a gravity environment such as on Earth (1G) or Mars (0.4G). Countermeasures for bone health maintenance include calcium supplements and exercise for maintenance of the muscles and bones.

1.2 Bone Health Maintenance

Of the three responses, the adaptation period of the musculoskeletal system is the only one that is measured in units of months. The neurovestibular and cardiovascular systems usually stabilize within a week. Usually in the first three days, the symptoms of motion sickness are not present and fluid distribution has stabilized. The remodeling of the bones continues as evidenced by bone mineral density measurements taken post flight and continued raised levels of calcium present in the vascular system. Regeneration of the bones occurs at a rate similar to the degeneration rate as evidenced by the time required for BMD levels to return to pre-flight levels after return to Earth. Maintenance of bone health during space flight appears to be the best way to ensure the completion of a long duration spaceflight mission with a return to gravity activity segment scheduled during the trip. For Earth-orbital and lunar expeditions, this decrease has not been critical. Medical care on earth is less than two weeks away for a lunar mission and hours away for an Earth-orbital mission. However, for a Mars mission, rescue time and increased investment loss due to a possible mission ending injury has increased the need to explore improved bone health maintenance programs for space travel and working in a less than 1G environment.

2 BACKGROUND

2.1 Bone Adaptation to Microgravity

With current technology, travel to Mars will take no less than several months and several months to return. If the itinerary consisted of only microgravity flight and return to Earth, then bone health could be restored on return to low Earth orbit via a rehabilitation period aboard the International Space Station (ISS). Human explorers going to Mars will be going to explore the planet, not just "fly-by". The Mars crew will most likely have extra-vehicular-activity (EVA) suits specific for strenuous operations in the Mars gravity and atmosphere. The explorers will require bones that can support their mission activities while on Mars. Bone health maintenance or rehabilitation will be necessary for exploration of Mars.

Living bone tissue constantly adapts to the environmental loading requirements. In microgravity, the loading of gravity is removed which provokes the skeletal system to shed the excess bone mass. This adaptation is accomplished by remodeling of the weight bearing trabecular bone by osteoclastic and osteoblastic activity (Ralston 2002). The trabecular bone is the relatively spongy bone material located at the ends of bones. The bone material at the joints is trabecular bone. Since trabecular bone is relatively spongy bone material, it exposes more surface area. This allows the trabecular bone to be more sensitive to remodeling. The osteoclasts and osteoblasts perform the task of bone remodeling. The osteoclasts remove excess bone structure and the osteoblasts build needed bone structure. If the osteoblast building rate does not match the osteoclast resorption rate, the result is a decrease in the trabecular bone structure that can be measured as Bone Mineral Density. This osteoclastic action raises the calcium and phosphate levels in the body. The body purges the excess calcium and phosphates through the kidneys. The presence of high levels of calcium and phosphates in the kidneys increases the risk of kidney stone formation. Microgravity causes bone remodeling that increases the risk of bone fracture upon return to the gravity environment and increases the risk of kidney stone formation. Both of these conditions could end an explorer-class mission or be fatal to an explorer.

2.2 Current countermeasures

The goal of current countermeasures is to prevent deconditioning of muscle, bone and the cardiovascular system. The standard countermeasures employed by astronauts during spaceflight include a cycle ergometer, a treadmill and the interim Resistance Exercise Device (iRED). The three different types of exercise equipment are meant to target a component of the astronauts' cardiovascular or musculoskeletal system with the goal of maintaining the bone and muscle health along with cardiovascular fitness. The absence of gravity presents a unique challenge to the application and use of equipment meant to maintain the astronauts' health in spaceflight (National Aeronautics and Space Administration 2001). Bungee cords, unique elastic devices, and harnesses secure the astronauts to the exercise equipment and must be utilized to provide a resistive, restoring, or restraining force in the absence of gravity. With the current countermeasures, when pre and post-flight bone mineral density is measured, there is a still a significant decrease in the weight bearing components of the skeletal system (lower back, hip and legs).

The goal of countermeasures is to maintain the measured health levels, so that there is no significant difference between pre-flight and post-flight levels. Ideally, spaceflight would have no detrimental effect on the astronauts' health. An exercise regimen along with equipment is utilized in an attempt to maintain the health of the crew. The exercise regimen is still under development as evidenced by the current differences in the Russian and American (USA) 2.5-hour exercise prescriptions (National Aeronautics and Space Administration 2005). The Russian cosmonauts exercise 1.5 hours on treadmill and 1.0 hour on cycle ergometer in a 4-day micro-cycle (3 day exercise, day 4-rest), while the American astronauts exercise daily on all of the available exercise equipment (treadmill, ergometers and iRED).

2.2.1 Cycle Ergometer

The cycle ergometer is a type of exercise device that is currently in use on the International Space Station. The two types on the International Space Station are the American Cycle Ergometer with Vibration Isolation (CEVIS) and the Russian VELO cycle ergometer (National Aeronautics and Space Administration 2001). Both cycle ergometers utilize dynamic resistance that can be set in units of Watts to the desired resistance of the rider. The cadence for exercise on the ergometers is approximately 40-80 Revolutions Per Minute (RPM). The exercise motion is similar to riding a bicycle, but in microgravity, there is no real need for a seat. There is a need for restraints to secure rider to ergometer. The CEVIS straps the rider to the wall of the spacecraft in a standing position. The VELO provides a recumbent style seat and riding position with the necessary restraints. The ergometers can be configured for arm exercise, when required for EVA training and EVA pre-breathe protocol. The cycle ergometers target maintenance of the aerobic/anaerobic capacity of the cardiovascular system and the muscles.

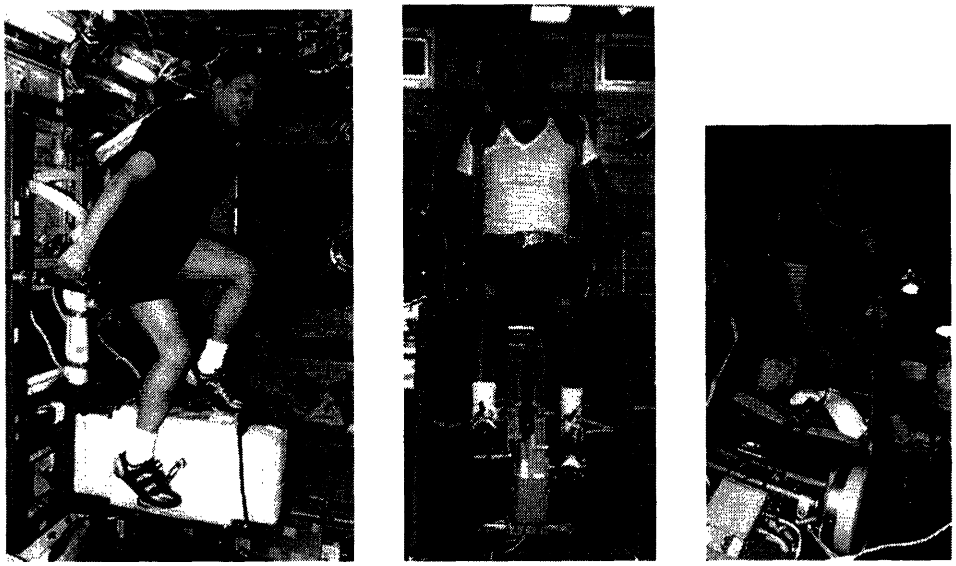

Figure 1. (Left) Astronaut on ISS using CEVIS. (Middle) Cosmonaut on ISS using VELO cycle ergometer. (Right) Cosmonaut on ISS using VELO cycle ergometer in configuration to exercise arm. (images from spaceflight.nasa.gov/gallery/images/station, accessed 8/10/05)

2.2.2 Treadmill

The Treadmill Vibration Isolation System (TVIS) is a countermeasure device used to facilitate a running motion type exercise (National Aeronautics and Space Administration 2001). The runner is secured to the treadmill by a harness that can be adjusted to provide variable tensile force to simulate the loading encountered while running. The treadmill can be operated in powered or passive mode. In powered mode, the running surface is moved under the runner. Running in powered mode requires less work of the runner. The runner can receive more cycles of impact loading. Passive mode of the treadmill requires that the runner perform more work since the belt is not moving beneath the runner. The treadmill regimen is designed to train the muscles and bones in four areas: 1) neuromuscular patterning (muscle coordination), 2) endurance exercise of postural musculature, 3) high impact skeletal loading and 4) aerobic exercise.

Figure 2. Astronaut using Treadmill Vibration Isolation System (TVIS) on ISS. (image from spaceflight.nasa.gov/gallery/images/station, accessed 8/11/05) interim Resistance Exercise Device (iRED)

2.2.3 Interim Resistive Exercise Device

The interim Resistive Exercise Device (iRED) is used for strength and endurance training of the major muscle groups. The iRED provides a selectable constant resistance similar to the resistance that free weight training exercise equipment provides here on Earth without the high mass cost. The iRED can be configured for many different types of exercises (National Aeronautics and Space Administration 2001). The regimen emphasizes strength and endurance training of the muscles necessary to maintain posture here on Earth. The iRED is the only exercise equipment that provides high-strain skeletal loading in an attempt to maintain the health and strength of the bones (Schneider 2003).

The iRED does not produce similar increases in Bone Mineral Density (BMD) when compared to similar exercises with Free Weights in studies conducted here on Earth (Schneider 2001).

Figure 3. Astronaut using interim Resistance Exercise Device (iRED) in Dead Lift configuration. (image from spaceflight.nasa.gov/gallery/images/station, accessed 8/10/05).

2.3 Short-radius Centrifuges as Alternative Countermeasures

Short-radius centrifuges are currently being studied for possible countermeasure use. The centrifuge's radial force (Equation 1) can be used to mimic the gravity vector and maintain bone and cardiovascular health. Short-radius centrifuges typically have a radius of approximately six feet to accommodate a human with head at center of rotation. The rotation speed is set to provide 1G at the feet, which is about 23 revolutions per minute. Current working centrifuges employ different modes of power, orientation and rigidity.

Equation 1. Artificial Gravity

$$a_{AG} = \omega r^2$$

a_{AG}: centrifuge acceleration to produce artificial gravity
ω: angular velocity
r: radius

2.3.1 Advantages of Centrifugation

The advantage of short-radius centrifugation is that the subject experiences a force, in a similar manner, as gravity on Earth. To put it simply, instead of treating the symptoms of microgravity exposure—provide an artificial gravity as a countermeasure. To model the fluidic system in the body here on Earth, the heart becomes a pump and the fluid becomes a hydrostatic column. The pressure in the column is a function of the height and the heart is at the datum. During centrifugation, a similar pressure profile exists. The centrifugation profile varies with the square of the linear velocity that is a function of the radius as shown in Figure 4.

Equation 2. Relationship between hydrostatic column blood pressure and blood pressure as function of distance from center on centrifuge.

HYDROSTATIC COLUMN

$$P = \rho g h$$

P : blood pressure
ρ : density of blood
g : 1 Earth gravity
h : height

PRESSURE AS FUNCTION OF DISTANCE FROM CENTER

$$P = \rho \omega r^2$$

P : blood pressure
ρ : density of blood
ω : angular velocity
r : radius

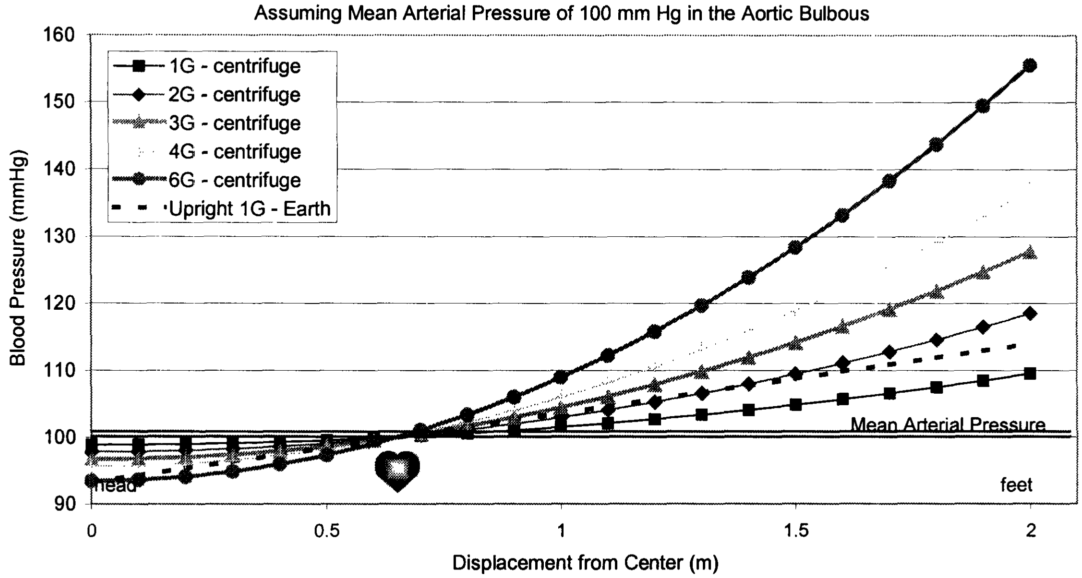

Figure 4. Excel chart showing blood pressure as a function of radius and G level on centrifuge compared to Upright 1G on Earth.

2.3.2 Disadvantages of Centrifugation

One disadvantage of centrifugation is that the movement that occurs outside of the plane of rotation causes the subject to experience Coriolis accelerations. The Coriolis acceleration was recorded when exercise was implemented on the MIT centrifuge (Edmonds 2005). The subject's leg flexion and extension movements were visibly and measurably elliptical. The Coriolis effect is minimized by placing the head at the center of rotation, but the out-of-plane movements become more pronounced as the radius increases. Another argument against centrifugation is that it will not allow the body to fully adapt to weightlessness. Each session of artificial gravity will possibly renew the adaptation cycle when the crewmembers are subjected to a session on the centrifuge.

2.4 Types of Short-radius Centrifuges

On the centrifuge at the Massachusetts Institute of Technology, the subjects lie in a supine position with the head at the center of rotation and the feet at the outer radius. A helmet is installed to facilitate head rotation testing and the labeled exercise device has been added (Figure 5).

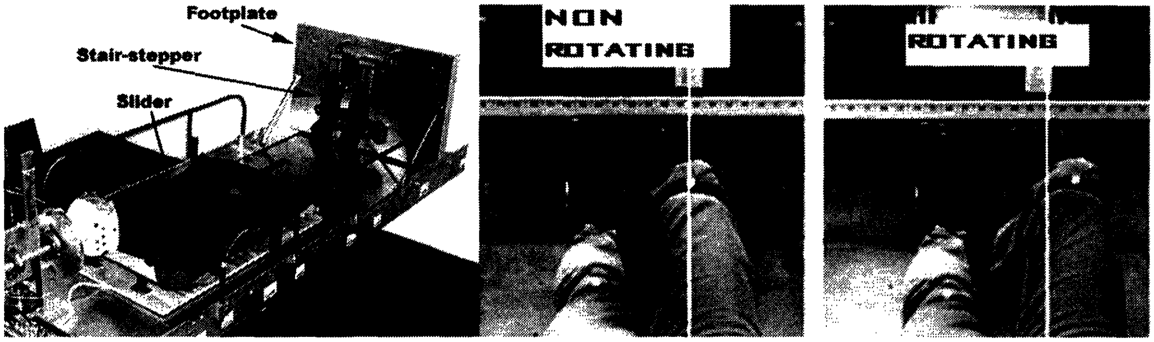

Figure 5. (Right) MIT centrifuge with exercise device. (Left) MIT centrifuge with subject showing effects of Coriolis effect. (images from SM Thesis, Edmonds 2005).

The Space Cycle at UC Irvine has a variable radius and angle that is a function of the angular velocity. The subjects pedal to power the centrifuge (Figure 6).

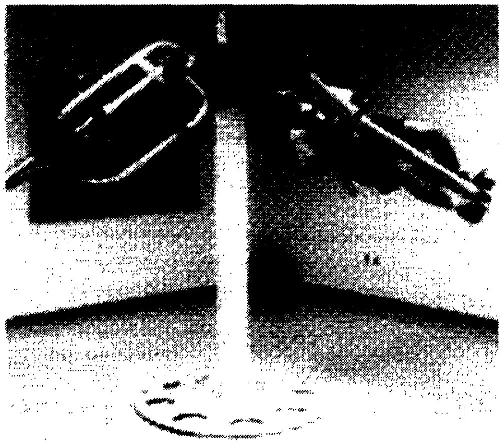

Figure 6. Space Cycle at UC Irvine (Kreitenberg 2000)

The centrifuge at NASA Ames Research Center that is human powered, either by subject on centrifuge or external stationary bicyclist. The subjects lie in a supine position and pedaling while on centrifuge occurs perpendicular to plane of rotation.

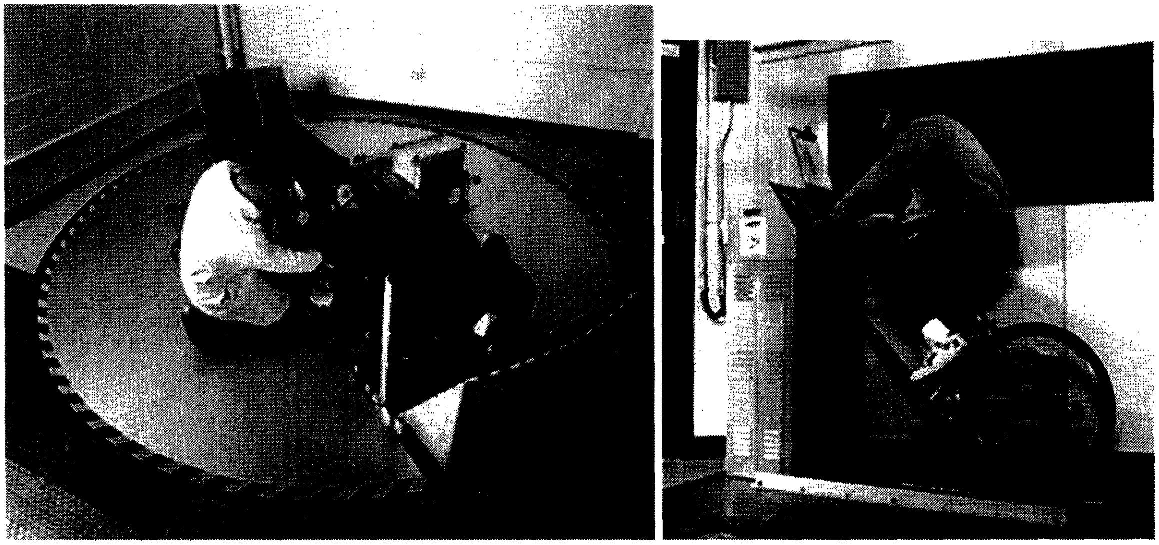

Figure 7. (Left) Subject on centrifuge. (Right) Rider providing alternate rotation power for centrifuge (lifesci.arc.nasa.gov/CGBR/hpc.html, accessed on 8/10/05).

The newly constructed centrifuge at the University of Texas Medical Branch at Galveston can accommodate two subjects. The subjects lie in a six-degree head down, supine position. This position induces similar effects in the body as that of microgravity exposure to produce a similar fluid shift as experienced in microgravity (Figure 8).

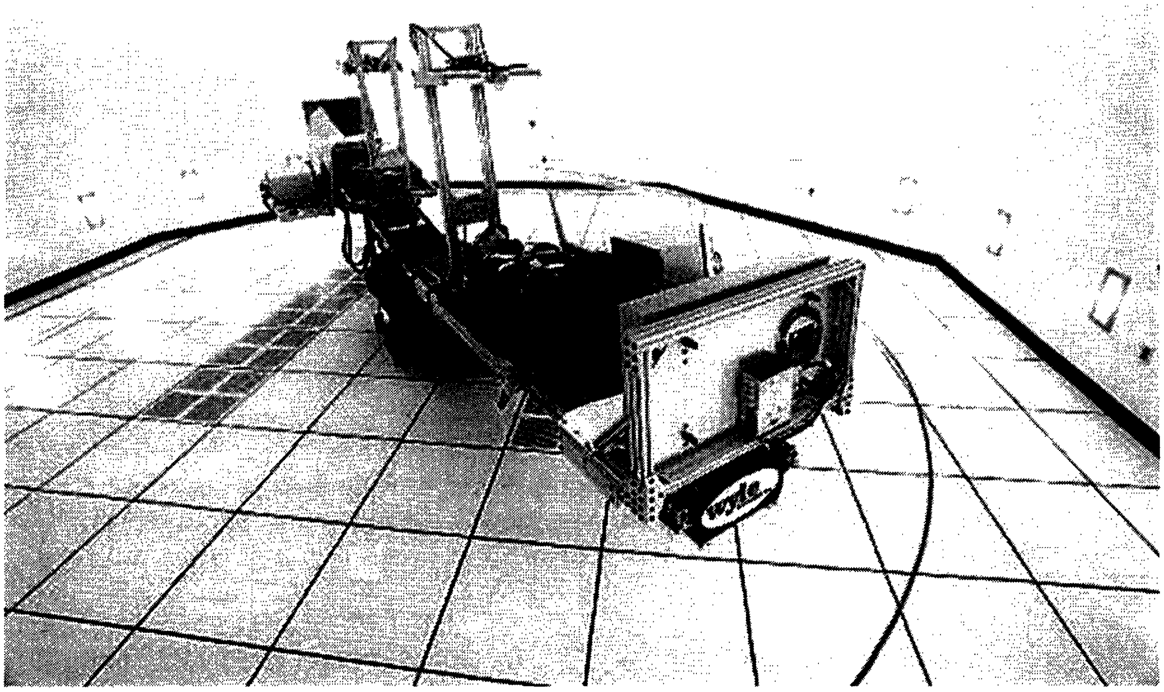

Figure 8. UTMC centrifuge with 6-degree head down position (www.nasa.gov/vision/space/preparingtravel/human_centrifuge_08315.htm accessed 9/3/05).

The MIT Human Powered Artificial Gravity cycle can accomodate two riders, lying on their left hip. This centrifuge is powered by the subjects. The angular velocity is determined by the rider's pedaling cadence and the configuration of the adjustable gearing.

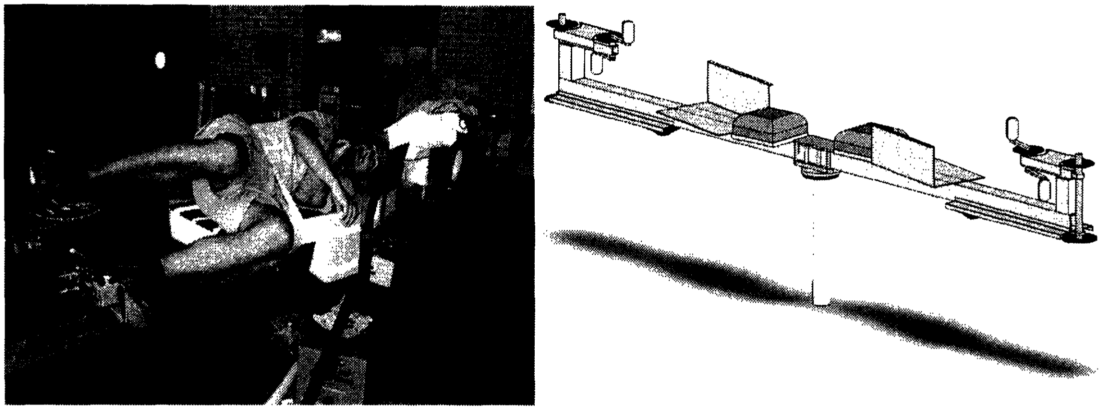

Figure 9. (Left) MIT Human Powered Artificial Gravity (HPAG) cycle with subjects and (Right) Drawing of MIT HPAG cycle (drawing by Ellman 2005).

2.5 Possible Lethal Combination (lethal to bone degeneration)

The application of a high frequency vibration of low magnitude may provide the missing signal for bone health maintenance. Rubin (2001) has shown that low-magnitude strains (<5microstrain) applied at a high frequency (30 Hz) can contribute significantly to bone tissue maintenance. The application of higher frequency (90 Hz) at similar strain levels (<5microstrain) has been shown to maintain the bone health (Rubin 2001). Further studies have reveale a non-linear relationship with loading frequency and strain level. At a relatively high stimulus frequency of 30 Hz, the loading level can be on the order of 50 microstrain and still provoke the bone to maintain the current structure (Qin 1998).

The combination of centrifugation and foot application of a high frequency, low magnitude vibration was investigated in this thesis. To be more specific, the goal was to add a vibration device to the human powered artificial gravity cycle. This device would provide a low magnitude, 30 Hz vibration to the foot. A vibration of this type may provoke a signal similar to the signal provoked by the persistent, postural maintenance, muscle contractions. When in microgravity, there is no need to remain upright or to keep from falling. The absence of these postural maintenance muscle contraction signals may provoke the bones to shed their excess structure. A high frequency, low magnitude vibration device is an attempt to replace that signal to the bone loading sensors that control bone remodeling.

Astronaut bone health countermeasures have focused on providing impact loads similar to that experienced on Earth in high impact activities associated with running or leaping movements. Although beneficial, these countermeasures have not succeeded in stopping the bone degeneration experienced in microgravity. The high frequency, low magnitude vibration combined with centrifugation does not presume to replace impact and high resistance loading, but add to the beneficial current countermeasures. In a gravity environment, the loads placed on the skeletal system are diverse, differing in frequency, intensity and duration and the countermeasures available to the spaceflight crews must reflect this diversity.

