Load Carrying Assistance Device:

Pogo Suit

by

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ABSTRACT

Wearable robots including exoskeletons, powered prosthetics, and powered orthotics must add energy to the person at an appropriate time to enhance, augment, or supplement human performance. Adding energy while not being in sync with the user can dramatically hurt performance making it necessary to have correct timing with the user. Many human tasks such as walking, running, and hopping are repeating or cyclic tasks and a robot can add energy in sync with the repeating pattern for assistance. A method has been developed to add energy at the appropriate time to the repeating limit cycle based on a phase oscillator. The phase oscillator eliminates time from the forcing function which is based purely on the motion of the user. This approach has been simulated, implemented and tested in a robotic backpack which facilitates carrying heavy loads. The device oscillates the load of the backpack, based on the motion of the user, in order to add energy at the correct time and thus reduce the amount of energy required for walking with a heavy load. Models were developed in Working Model 2-D, a dynamics simulation software, in conjunction with MATLAB to verify theory and test control methods. The control system developed is robust and has successfully operated on a range of different users, each with their own different and distinct gait. The results of experimental testing validated the corresponding models.

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CHAPTER 1

INTRODUCTION

Soldiers are routinely required to carry between 60-100 pounds of gear including body armor, weapons, ammo and batteries [1-2]. Carrying this excessive weight while running, jumping and other various activities causes strain on the lumbar. Only 13% of soldiers evacuated due to back pain return to active duty [3]. There is a need for a device that can alleviate the pains associated with carrying heavy loads.

The development of exoskeletons to add energy to the human user is a growing field of interest. Exoskeletons can assist users in a variety of situations whether they be rehabilitation, joint torque assistance or load carrying assistance. Companies such as Google, Lockheed Martin, Raytheon and Honda are currently developing and improving such exoskeletons.

In this research, the objective is to develop an exoskeleton that can facilitate load carrying by reducing the energy required to walk with heavy loads. The ultimate goal is to allow the user to walk further and faster than they could otherwise do without the device.

CHAPTER 2

BACKGROUND

Wearable robots including exoskeletons, powered prosthetics, and powered orthotics must add energy to the person at an appropriate time to enhance, augment, or supplement human performance. Adding energy while not being in sync with the user can dramatically hurt performance making it is necessary to have correct timing with the user. Many human tasks such as walking, running, and hopping are repeating or cyclic tasks and the robot must add energy in sync with the repeating cycle.

To be able to add energy to the gait cycle it is important to understand the different stages in the gait cycle and how the body moves over time. It has been shown that the human moves up and down a span of approximately two inches [4-5]. By understanding when muscles are being activated and whether they are in concentric or eccentric contraction is important because it has been shown that muscles that are eccentrically contracted can produce three to six times the amount of work of the same muscles concentrically contracted [6].

Armed with this knowledge, one can begin to understand when energy can be added to the gait cycle that will benefit the user and not harm them. The University of California at Berkeley has developed an exoskeleton that transfers backpack loads to the ground making it easier to carry heavy loads [7-8]. Harvard, Massachusetts Institute of Technology and Arizona State University have functioning exoskeletons that are adding energy to the user by adding torque to the user's joints [9-11]. Kerestes at Arizona State uses a phase oscillator controller and pneumatic actuators to add torque to the user's hips [12]. Rate gyros are placed on the thighs which measure angular velocity which can be

integrated to a relative angle. A phase angle, described in detail in Chapter 3, is used to trigger actuators which add torque to the user's hips. This device was taken to the Army Research Laboratory where two subjects wore the device. The device was too large for the first subject and showed a metabolic increase with the device on versus no device at all. The device was a better fit for the second subject and was able to reduce metabolic cost by 8% for running at 6mph and by 10.2% at 8mph. This device achieved metabolic augmentation.

Kerestes also developed an initial Pogo Suit to assist with human running [13]. The device used a small secondary mass that oscillated while the human ran or hopped to add energy and reduce metabolic cost. This device showed an increase in hop height of approximately four inches. Initial testing did not indicate metabolic augmentation but allowed the user to carry the additional weight of the device, approximately 10 pounds, with no additional cost. The device was able to overcome its weight but no more.

This device is the basis for the mechanical design of the device developed in this paper. The researcher will apply the principles in loaded walking in the place of running, using the load of the backpack mass as the secondary oscillating mass.

The control method used to control the device discussed in this paper is called a phase oscillator. Other groups use different forms of oscillators to control exoskeletons. Rinderknecht et al. use a phase angle to estimate joint angles, velocities and accelerations in order to provide an assistive torque to human elbow movements [14]. Using a modified adaptive oscillator developed by Righetti [15] and a position sensor, they are able to extract estimates of the fundamental frequency, amplitude and phase shift from the elbow motion. These are the inputs to a system loop which estimates the elbow's

current state and adds a corresponding assistive torque, see Figure 2.1. The results on two subjects showed that the exoskeleton was able to get in phase with the user in approximately 10 cycles [14].

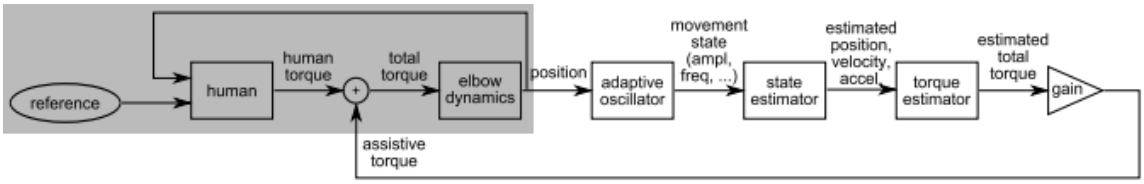

Figure 2.1: Block diagram of human and exoskeleton system developed by Rinderknecht et al. [14]

The approach described in this thesis adds energy to the user by applying a force from a secondary mass at the correct time during gait by means of a phase oscillator controller.

CHAPTER 3

PHASE OSCILLATOR

A general equation for a mechanical system is described by a 2nd order system with a given mass, m, damping, b, and stiffness, k.

$$m\ddot{x} + b\dot{x} + kx = 0 \tag{3.1}$$

$$x = -A\,cos\,\omega t \tag{3.2}$$

$$\dot{x} = A\omega sin\,\omega t \tag{3.3}$$

$$\ddot{x} = A\omega^2 cos\,\omega t \tag{3.4}$$

The frequency of oscillations of the system modeled by equation 3.1 is dependent on the mass, m, and the spring constant, k. The behavior of the amplitude of the oscillations is dependent on the damping coefficient, b. If $b > 0$, the system has positive damping, and the oscillations will shrink and disappear over time. If $b < 0$, the system has negative damping, and the oscillations will continue to grow. If $b = 0$, the system has no damping, and the oscillations will remain at a constant amplitude. A "phase oscillator method" cancels the damping of the system to create a limit cycle and is based on the phase plane of the system. The method adds energy to the system based on the phase angle, ϕ, shown in Figure 3.1.

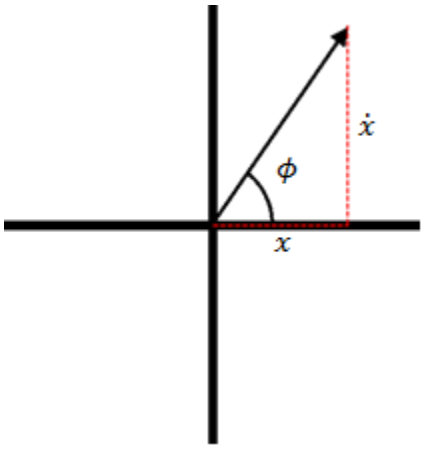

Figure 3.1: Phase angle is defined as $atan2(\dot{x}, x)$

The phase angle can be used to determine when to add energy to the system and how much energy to add. Figure 3.2 shows the phase plot for the case where $b = 0$, and Figure 3.3 shows the phase angle over time.