3 CONCEPT PATH

3.1 Design Requirements

The following are the requirements that must be met if a high frequency/low magnitude vibration device is to be implemented with a short-radius centrifuge.

3.1.1 Operational Environment

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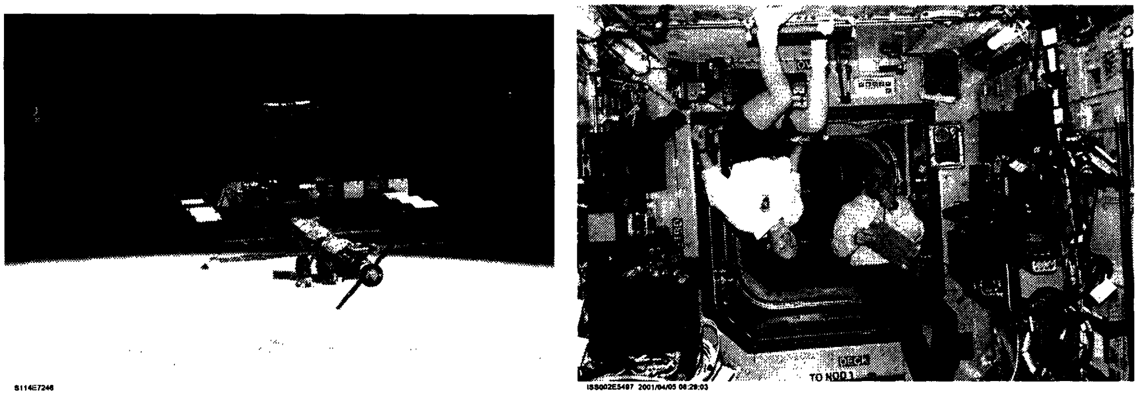


Figure 10. (Left) ISS in low Earth orbit. (Right) Interior of ISS (photographs from spaceflight.nasa.gov, accessed 8/10/05).

The International Space Station (ISS) is small and confined when compared to working and living spaces here on Earth. Compared to the shuttle, the International Space Station is spacious with room to move and ambulate. The International Space Station crews are exposed to microgravity for months at a time and exposure time presents a great danger to a crewmember's health. Mass is at a premium for launch and volume (or space) is at a premium once on board the International Space Station. In the sealed environment, chemical stability and odor of materials are subjected to standards to prevent making the crew living unpleasant or unhealthy. The block of time that a crewmember is scheduled to exercise should be spent exercising and not configuring equipment for use. The final design will be lightweight, durable, compact, and not offensive to the crew.

The mass, volume, and chemical properties are a consideration when designing equipment for use on the International Space Station. Mass cost for an Earth-to-ISS delivery by shuttle of 1 kilogram is currently $3000-10,000 (U.S. Congress 1990). The mass-cost associated with the equipment must include the initial launch for equipment, maintenance costs and life cycle. The unit's mass has a cost associated with it. The maintenance of the unit has a cost associated with it in the form of replacement parts, lubricants and possibly tools. The life cycle of the equipment has a cost associated in the form of the cost to launch a replacement. Ideally, the equipment would have no mass, would require no tools or lubricants, would have no wear, and would last forever, never needing replacement. The volume of the equipment must be considered in the design, both for stowage and "in use" configuration. The equipment should not be bulky and difficult to use or to store. The chemical properties of the equipment and associated equipment must pass the standards required for spaceflight. A piece of equipment that causes no problems here on Earth may seriously affect crew health in the sealed confines of the International Space Station.

3.1.2 Incorporation with Human Powered Artificial Gravity Cycle

The subjects power the rotation of the human-powered artificial gravity (HPAG) cycle by pedaling. The subjects' required output workload to rotate the HPAG cycle is small. Currently, the subjects must coast or pedal slowly and this low intensity pedaling does not provide a meaningful cardiovascular workout. The foot vibration device, if mechanically powered, will add to the subjects' workload by resisting the rotation of the pedals and apply a vibration of about 30 Hz. On the MIT HPAG cycle with two subject positions, there are four pedal stations that are available for mounting a foot vibration device. Originally for this study, four different mechanical foot vibration devices were to be constructed and tested: 1) a gear driven device, 2) chain driven device, 3) timing belt driven device and 4) heel impact device. Only the gear driven device and the chain driven device were constructed. Of those two designs, only the gear driven device was instrumented and used in testing. The design, fabrication and implementation of the two designs provided an opportunity to study each device. The other two devices were not constructed because it became clear that comparative studies should be reserved for the next phase of research.

3.2 Motion Production and Multiplication

There are books filled with mechanisms and devices that were conceived and birthed long ago. Three of these books were useful in the research presented in this thesis (Classic and Modern 1971, Mechanics and Dynamics 1967, Mabie 1978)

3.2.1 Electrically or Mechanically Powered?

Two electrically powered designs arose during initial brainstorming sessions. The design of the voice coil and the motorized vibration device are from a child's toy (Figure 11). The voice coil moves the cone within a speaker to produce sound. A voice coil could provide a low frequency vibration with a 30Hz audio signal. The other powered unit was the vibration device from a child's toy. The toy was a stuffed animal constructed to vibrate to simulate a laughing motion. The vibration was created with the rotation of an unbalanced weighted rotor. For our device, the voice coil unit and vibration unit could be fastened under the heel in a normal foot-pedaling configuration. The power to the units would run adjacent to the subject's leg, past the foot and to the vibration units.

The decision was made to pursue a totally mechanically driven device for the following reasons.

- A mechanical system is much simpler than an electric one.
- A mechanical device will not require a battery or place a load on power production on board the ISS.
- No electrical danger.

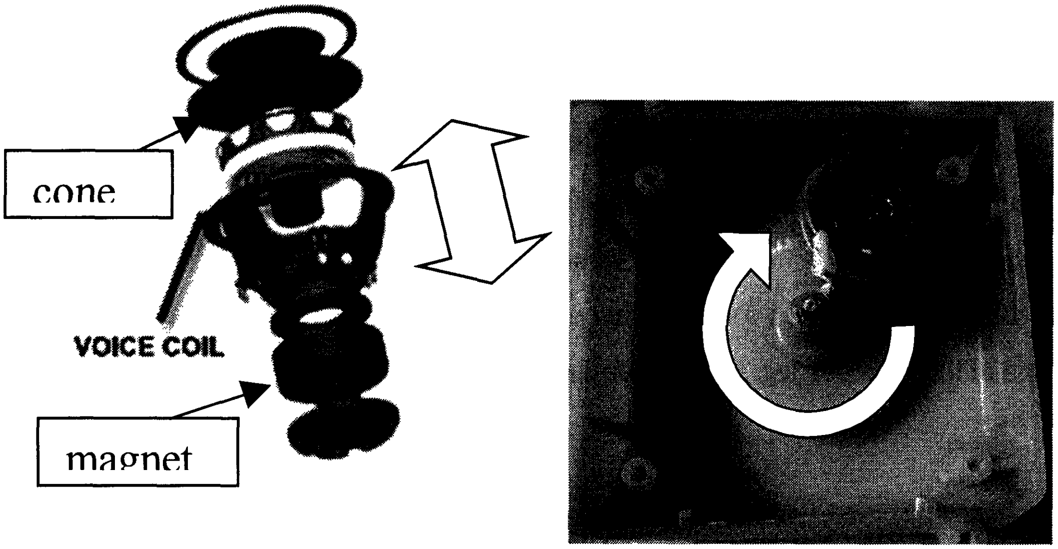


Figure 11. Two examples of powered vibration devices. (Left) Voice Coil, magnet drives voice coil that moves vibrates cone to produce sound.. (Right) Vibration device from child's toy. (images from electronics.howstuffworks.com/question368.htm and www.caraudiomag.com/specialfeatures/0109cae_subwoofer30.jpg, respectively, accessed 8/10/05)

3.2.2 Strictly Mechanical Devices

There are many and varied choices for mechanical devices to produce a load, impact or vibration. Only a few samplings of general types are illustrated here. Most devices incorporate the motion of the examples presented. Consideration and attention was paid to the amount of noise and the rate of wear that each design would produce.

In Figure 12 are two examples of mechanical devices that impart a sharp load. The Automatic Punch tool produces a sharp load by resisting the force and then releasing the load quickly. The amount of impact load is determined by the adjustment of the internal spring. The other device is a toy clicker. The toy clicker simulates the sound of either crickets or frogs by compressing the toy between the thumb and index finger until the metal buckles and then returns to original shape producing an audible clicking sound.

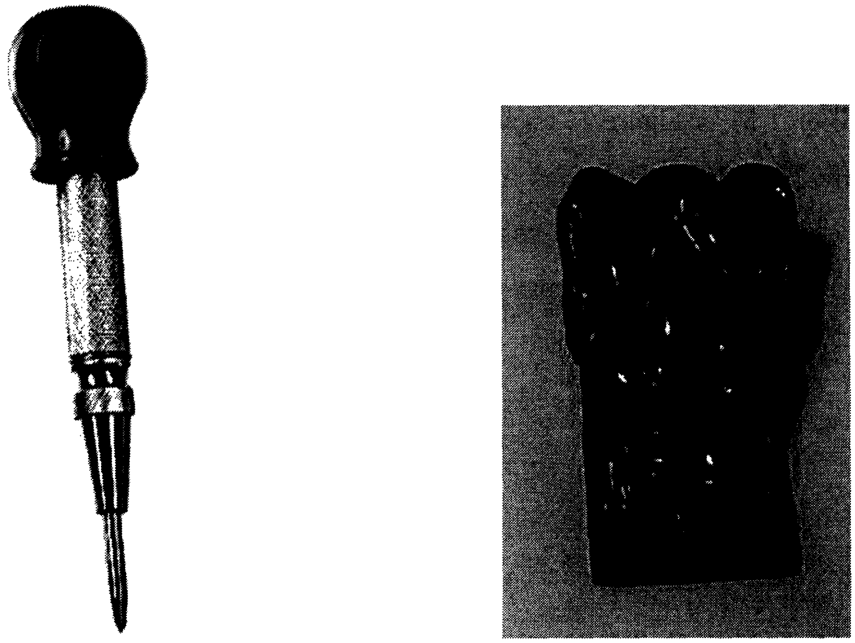
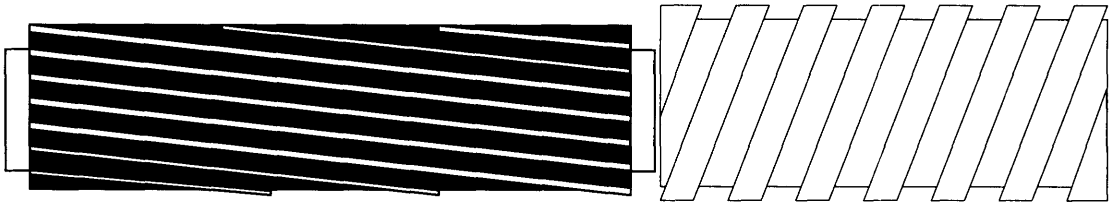


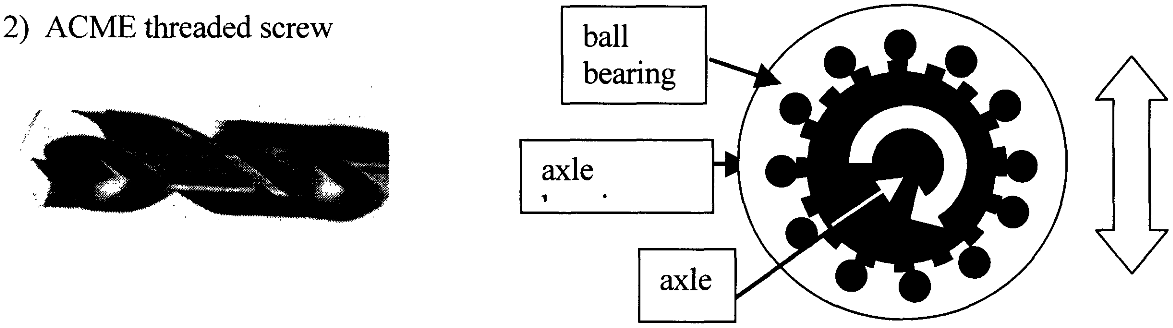
Figure 12. (Left) Automatic Punch Tool (Right) Toy Clicker. (images from http://www.chiefsupply.com/cat_punch.phtml and, http://classifieds.aol.com/listing/details.aspx?listingid=A4577468 respectively, accessed 8/9/05)

The axle devices shown in Figure 13 were considered for their simplistic properties. It may be possible to replace the axle from a conventional pedal and install a modified axle to produce vibrations. The vibration would come from ball bearing riding on a splined surface. The idea was that as the axle rotated and came into contact with the loaded bearing (possibly ball or roller bearing), the race or housing of the pedal would be displaced slightly with a slight vibration. The ball bearings could be mounted on a compliant surface or a sprung surface in an attempt to float the pedal and allow pedal to vibrate at a specified frequency when axle is rotated. The number of splines could be specified and fabricated into the axle. This idea relied on a slight displacement for vibration. It would simulate a poorly running pedal with the rough spot being controlled by the load that the spring loaded bearing surface would apply. The splined axle (1) in Figure 13) was the simplest form and the frequency can be varied with the number of splines cut in the axle. A variation of the parallel splined axle turns the splines toward a direction perpendicular to the axle. In this near perpendicular orientation, the splines would be similar the square-shoulder threaded, ACME screw (2) in Figure 13). If the spline is moved to perpendicular to axle, then it would effectively become a ring and provide no vibration. A drill bit (3) in Figure 13) was also studied for the grooved shape similar to that of the ACME threaded screw. An axial view of a possible axle installation in a housing with bearings surrounding the splined axle (4) in Figure 13). The idea of a controlled rough surface bearing held many complications and the likelihood of extreme wear.



1) splined axle

2) ACME threaded screw



3) drill bit

4) axial view down proposed axle, screw or bit surrounded by ball bearings

Figure 13. Examples of splined designs as a method to produce vibrations in a possible pedal device. (3) drill bit image from media.popularmechanics.com/images/tb_0012HITOAI.jpg, accessed 8/05/05).

A device as shown in Figure 14 is similar to the splined axle, but applied to the gear with a sprung plunger device providing the restoring force. The spring-loaded plunger can only move horizontally. The tip of the plunger is intended to press against the edge of the geared surface creating a sort of ratcheting effect. As the gear or possibly ratcheted wheel rotates, the plunger is forced into cavity compressing the spring. The gear rotates further and the plunger is forced back by the spring into the valley between the gear teeth. The plunger oscillates back and forth in this manner. Plunger could be weighted or provide an impact force to target area, such as the foot.

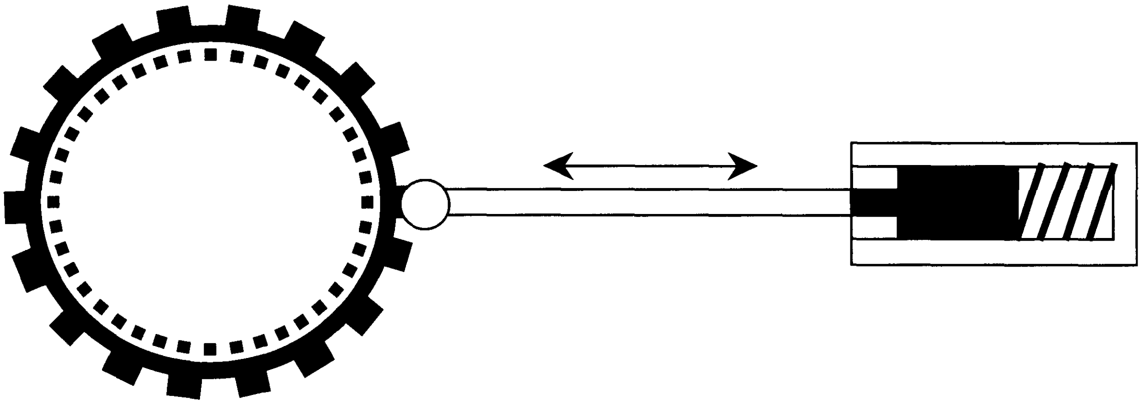


Figure 14. This ratcheted plunger device can provide an impact or vibration as the geared wheel rotates, the plunger tip is forced by crest of gear tooth to compress spring, then spring provides restoring force as plunger moves to trough of gear. A 20-teeth gear could provide 20 cycles for one turn of the axle.

A mechanism with a gear/linkage couple that provides a resultant vibration about the top pivot point was considered next. This mechanism served to illustrate that a linked segment could replace a gear couple and the resultant motion would be equal. This mechanism was intriguing since it took a rotary motion and converted to a vertical oscillation about a distant pivot point. This mechanism held important value in that it closely modeled the movement and linkage of the hip, knee and foot about a rotating link (or crank arm of a bicycle). This made the possibility of transmitting a vibration to the hip from the foot more plausible.

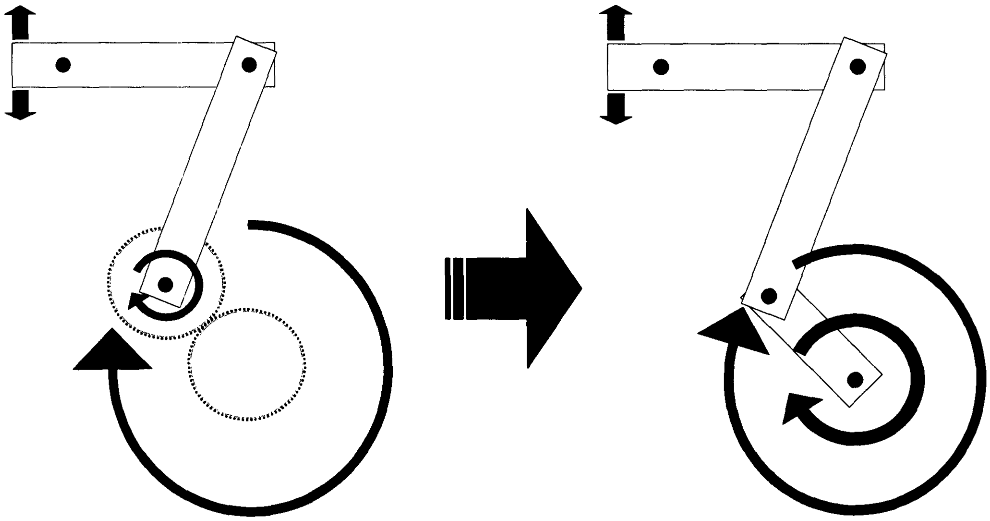


Figure 15. (Left) Geared mechanism and (Right) Equivalent Mechanical Linkage. This device takes a resultant rotation and transforms to vertical oscillation at end located at top left of device past last pivot point. This device is analogous to foot, knee, and hip mechanism with foot rotating at bottom and vertical oscillation past hip joint.

A 2-dimensional vibrating device illustrated that a rotary motion could be converted to a horizontal motion (Figure 16) . That horizontal motion could then be converted to a vertical motion. The wheel rotates and drives the piston back and forth in a horizontal motion. The linked motion is transmitted to the vertical piston and drives this piston up and down.

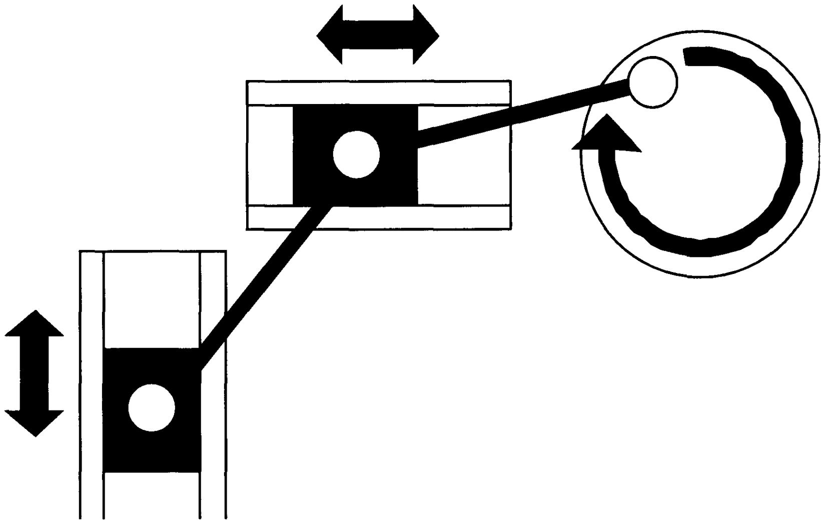


Figure 16. This mechanism takes an input rotation and converts motion to linear horizontal motion and then is converted to vertical motion.

A linked mechanism took the action of two counter-rotating wheels and converted the rotary motion to an oscillation motion in one direction (Figure 17). This device was important in the development of the final mechanism because it illustrated the summing properties that were possible with a mechanical linkage.

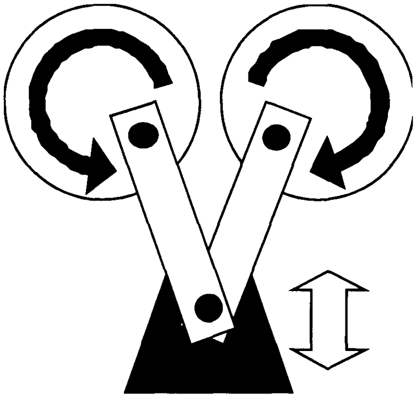


Figure 17. Mechanism that converts rotary motion of two counter-rotating wheels and to vertical, vibration output.

Finally, a complicated mechanism took the summing linkage further by adding a transverse axle driven rod. The rod takes the rotary motion (pedal axle) and transfers to a distant location (the heel) as illustrated in Figure 18. A summing linkage mechanism has also been added to the output (similar to Figure 17).

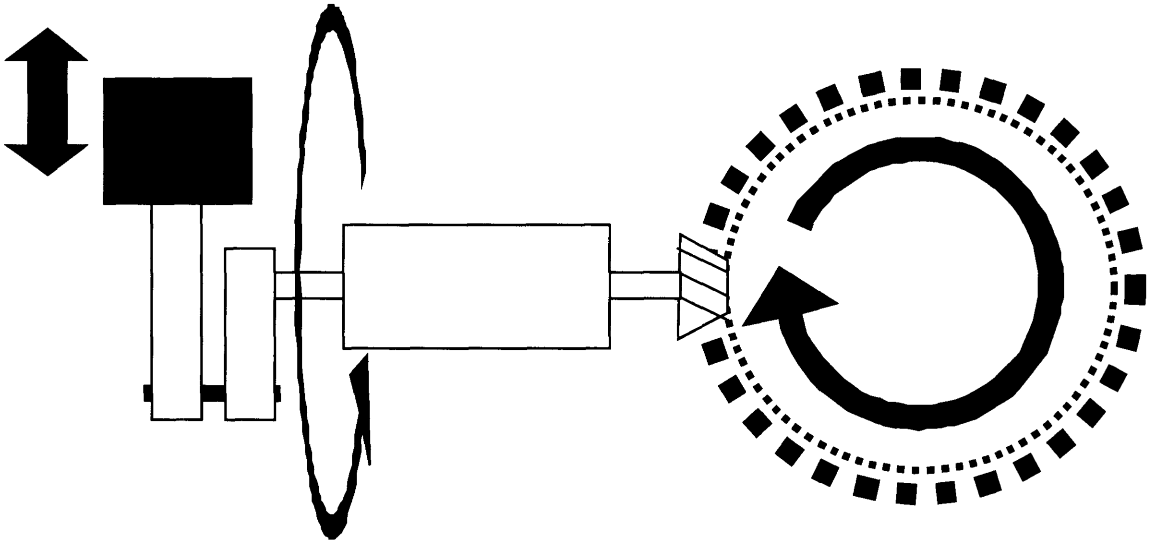


Figure 18. Mechanism taking a rotary input, convert to rotation on transverse axle and converting to vertical output motion.

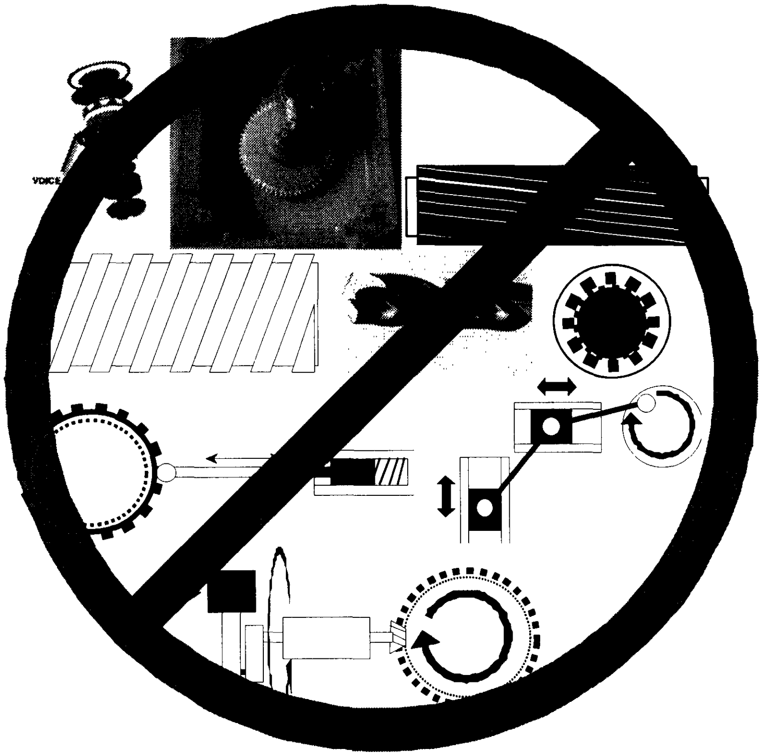


Figure 19. Rejected ideas from the assortment of possible solutions

- The voice coil was eliminated since it required a magnet that added significantly to the weight, plus the power required to drive it was significant. The main advantage was the simplicity of the device and control of the frequency, but mass and power cost were too great.