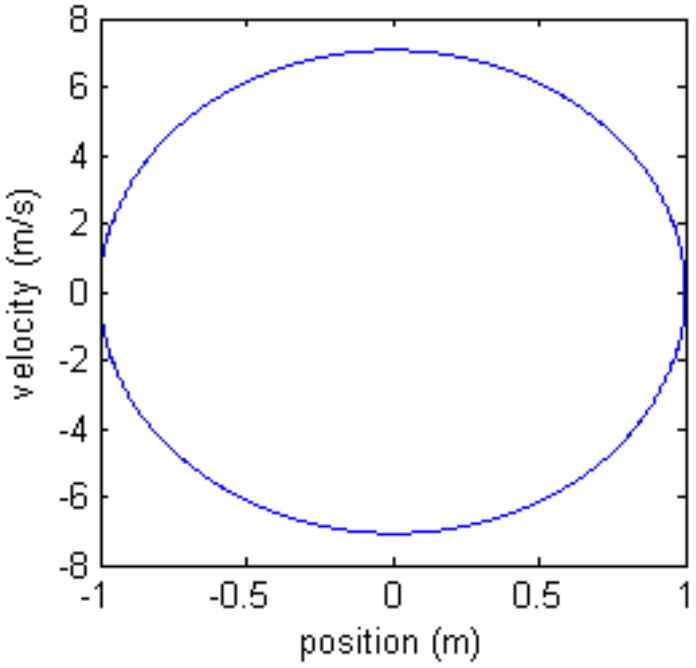

Figure 3.2: Phase plot of an oscillating system with no damping. $m = 1$ kg, $k = 50$ N/m, $b = 0$ Ns/m, initial position = 1 m, initial velocity = 0 m/s

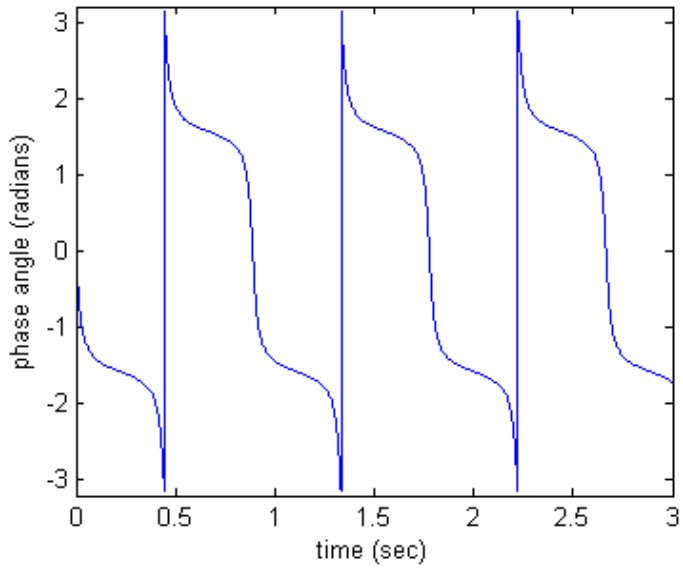

Figure 3.3: Phase angle of an oscillating system with no damping.

With the first definition of the phase angle, the phase angle remains close to $\pm\frac{\pi}{2}$ for the majority of each oscillation, despite the smooth oscillations. This is because the velocities are almost an order of magnitude higher than the positions which causes the phase plot, if plotted on the same scale, to be more elliptical rather than circular. When the velocity is divided by the natural frequency, $\frac{\left(\frac{\dot{x}}{\omega}\right)}{x}$ becomes unitless, the phase plot becomes a perfect circle and the phase angle becomes linear as seen in Figures 3.4 and 3.5.

$$\omega = \sqrt{\frac{k}{m}} \tag{3.5}$$

$$\phi = atan2\left(\frac{\dot{x}}{\omega}, x\right) \tag{3.6}$$

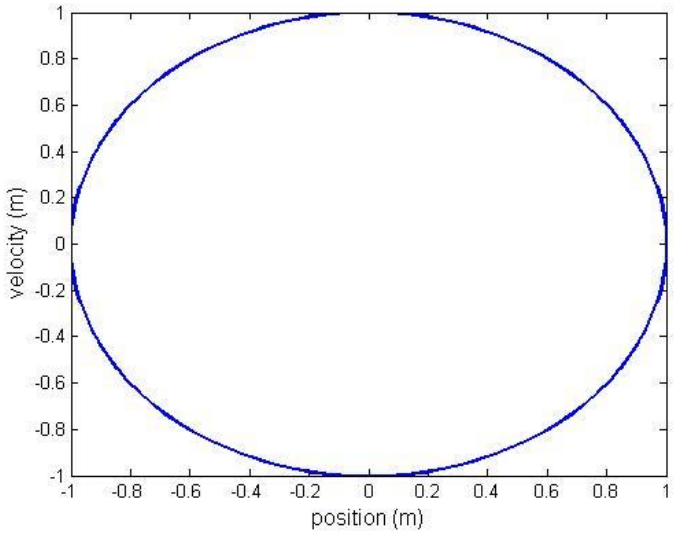

Figure 3.4: Phase plot of an oscillating system with the velocity divided by the natural frequency.

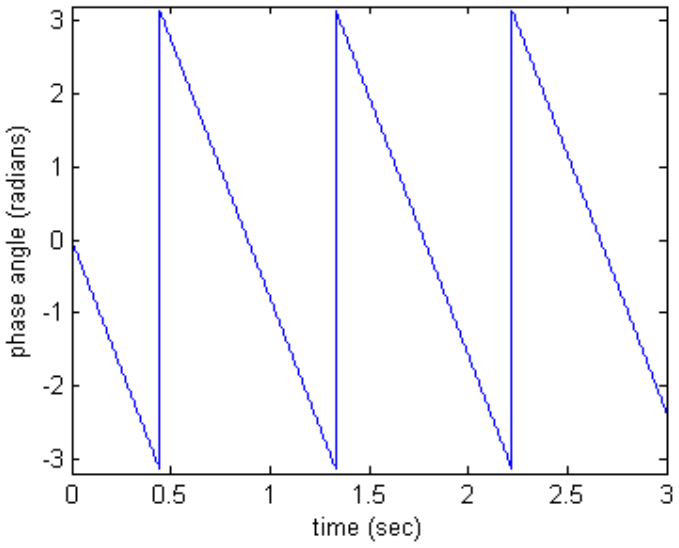

Figure 3.5: Phase angle when velocity is divided by the natural frequency.

A forcing function proportional to the sine of the phase angle can be used to add energy to the system. The forcing function puts the system into a limit cycle by canceling the damping term. Equation 3.7 models the system with the phase oscillator.

$$m\ddot{x} + b\dot{x} + kx = c \sin \phi \tag{3.7}$$

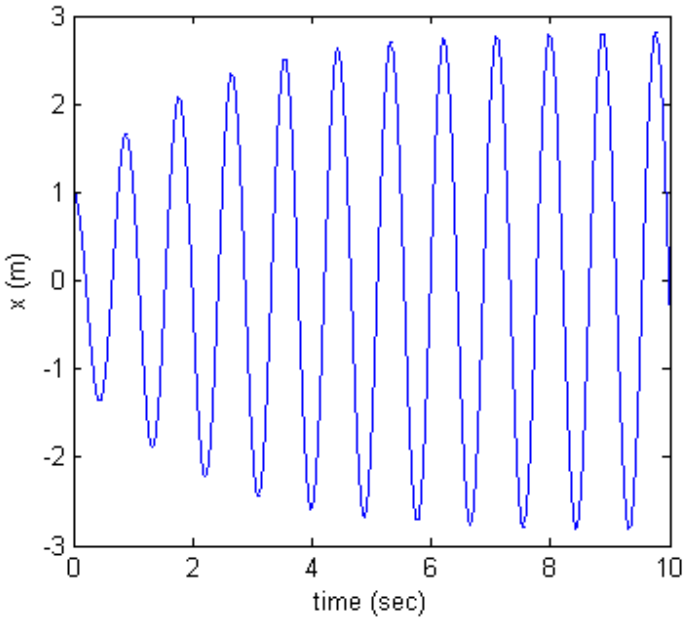

Figure 3.6: Spring response with phase oscillator. $m = 1$ kg, $b = 1$ Ns/m, $k = 50$ N/m, c = 20, initial position = 1 m, initial velocity = 0 m/s.

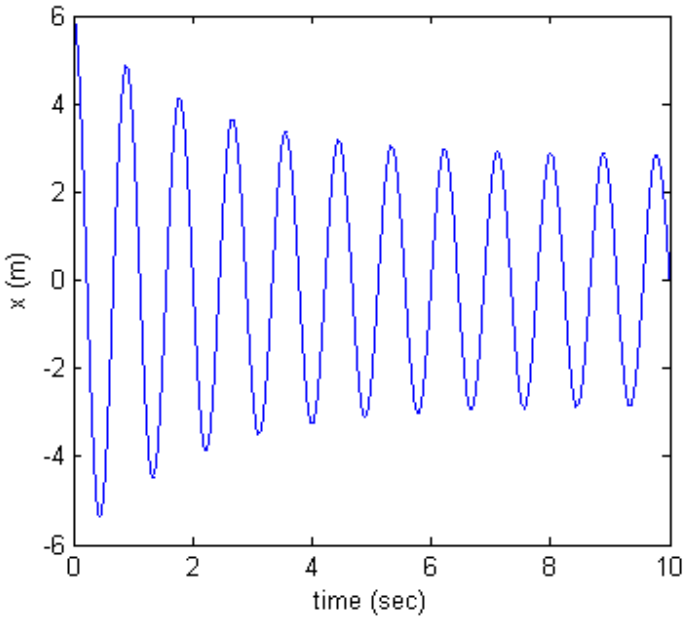

Figure 3.7: Spring response with phase oscillator. $m = 1$ kg, $b = 1$ Ns/m, $k = 50$ N/m, c = 20, initial position = 6 m, initial velocity = 0 m/s.

When implementing a negative damping control method in a 2nd order system, the value for the negative damping must perfectly match the linear damping term for the system to achieve oscillatory behavior. This is implemented simply in simulations but is difficult to achieve empirically. When oscillatory behavior is achieved experimentally, it is highly dependent on initial conditions. Figures 3.6 and 3.7 show that using the phase oscillator controller the system will achieve steady state independent of the initial conditions [16]. This limit cycle can be found by solving equation 3.7 analytically. Substituting equation 3.8 into equation 3.7 determines a sinusoidal solution given by equation 3.9. The amplitude, A, of the solution is given by equation 3.10.

$$\sin\phi = \frac{\left(\frac{\dot{x}}{\omega}\right)}{\sqrt{\left(\frac{\dot{x}}{\omega}\right)^2 + x^2}} \tag{3.8}$$

$$x(t) = A\sin(\omega t) \tag{3.9}$$

$$A = \frac{c}{b\omega} = \frac{c\sqrt{m}}{b\sqrt{k}} \tag{3.10}$$

Using the phase oscillator control method, the amplitude of the system can be changed directly by adjusting c.

CHAPTER 4

POGO PRINCIPLES

Walking is a repeating or cyclical task which provides an ideal platform to use a phase plane based control approach to add energy to the human. As a person walks, the vertical motion of the trunk appears to be almost sinusoidal but because there is a moment when both feet are on the ground, the trunk acceleration is not sinusoidal but has a 'double bump' caused by the opposite foot hitting the ground as seen in Figure 4.1 [4]. By integrating the accelerometer data twice to achieve position, it can be argued that the position of the human closely resembles a sinusoidal signal so the assumption of sinusoidal motion for modeling purposes can be justified.

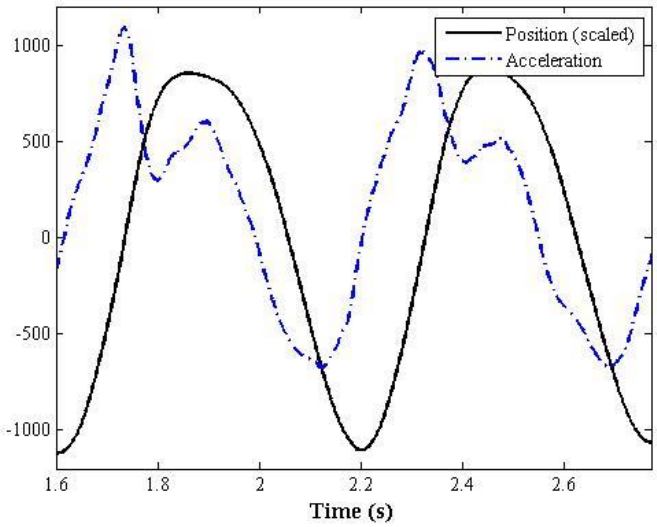

Figure 4.1: Acceleration and position signal of subject walking on treadmill at 3mph showing that the human's COM position can be assumed to be sinusoidal.

By assuming the vertical motion of the trunk to be sinusoidal, position, x_h , velocity, $\dot{x}_h$, and acceleration, $\ddot{x}_h$, can be defined in the same way as in the previous modeling shown in equations 3.2 - 3.4. Using Working Model 2D, a dynamics simulation software, a human with mass, m_h , can be modeled as a 2nd order system mass-spring-damper system with a linear actuator creating the trunk's sinusoidal motion[17-21]. A back pack can be modeled by adding a mass, m_p , pinned to the trunk, as seen in Figure 4.2. The human motion is simulated using a position controlled actuator attached to the trunk, a 73 kilogram mass. The pack is attached to the trunk and has a mass of 27 kg. Working Model allows the user to add forces, actuators, motors and other modeling tools to create a specific dynamic system.

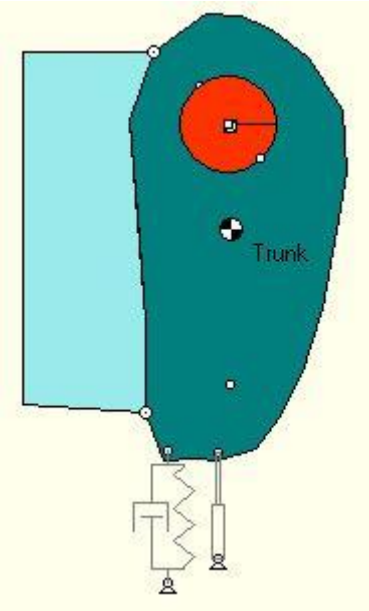

Figure 4.2: Working Model 2D model of human trunk with a linear actuator to simulate vertical motion.

The linear actuator is driven with a position command of $x = -0.0254\cos wt$ to simulate the trunk oscillating with a magnitude of one inch [5]. Working Model allows the user to 'monitor' different parameters, typically displayed as a graph, of the modeled system in order to visualize the dynamics. The power of the actuator can be monitored in order to understand the energy involved forcing the trunk up and down. A successful exoskeleton to assist with load carrying would add positive power at all times thus reducing the power required by the legs, or actuator in the case of the model, to move the trunk.

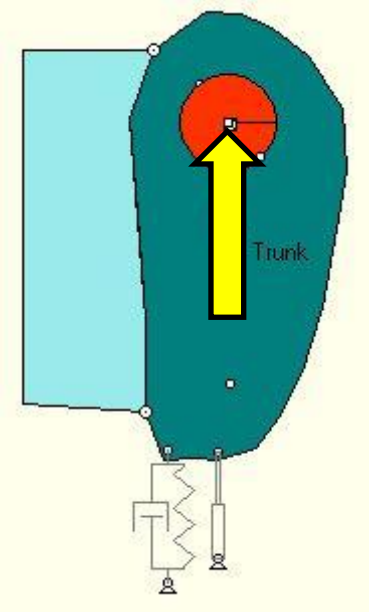

Figure 4.3: Working Model 2D model of human trunk with a linear actuator to simulate vertical motion and an added force.

A force based on the sine of the phase angle can be added to this gait model which pushes the center of mass, COM, up as it moves up and pushes down as the COM

moves down, seen in Figure 4.3. Figure 4.4 gives a visual of when the force acts during the gait cycle. Using Working Model 2D it can be shown that this forcing function reduces the powers needed for walking.

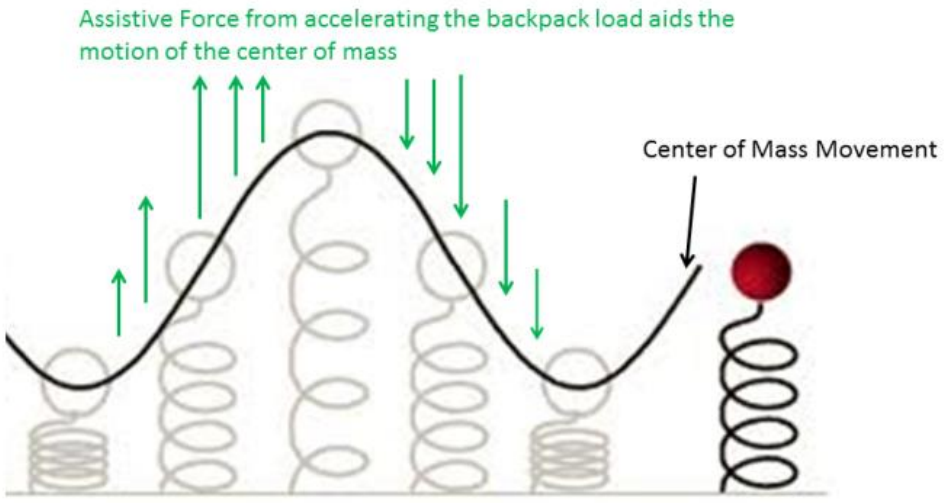

Figure 4.4: The forcing function based on the sine of the phase angle pushes up as the COM moves up and pushes down as the COM moves down.

To validate the theory, a force based on the phase angle, $f = 100sin\phi$, is applied to the trunk. Potential metabolic savings can be estimated by monitoring the actuator power required to oscillate the trunk with no force versus with an applied force, f. The results of this simulation are shown in Figure 4.5. We can see that the positive power peak are reduced but the negative power peaks are increased. Research has shown that concentric muscle contractions require three to six times more energy to produce the same amount of work as eccentric muscle contractions [6]. The argument can be made that the increased negative power peaks are easier for the human to absorb in the walking gait because the required muscles are eccentrically contracting until roll over where they

begin to concentrically contract. Using that knowledge, the benefit in the reduction of positive power peaks will have more impact on the user than the addition of increased negative power peaks because of where they happen in the gait cycle.

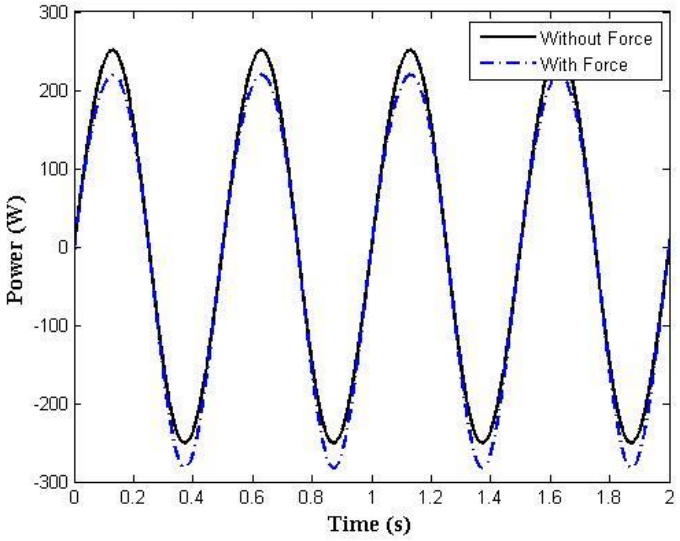

Figure 4.5: Positive power peaks required to oscillate the human are reduced and negative power peaks are increased.