- The off-center weight of the vibration device from child's toy was eliminated since it was an externally powered device.

- The splined, threaded surfaces or drill bit like devices were rejected, because the idea of a controlled rough surface bearing held many complications and the likelihood of extreme wear.

- The ratchet plunger was an impact device and had the characteristics that it would be an annoyance due to audible impact and the impact would cause excessive wear.

- The rotary>horizontal>vertical motion converter was rejected since the number of linkages and motion control devices consumed a large percent of the mass cost.

- The heel mass summing linkage device was rejected since location of mass did not have to be located at heel and added transverse linkage complicated the mechanism for no benefit.

4 VIBRATIONAL PEDAL DESIGN FOR HUMAN POWERED ARTIFICIAL GRAVITY (HPAG)

4.1 Understanding Gears

A gear system provides torque or speed changes depending on the ratio of the drive gear to the driven gear. If the gear diameters are equal, only motion is transmitted. The gear's value comes through when its attributes are fully exploited, by creating differences in gear ratios. The diameters of the gears determine whether speed is increased or torque is increased. To conserve work, either torque or speed can be increased; never both. In the Conservation of Work Equation illustrated in Equation 3., the relationship of force and distance or torque and angle determines the amount of work done, the input work equals the output work.

Equation 3. Conservation of Work

Work (W) Equation Relating Force (F) and Distance (D)

INPUT						OUTPUT				
W_{input}	=	F_{input}	*	D_{input}	=	F_{output}	*	D_{output}	=	W_{output}

Work (W) Equation Relating Torque (τ) and Angular Displacement (θ)

INPUT						OUTPUT				
W_{input}	=	τ_{input}	*	θ_{input}	=	τ_{output}	*	θ_{output}	=	W_{output}

Examples of gearing to produce increased torque or increased speed are common. A gear reduction pair increases the torque output of a powered screwdriver as illustrated in Equation 4. The small low-torque power screwdriver motor develops significant torque with the use of gearing. The small input torque multiplied by the angle in radians transforms to give an output that has a large torque and decreased radian output rate. A bicycle utilizes the gear ration for a speed increase. The bicycle driver gear takes the input torque of the rider and multiplies the speed with the driven gear to allow the bicyclist to move at a faster speed. The work done in each case would be similar without gearing.

For the power screwdriver the small motor inputs many turns to have a single turn on the output. In the Work equation, the many turns of the motor represents the Distance and the Force is the torque applied by the motor at input. In the example of a person using a screwdriver to turn a screw, no mechanical advantage is exhibited (Equation 5).

Equation 4. Relationship of torque and number of turns in powered screwdriver.

Powered Screwdriver

INPUT						OUTPUT				
W_{input}	=	τ_{input}	*	θ_{input}	=	τ_{output}	*	θ_{output}	=	W_{output}
relatively small motor torque turns gear many times						outputs a large torque turning few times				

τ_{input}	<	τ_{output}
θ_{input}	>	θ_{output}
W_{input}	=	W_{output}

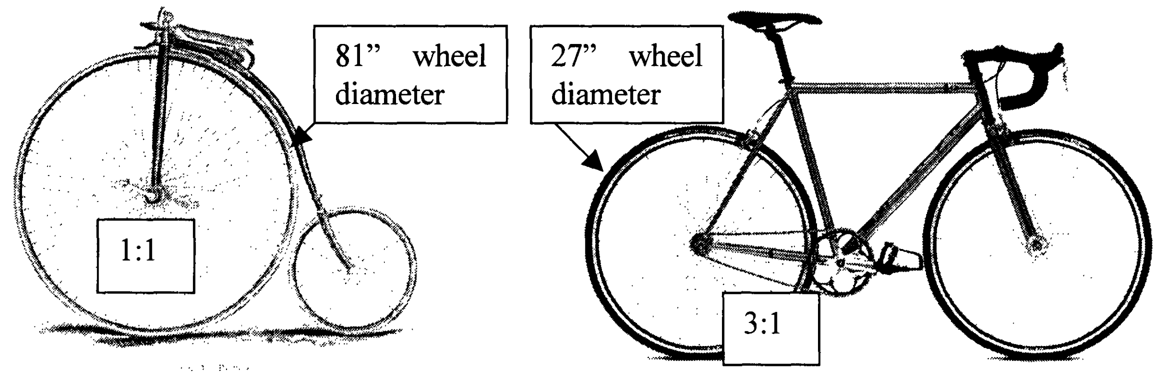
Equation 5. Relationship of equal torque and number of turns in unpowered screwdriver.

Unpowered Screwdriver

INPUT						OUTPUT				
W_{input}	=	τ_{input}	*	θ_{input}	=	τ_{output}	*	θ_{output}	=	W_{output}
hand turning screwdriver at torque necessary to turn screw						flat blade of screwdriver turning at same rate and torque as hand				

τ_{input}	=	τ_{output}
θ_{input}	=	θ_{output}
W_{input}	=	W_{output}

In the case of the bicyclist, the speed is increased with the aid of gearing made possible by the gears of the chain driven system and the diameter of the wheels. The earliest bicycles to experiment with giving the bicycle a mechanical speed advantage were the high wheelers. These tall bikes had large drive wheels to increase the distance covered in one rotation of the crank arm. The wheels grew taller and speeds increased. Thankfully, a geared system was introduced and today we have geared systems that make cycling enjoyable and a versatile mode of transportation.



HIGH WHEELER		BICYCLE TYPE		SINGLE SPEED	
1:1	(1/1)	**Gear Ratio**	(Drive Gear/Driven Gear)	**3:1**	(48/16)
81	[(1:1)*(81 inches)]	**Gear Inches**	(Gear Ratio*Wheel Diameter)	**81**	[(3:1)*(27 inches)]

Figure 20. (Left) High Wheeler. (Right) Single Speed Geared Bicycle (images from http://hrsbstaff.ednet.ns.ca/starr/Andrea/History of the bicycle/high_wheeler_or_penny_farthing.htm and http://www.sheldonbrown.com/harris/fixed.html, respectively, accessed 8/08/05)

Geared Bicycle

In the example of the geared bicycle, a large input torque is converted to a large output speed with a proportional decrease in output torque (Equation 6).

Equation 6. Example of high torque/low speed input converted to low torque/high speed output.

Geared Bicycle

INPUT						OUTPUT				
W_{input}	=	τ_{input}	*	θ_{input}	=	τ_{output}	*	θ_{output}	=	W_{output}

high torque applied to crank arm by leg

outputs a small torque turning rear wheel many times

τ_{input}	>	τ_{output}
θ_{input}	<	θ_{output}
W_{input}	=	W_{output}

High Wheeler*

The high wheeler example (if crank arm length = wheel diameter), the input force equals the output force. No torque increase or speed increase.

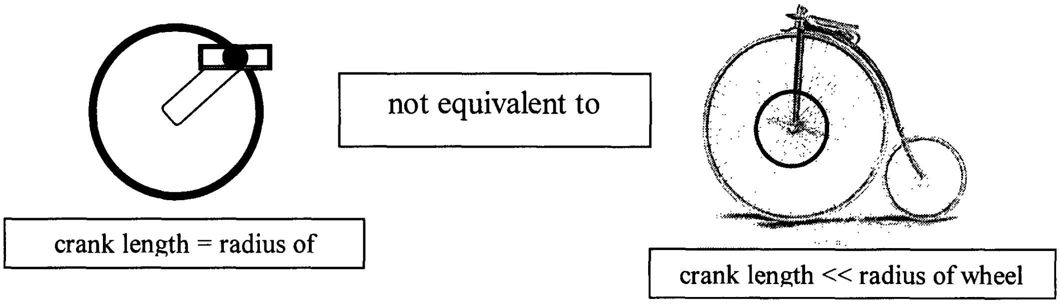


Figure 21. Figure showing mechanical advantage employed by high wheeler compared to simple crank and wheel .(image from hrsbstaff.ednet.ns.ca/starr/Andrea/History of the bicycle/high_wheeler_or_penny_farthing.htm, accessed 8/10/05)

Equation 7. Higher Wheeler as Ungeared Bicycle

High Wheeler (crank arm length = wheel radius)

INPUT						OUTPUT				
W_{input}	=	τ_{input}	*	θ_{input}	=	τ_{output}	*	θ_{output}	=	W_{output}
crank is turned by leg						wheel is turned at same rate				

τ_{input}	=	τ_{output}
θ_{input}	=	θ_{output}
W_{input}	=	W_{output}

**high wheelers took advantage of a larger diameter wheel, but as wheel radius increased, the high wheelers bicycle became taller and more difficult to handle*

The application needed for the high-frequency/low-magnitude device requires a geared system. This geared system will take the input of the crank turning at approximately 90 RPM and multiply the input to get an output frequency of 30 Hz as shown in Table 1. The application needed will increase the speed of rotation. The input is low frequency (θ) with high torque (τ) and the output needs to be high frequency, which the Conservation of Work Equation (Equation 3) dictates that the output will be low torque.

Bicycling Operating Rate (RPM)	90
Minimum Required Frequency (Hz)	30
Bicycling Operating Frequency (Hz)	1.5
Required Freq. Multiplication	**20**

Table 1. Frequency multiplication calculation.

4.1.1 Direct Drive

Spur gears are the gears that are meant to be mounted and to mesh with other spur gears on parallel axes (Figure 22). The spur gears mesh directly together and counter rotate relative to each other. Spur gears of different diameters mesh together to output a specified gear ration. Multiple gears may be located on a single axle, which is called a compound gear train. Multiple compound gears may be combined with other multiple compound gears to form a gear train (Figure 23). Since the gears mesh directly, the gears must be lubricated directly. The engagement of the gears requires strict tolerance of the placement of the gears. If the gears are placed too close together the gears will bind and if placed too far apart, the gears have a significant amount of play when engaged. With spur gears, the load is carried only where the teeth of a gear engage the teeth of the mating gear.

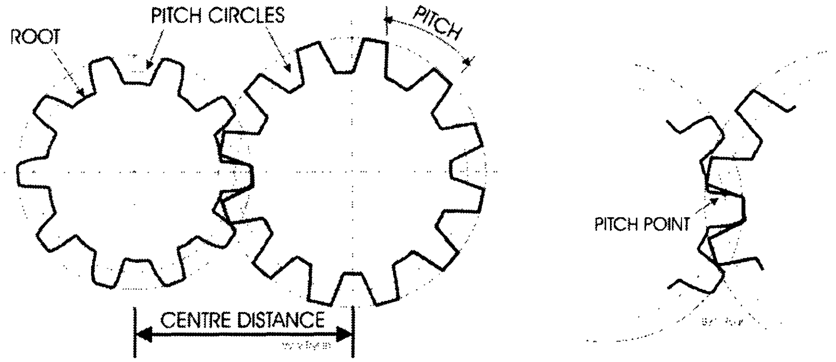


Figure 22. (Left) Diagram of gear components. (Right) Pitch point or mesh point. (www.technologystudent.com/gears1/grdetail.htm, accessed 8/10/05)

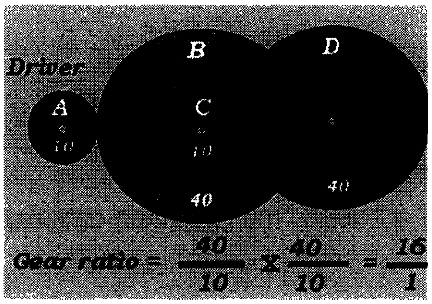


Figure 23. A 2-stage compound gear train with 1:16 gear ratio (www.dynamicscience.com.au/tester/solutions/hydraulicus/gears1compound.htm, accessed 8/10/05)

4.1.2 Chain Drive

A chain drive utilizes gears that do not mesh, but are instead linked together by a chain. A bicycle is an example of a chain drive. A chain drive system can tolerate some chain slack and still operate adequately (Figure 24). If the gear axles are positioned too far apart, the chain will be tight. If the gear axles are placed too close, the slack in the chain will be excessive. A simple chain drive does not allow counter rotation; the driven gear turns in the same direction of the driver gear. Most chains will flex in both directions, parallel to gear plane, so that a chain may travel under one gear and over the next gear. The chain drive gear placement is not as critical as with the direct gear drive. Since the gears do not mesh, no direct lubrication of gears is required, but the chain must be adequately lubricated. The chain drive functions best when the gear plane is parallel to the gravity vector. When the gear plane is not parallel with gravity vector, gravity tends to derail the chain. A chain spreads the driving force over many gear teeth, but the chain links the two gears and carries the entire load on side in tension.

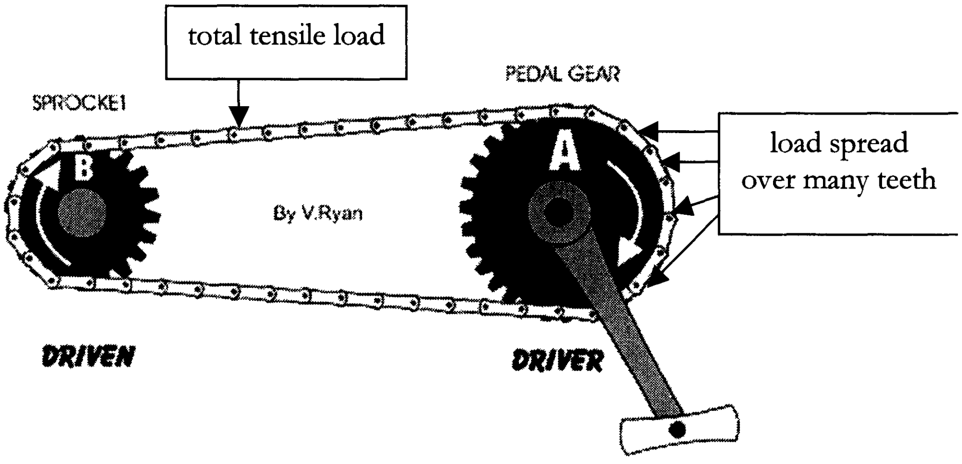


Figure 24. A bicycle chain drive, (http://www.technologystudent.com/gears1/chain1.htm, accessed 8/10/05)

4.1.3 Belt Drive

In a belt drive system (Figure 25), the belt operates on pulley wheels that utilize friction to transmit motion and torque. Belt drives are relatively quiet, can utilize teeth on the pulley to prevent slippage and are typically formed as a single composite unit. The belt is usually constructed of a polymer reinforced with cable of steel, kevlar or nylon. A belt drive is slightly elastic, so it is meant to operate in tension without the slack associated with a chain. A belt does not perform well or have a long performance life if it is operated to flex and compress in a single cycle, which would usually occur in a situation where the belt moves over one pulley and under another pulley. The tension in the belt drive also makes operation out of plane with the gravity vector more favorable than the chain drive system. A belt spreads the driving force over many the contact surface, similar to the gear drive. Similar to the chain in the chain drive system, the belt links the two gears and carries the entire load.

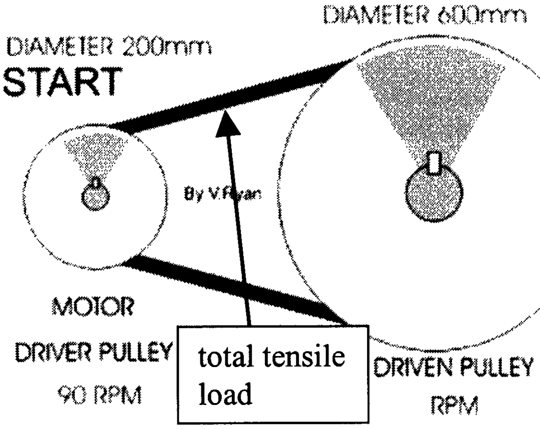


Figure 25. Example of a belt drive system (technologystudent.com/gears1/pulley3.htm, accessed 8/10/05).

5 TANGIBLE DESIGN PROGRESSION

5.1 Evolution of the Lego^{TM} Models

The first model (Figure 26) used a two-stage gear train with two compound gears of 5:1 ratio. When the two stages were combined, the resultant gear ratio was 25:1. The large 40-teeth gear was combined with the 8-teeth pinion for the 5:1 ration. The gears were mounted externally on a block. A linkage constrained the rotation of the counter-rotating gears that resulted in moving a mass up and down in a vertical motion. The linkage served to put all of the motion of the mass in the vertical direction.

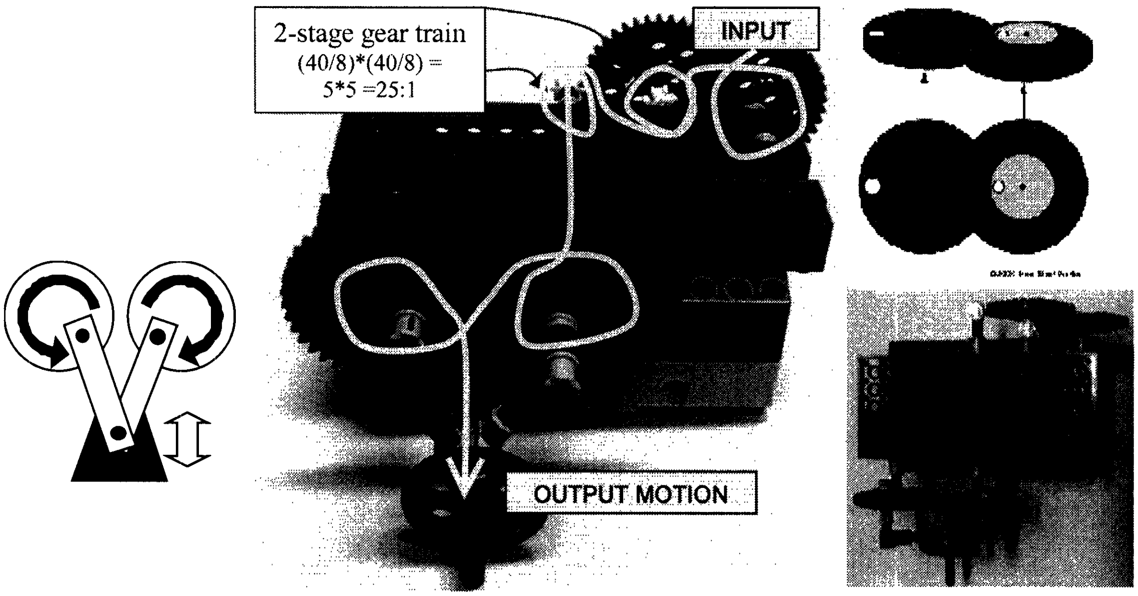


Figure 26. First Lego^{TM} model with linkage to transfer circular motion of counter-rotating gears to vertical motion. Driving gear opposite of moving mass. Two-stage gear train of two gear diameters.

The next iteration moved the gears internal to a chassis. The same compound gear train was used for the speed increase (2 * 5:1 = 25:1). Smaller 24-teeth gears (red) were added to transfer the motion and elongate the gear train. The mass was moved directly under chassis. The linkage that facilitated the vertical motion of the mass was slimmed to reduce weight, but was subject to a twisting motion that occasionally caused the linkage to bind. A makeshift crank arm was implemented to illustrate the motion of the "pedal" relative to the bicycle frame.

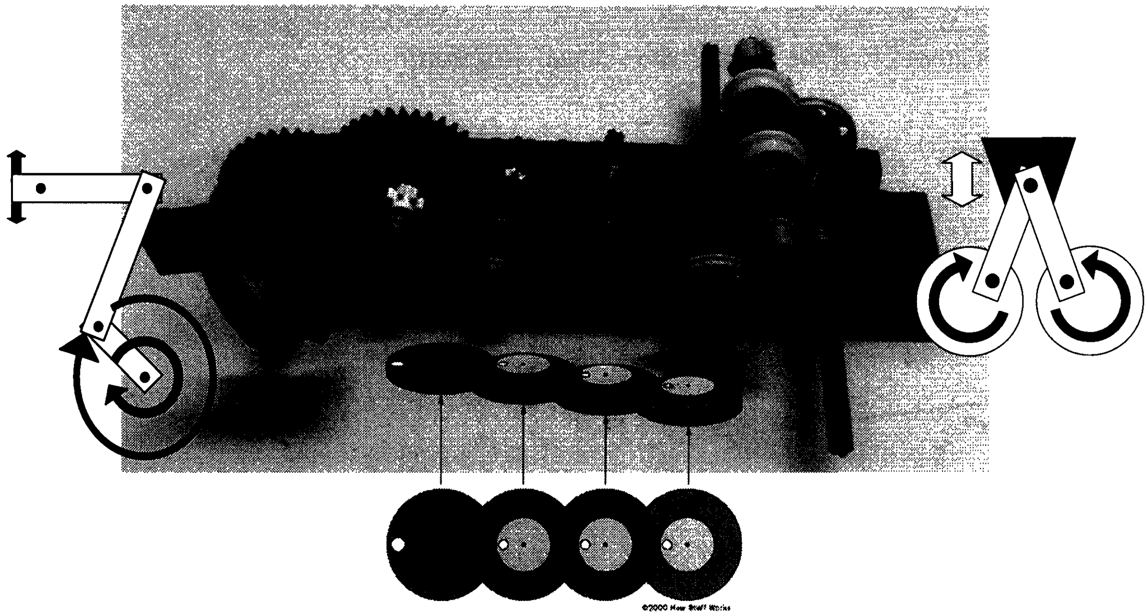


Figure 27. Lego™ model with linkage to transfer circular motion of counter-rotating gears to vertical motion. Mass has been centered above gear train. Two-stage gear train (green gears) with smaller gears transferring motion (red gears). The pinions (white gears) bring total to three gear diameter sizes. Crank arm added to simulate motion of bicycle crank arm. (image of gear train from articles.roshd.ir/articles_folder/mohandesiScience/mechanic/Howstuffworks How Gear Ratios Work.htm, accessed 8/10/05)

The third iteration of the model kept the gear train in the chassis. Three gear sizes were still used (40, 24, and 8). The gear train remained housed inside the chassis. The linkage to mass was removed. The friction and complication of the linkage was not worth the slight advantage provided by the mass moving vertically. Weights were placed on smaller, red

24-teeth gears. The weights were positioned on the gear, so that the weights mirrored the other weight's movement. This orientation of the weights coupled with the counter-rotation, allowed the weights to sum in the vertical direction and cancel in the horizontal direction. Some mass movement in the vertical direction was sacrificed in the summing motion, but simplification of design worth the mass movement loss.

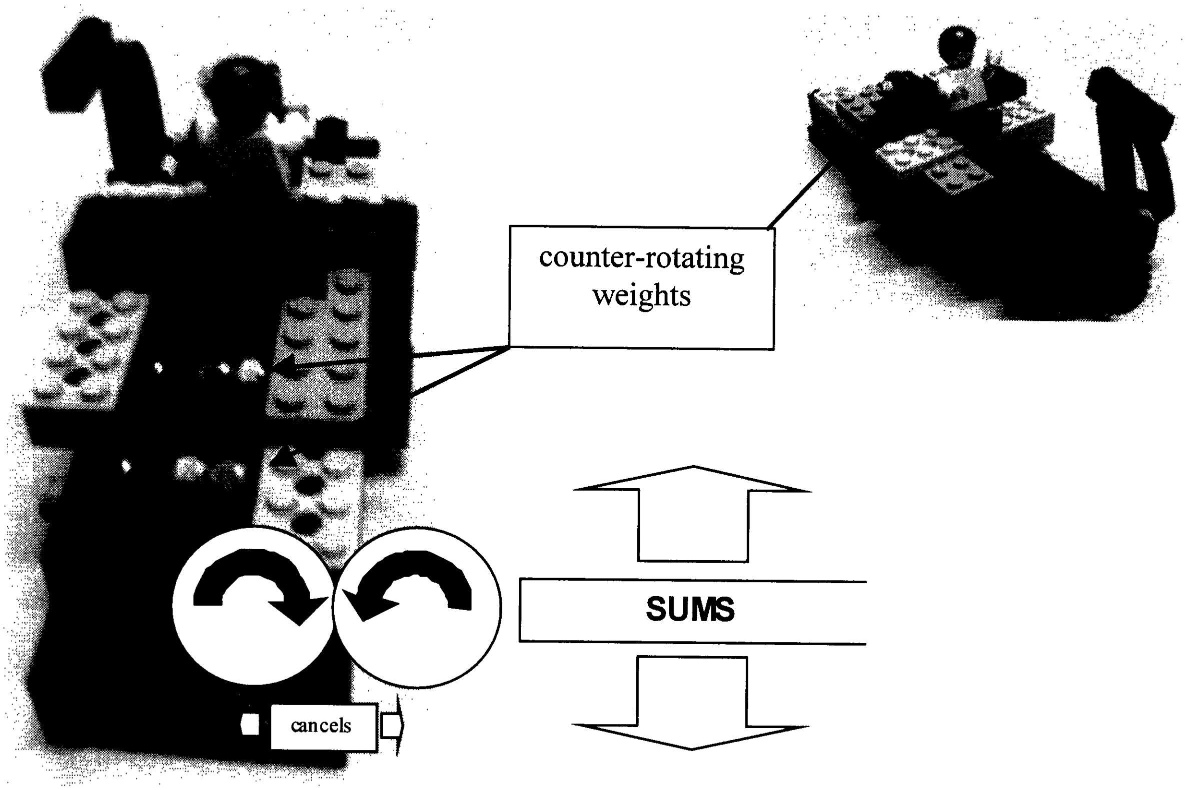


Figure 28. Weights replace linkage on counter-rotating gears, two-stage gear train and crank arm unchanged from previous model. Three different gear sizes utilized.