CHAPTER 5

POGO SUIT SIMULATIONS

The pogo suit uses a secondary mass that is linearly displaced resulting in a reaction force on the user opposite the mass' acceleration. This is modeled in Working Model by adding a second linear actuator that is attached to the backpack at one end and another mass at the other as seen in Figure 5.1.

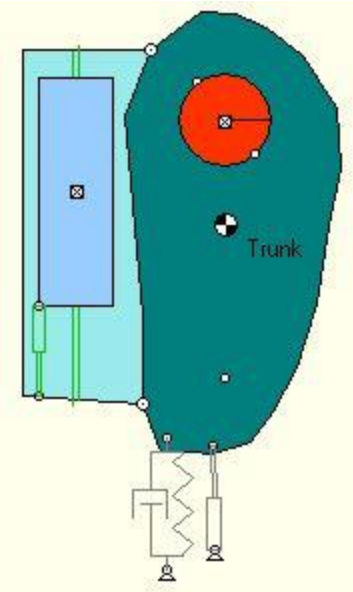

Figure 5.1: Working Model 2D model of human trunk with pogo suit actuator modeled in the backpack as a secondary mass on a linear actuator.

From the previous force model, the desired additional forcing function is a pure force based on the sine of the phase angle. In this case, the force, f, is negative because the pogo suit applies a force to the user based on a reaction force. Solving the basic dynamic equations gives an expression for the acceleration of the pogo suit mass, which can be integrated to find the position of the mass to deliver the desired force.

$$f = f_o \sin\phi \tag{5.1}$$

$$m_{load}\left(\ddot{x}_h + \ddot{x}_{pogo}\right) = -f_o \sin\phi \tag{5.2}$$

$$\ddot{x}_{pogo} = \frac{-f_o}{m_{load}} sin\phi - \ddot{x}_h \tag{5.3}$$

$$\ddot{x}_{pogo} = \frac{-f_o}{m_{load}} sin\phi - A\omega^2 \cos\omega t \tag{5.4}$$

$$x_{pogo} = \frac{f_o}{\dot{\phi}^2 m_{load}} sin\phi + A\cos\omega t \tag{5.4}$$

The subscript, *h*, represents the motion of the human. The subscript, *pogo*, represents the motion of the oscillatory, secondary mass. The position equation for the pogo suit, x_{pogo}, has a term that is related to time which comes from the $\ddot{x}_h$ term in the equation 5.2. By looking at the definition of the phase angle we can develop an expression for $cos\omega t$ in terms of the phase angle, ϕ, and eliminate time from the equation, see equations 5.5 – 5.7. This is significant because the control signal will then only depend on the motion of the human's COM and be independent of time. Table 5.1 shows that independent of the definition of the human position, x_h , the portion of the pogo suit position related to the human acceleration and time is equal to $-cos\phi$.

$$\sqrt{\left(\frac{\dot{x}}{\omega}\right)^2 + x^2} = \sqrt{A^2(\cos(\omega t))^2 + A^2(\sin(\omega t))^2} = A \tag{5.5}$$

$$cos\phi = \frac{x_h}{\sqrt{\left(\frac{\dot{x}_h}{\omega}\right)^2 + x_h^2}} = \frac{x_h}{A} = -\frac{Acos\omega t}{A} = -cos\omega t \tag{5.6}$$

$$\sin\phi = \frac{\frac{\dot{x}_h}{\omega}}{\sqrt{\left(\frac{\dot{x}_h}{\omega}\right)^2 + x_h^2}} = \frac{A\sin(\omega t)}{A} = \sin(\omega t) \tag{5.7}$$

$Position$	$x_h = A cos\omega t$	$x_h = A sin\omega t$	$x_h = -A cos\omega t$	$x_h = -A sin\omega t$
$Velocity$	$\dot{x}_h = -A\omega sin\omega t$	$\dot{x}_h = A\omega cos\omega t$	$\dot{x}_h = A\omega sin\omega t$	$\dot{x}_h = -A\omega cos\omega t$
$Acceleration$	$\ddot{x}_h = -A\omega^2 cos\omega t$	$\ddot{x}_h = -A\omega^2 sin\omega t$	$\ddot{x}_h = A\omega^2 cos\omega t$	$\ddot{x}_h = A\omega^2 sin\omega t$
$sin\phi$	$-sin\omega t$	$cos\omega t$	$sin\omega t$	$-cos\omega t$
$cos\phi$	$cos\omega t$	$sin\omega t$	$-cos\omega t$	$-sin\omega t$
ϕ	$-\omega t$	$-\omega t + \frac{\pi}{2}$	$-\omega t + \pi$	$-\omega t - \frac{\pi}{2}$
$\ddot{x}_h \; term \; in \; x_{pogo}$	$-A cos\omega t$	$-A sin\omega t$	$A cos\omega t$	$A sin\omega t$
$\ddot{x}_h \; term \; in \; x_{pogo}$ $in \; terms \; of \; \phi$	$-cos\phi$	$-\cos\phi$	$-cos\phi$	$-cos\phi$

Table 5.1: Each definition for the position of the COM results in the human acceleration term being equivalent to $-cos\phi$.

From this we have a complete solution for the position of our secondary mass which will achieve the desired force, defined purely by the phase angle of the user's trunk. The multipliers on the sinusoidal functions simply scale the amplitude of the combined sinusoid that is shown in equations 5.8 – 5.13. This shows that the amplitude of the force is changed by simply changing the amplitude of the secondary mass' position function.

$$x_{pogo} = \frac{f_o}{\dot{\phi}^2 m_{load}} sin\phi - A\cos\phi \tag{5.8}$$

$$let \; a = \frac{f_o}{\dot{\phi}^2 m_{load}} \; and \; b = A \tag{5.9}$$

$$asin\phi - bcos\phi \equiv Rcos\alpha sin\phi - Rsin\alpha cos\phi \equiv Rsin(\phi - \alpha) \quad (5.10)$$

$$tan\alpha = \frac{b}{a} \therefore \alpha = \text{atan2(b, a)} \quad (5.11)$$

$$R = \sqrt{a^2 + b^2} \quad (5.12)$$

$$x_{pogo} = Rsin(\phi - \alpha) \quad (5.13)$$

By choosing the amplitude, a, of both the $sin\phi$ and $cos\phi$ terms to be the same, α is then equal to $\frac{\pi}{4}$. Each user will then be able to choose the amount of force preferred by choosing the amplitude of the pogo position.

Figures 5.2 and 5.3 show the simulated position of the trunk and actuator and the actuator position for $x_{pogo} = 0.0254 \sin\left(\phi - \frac{pi}{4}\right)$.

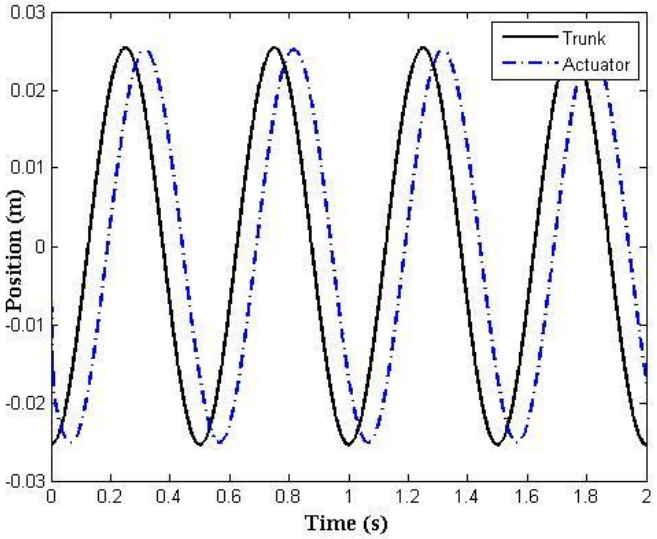

Figure 5.2: Working Model 2D simulation of the trunk and pogo actuator position for the derived position found in eq. 5.10

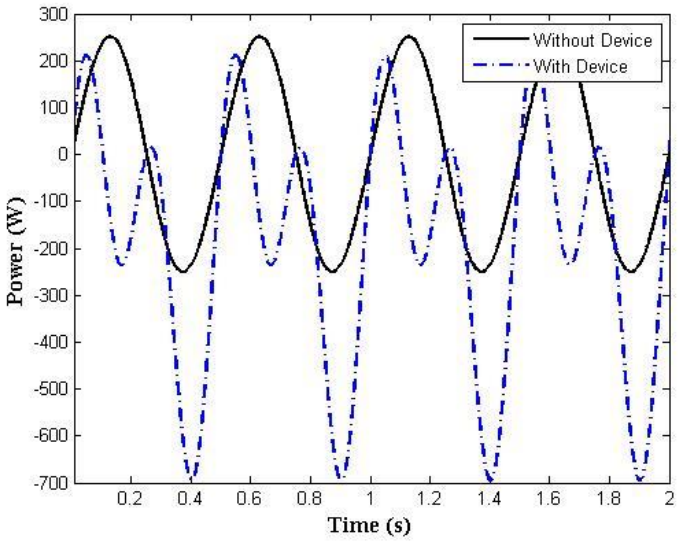

Figure 5.3: Simulated powers required to oscillate trunk with and without pogo suit device.

Once the Working Model 2D model was created and being driven by MATLAB, it was simple to try other potential control methods. Figures 5.4 and 5.5 show $x_{pogo} = cos\phi$ which if the amplitude matches the amplitude of the user would completely cancel the motion of the user and the load would not appear to be moving. Simulation shows that positive and negative powers are increased substantially meaning this might feel awful to the user.

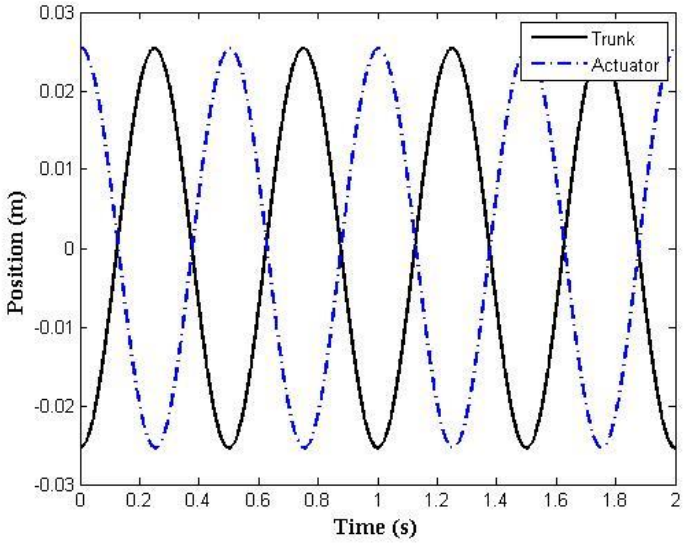

Figure 5.4: Working Model 2D simulation of the trunk and pogo actuator position for $x_{pogo} = cos\phi$.

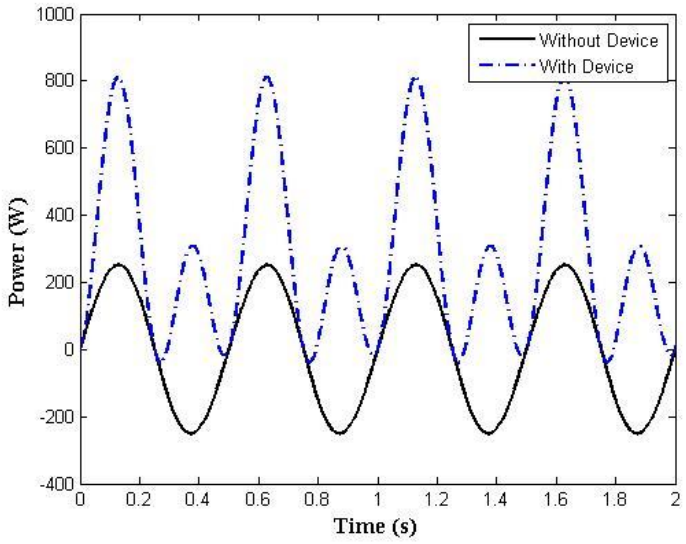

Figure 5.5: Simulated powers for $x_{pogo} = cos\phi$.

Because $cos\phi$ showed almost the complete opposite of the desired powers, $-cos\phi$ should give the desired powers. Figures 5.6 - 5.7 show the simulated positions

and powers which appear to be a good. Another way to get these same results is to take the accelerometer signal, apply a low pass filter, scale it to the desired amplitude and send that signal as the position command of the pogo device. This method is simpler but might not work because of the double bump in the acceleration signal seen in Figure 4.1.

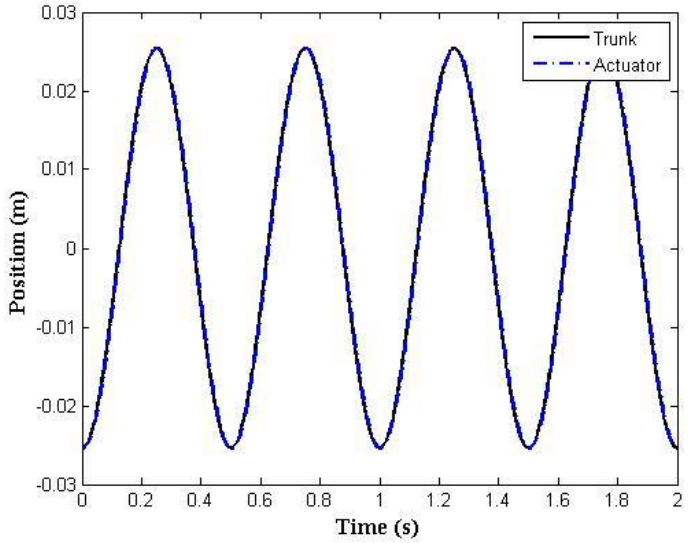

Figure5.6: Working Model 2D simulation of the trunk and pogo actuator position for $-cos\phi$.

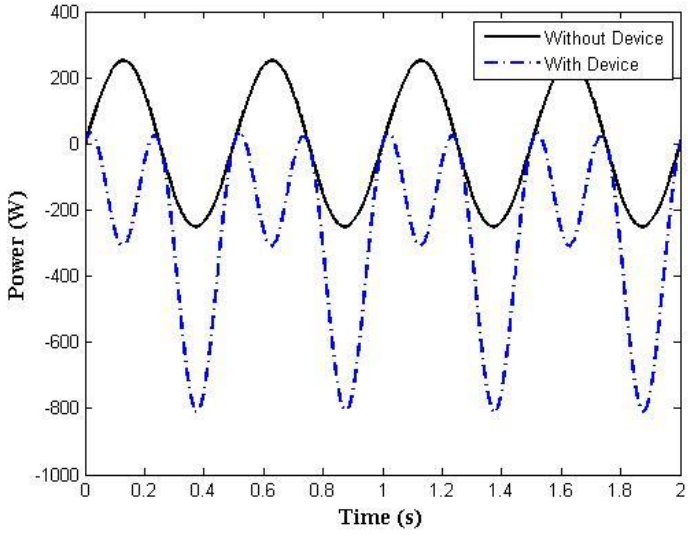

Figure 5.7: Simulated powers for $-cos\phi$

Figures 5.8 and 5.9 show simulations of $x_{pogo} = sin\phi$. It is unclear whether this command would help or hurt the user's performance based on the power curve.

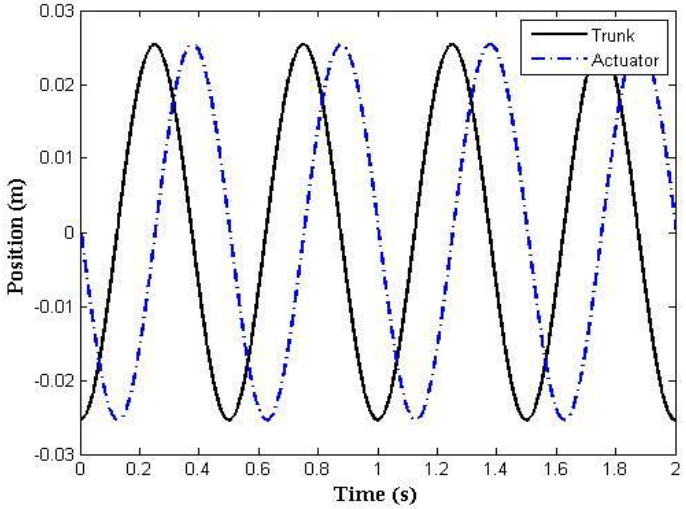

Figure 5.8: Working Model 2D simulation of the trunk and pogo actuator position for $x_{pogo} = sin\phi$.

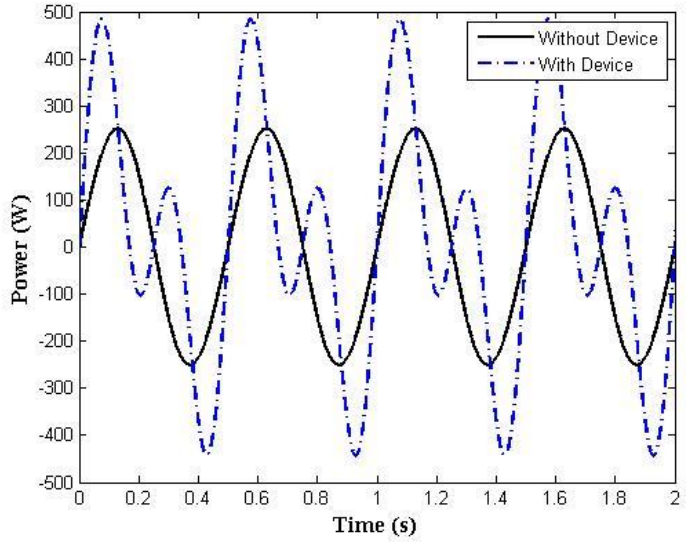

Figure 5.9: Simulated powers for $x_{pogo} = sin\phi$.