The final Lego model increased the stage number to three and reduced the gear type to two; the 24-teeth and 8-teeth gears. The reduction of gear number would ease maintenance and reduce spare number and type. The three-stage gear train consisted of three compound gear pairs of 3:1 (24:8) that resulted in a final ratio of 27:1 (3:1 * 3:1 * 3:1). The addition of the extra stage lengthened the gear train and lowered the profile. The rotating mass couple added after the second stage to increase the vibration frequency resulted in an increased frequency riding a lower frequency of less amplitude than that of original frequency

(Figure 30). In Figure 31 illustrates that adding rotating masses increases frequency, but decreases amplitude of resultant frequency. If enough rotating masses are added, the vibration would be cancelled.

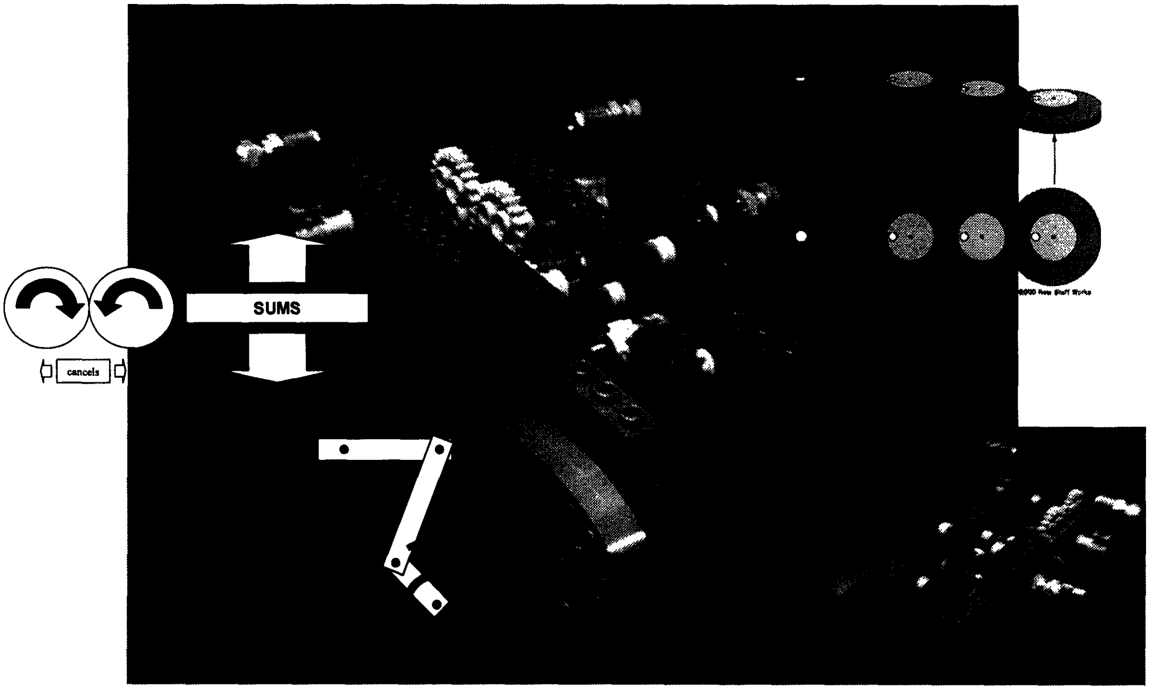


Figure 29. Three-stage gear train with identical gear diameters utilized. Weights moved out to end of counter-rotating crank arms to increase moment. Drive crank arm unchanged. On top of gear train, a gear with weight was added to add additional vibration at 1/3 output frequency (not used). (image from articles.roshd.ir/articles_folder/mohandesiScience/mechanic/Howstuffworks How Gear Ratios Work.htm, accessed 8/10/05).

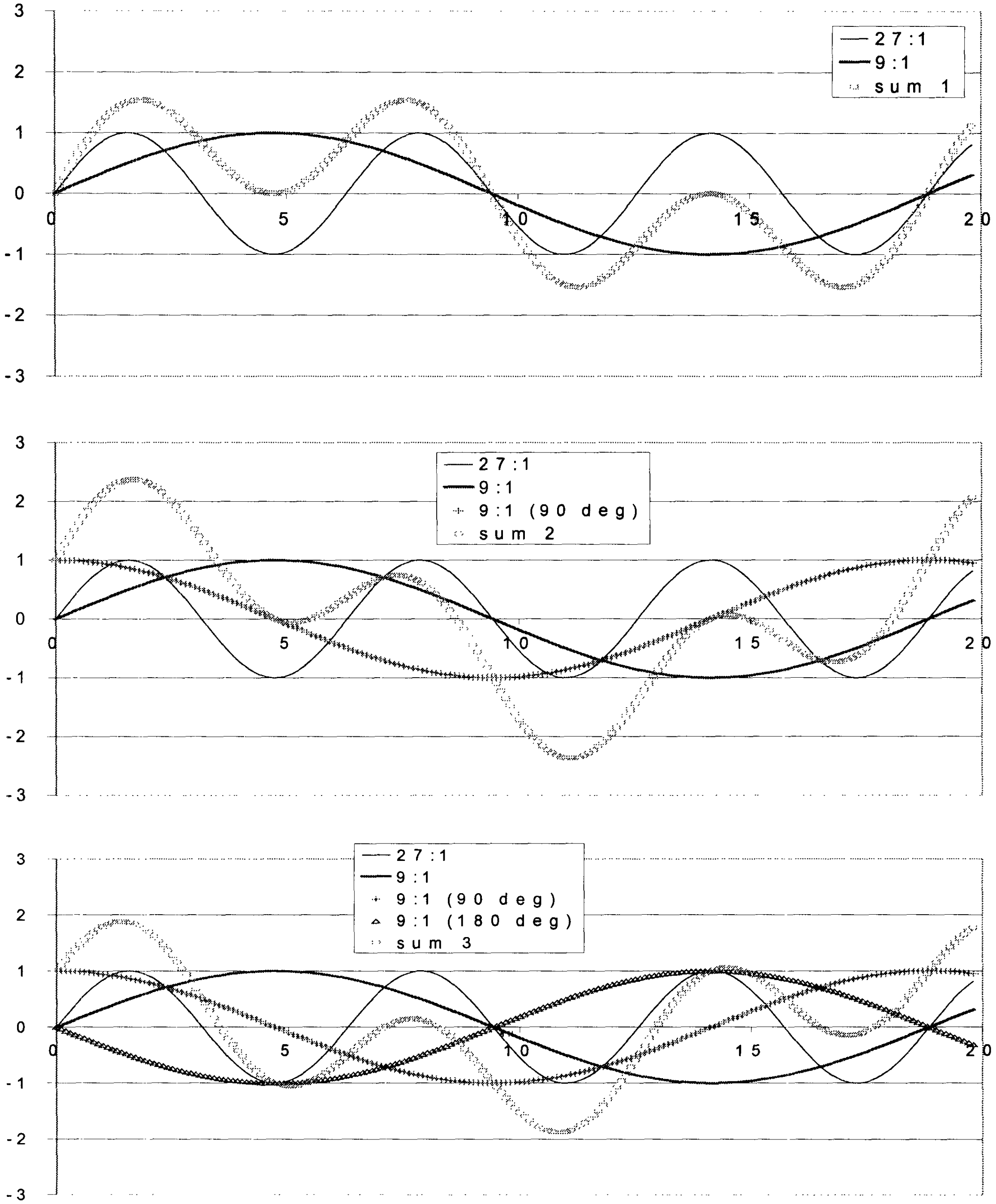


Figure 30. (Top) 27:1 ratio with additional 9:1 ratio added to increase frequency, amplitude increased, but resultant frequency reduced to 9:1. (Middle) Additional frequency added and average amplitude degraded along with frequency. (Bottom) 180 degreed out-of-phrase frequency added and resultant frequency lowered along with amplitude.

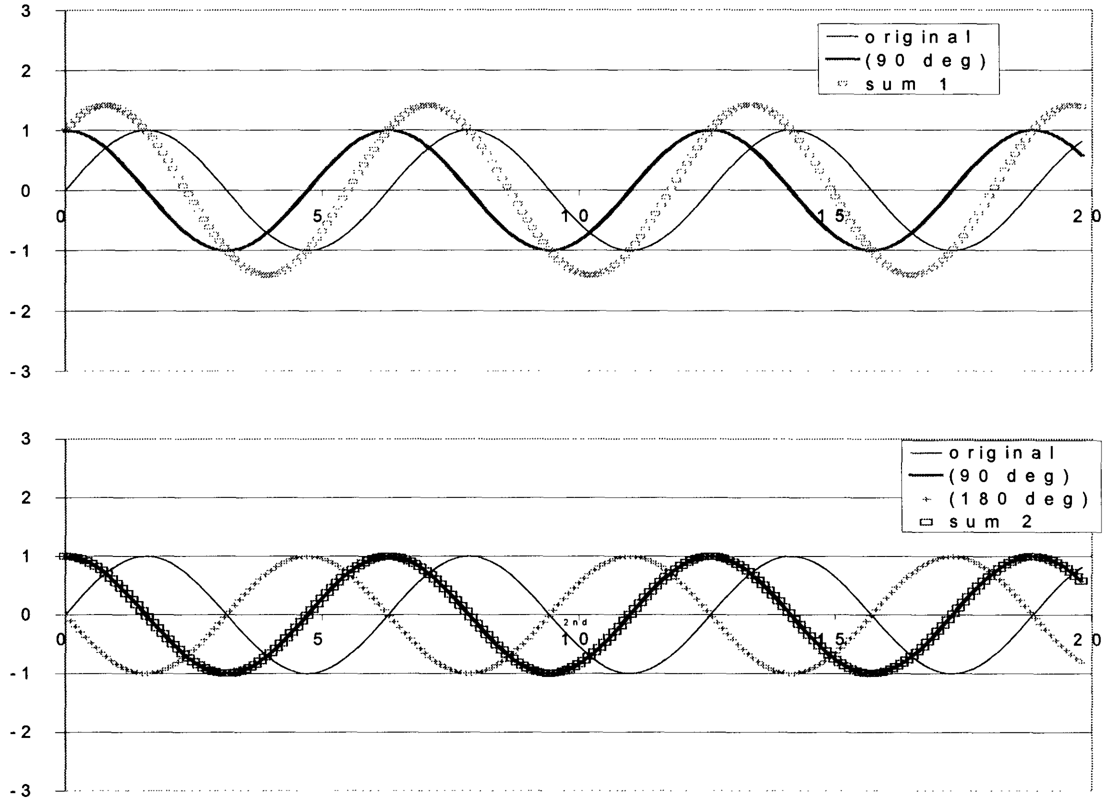


Figure 31. (Top) An original frequency summed with a frequency lagging 90 degrees and summed. Increased amplitude and same frequency. (Bottom) 180 degree out-of-phrase frequency added, cancels original frequency, leaving 90 degree lagging frequency.

5.2 Initial Prototype

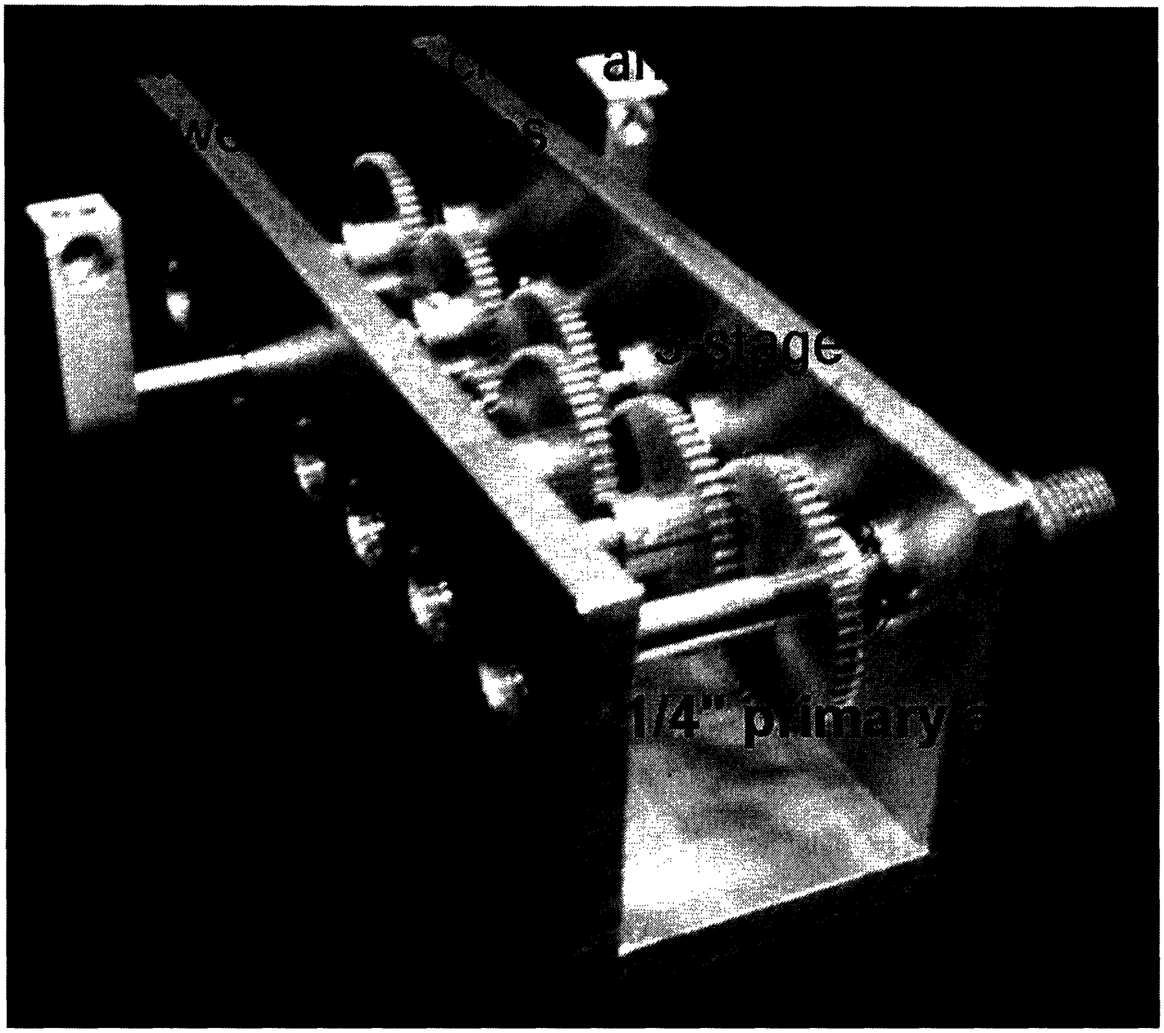


Figure 32. Initial Gear Drive Vibrating Pedal with ¼" drive primary axle. Counter-rotating crank arms without lead weights formed into aluminum end cavities.

The prototype gear drive or the Prototype Direct Drive Vibrating Pedal (DDVP) was constructed with a 3-stage gear drive driven by a ¼" primary axle, all housed with a 2"x2" aluminum U-channel. The axles rode on ABEC1 bearings and were secured with E-clips that were internal to the chassis. The gear assemblies were secured to axles with tightened setscrews secured on the flat spots of the axles. A more detailed description of final design is given in the Final Design section.

5.2.1 Initial Test Run

Before the prototype failed, it was noted that the vibration intensity of the duty cycle of the DDVP and CDVP was much more harsh than designed for in the use of fasteners. Almost immediately, the pedal became loose from unscrewing from the crank arm and the setscrews fastening gears to axles became loose. The pedal problem was solved by ensuring pedal was tightly secured to crank arm. The setscrews were removed and a thread locking material was applied and given appropriate cure time. Locking the threads was essential in securing the setscrews in place.

The vibrating performance of the DDVP exceeded expectations. The DDVP provided a clearly perceptible vibration. The vibration was even perceived in the off-DDVP side in the normal pedal. This characteristic of vibration performance raised the question of vibration application. The original plan had been to utilized a vibrating pedal for each foot. The plan was to simultaneously use a vibrating pedal on the left side and on the right side. The new information of the vibration transmission via crank arms and bottom brackets indicated that the applied vibrations may attenuate and possibly cancel each other, similar to phenomenon illustrated in Figure 31.

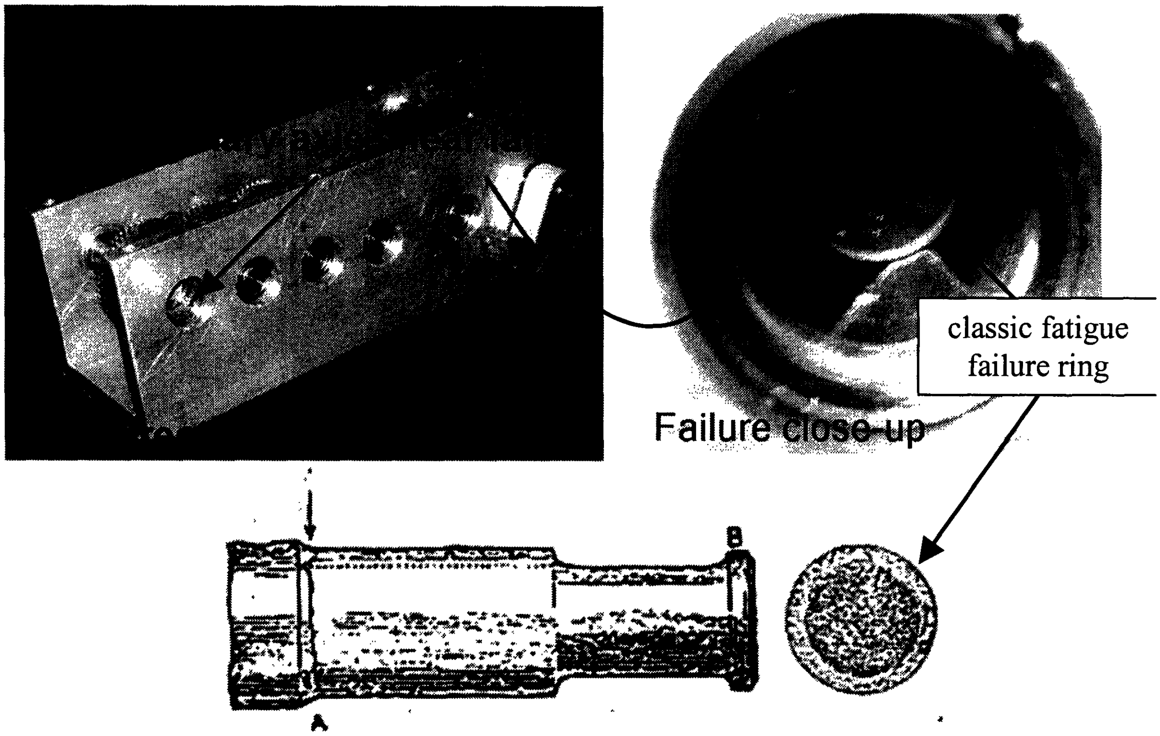


Figure 33. Primary axle fatigue and shear failure during testing when installed on conventional bicycle. Fatigue and shear failure evident by presence of fatigue ring. (image from www.answers.com/topic/classic-fatigued-axle-jpg, accessed 8/10/05.)

During initial testing of the first prototype design, the primary axle failed. Upon inspection of the failure, it was determined that the ¼" stainless steel had failed due to three reasons:

1. Fatigue failure as evident in Figure 33.
2. Shear loading failure.
3. Location of square-edged groove for E-ring retaining clip.

A robust solution was sought to add to the design. The parameters of available material and cost guided the design. First, the pedal axles needed to be replaced with a substantially stronger design. Pedal axles and the associated bicycle crank arms that the pedals are fasten to, currently are Left Hand threaded for the left pedal and Right Hand threaded (common threading) for the right pedal. Three solutions were pursued.

1. Contract the MIT Central Machine Shop to fabricate custom axles out of tool steel. Cut threads on axles to accommodate the Left Hand thread of the Left Pedal.

Rejected: CMS turn-around time at least two weeks and prohibitive cost.

2. Fabricate custom axles with Right Hand thread for both left and right pedal. Bicycle crank arms would need to be drilled and tapped to accept the custom axles.

2nd choice: Crank arms, once customized, would always require custom axle, since drilling and tapping would not only change thread direction, but thread size also.

3. Modify a current pedal.

Best of 3 choices: Current and past pedal designs are diverse, so choices are plentiful.

The author's extensive experience[1] of bicycle racing allowed a logical approach to finding a pedal solution. In bicycle component design, there are three major philosophies. There are the components of Asian design origin, the components of English origin (USA included) and the components of French origin. The Asian designs tend to be of metric sizing and somewhat more contemporary. The English designs tend to be more traditional and utilize standard measurements of inches and fractions. The French designs tend to have no consistency except to be unlike the Asian and English designs. Currently, the most widely available designs were those of Asian origin, so these were the first to be examined. Two pedals of Asian origin were dissected and examined for compatibility with design needs and chassis requirements. Although the construction of each pedal was quite ingenious, it became obvious that neither Asian design would serve the purpose. These pedals illustrated the need for a sealed bearing cartridge. The current chassis of aluminum could not support the extreme pressure of a loaded ball bearing. A sealed bearing cartridge consists of the inner and outer race fastened together with the bearings internal to the device. Sealed bearings on pedals are not common, but for some reason, pedals of French design were always perceptibly the heaviest, but also most durable of pedals, so next for examination were the French pedals.

Immediately upon dissection, it became obvious that the French pedals were different. There were roller bearings, C-clips and sealed bearing cartridges—large sealed bearing

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[1] ABA BMX racer 1979-1987, 1990 military and civilian Panamanian road race champion, United States Cycling Federation Category IV racer (1991) and National Off-Road Bicycle Association Sport racer (1991-1993), bicycle shop mechanic 1990-1993.

cartridges. After measurements were made, it was obvious that the French pedals would serve the purpose and fulfill the requirements for pedal modification.

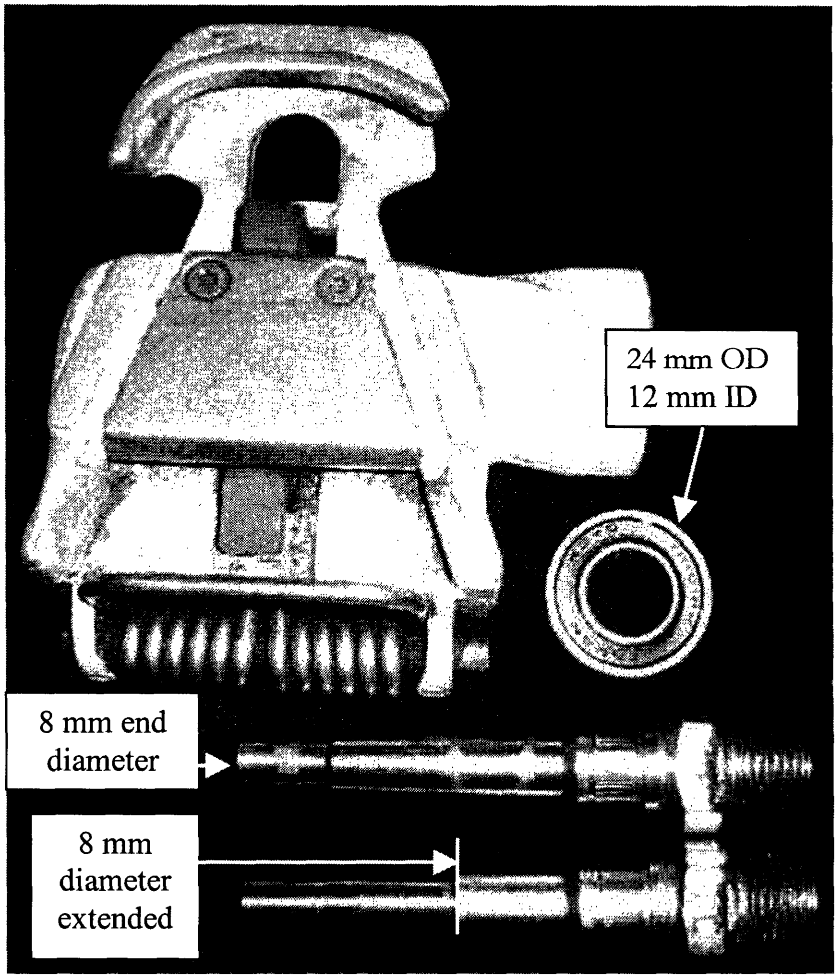


Figure 34. Dissected pedal of French origin

The pedal axles were modified as shown in Figure 34. The axle end diameter of 8mm was extended to approximately half the length of axle. This was necessary to accommodate the modified primary gear of first gear couple. The gear's inner diameter of ¼" was increased to 8mm (~0.3150"). This decrease of the axle diameter was a compromise by opening the gear inner diameter a small amount and decreasing the axle size a small amount, the strength of each was affected a small amount. The new axle diameter at failure point of prototype was increased to 12mm. This was almost double the diameter of original ¼" stainless steel axle.

5.3 Final Design

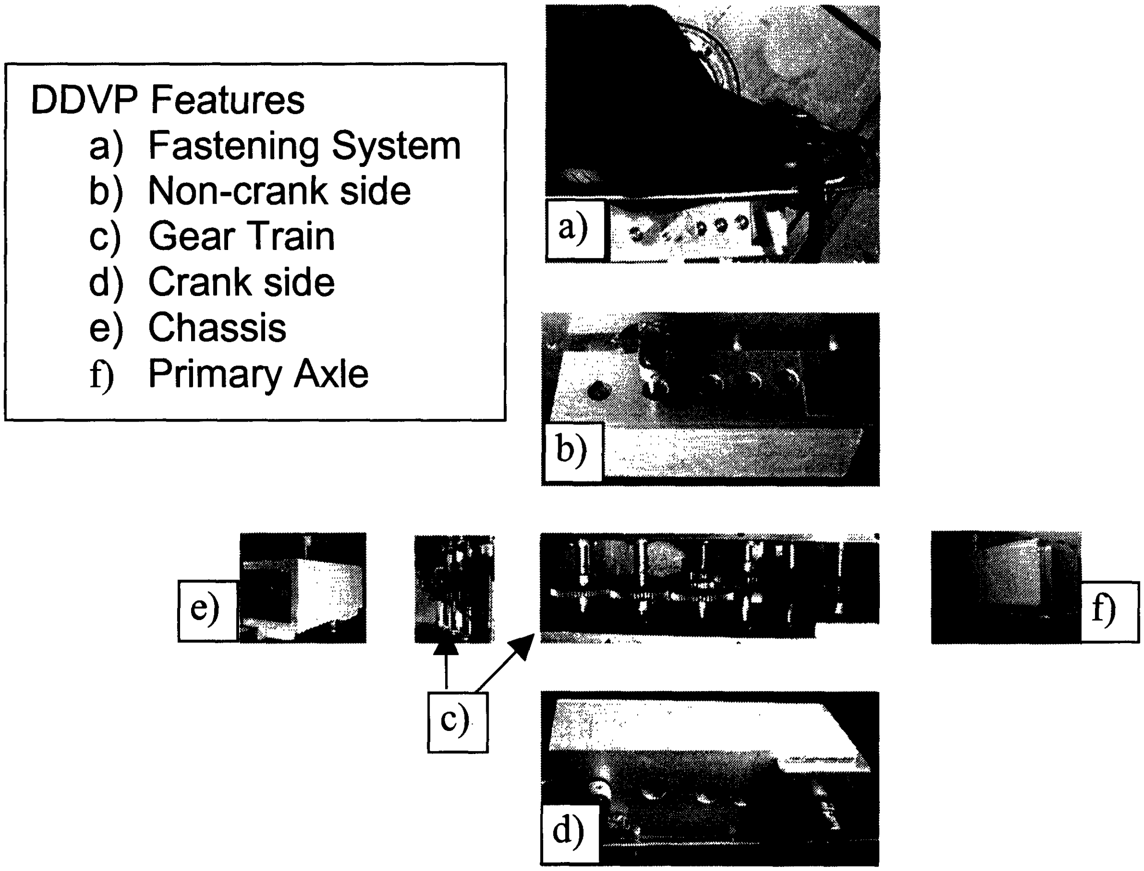


Figure 35. The exploded photographic view of the Direct Drive Vibration Pedal (DDVP).

5.3.1 Fastening System

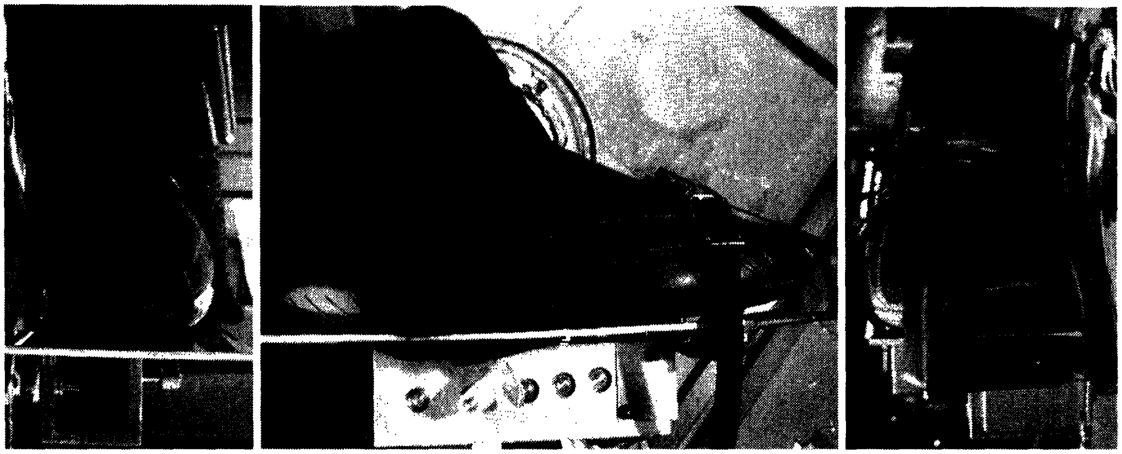


Figure 36. Fastening system of foot restraint system. (Left) Rearview, (Center) Side View, (Right) Front View.

The fastening system secured the foot to the vibrating pedal to facilitate the transmission of vibration to the foot. A standard plastic, mountain bike, toe clip with nylon strap secured the forefoot to the pedal and positioned the metatarsal head of the foot near the pedal axle. Velcro strapping was used in a crossing pattern in conjunction with the footplate to secure the heel to the pedal as shown in Figure 36.

5.3.2 Non-crank Side

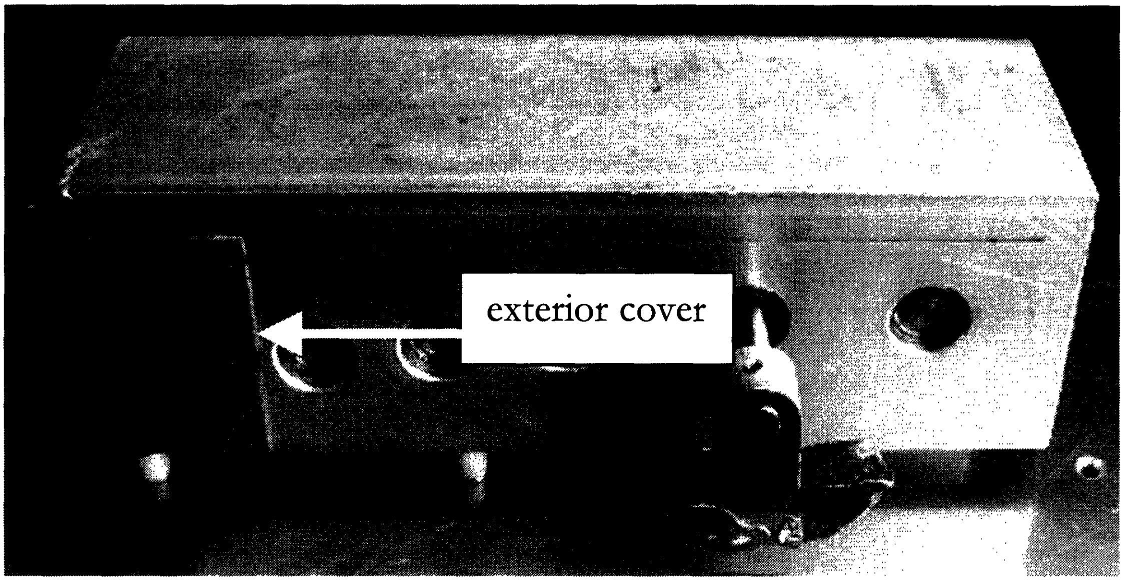


Figure 37. Photograph of non-crank side of Direct Drive Vibrating Pedal in inverted position.

The feature of the Non-crank Side of the vibrating pedal is the exterior cover. The cover is necessary for lubrication confinement and protection of the bearing from exterior contaminants. The two screws, fastening the cover to pedal unit, tighten into the primary axle reinforcement. The cover of aluminum sheet stock does not provide structural support.

5.3.3 Gear Train

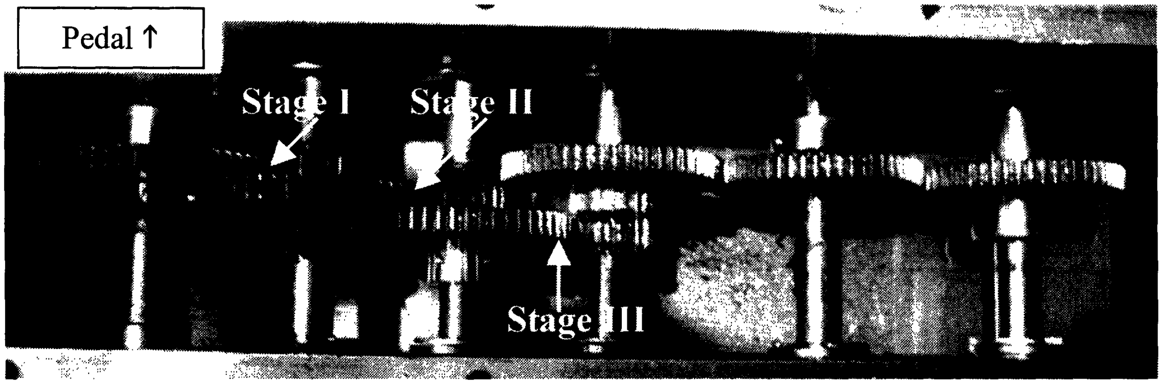


Figure 38. Close view of geartrain.

The gear train consisted of three stages. Only two diameter gear sizes were selected to construct the gear train to ensure simplicity in construction and maintenance. There is a large driver gear and a smaller driven or pinion gear. This would greatly simplify the need for spare parts. Table 2 illustrates the method and calculations used to determine gear stage number and gear selection suitable of for the required frequency output. Table 3 shows the table that was constructed for gear selection. This table was not needed as the cluster gears chosen had a limited selection of gears. The smallest pinion gear was chosen and the driver gear was selected to provide the specified gear ratio. For the Direct Drive Vibrating Pedal (DDVP), the pinion gear had 20 teeth and the driver had 55 teeth, which provided an output gear ration of 1:2.75. In the 3-stage configuration this provided a 20.8 (2.75*2.75*2.75) frequency multiplication of the input pedaling frequency.

Gear ratio		Number of stages			
input	output	I	II	III	IV
		1	2	3	4
1	**20**	20	4.472136	2.714418	2.114743
1	25	25	5	2.924018	2.236068
1	30	30	5.477226	3.107233	2.340347

Table 2. Example of stage number determination process for use in gear train.

Spur Gear-20 pitch-3/8 face width-20degree pressure angle

	18	20	24	28	30	36	40	48	56	60	72	80	84	96	100
18	1	0.9	0.75	0.643	0.6	0.5	0.45	0.375	0.321	0.3	0.25	0.225	0.214	0.188	0.18
20	1.111	1	0.833	0.714	0.667	0.556	0.5	0.417	0.357	0.333	0.278	0.25	0.238	0.208	0.2
24	1.333	1.2	1	0.857	0.8	0.667	0.6	0.5	0.429	0.4	0.333	0.3	0.286	0.25	0.24
28	1.556	1.4	1.167	1	0.933	0.778	0.7	0.583	0.5	0.467	0.389	0.35	0.333	0.292	0.28
30	1.667	1.5	1.25	1.071	1	0.833	0.75	0.625	0.536	0.5	0.417	0.375	0.357	0.313	0.3
36	2	1.8	1.5	1.286	1.2	1	0.9	0.75	0.643	0.6	0.5	0.45	0.429	0.375	0.36
40	2.222	2	1.667	1.429	1.333	1.111	1	0.833	0.714	0.667	0.556	0.5	0.476	0.417	0.4
48	2.667	2.4	2	1.714	1.6	1.333	1.2	1	0.857	0.8	0.667	0.6	0.571	0.5	0.48
56	3.111	2.8	2.333	2	1.867	1.556	1.4	1.167	1	0.933	0.778	0.7	0.667	0.583	0.56
60	3.333	3	2.5	2.143	2	1.667	1.5	1.25	1.071	1	0.833	0.75	0.714	0.625	0.6
72	4	3.6	3	2.571	2.4	2	1.8	1.5	1.286	1.2	1	0.9	0.857	0.75	0.72
80	4.444	4	3.333	2.857	2.667	2.222	2	1.667	1.429	1.333	1.111	1	0.952	0.833	0.8
84	4.667	4.2	3.5	3	2.8	2.333	2.1	1.75	1.5	1.4	1.167	1.05	1	0.875	0.84
96	5.333	4.8	4	3.429	3.2	2.667	2.4	2	1.714	1.6	1.333	1.2	1.143	1	0.96
100	5.556	5	4.167	3.571	3.333	2.778	2.5	2.083	1.786	1.667	1.389	1.25	1.19	1.042	1

Multiplication Factor	III	IV
	3	4
x20	**2.71**	**2.11**
x25	2.92	2.24
x30	3.11	2.34

Table 3. Example of table used in gear selection to fit stage number parameters.

5.3.4 Crank Side

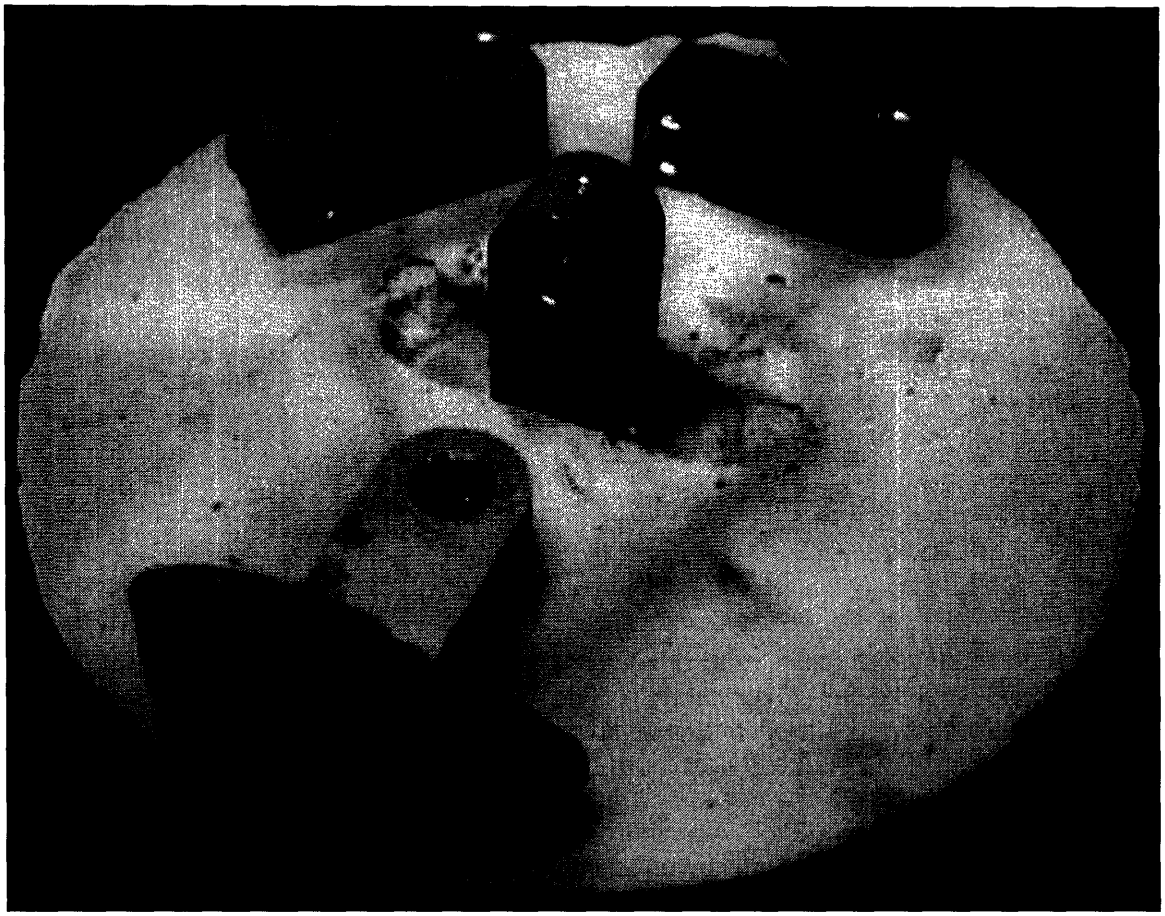


Figure 39. Weight molding and securing method. (Top) Aluminum arms (1" x 1/2" x 3/8") with ¼" holes drilled for lead weighting and securing to end of axle arm. (Middle) Upright arm seated in Plaster of Paris mold for molten lead weight formation. (Bottom) Arm with clay mold used for shaping of Plaster of Paris mold.

The construction of the lead weighted aluminum crank arms was a four-step process.

1) The aluminum crank arms were cut with a garnet water-jet to 1" x 1/2" x 3/8" shape.
2) Three ¼" holes were drilled, one to fasten the arm onto the axle with a setscrew, the other two holes would be filled with lead as part of the integrated lead fastening design.
3) A clay model of the lead weight design sculpted and used with plaster of Paris to fabricate a lead weight mold (the large white circular shape in Figure 39).
4) The crank arm was placed in the plaster of Paris mold as shown in Figure 39 and molten lead filled the cavity in crank arm to fasten and form lead weight.

5.3.5 Chassis

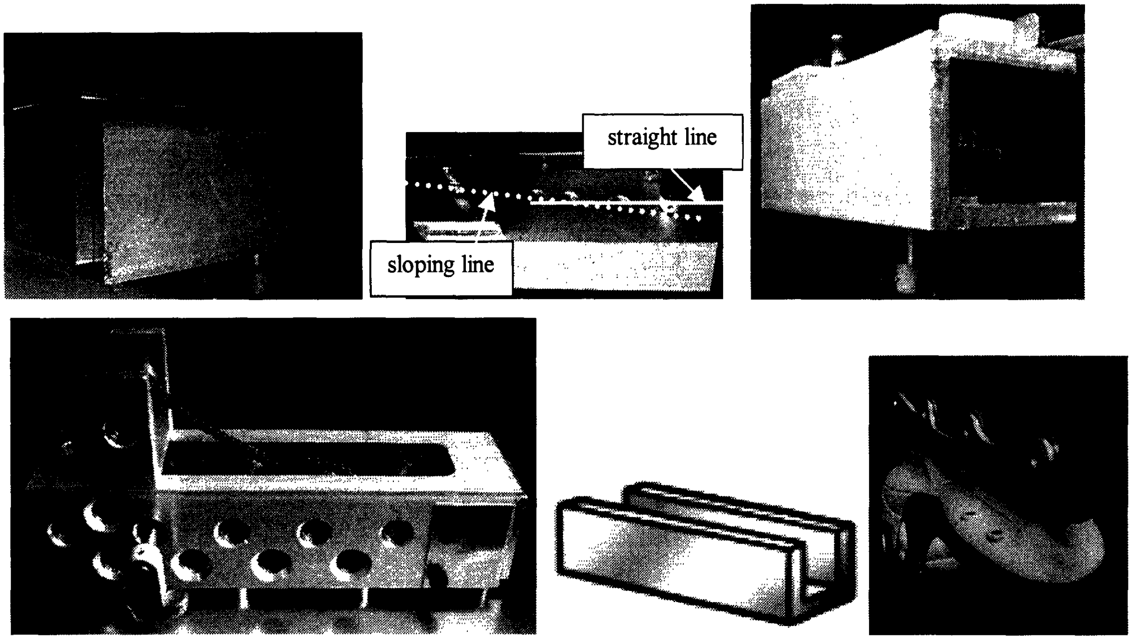


Figure 40. (Top left) Chassis, gear drive, front, showing reinforced area for pedal load application. (Top center) Side view of gear drive with fastened reinforced pedal area and axle lines. (Top left) Rear view of chassis showing 2" x 2" square aluminum channel used in construction. (Bottom left) Chain drive chassis showing lighten holes inserted to reduce mass. (Bottom center) 2"x2" Aluminum U-channel (McMaster.com accessed on 9/4/05). (Bottom left) Inverted inline skate showing chassis.

The chassis' design roots lie in an inline skate chassis. A skate chassis supports the skater by housing the axles, bearings and wheels. The Direct Drive Vibrating Pedal (DDVP) chassis performs similarly with gears replacing the wheels. The DDVP chassis was drilled on a computer-controlled mill to mount the gear axles at precise distances. The axles were mounted on a sloping line as illustrated in Figure 40 (Top center), because it was necessary to keep the primary axle (pedal axle) within 1" of the bottom of the footbed. The axles for the crank arms needed at least 1" to clear the footplate. The final two gears with crank arms were placed an equal distance from footbed.

The Chain Drive Vibrating Pedal (CDVP) is shown to illustrate the differences and flexibility in chassis design. The CDVP is about 2" longer than the DDVP and the gears are larger in diameter. The extra length, ~33% increase, correlates to an increase in mass. The chassis needed to be lightened. A need to lighten the chassis fit with the need to remove some of the chassis web material to allow gear and chain clearance. Lightening holes were drilled in non-strategic places. Additional photographs and description of CDVP are in Appendix A. Chain Drive Vibrating Pedal (CDVP).

5.3.6 Primary Axle

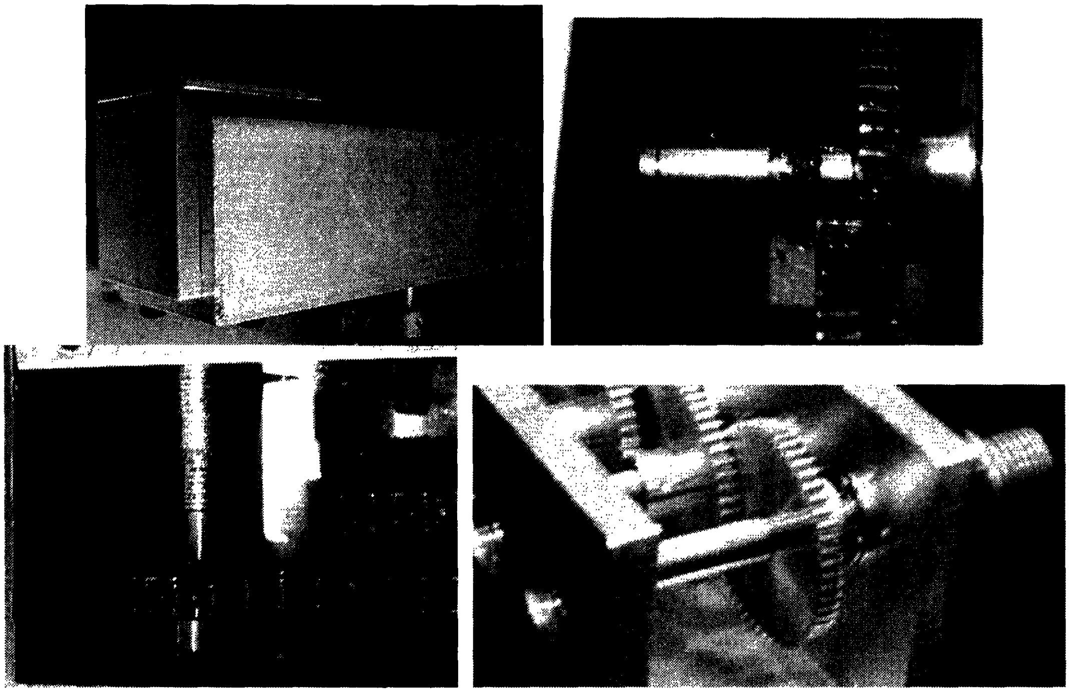


Figure 41. (Top left) Chassis photo showing location of primary axle. (Top right) Direct Drive improved primary axle. (Bottom right) Chain drive improved primary axle. (Bottom left) Original ¼" axle that failed.

The prototype primary axle failed in initial testing. In Figure 42, the range of maximum load values are presented. With the original prototype axle of ¼" diameter, the maximum load that could be applied and not exceed the bending stress of the stainless steel axle was in the range of a low 84 lbs. Originally, the vibrating pedal was to be used only on Human Powered Artificial Gravity (HPAG) cycle and only loaded by the subject and not subjected to operation in the gravity vector. The question arose as to how sturdy the DDVP would be when subjected to the artificial gravity on HPAG, which can exceed 1G. In previous testing, the subjects were able to generate an angular velocity that was in excess of 3.9G's on HPAG. That is how the DDVP came to be "road" tested on a normal cycle. The failed axle showed signs of fatigue and shear failure as illustrated in Figure 33.

The solution to replace the ¼" axle with a 12mm axle greatly increased the loading capability by a factor of 4. The primary axle was fastened to the original chassis by a reinforcement section of U-channel that also stiffened the U-channel.