The position command of $-sin\phi$ was also simulated and again is not clear by the power curve whether this will help or hurt the user.

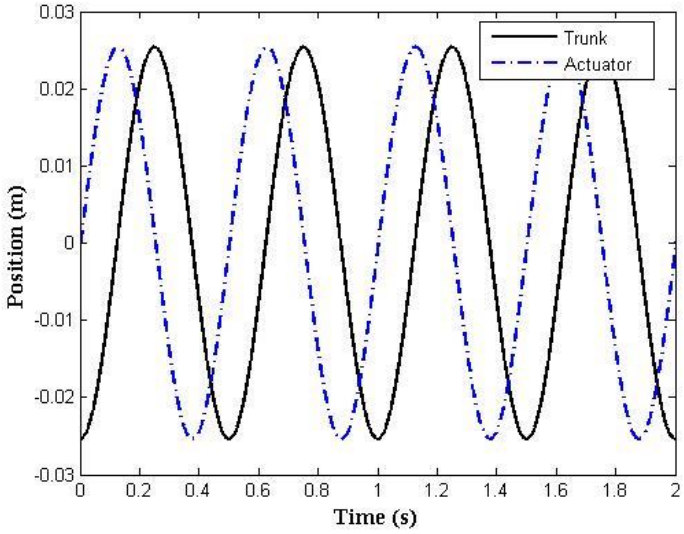

Figure 5.10: Working Model 2D simulation of the trunk and pogo actuator position for $-sin\phi$.

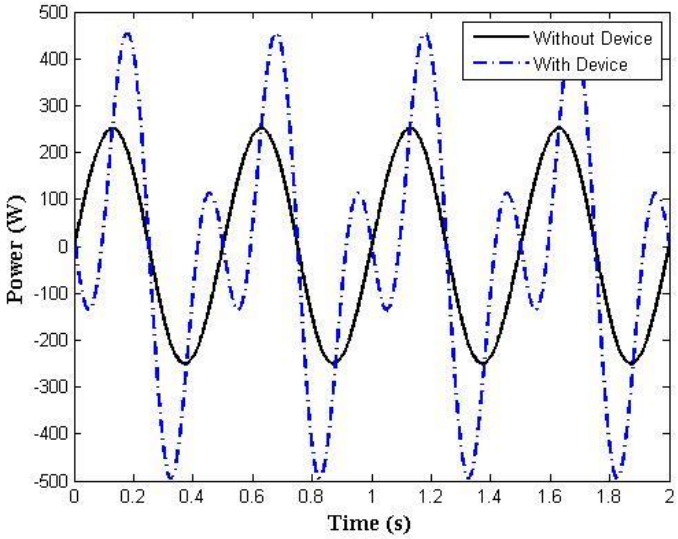

Figure 5.11: Simulated powers for $-sin\phi$.

Adding energy to a human through an exoskeleton needs to be timed perfectly or else the device could dramatically hurt the performance of the human. After the simulations are complete, it is important to validate the results of the simulations and physically understand how each of the control methods feels to the user. From there, it is possible to eliminate bad control methods and focus on improving methods that feel good.

CHAPTER 6

POGO SUIT IMPLEMENTATION

Using a control method based on the phase angle of the user requires the system to have the position and the velocity of the COM of the user. This can be achieved by collecting an acceleration signal from the user and integrating once to get velocity and twice to get position. This can prove to be a problem due to integral drift unless a pseudo-integrator is used, seen in equations 6.1 - 6.2.

$$Single\ Integrator \Rightarrow \frac{s}{(s+\tau)^2} \tag{6.1}$$

$$Double\ Integrator \Rightarrow \frac{s}{(s+\tau)^3} \tag{6.2}$$

Dr. Matthew Holgate uses this pseudo integrator in control of a transtibial prosthesis.

> "*The principal desirable property of the pseudo-integration method is the removal of integration drift. It can be seen that for frequencies smaller than τ the transfer function attenuates the input. The drift that occurs is in this frequency range and is thus attenuated. An integrator has a pole on the imaginary axis, which makes it marginally stable and there for the output is able to drift. The pseudo-integration transfer function has two stable poles, which eliminate the drift. By choosing τ one can choose how fast the poles are. This has the effect of constantly pulling the output toward the input, which is the angular velocity. Since the angular velocity is always centered around zero, the pseudo-angle will also be approximately centered around zero, it is stable and attracted to the input.*"[22]

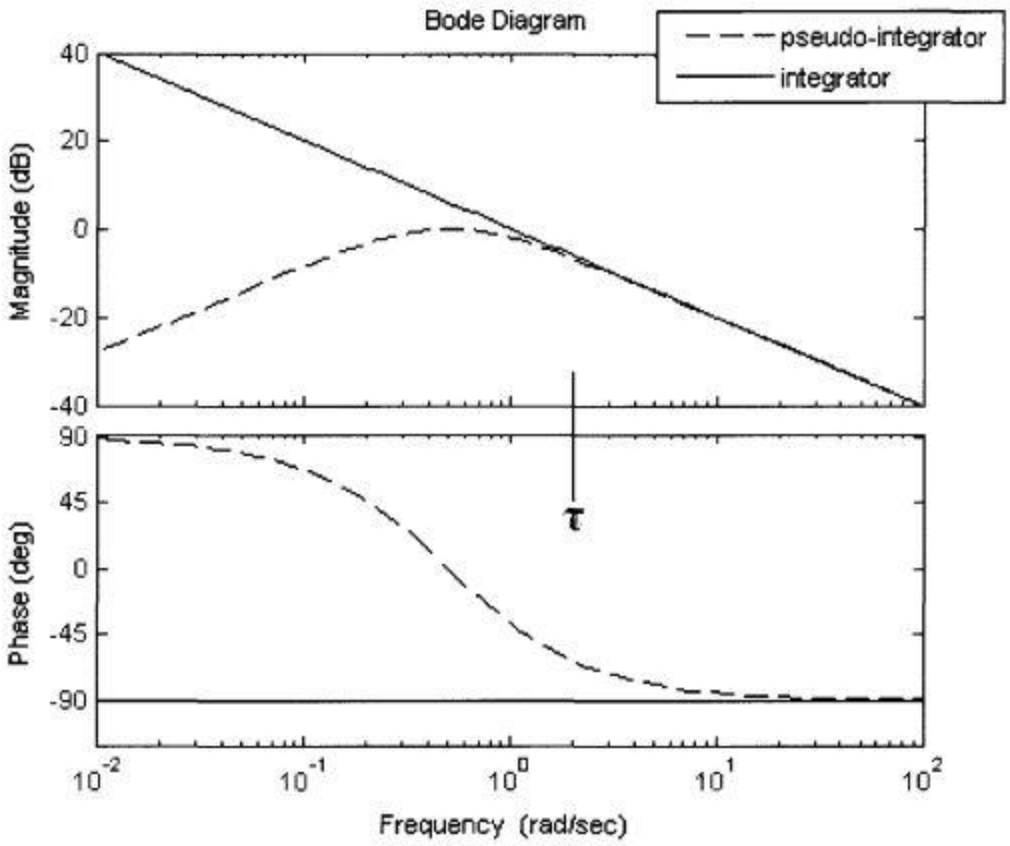

Figure 6.1: Bode plots for pseudo-integrator transfer function and integrator [22]

With position and velocity signals that center around zero, a phase plane can be developed and a phase angle extracted. Figures 6.2 - 6.4 show the acceleration, velocity and position signals of a subject walking on a treadmill at three miles per hour and the corresponding phase plane, and the phase angle, ϕ. It can be seen that the phase plane is not perfectly circular causing the resulting phase angle not to be perfectly linear. This in turn will cause the sinusoidal position signals to be imperfect.

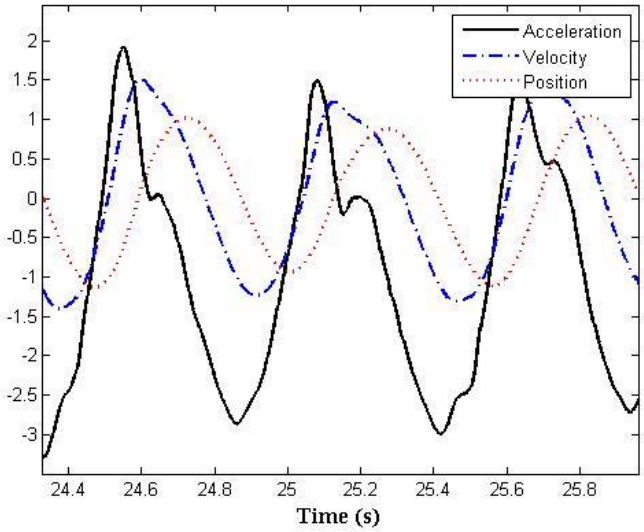

Figure 6.2: Human acceleration, velocity and position signals used to control the pogo suit.

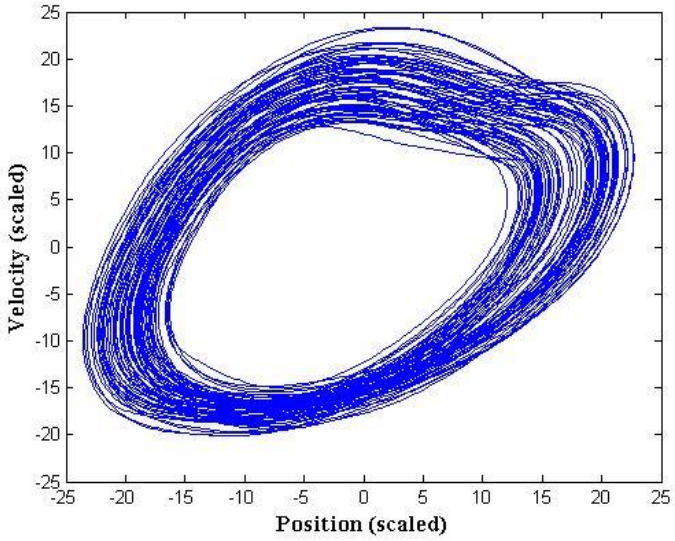

Figure 6.3: Phase plane of subject walking on a treadmill at 3mph.

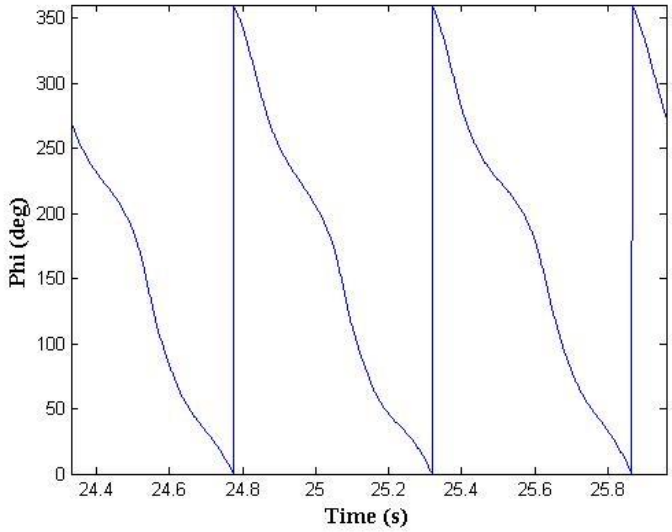

Figure 6.4: Phi versus time for a human subject walking at 3mph.

The actual device is made up of a DC motor, lead screw, and linear carriage on a military grade pack. The device is powered by a 6 cell lithium polymer battery and weighs approximately eight lbs. The device uses a Digilent Cerebot MC7 board with a Microchip dsPIC33FJ128MC706A as the microcontroller to read in accelerometer and encoder signals and send out motor position commands. The C code was developed using MATLAB and Simulink in conjunction with Simulink Coder which takes a Simulink model and converts it to C. The code is then compiled and programmed to the microprocessor using MPLAB. Using this method of writing and building code allows the designer to quickly write and test controls. Having simulated a variety of control functions, it was easy to check whether they felt like they were assisting or hurting the user by simply changing the program slightly to reflect the desired control. Three

different users tried each control method with the device oscillating 30 pounds and gave feedback which will be summarized.

Figure 6.5: Pogo Suit physical device.

Figure 6.6 shows the derived and simulated control position of $x_{pogo} = 0.0254 \sin\left(\phi - \frac{\pi}{4}\right)$. Appendix B contains side by side comparisons of each of the simulated control signals with actual control signals. This control method felt the best. Intuitively one can look at the position curves and see that when the user reaches the lowest point in the gait, heel strike, the device is accelerating down, giving an upward force. This makes the weight of the pack feel lighter and relieves the leg muscles. When walking with the device on for a minute and then turning it off, it is easy to feel that the device is adding energy to the user at the right times making it feel better to walk with the heavy load.

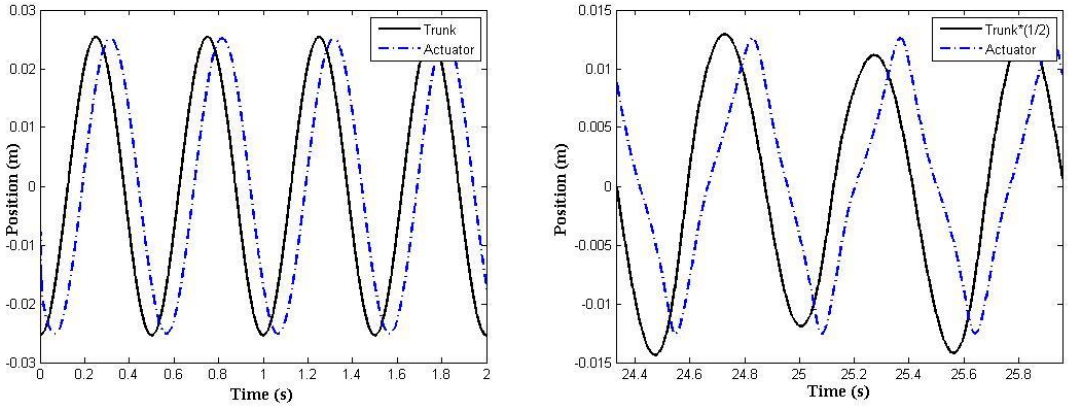

Figure 6.6: Simulated (left) versus actual (right) human and pogo suit position for $x_{pogo} = 0.0254 \sin\left(\phi - \frac{\pi}{4}\right)$.

Even though the device 'feels good' to the user, it is necessary to verify the feeling with empirical data. There must be either a metabolic augmentation or else an increase in walking speed in order to justify the added weight of the device to the pack. A set of experiments was developed to determine the effectiveness of the device and whether or not the device could overcome its weight. To comply with Arizona State University's human subject testing guidelines a testing protocol was developed, reviewed and approved by their Internal Review Board, IRB. All documents relating to the IRB submission and approval can be found in Appendix A.

CHAPTER 7

TESTING AND RESULTS

The testing protocol that follows was used to collect and analyze data. Before any physical tests were conducted, the subject was provided an opportunity to gain familiarity with the device. Basic training on the operation of the device and user controls was administered by one of the research team members. The subject was allowed to gain familiarity while walking at their own set pace. This training session included step-by-step instructions covering the basic operation of the device; controlling the device while it is on and turning it off. Device training consisted of a 10 minute information session in the robotics lab on how the device works, what to expect and how to use the controls.

After the subject was comfortable with the device, the testing commences first on the treadmill. The tests listed below are not randomized, but in order to insure independent results, statistical software was used which randomized trials and levels. The subject was allowed to rest 10-15 minutes before performing four tests on the treadmill.

- Test subjects first walked 800 meters at 3mph with the device turned off with a 22lb payload (to account for the weight of the device) and then were allowed to rest 10-30 minutes depending on subject's stamina.
- Test subjects then walked 800 meters at 3mph with the device turned on with a 30lb payload and then were allowed to rest 10-30 minutes depending on stamina.
- If and only if the subjects felt able to do so, the previous two tests were repeated with 10-30 minute breaks between them.
- Subjects wore a heart rate monitor and a V02 mask

- Resting heart rate and resting V02 rate were collected before each of the 4 trials. This resting V02 rate set the baseline for each trial.

The subject then had the opportunity to rest a minimum of half an hour up to an hour and then went outside to do over ground testing. Again, the trials as presented are not randomized but were when the subject performed them. There will be the same 4 tests performed.

- Test subjects first walked 800 meters at 3mph with the device turned off with a 22lb payload (to account for the weight of the device) and then were allowed to rest 10-30 minutes depending on subject's stamina.
- Test subjects then walked 800 meters at 3mph with the device turned on with a 30lb payload and then were allowed to rest 10-30 minutes depending on stamina.
- If and only if the subjects felt able to do so, the previous two tests were repeated with 10-30 minute breaks between them.
- For each test, a heart rate monitor and a GPS watch was worn to measure heart rate, speed, and time during the test.

While performing all tests, the subjects were be monitored for their heart rate via a wireless Bluetooth heart rate wrist watch. For over ground testing, the watch will also track subjects speed and distance walked. If the subject is comfortable and able, we will repeat the tests to get more iterations.

The results of one subject's metabolic tests of the device on with 30 pounds and the device off with 22 pounds were analyzed using Minitab as seen in Table 7.1. The results showed that difference between the metabolic outputs are statistically significant

using a 95% confidence level. With a p-value of much less than 0.001 it is shown that the device causes a statistically significant increase in the metabolic output.

```
Two-sample T for Off 22lb vs On 30lb

           N   Mean  StDev  SE Mean
Off 22lb  38  11.83   1.86     0.30
On 30lb   38  14.11   2.22     0.36


Difference = μ (Off 22lb) - μ (On 30lb)
Estimate for difference:  -2.279
95% CI for difference:  (-3.215, -1.343)
T-Test of difference = 0 (vs ≠): T-Value = -4.85  P-Value = 0.000  DF = 71
```

Table 7.1: Minitab output for a two-sample T test of one subjects metabolic tests.