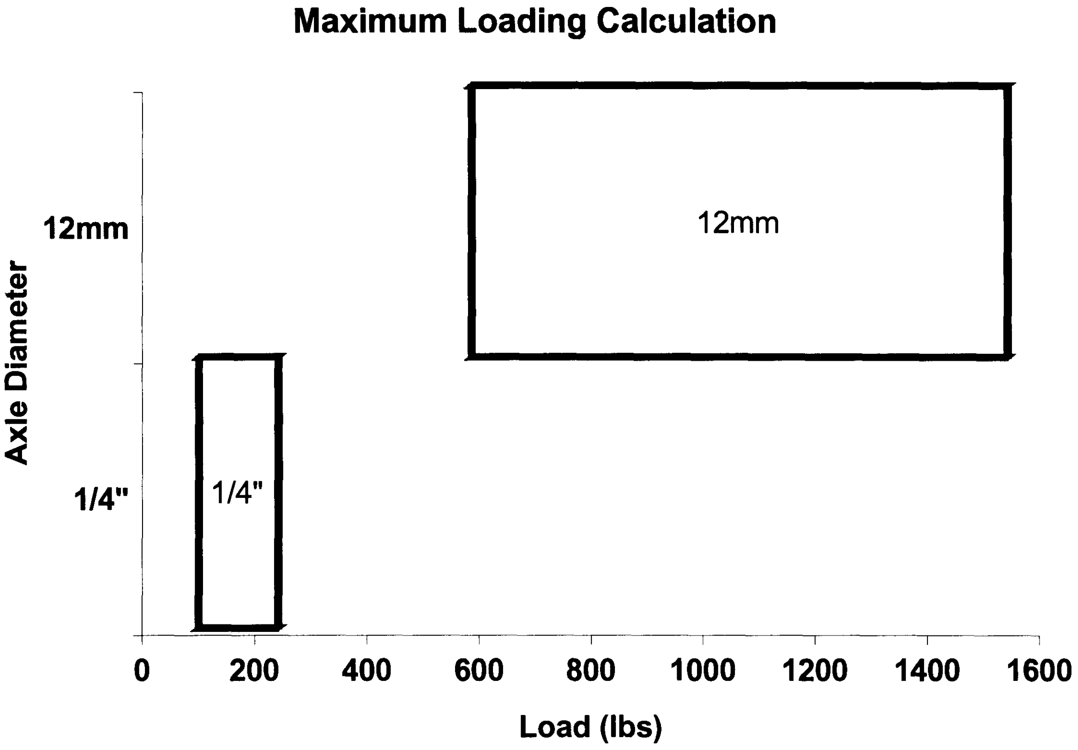


Figure 42. Maximum Loading of Pedal as a Function of Axle Diameter

Axle Diameter	Maximum Load (lbs)	
	Tensile Strength @ 758 MPa*	Tensile Strength @ 2030 MPa*
1/4"	84.3	141.5
12mm	570.0	956.5

**stainless steel not rated, so range of max. loads calculated*

Table 4. Maximum Loading of Pedal as a Function of Axle Diameter.

5.4 Design Discussion

5.4.1 Critique of the Design

The vibrating pedal design was a success. The pedal provided a vibration that could be perceived and was measured. The measured output vibration was approximately 20 times that of the input pedaling frequency.

The setscrews did not function well in the vibration environment. The setscrews initially vibrated loose, but were secured with a thread-locking material. After locking threads down, there remained the tendency for the gears to rotate with respect to the axle. This presented a problem because once rotated, the setscrews became extremely difficult to tighten or loosen.

A location improvement suggestion would be would be to relocate the vibrating device. The present location does not offer much protection. The vibrations occur about the axle of the pedal, so a vibrating device located in a place other that under the heel should be pursued.

The foot fastening system should be simplified. Alternative fastening systems include a "clip-in" bicycle pedal device or a shoe or boot with a rigid outsole that can be secured to a restraining system, such as those that are used for skiing, snow shoeing or snowboarding.

5.4.2 Space Deployment

With more funding, a higher quality version could be implemented. The two versions constructed cost no more than $600 in mostly readily available components. Using finite element analysis, improvements in chassis construction could be implemented to reduce mass of structure. Instead of steel and aluminum, parts could be made from more exotic materials such as magnesium, beryllium, titanium and tungsten (replace lead weight).

6 EXPERIMENTAL RESULTS

6.1 Test Methods

6.1.1 Measurement Equipment

A Crossbow Accelerometer 3-Axis measurement device was used to measure accelerations in the plane of rotation. The Crossbow sampled data at a rate of 1500 Hz with 16-bit resolution. The data was downloaded to and analyzed as a MS Excel file.

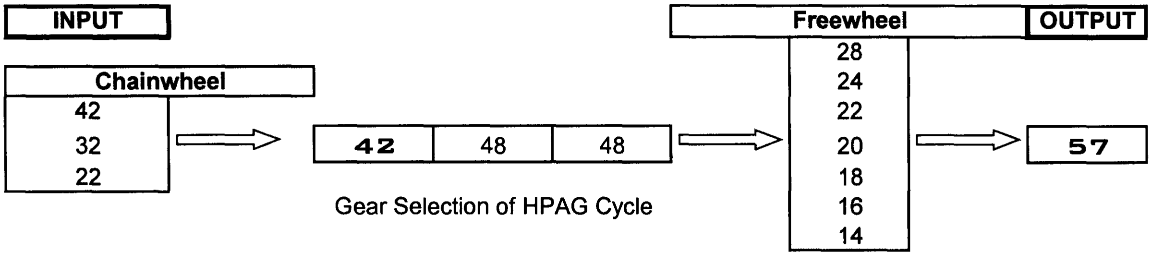
The MIT HPAG cycle, illustrated in Figure 44, was utilized for testing. A woven nylon strap secured subjects. Two subjects operated at the two positions. The positions were named Position One and Position Two.

Position One utilized the Direct Drive Vibrating Pedal (DDVP). Position One was the tested position that measured vibrations with the Crossbow Accelerometer.

Position Two utilized the Chain Drive Vibrating Pedal (CDVP). Position Two provided perception data on the use of the CDVP. Position Two provided a necessary counter-balance for Position One. Position Two provided additional locomotive rotation power.

Due to the harshness of the duty cycle when the vibrating pedals were initially tested, the validation testing was performed with extreme care and caution given to the pedals. Subjects were instructed to pedal smoothly with the majority of the work concentrated on the normal pedal. Pedaling smoothly was defined as gradual pedal force and slow acceleration with no quick or sudden loading. This strategy was intended to facilitate the testing in two ways: 1) Remove majority of drive force from vibrating pedal. 2) By driving the system with the off pedal, the vibrating pedal leg could remain supple and facilitate vibration.

The target input cycling frequency was 90 revolutions per minute. The HPAG cycle has a three-ring chain ring driving the gear train and has a 7-speed freewheel cog driving the output. For theFirst Run, the cycling RPM was driving the HPAG cycle too quickly and subjects were forced to reduce their cycling pedaling frequency. For the Second Run, the gear ratio was reduced to provide 1.04G at 90 RPM.



HPAG GEAR RATIO		FREEWHEEL COG GEAR SELECTION (* /57)						
		28	24	22	20	18	16	14
Chainwheel	42	0.491228	0.421053	0.385965	0.350877	0.315789	0.280702	0.245614
Gear (* /42)	32	0.374269	0.320802	0.294069	0.267335	0.240602	0.213868	0.187135
Selection	22	0.25731	0.220551	0.202172	0.183793	0.165414	0.147034	0.128655

HPAG G-LEVEL @90 RPM input		FREEWHEEL COG GEAR SELECTION (* /57)						
		28	24	22	20	18	16	14
Chainwheel	42	4.35	3.19	2.68	2.22	1.80	1.42	1.09
Gear (* /42)	32	2.52	**1.85**	1.56	1.29	**1.04**	0.82	0.63
Selection	22	1.19	0.88	0.74	0.61	0.49	0.39	0.30

Figure 43. Human Powered Artificial Gravity (HPAG) Gear Ratio and G-Level selection.

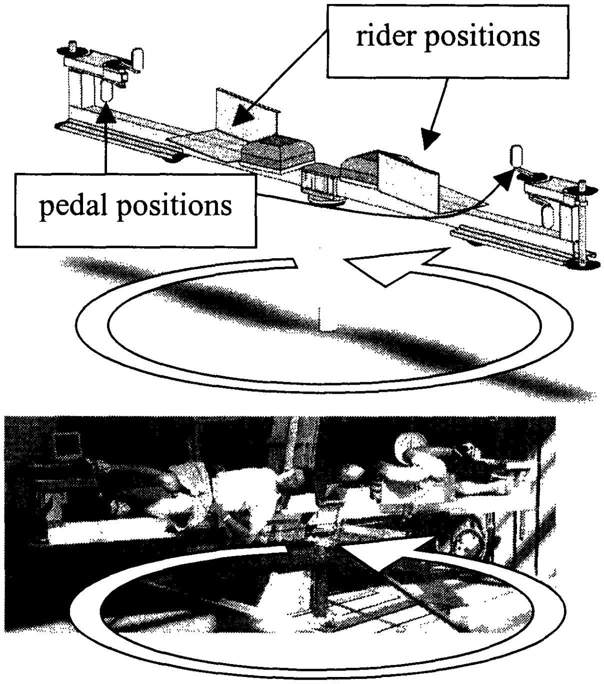


Figure 44. (Top) Drawing of Human Powered Artificial Gravity (HPAG) cycle at MIT (drawing by Ellman 2005). (Bottom) Photograph of HPAG in use with subjects in riding positions.

6.1.2 Excel Test Data Extraction

The data was prepared and analyzed using MS Excel. The signals were extracted from the composite frequency signal in two steps.

Step 1: Each data point in the composite frequency data over an 80-millisecond range was averaged using the AVERAGE function in MS Excel. This step necessary for two reasons. First, it was necessary to facilitate selection of a complete cycle for the pedal frequency calculation. The second reason was that the composite Crank signal needed to be subtracted from the Composite Frequency signal.

Step 2: Each Crank value calculated in Step 1 was subtracted from the Crank frequency value. This step was necessary to calculate a Pedal (High Frequency) value.

6.2 Testing and Design Validation

The First Run test was conducted with two subjects, two vibrating pedals (one with each position). The Direct Drive Vibrating Pedal (DDVP) was instrumented for measurement n Position One. The Chain Drive Vibrating Pedal was utilized for perception and operation testing in Position Two of HPAG.

The data illustrated in Figure 45 shows a higher frequency/lower amplitude signal riding lower frequency/higher amplitude accelerations measured from the DDVP. Although there is a lot of noise in the measured data, it is evident that there is a higher frequency output vibration that is twenty times (20x) the input pedaling frequency.

The differences between the First Test and the Second Test were the cyclists and the gearing of the HPAG cycle. For the first run, the cyclist in Position One was a skilled competitive rider. For the Second Run, the cyclist in Position One was a short commute cyclist. The original plan called for the same cyclist to be tested, but the first run, Position One cyclist was not available for the Second Run. The differences in pedaling frequency may be a product of my warnings to cyclists after first test stoppage on previous test.

When the two test runs were compared, it became evident that on the Second Run, the amplitude of vibrations was greater than that of theFirst Run. A possible explanation may be that this is a product of the stiffness of the legs of the cyclist. On previous test run, HPAG cycle was geared higher, which decreased the cycling frequency, but caused the legs to provide a higher torque, which may have increased the leg's stiffness. On the Second Run, with a higher input frequency required and less intensity required to spin the cranks, the leg may be more relaxed and more supple, thereby allowing more vibration in crank.

In Figure 45 and Figure 46, the results of frequency extraction are shown. The measured frequencies at the output are presented in Table 5. Although the data is “fuzzy”, the analysis is equally approximate. The importance was in the frequency multiplication and getting a frequency near 30 Hz.

Test Run	**Period**		**Crank Freq (RPM)**		**Crank Freq (Hz)**		**Vibration (Hz)**	
First	0.57	0.53	105	113	1.8	1.9	35	38
Second	1.06	1.01	57	59	0.9	1.0	19	20

Table 5. Measured output frequencies of First and Second Test Runs. Period was one period of the Crank Arm on HPAG. Crank Freq (RPM) and Crank Freq (Hz)are calculated from Period. Vibration(Hz) was calculated from number of cycles counted per Period.

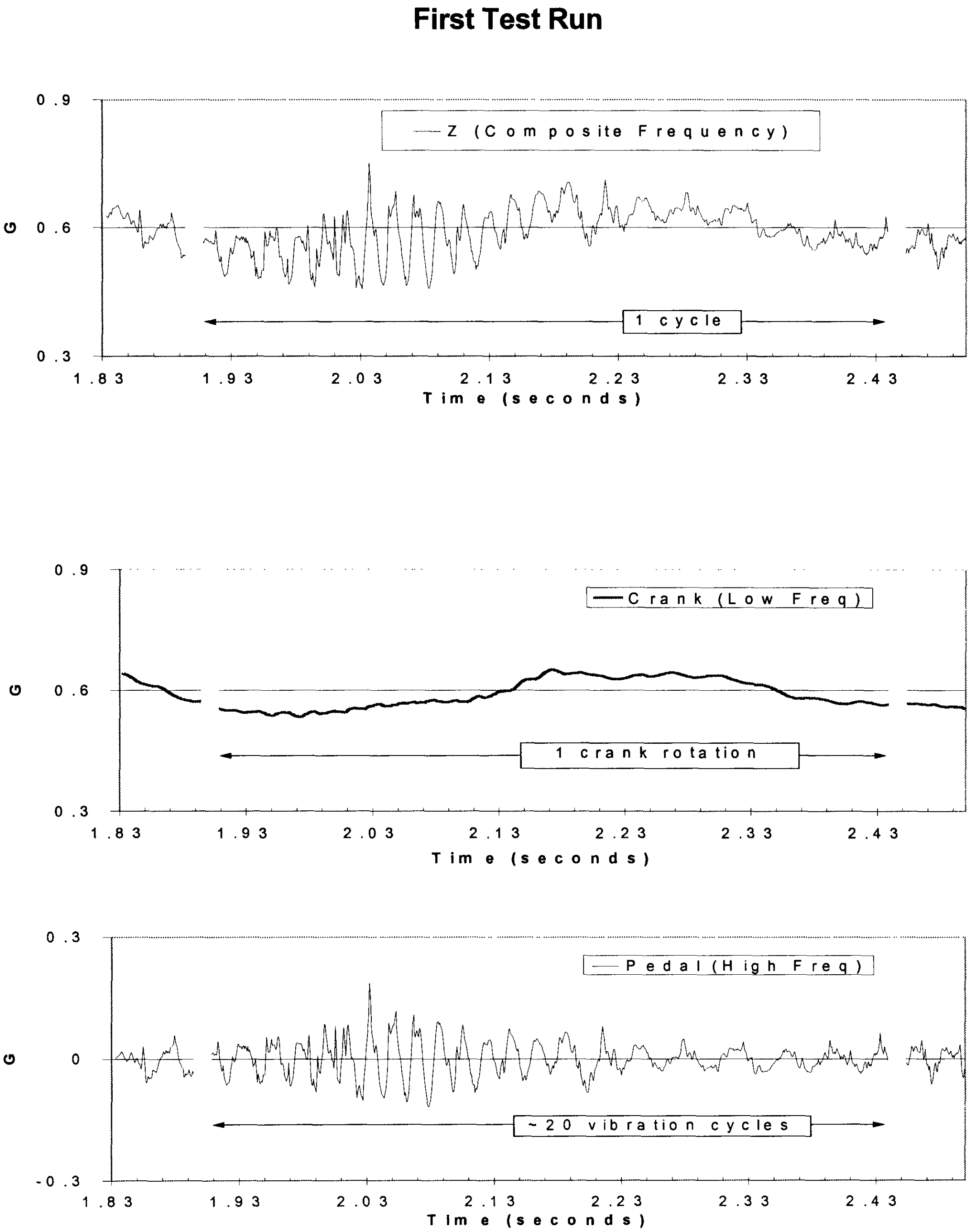

First Test Run

Figure 45. First Test Run: (Top) Measured frequency of first test, (Middle) Extracted crank frequency, (Bottom) Extracted vibrating pedal frequency.

Second Test Run

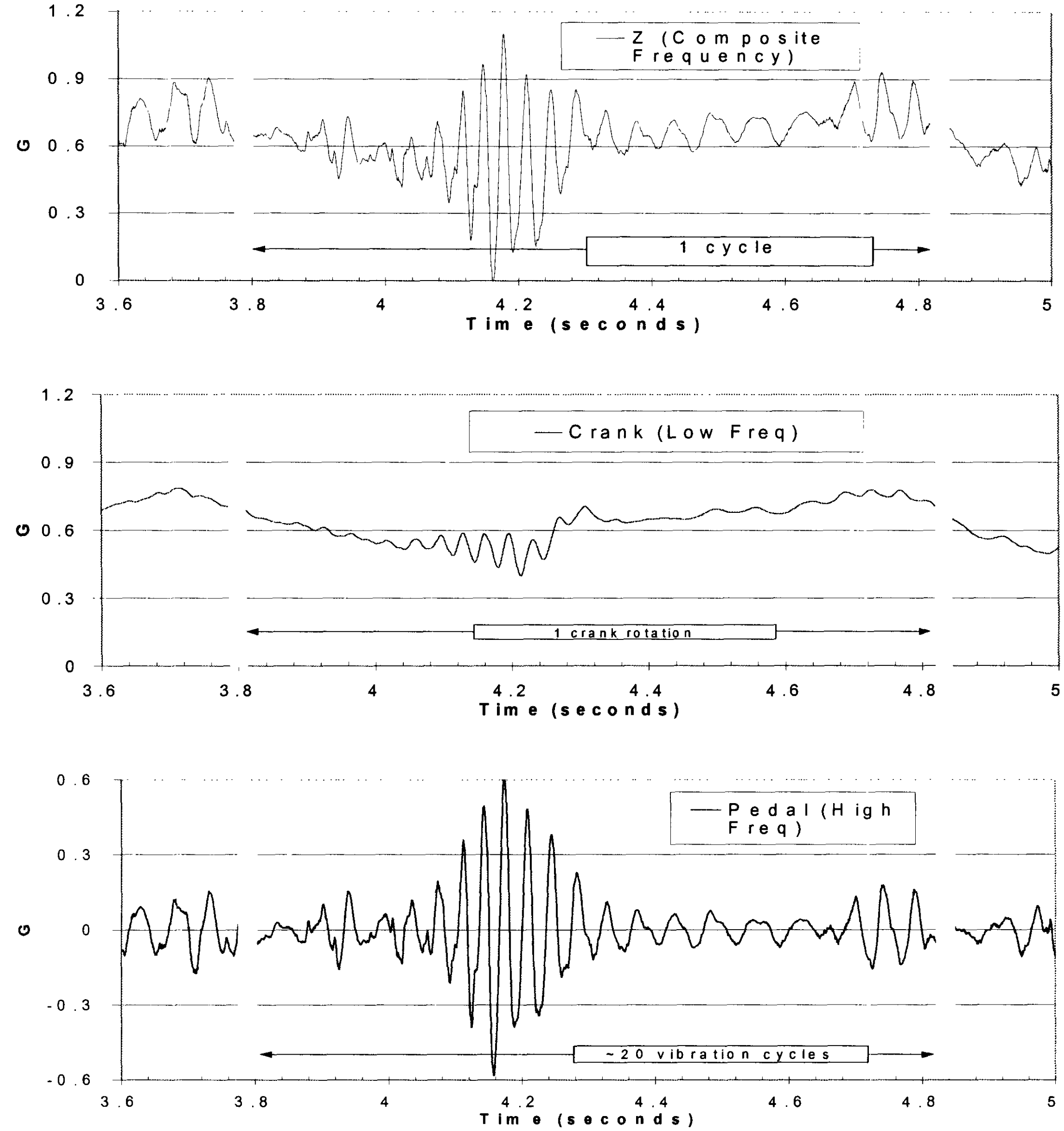


Figure 46. Second Test Run: (Top) Measured frequency of first test, (Middle) Extracted crank frequency, (Bottom) Extracted vibrating pedal frequency.

7 CONCLUSION

7.1 Accomplishments

A vibrating pedal design was taken from conception to working and testable final design. The pedal design succeeded in providing a 30 Hz vibration that was both perceptible and measurable.

The speed multiplication direction that was taken in this project places great stress and strain on the input components. Most of the problems stemmed from the primary axle. If there was going to be a failure, that's where it was thought to come from and true to predictions, the primary axle did fail.

7.2 Future directions and improvements

The sturdiness of the vibrating pedal needs to be improved. Improvements in the construction and configuration of the axle and gear interface should be the first problem solved. In construction and development, it became apparent that each solution revealed the next weak link.

Vibration production and transmission, especially in the artificial gravity environment are still not understood. Oscillations and vibration production at the artificial gravity forces of 1G and beyond require further research to study behavior. Canceling and additive motion needs to be examined. The different modes of vibration production are plentiful and endless. Possible ideas include rod and linkage configurations and variable pitch diameter gears in a gear drive system. The idea of a constantly variable transmission should be explored.

Implementation shown in Figure 47 of Human Powered Artificial Gravity (HPAG) in a microgravity or parabolic flight environment would advance the current technology greatly. The current testing in a gravity environment has problems that are unique to a gravity environment. Implementing a HPAG cycle in a microgravity environment may remove most of obstacles to comfort and durability. Operation in microgravity could reduce construction requirements and present new design challenges to be overcome.

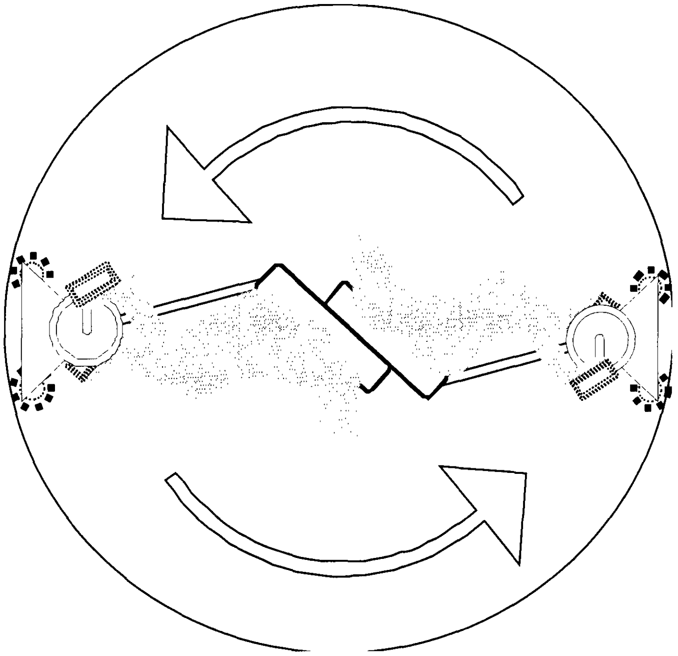


Figure 47. Possible implementation of Vibrating Pedal on Human Powered Artificial Gravity cycle aboard a spacecraft.

REFERENCES

Classical and Modern Mechanisms for Engineers and Inventors., New York, New York: Mercel Dekker Inc., (1971).

Edmonds, J. (2005). "Exercise in Artificial Gravity." S.M. Thesis, Aeronautics and Astronautics, MIT, Cambridge, MA.

Ellman, R., R. Sampson (2005). Solid Works Drawing of MIT Human Powered Artificial Gravity Cycle.

Ingenious Mechanisms for Designers and Inventors-Volume IV., New York, New York: Industrial Press Inc., (1967).

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

Leblanc, A.., Shackleford, L., and Schneider, V. (1998) Future human bone research in space. *Bone* 22, 113S-116S

Mabie, H., Mechanics and Dynamics of Machinery. John Wiley & Sons, Inc., 1978.

National Aeronautics Space Administration. (2001) Summary of International Space Station Exercise Countermeasures. Lyndon B. Johnson Space Center, Science and Life Sciences.

National Aeronautics Space Administration. (2005) NASA Space Station On-Orbit Status 6 March 2005. Lyndon B. Johnson Space Center.

Newman, D., Schaffner, G., (2002), *Skeletal Consequences of Space Flight*, Massachusetts Institute of Technology.

Qin, Y., C. Rubin, et al. (1998) "*Nonlinear dependence of loading intensity and cycle number in the maintenance of bone mass and morphology.*" J. Orthop. Res. 16, 482-489.
Rubin, C., R. Recker, et al. (2004). "*Prevention of postmenopausal bone loss by a low-magnitude, high-frequency mechanical stimuli: a clinical trial assessing compliance, efficacy, and safety.*" J Bone Miner Res 19(3): 343-51.

Rubin, C., A. S. Turner, et al. (2001). "*Anabolism. Low mechanical signals strengthen long bones.*" Nature 412(6847): 603-4.

Rubin, C., G. Xu, et al. (2001). "*The anabolic activity of bone tissue, suppressed by disuse, is normalized by brief exposure to extremely low-magnitude mechanical stimuli.*" Faseb J 15(12): 2225-9.

Rubin, C. T., Y.-X. Qin, et al. (2005). Is exercise an effective countermeasure for bone loss during spaceflight? Bone Loss During Spaceflight, Cleveland, OH.

Schneider, S.M., et al. (2003). "*Training with the International Space Station interim resistive exercise device.*" Medicine and Science in Sports and Exercise. 35(11): p. 1935-45.

U.S. Congress, Office of Technology Assessment (1990). *Access to Space: The Future of U.S. Space Transportation Systems, OTA-ISC-415.* Washington, DC: U.S. Government Printing Office, April 1990.

Ward, K., C. Alsop, et al. (2004). "*Low magnitude mechanical loading is osteogenic in children with disabling conditions.*" J Bone Miner Res 19(3): 360-9.

Connors M., Harrison A. and Akins F., Living Aloft: Human Requirements for Extended Spaceflight. Chapter 3, Habitability, The Physical Environment. *NASA SP-483* (1985) Washington, DC .

Appendix A. Chain Drive Vibrating Pedal (CDVP)

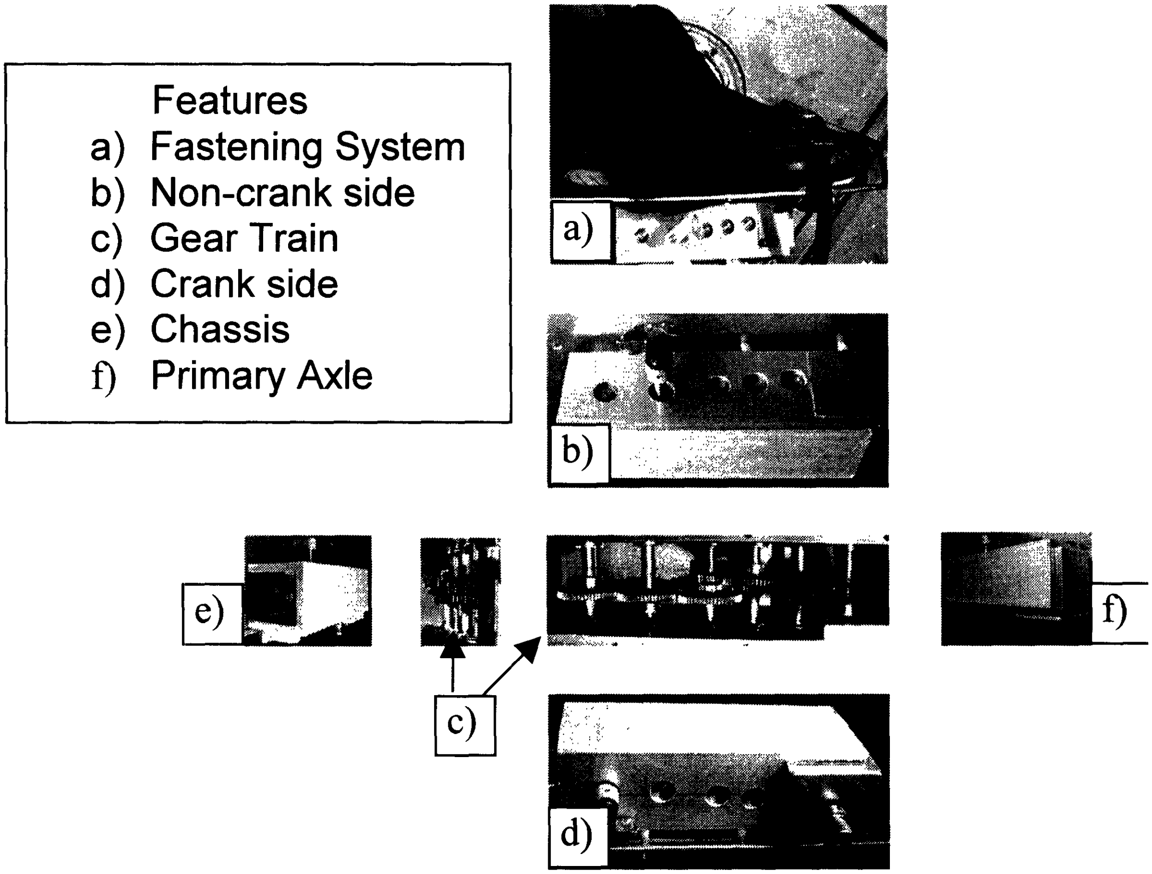


Figure 48.The exploded photographic view of the Direct Drive Vibration Pedal (DDVP) used to organize presentation of Chain Drive Vibration Pedal (CDVP).

a) Fastening System: The fastening system is similar to Direct Drive Vibration Pedal (DDVP).

b) Non-crank Side: Features similar to DDVP with non-structural axle end cover and the outboard idler chainwheel axle assembly is visible in photo. The outboard idler allows counter-rotation and tension adjustment of chain.

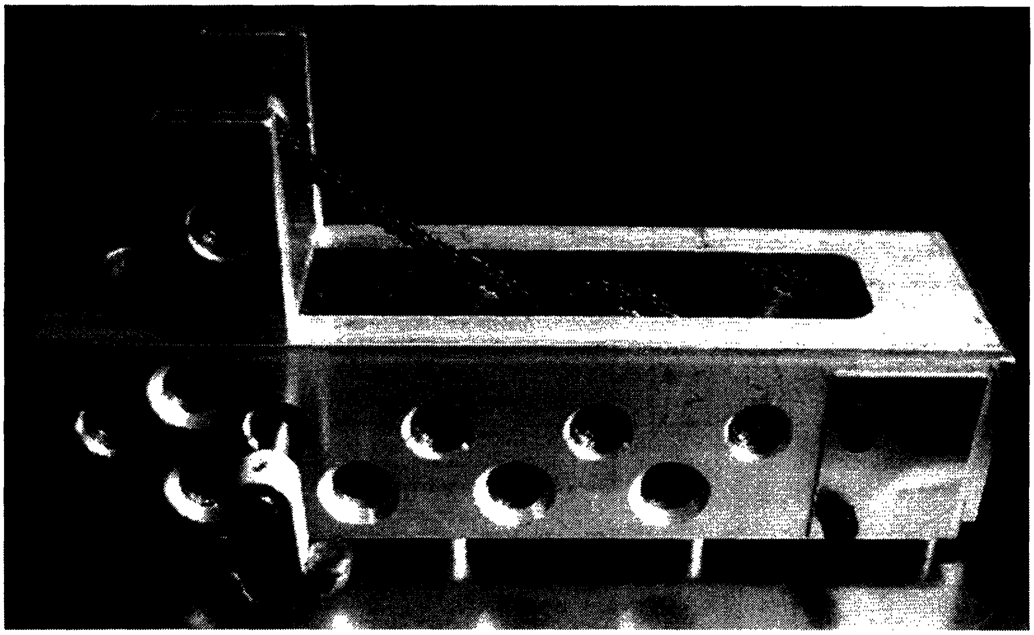


Figure 49. Photograph of Non-crank Side of Chain Drive Vibrating Pedal (CDVP).

c) Gear Train: Footbed removed to show geartrain, chain allows space so that spacing is not critical, large primary axle visible.

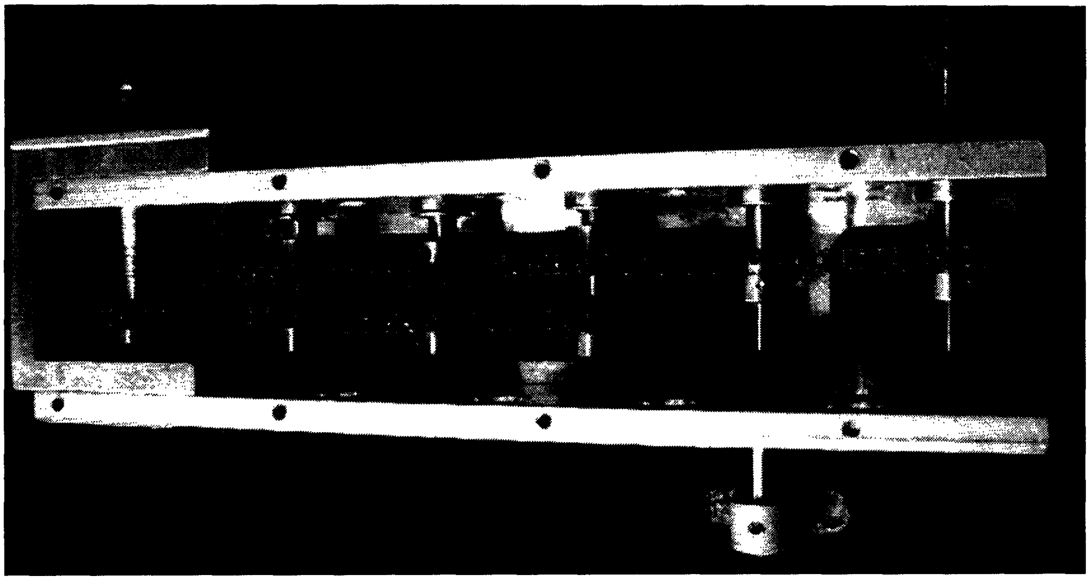


Figure 50. CDVP geartrain

d) Crank Side: Primary axle reinforcement similar to DDVP, lightening holes visible and weight crank arms

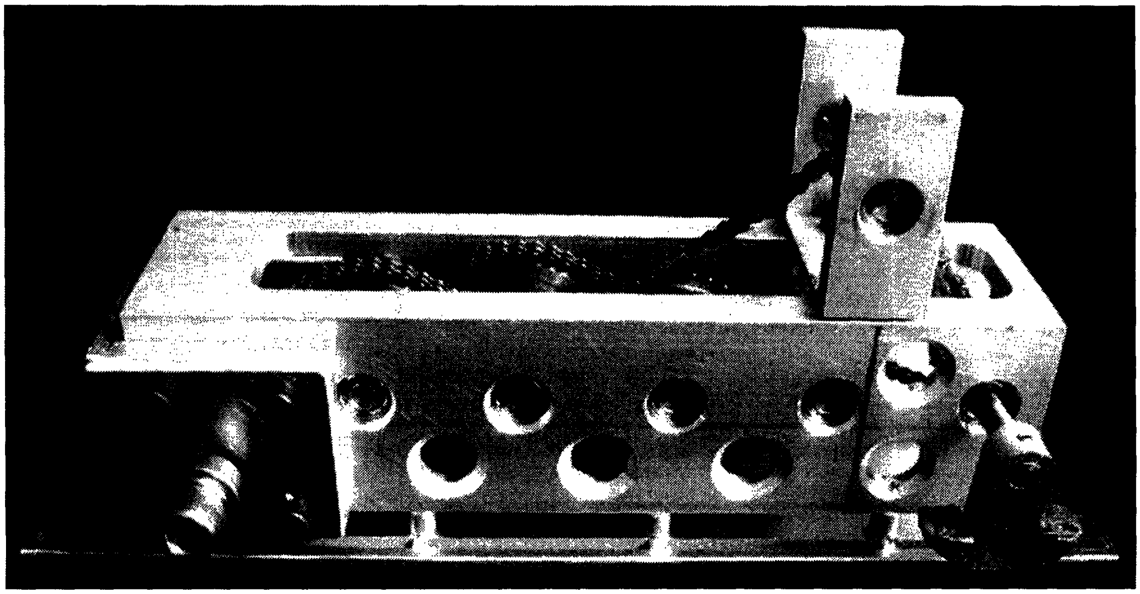


Figure 51. Crank side photograph showing primary axle with reinforcement and outboard idler pulley.

e) Chassis: Same U-channel material as DDVP, although material removed from webbing to allow clearance for larger chainwheels to rotate.

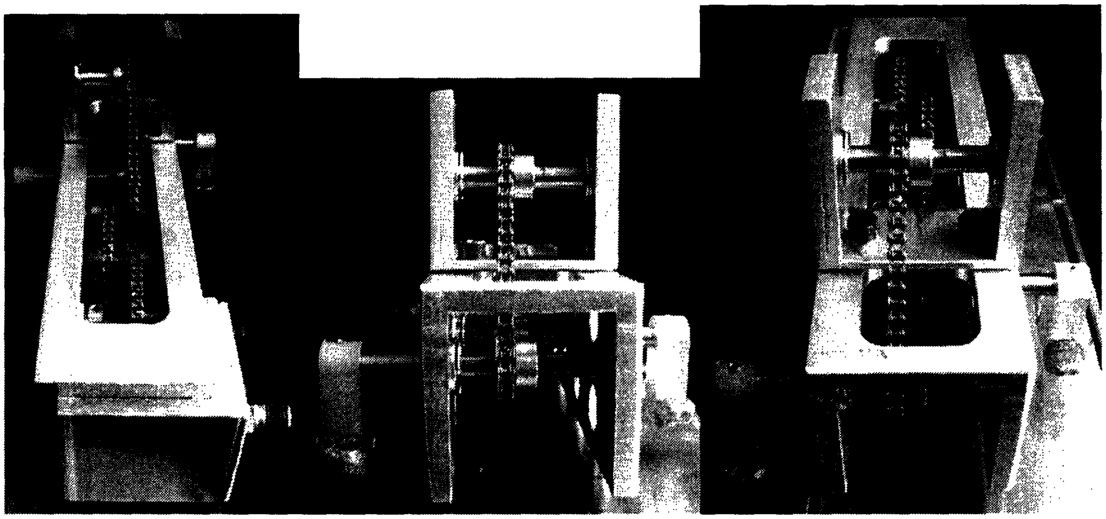


Figure 52. CDVP chassis differs from DDVP chassis with webbing removal and outboard idler pulley.

f) Primary Axle: Modification similar to that of DDVP, major difference is presence of smaller gear assembly driving 1st stage of geartrain. The small gear assembly was necessary to maintain 1" proximity of footbed to primary axle.

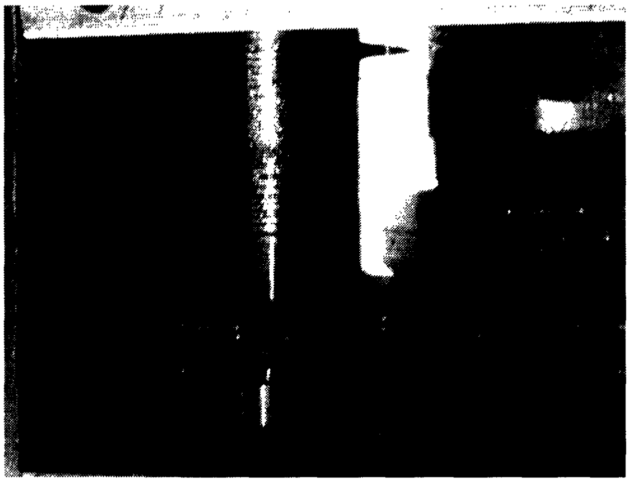


Figure 53. Close-up photograph of improved and much stronger axle and hardware.

Appendix B. Direct Drive Vibrating Pedal (DDVP), additional photographs

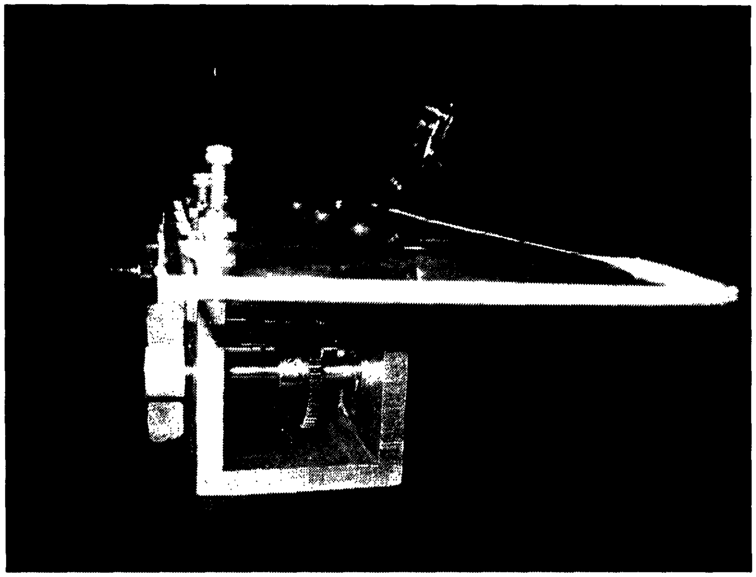


Figure 54. Rear View of DDVP showing footbed platform and gearing.

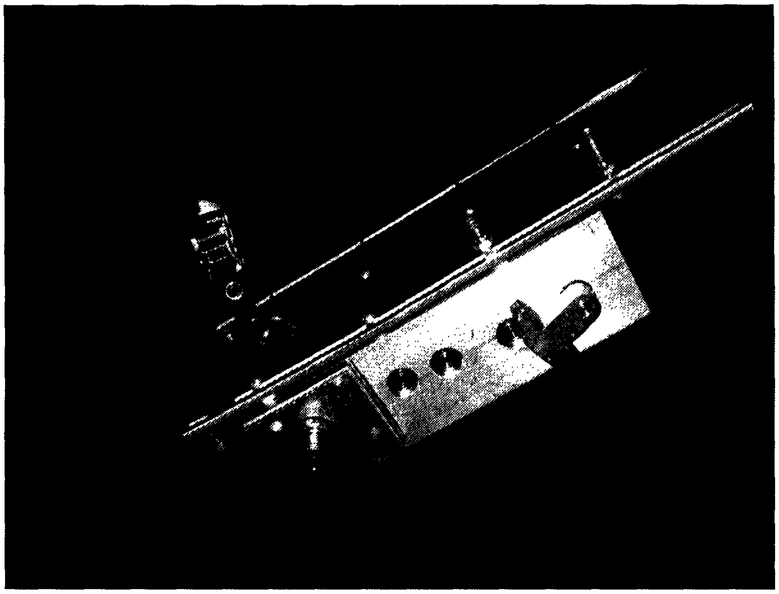


Figure 55. Crank side view of DDVP showing mountain bike toe clip, pedal axle, reinforced webbing structure and counter-rotating weight.

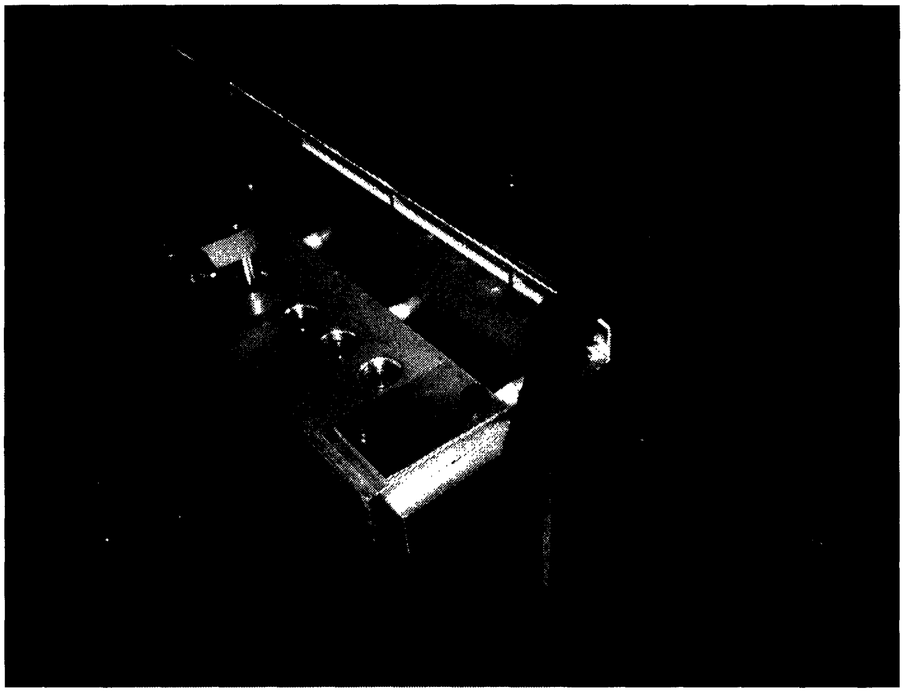


Figure 56. Close-up of DDVP installed on HPAG showing front webbing structure reinforcement.

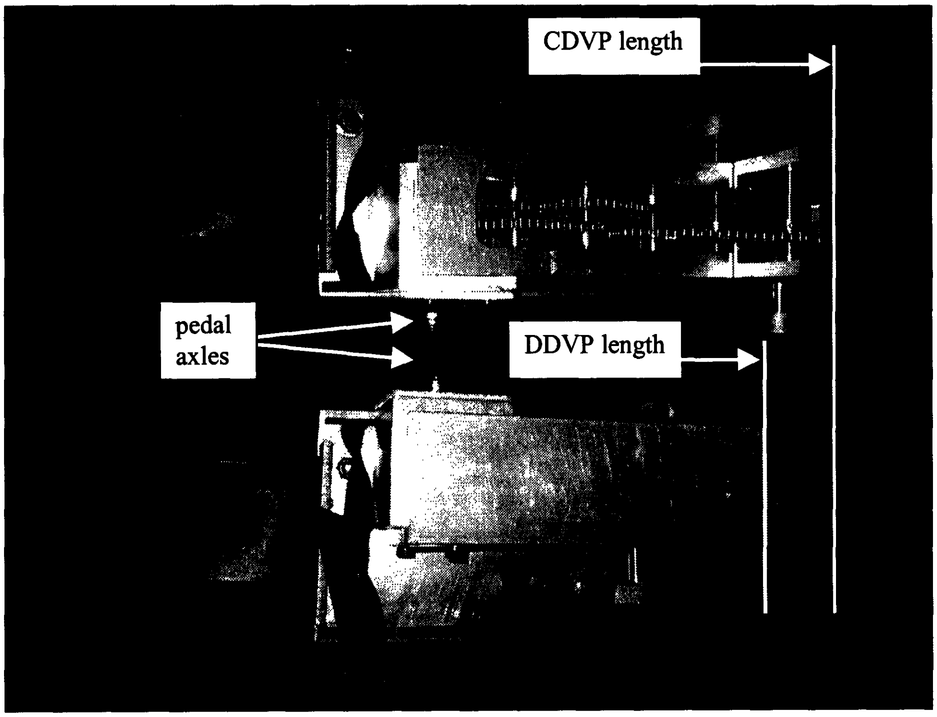


Figure 57. Illustration of differences in length between DDVP and CDVP. CDVP is longer.

Appendix C. Photographs of Incorporation of DDVP and CDVP with HPAG

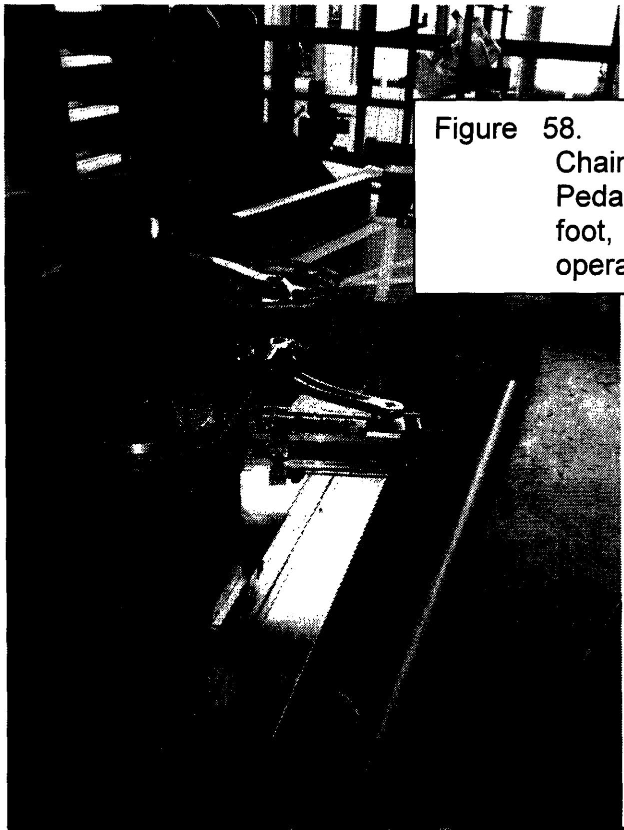


Figure 58. Position Two with Chain Drive Vibrating Pedal in position for left foot, left hip down operation.

Figure 59. Position One, Direct Drive Vibrating Pedal in position for right foot, left hip down operation.

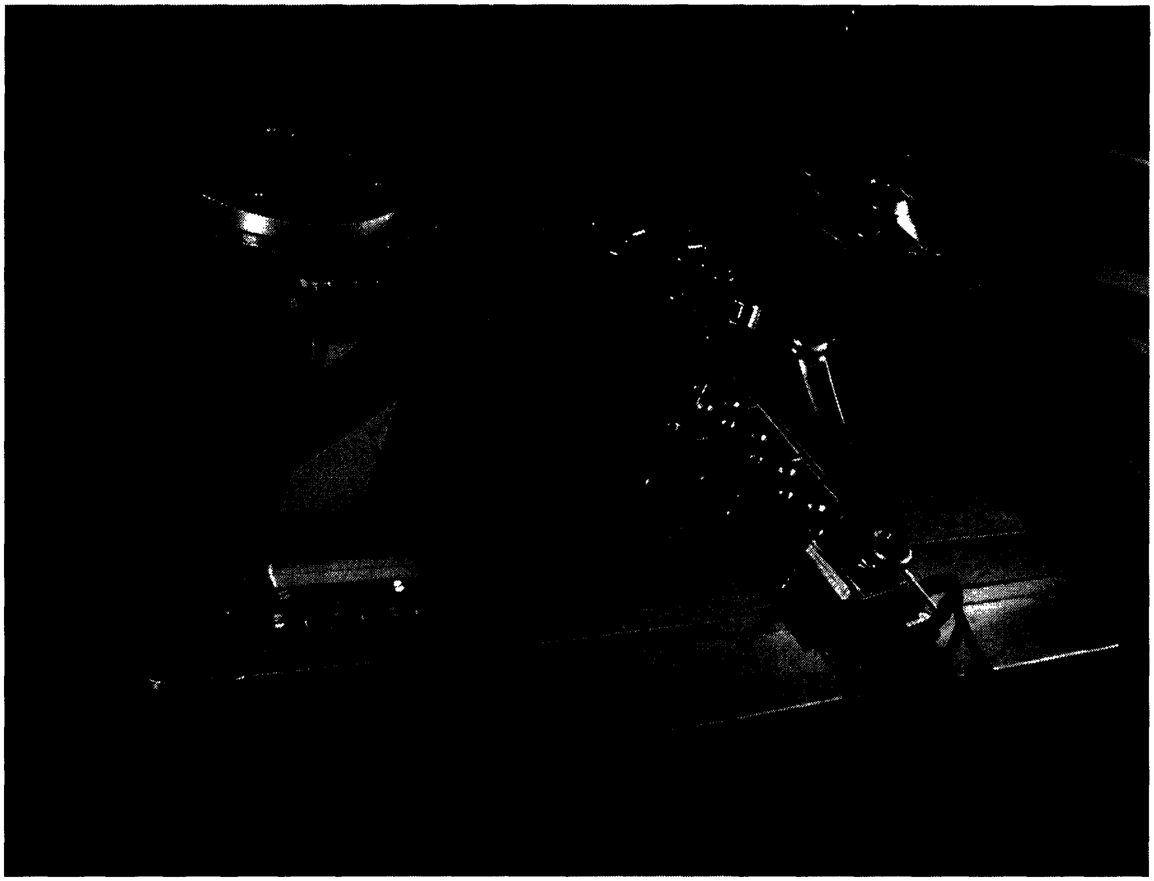


Figure 60. Illustration of HPAG Position Two showing CDVP with derailleur chain tensioner.

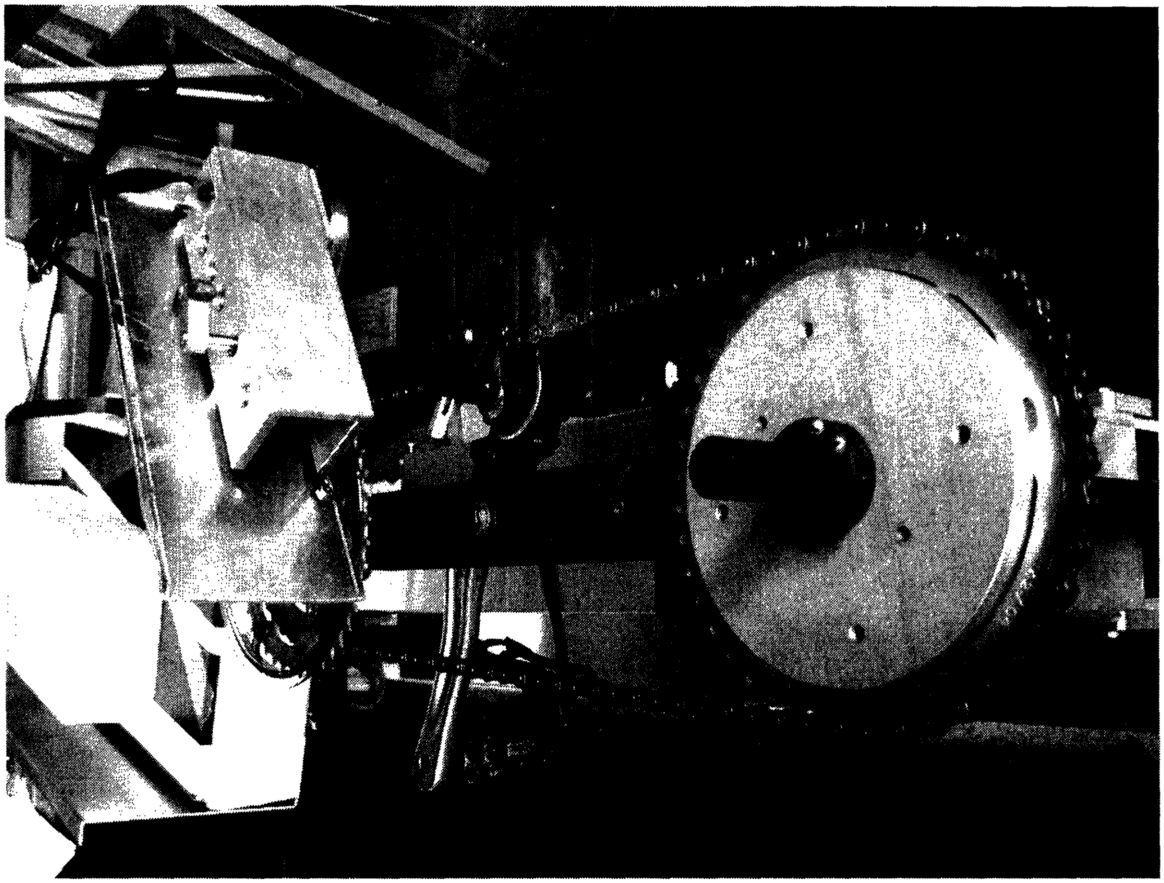
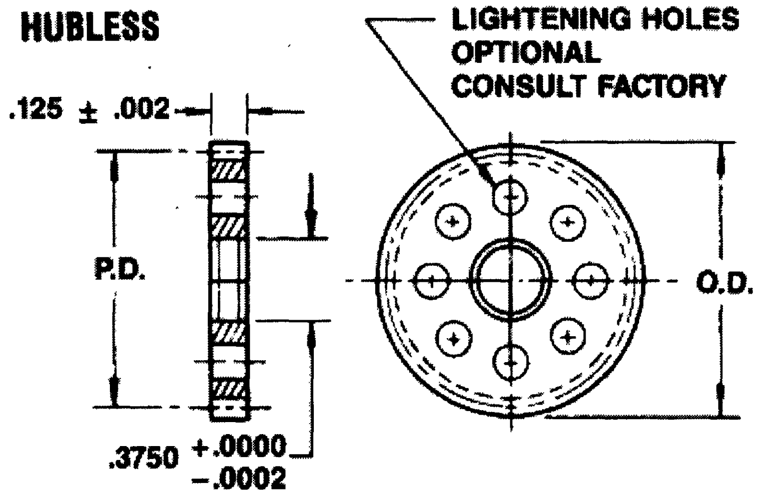


Figure 61. Illustration of HPAG Position One with DDVP and derailleur chain tensioner.

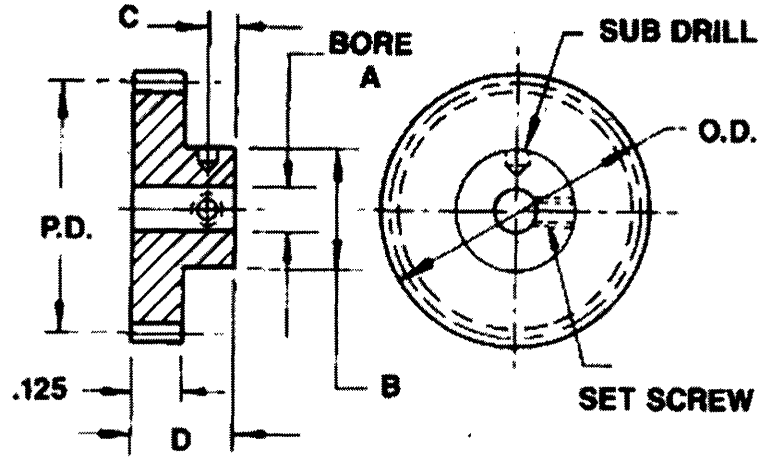
Appendix D. Technical Drawings of Gears



dimensions in inches

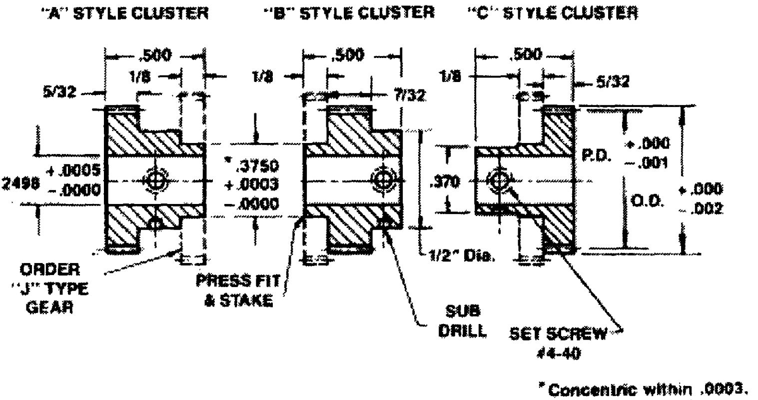
PD	1.1458
OD	1.188

Figure 62. Technical Drawing of 55-teeth, hubless, spur gear with specified Pitch Diameter (PD) and Outer Diameter(OD).



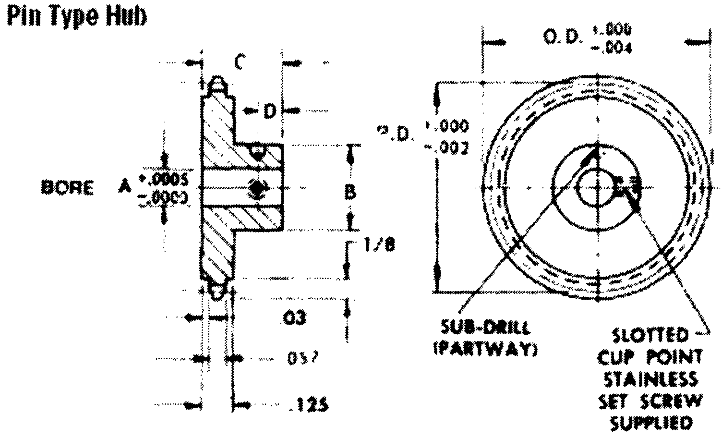
PD	1.1458
OD	1.188
A	0.2498
B	0.5
C	0.12
D	0.375
E	0
G	0.12
Set1	0.138
PWID	0.125
BoreSize	.2498

Figure 63. Technical Drawing of 55-teeth, hubless, spur gear with specified Pitch Diameter (PD) and Outer Diameter(OD) (PIC Design catalog).



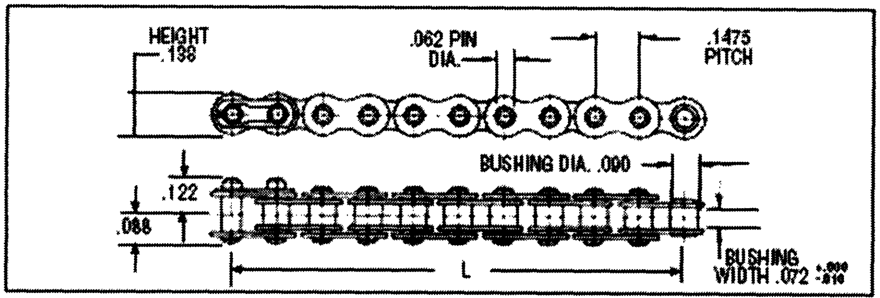
PartNumber	CN-32	CN-95	CN-158
OD	0.458	0.458	0.458
PD	0.4166	0.4166	0.4166
Cluster_Style	A	B	C
Number Teeth	20	20	20

Figure 64. Technical Drawing of cluster, compound, gear with specified Pitch Diameter (PD) and Outer Diameter(OD) (PIC Design catalog).



PartNumber	EM5-13	EM5-36
OD	0.668	1.744
PD	0.616	1.692
Bore Size	0.2498	0.2498
Number Teeth	13	36

Figure 65. Drawing of Chain Drive Vibrating Pedal chain sprockets. (PIC Design catalog)



Material: Stainless Steel Type 18-8 **Weight per Foot:** .035 lbs.
Tensile Strength: 180 lbs. Average

PartNumber	EL-4.4	EL-3.2
Number Links	44	32

Figure 66. Technical Drawing of Miniature Chain (PIC Design catalog).

Appendix E. Parts List

Drive Unit	*Part Number*	*Nomenclature*	*List Price ($)*	*Qty*	*Ext. Price ($)*
Gear	J1-55	SPUR GEAR-HUBLESS	9.60	3	$28.80
	G3-55	SPUR GEAR-PIN HUB	10.77	3	$32.31
	CN-32	CLUSTER GEARS & HUBS	16.25	1	$16.25
	CN-95	CLUSTER GEARS & HUBS	16.25	1	$16.25
	CN-158	CLUSTER GEARS & HUBS	16.25	2	$32.50
Chain	EM5-13	MINIATURE PITCH SPROCKET	9.41	7	$65.87
	EM5-36	MINIATURE PITCH SPROCKET	14.16	3	$42.48
	EL-4.4	*44 link chain*	12.13	3	$36.39
	EL-3.2	*32 link chain*	13.32	2	$26.64
Belt	FLG6-016	NO-SLIP GEARED PULLEY	9.79	2	$19.58
	FLG6-045	NO-SLIP GEARED PULLEY	17.27	3	$51.81
	F20TS-35	NO-SLIP BELT	8.09	2	$16.18
	F20TS-55	NO-SLIP BELT	10.70	3	$32.10
	E2-13-1	ABEC-1 BALL BEARINGS	9.70	40	$388.00
				TOTAL	$805.16

1, 2 *quoted chain length price*

3 *price is each*

Table 6. Parts Order List from PIC Inc.

Appendix F. Approved COUHES Application

1861	Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects	Application # (assigned by COUHES)	04110010 13
		Date	**11/24/04**

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

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

Basic Information

1. Title of Study	
Human Powered Artificial Gravity and Low Magnitude High Frequency Vibrations Applied to the Foot Through the Pedal	
2. Principal Investigator	
Name: Dava Newman	Building and Room #: 33-307
Title: Professor	Email: dnewman at mit dot edu
Department: Aeronautics & Astronautics	Phone: 617.258.8799
3. Associated Investigator(s)	
Name: Thomas Jarchow	Email: jarchow at mit dot edu
Title: Post Doctoral Associate	Phone: 617.253.0017
Affiliation: Artificial Gravity, Aeronautics & Astronautics	
4. Collaborating Institutions. *If you are collaborating with another institution(s) then you must obtain approval from that institution's institutional review board, and forward copies of the approval to COUHES)*	
5. Location of Research. *If at MIT please indicate where on campus. If you plan to use the facilities of the Clinical Research Center you will need to obtain the approval of the CRC Advisory Committee. You may use this form for simultaneous submission to the CRC Advisory Committee.*	
Building 33 Hangar	
6. Funding. *If the research is funded by an outside sponsor, please enclose one copy of the research proposal with your application. A draft of the research proposal is acceptable.*	
Source: Prof. Dava Newman	Contract or Grant Title:
Contract or Grant #: MIT 1455200	OSP #:
7. Human Subjects Training. *All study* personnel **MUST** *take and pass a training course on human subjects research. MIT has a web-based course that can be accessed from the main menu of the COUHES web site. COUHES may accept proof of training from some other institutions. List the names of all study personnel and indicate if they have taken a human subjects training course.*	

Bruce Webster, MIT COUHES trained	
8. Anticipated Dates of Research	
Start Date: 12/20/04	Completion Date: 9/1/05

I. STUDY INFORMATION

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

The goal of this experiment is to investigate the feasibility of countermeasures to combat the effects of long duration space travel, by applying a low magnitude/high frequency vibration to the foot and utilizing resistance to the application of human power on a human powered centrifuge.

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

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

You should provide sufficient information for effective review by non-scientist members of COUHES. Define al Attaching sections of a grant application is not an acceptable substitute.

The core of this study will have subjects complete a 20-minute exercise regimen followed by at least a 10-minute rest period. The subjects will cycle with a crank rotation rate of 70-90 rpm's with a resistance output of not greater than 200 watts. During this time, the subjects' heart rate, power output and acceleration will be monitored. The vibration to foot will be applied at a frequency of 30-60 Hz. The magnitude of the vibration will not exceed 10% of subjects' body weight. A DC motor will provide the locomotion for vibration.

3. Drugs and Devices. *If the study involves the administration of an investigational drug that is r approved by the Food and Drug Administration (FDA) for the use outlined in the protocol, then the princip investigator (or sponsor) must obtain an Investigational New Drug (IND) number from the FDA. If the stu involves the use of an approved drug in an unapproved way the investigator (or sponsor) must submit application for an IND number. Please attach a copy of the IND approval (new drug), or application (new use. If the study involves the use of an investigational medical device and COUHES determines the device pos significant risk to human subjects , the investigator (or sponsor) must obtain an Investigational Device a Equipment (IDE) number from the FDA.*

Will drugs or biological agents requiring an IND be used? YES☐ NO☒

If yes, please provide details:

Will an investigational medical device be used? YES☒ NO☐

If yes, please provide details: a readily available sport training heart rate monitor will be strapped to the subjects' chest and transmit a wireless signal of heart rate to a receiver

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

Will radiation or radioactive materials be used? YES☐ NO☒

If yes, please provide details:

5. Diets

Will special diets be used? YES☐ NO☒

If yes, please provide details:

HUMAN SUBJECTS

1. Subjects

A. Estimated number: 10	**B. Age(s): 18-50**

C. Inclusion/exclusion criteria

i. *What are the criteria for inclusion or exclusion?*

subjects will be of average fitness, weight not to exceed 250 lbs., and size range will be restricted to the height limitations for astronauts

ii. Are any inclusion or exclusion criteria based on age, gender, or

no

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

N/A

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

MIT Cycling Club members, students associated with Man Vehicle Lab will be by verbal requests and an e-mail sent to the MIT Cycling Club.

The e-mail will contain the information:
"Aerospace Engineering Graduate project team seeks volunteers in a human factors experiment to determine the physiological effects of a human powered centrifuge. Subjects will be required to complete 30 minutes of pedaling in multiple tests on a rotating structure similar to a bicycle oriented on its side. The time commitment is approximately 1 hour per subject."

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

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

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

none

Will subjects be reimbursed for travel and expenses?

no

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

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

Physical risks include catastrophic failure of centrifuge, moving machinery presents possible physical injury including pinch points, long hair entanglement. Physical overexertion is possible. Rotation may produce nausea, dizziness or headache.

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

Inspection of centrifuge, centrifuge fasteners and centrifuge supports prior to testing will minimize risk of catastrophic failure. Chain guards are fitted to machine, supporting harness and rails will minimize physical risks to subject. Subject's condition will be assessed by verbal reports. If subject reports nausea, dizziness, headache or other physical discomfort, testing will cease to minimize risk. MIT Health will be summoned if necessary.

5. Potential benefits

What potential benefits may subjects receive from participating in the study?

None

What potential benefits can society expect from the study?

Society can reap the benefits of the investigation of a countermeasure to combat the detrimental effects of exposure to less than Earth's gravity during long duration space travel. This technology may be beneficial in the treatment of osteoperosis.

6. Data collection, storage, and confidentiality

How will data be collected?

Data will be acquired through a computer base data collecting system measuring powe output, centrifuge acceleration and intensity of output of subject.

Is there audio or videotaping? YES ☒ NO☐ ***Explain the procedures you plan to follow.***

A few subjects may be videotaped strictly for documentation purposes.

Will data be associated with personal identifiers or will it be coded?

Personal identifiers ☐Coded ☒

Explain the procedures you plan to follow.

Coded procedures will assign numbers to subjects.

Where will the data be stored and how will it be secured?

Data will be stored in computers accessible only to members of the Man Vehicle Lab.

What will happen to the data when the study is completed?

Research data collected during the experiment will be stored in coded files that contain n personal information. The coding of the data will prevent linking personal data to researc data when data is analyzed or archived. Research data is stored in a database or in ASCI files.

Can data acquired in the study affect a subject's relationship with other individual (e.g. employee-supervisor, patient –physician, student-teacher, family relationships)?

Data acquired in study will not affect subject's relationship with other individuals.

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

Will information about the research purpose and design be withheld from subjects?

YES ☐ **NO☒** ***If so, explain and justify.***

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

What follow-up efforts will be made to detect any harm to subjects and how will COUHES be kept informed?

Subjects will be monitored during testing and instructed to report any subsequent effects experienced that may be due to testing. COUHES will be informed by reporting using the Adverse Event Reporting Form.

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

Attach informed consent forms with this application.

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

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

YES ☐ **NO☒**

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

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

Are you requesting a Waiver of Authorization?

YES ☐ **NO☒**

If YES, explain and justify.

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

YES ☐ **NO☒**

Will you be using or disclosing a limited data set?

YES ☐ **NO☒**

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

Investigator's Assurance

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

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

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

- **ensuring all study personnel satisfactorily complete human subjects training**
- **performing the study according to the approved protocol**

- **implementing no changes in the approved study without COUHES approval**
- **obtaining informed consent from subjects using only the currently approve consent form**
- **protecting identifiable health information in accord with the HIPAA Privac Rule**
- **promptly reporting significant or untoward adverse effects**

Signature of Principal Investigator ______________________ Date __________

Print Full Name and Title ____

Signature of Department Head _________________________ **Date** __________

Print Full Name and Title ____

Please return a signed hard copy of this application to the COUHES office at E32-335

Please also return additional copies, either by email or regular mail, in accord with the instructions on the COUHES web-site.

Appendix G. Consent Form, Human Powered Artificial Gravity

CONSENT TO PARTICIPATE IN NON-BIOMEDICAL RESEARCH

Human Powered Artificial Gravity and Low Magnitude High Frequency Vibrations Applied to the Foot Through the Pedal.

You are asked to participate in a research study conducted by Dava Newman, Ph.D., Thomas Jarchow, Ph.D., and Bruce Webster, 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 that 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 or ever had vestibular or balance disorders (labyrinthitis and vertigo). Please tell us if you have a history of hearing impairment, as this may be correlated with vestibular dysfunction. The experimenter will check to see if you meet these requirements.

PURPOSE OF THE STUDY

The goal of this experiment is to investigate the feasibility of countermeasures to combat the effects of long duration space travel, by applying a low magnitude/high frequency vibration to the foot and utilizing resistance to the application of human power on a human powered centrifuge. Short radius centrifugation, wich produces artifical gravity (AG) is currently being investigated as a countermeasure to the deleterious effects of weightlessness experienced during long duration spaceflight, and we are investigating methods to increase the effectiveness of AG as a countermeasure.

PROCEDURES USED IN THIS STUDY

If you volunteer to participate in this study and if you qualify for the participation, you may be exposed to the following movements and forces during the experiments:

- G level at your feet does not exceed 3G for a sustained amount ("G-level" is defined as the acceleration or force that you would experience normally standing on earth)
- the time of rotation is 1 hour at most, there may be 2 sessions of testing done in an hour (1 session = 20 minutes of rotation with 10 minutes of rest).
- during rotation on the centrifuge, a low-magnitude vibration will be applied to your feet.

These parameters are well within the safe limits for short-radius centrifugation.
During an experiment you may be asked to do one or more of the following…

- report your sensations when asked, and
- perform simple tasks (like pressing a button to indicate a sensation).

You will be instructed on what you have to do in detail by the experimenter.
During an experimental session the experimenter may record one or more of the listed parameters:

- gender, body height, body mass, and other physiological characteristics.
- the acceleration/velocity and position of the centrifuge.
- power output of pedaling.
- heart rate.

You may terminate the experiment at any time
by telling the experimenter you wish to stop.

POTENTIAL RISKS AND DISCOMFORTS

During an experiment you may experience the one or more of the following…

- sleepiness, headache, pressure in you legs due to fluid shifts, nausea, and motion sickness.
- sensation of turning, tumbling, dizziness, and tilting of parts or the whole of your body.
- an increase of heart rate, sweating, etc.

The experimenter will frequently ask you about your motion sickness to ensure your comfort and will monitor your alertness through communication. The experiment may be discontinued if your motion sickness reaches a certain level. The increase of heart rate will not be greater than during sustained exercise.

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.
You will be continuously monitored by at least one experimenter in the same room. The investigator will monitor your well being and address any problems that arise.

ANTICIPATED BENEFITS TO SUBJECTS

You will receive no benefits from this research.

ANTICIPATED BENEFITS TO SOCIETY

Society can reap the benefits of the investigation of a countermeasure to combat the detrimental effects of exposure to less than Earth's gravity during long duration space travel. This technology may be beneficial in the treatment of osteoperosis.

PAYMENT FOR PARTICIPATION

None.

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 power output and heart rate, information from the computer on an experimental 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 may videotape for purposes of documentation. You have the right to review and edit the tape. Recorded videotapes may be used for demonstration of operation of human powered centrifuge.

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 Man Vehicle Lab 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, Prof. Dava Newman, Dr. Thomas Jarchow, or Bruce Webster 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.

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:

Principle Investigator:	**Co-Investigators:**
Dava Newman (33-207) 77 Massachusetts Avenue Cambridge, MA 02139 (617) 258-8799	Thomas Jarchow (37-219) 77 Massachusetts Avenue Cambridge, MA 02139 (617) 253-0017

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

________________________________ ________________________
Signature of Witness Date (must be the same as subject's)