Table 7.2 shows the results of a subject walking with no load, 22 and 30 pounds with the device off, and 30 pounds with the device on. By looking at the average metabolic cost during the trial, it can be shown that the main increase in metabolic cost is due to the additional weight of the device, 8 pounds. When comparing the data for 30 pounds with the device on versus off using a two sample t-test, the resulting p-value is 0.86 which shows that there is no statistical difference between the trials. This means that the device is not helping, but it also means that the device is not hurting. More tests will be performed in future work to verify the results found in this trial.

Metabolic Cost				
Time	No Load	Off 22lbs	Off 30lbs	On 30lbs
0.15	7.2	3.9	9.1	9.4
0.30	9.4	7.1	12.4	8.9
0.45	11.1	12.1	10.4	11.4
9.00	11.5	12.6	14.0	14.9
9.15	9.1	13.4	13.0	13.8
9.30	10.5	12.3	16.1	15.6
Average	11.0	11.8	14.0	14.1
% > No Load		7.1%	27.1%	27.8%
% > 22lbs Off			18.6%	19.3%
% > 30 lbs Off				0.5%

Table 7.2: Metabolic results for one subject with no load, 22 lbs, 30 lbs and 30 lbs oscillating based on the phase angle.

CHAPTER 7

CONCLUSION AND FUTURE WORK

A method for adding energy to the human gait based on the user's phase angle has been developed, implemented and tested. A physical system was built and controls developed using Simulink in conjunction with Simulink Coder. The device was tested with several control methods to determine which method felt best to the user. With this control method, metabolic data was collected for the device off with a 22 pound load versus the device on with a 30 pound load. The difference in load is to account for the device weight. By performing a two sample T test, there was a statistical difference when carrying 22 pounds versus 30 pounds when looking at oxygen consumption. There was not a statistical difference between carrying 30 pounds with the device turned on versus turned off when looking at oxygen consumption. The device weight of eight pounds was too significant

Metabolic augmentation is possible with future work. The team will continue to test the Pogo Suit device with more users to verify results of the one subject's results in discussed. The performance of an exoskeleton can be user dependent which could mean that other users could show better results.

The mechanical system was built with parts on hand and not specifically designed for the task. The lead screw and nut provided a lot of friction for the motor to overcome and the motor speed and torque were not optimal resulting in excess heat generated. This heat caused the linear system to drift due to the encoder getting too hot. If the motor is geared correctly, its efficiency will go up and reduce the heat generated most likely to a temperature level suitable for the encoder. With a linear system geared for this

application more weight could be added to the system which could help to overcome the device. It could be that the eight pound weight of the device was too significant of a percentage of the payload weight for there to be benefit of carrying the added weight. By reducing the weight of the device and designing the motor carriage system for heavy loads could improve the system. The device weight would be less significant if the payload weight were 80-100 pounds in which case the potential benefit could be more apparent.

Another study could be done on load placement. Currently the load is two thirds of the way up the user's back where having the mass closer to the user's hip may be beneficial. Studies have been done on load placement in packs which have shown that when both loads placed high on the back and low on the back cause the user to lean forward as to bring the total center of mass over their feet. Lower loads cause more strain because the body needs to rotate more to move the center of mass over the feet, but high loads increase dynamic moments which causes stability issues with the user [23]. It would be interesting to see the effect of lowering the load closer to the waist of the user.

A study can also be done on the phase shift, α, to find the optimal phase shift to decrease metabolic cost. A response curve can be developed for different phase shifts making it possible to find the value that yields the lowest metabolic cost. The current system is using a 45 degree phase shift which was chosen because of simplicity but could possibly not be the optimal solution.

Using hydraulic actuators is another method that could mitigate the issue of adding more weight because hydraulics can handle much higher loads.

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APPENDIX A

IRB DOCUMENTATION

Instructions and Notes:

- Depending on the nature of what you are doing, some sections may not be applicable to your research. If so mark as "NA".
- When you write a protocol, keep an electronic copy. You will need to modify this copy when making changes.

1 Protocol Title

Include the full protocol title: Wearable Robot for Load Carrying Assistance

2 **IRB Review History**

If you have submitted this protocol for review by an external IRB, provide the previous study identification number and provide details of the review including the IRB name, date of review, and IRB contact information.

3 **Background and Objectives**

Provide the scientific or scholarly background for, rationale for, and significance of the research based on the existing literature and how will it add to existing knowledge.

- Describe the purpose, specific aims, or objectives.
- State the hypotheses to be tested.
- Describe the relevant prior experience and gaps in current knowledge.
- Describe any relevant preliminary data.

The objective of the proposed investigation is to collect data from two environments; over ground and on a treadmill. Heart rate, speed, and distance will be collected in the over ground trials and in addition VO2 for treadmill trials. The purpose of the device is to decrease metabolic cost and therefore increase walking speed, stamina and/or increase distance traveled. The device uses a linear rail system to oscillate the mass of the pack, 0.5-1in, in phase with the user as they walk in order to reduce required forces and energy for walking. The primary purpose of this pilot study is to determine the effectiveness of the device.

4 **Inclusion and Exclusion Criteria**

Describe the inclusion and the exclusion criteria for the study.

Describe how individuals will be screened for eligibility.

How many participants do plan to enroll into the study?

- Provide a rationale for the proposed enrollment number
- What percentage of screened individuals will likely qualify for the study?

Indicate if you are specifically recruiting individuals of the following populations as participants. If this is the case, these populations must be indicated in your inclusion criteria.

- Adults unable to consent
- Pregnant Women
- Individuals who are not yet adults (individuals who are under age 18)
- Native Americans

The test subjects that will be used in the proposed investigation will be comprised of individuals that are physically capable of walking 800 meters with a pack that weighs 35-45lbs who and are in good health.

INCLUSION CRITERIA

1. Between the ages of 18-45 years of age

2. Can walk a distance of 800 meters with 45lb pack in multiple trials
3. Full range of limbs including arms, knees, legs and hips
4. Ability to wear test equipment and heart rate monitors
5. Ability to follow simple instructions
6. Must have proof of medical insurance
7. Must answer no to all of the questions in the Par-Q questionnaire

EXCLUSION CRITERIA

1. Excessive body mass or lack of stamina
2. Restricted joint movement in arms and legs
3. Inability to meet inclusion criteria
4. Any previous medical conditions involving the heart

Eight to ten individuals will be screened for eligibility and 5-10 individuals will be enrolled in the study. This pilot study is to determine if wearing the device turned on (with the30 lb additional load oscillating in phase with the user) versus the device turned off (22lb additional load is static) increases walking speed, stamina and walking distance and decreases heart rate. The participants in the proposed study will be comprised of individuals that are capable of performing the tests and are in good health.

Excessive body mass will be defined as a Body Mass Index greater than 30 which is considered obese.

Screening Tools will include the Par-Q questionnaire and the determination of the BMI Index

5 Recruitment Methods

- Describe when, where, and how potential participants will be identified and recruited.
- Describe materials that will be used to recruit participants. (Attach copies of these documents with the application.)

Test subjects will be recruited from within Arizona State University's student body who meet the physical requirements. Test subjects will be evaluated based on their physical abilities and information they provide to the research staff.

As part of the screening process, test subjects will be required to sign a consent form indicating they have been fully briefed on all of the possible physical dangers associated with the testing and the entire testing protocol.

A recruiting statement is given in a separate file.

6 Study Timelines

Describe:

- The duration of an individual participant's participation in the study.
- The duration anticipated to enroll all study participants.
- The estimated date for the investigators to complete this study (up to and including primary analyses).

Testing will be conducted over 5-10 days, one day for each subject, and will last approximately 4

hours.

The study will be finished by December 2014.

7 Procedures Involved

Describe and explain the study design. Provide a description of all research procedures being performed and when they are performed. Describe procedures including:

- The documents/ measures / devices/ records /sampling that will be used to collect data about participants. (Attach all surveys, scripts, and data collection forms.)
- What data will be collected including long-term follow-up.
- All drugs and medical devices used in the research and the purpose of their use, and their regulatory approval status.

A protocol is submitted as part of the package.

Device training will consist of a 10 minute information session in the robotics lab on how the device works, what to expect and how to use the controls. After this period, the subject will be allowed to try the device at their own pace in the robotics lab for 5-10 minutes.

After the subject is comfortable with the device, we will then commence testing on the treadmill. The tests are listed below, but in order to insure independent results, we will use a statistics software which will randomize trials and levels. The subject will be allowed to rest 10-15 minutes and we will perform 4 tests on the treadmill.

- Test subjects will first walk 800 meters at 3mph with the device turned off and a 22lb payload (to account for the weight of the device) and then be allowed to rest 10-30 minutes depending on subject's stamina.
- Test subjects will then walk 800 meters at 3mph with the device turned on and a 30lb payload and then be allowed to rest 10-30 minutes depending on stamina.
- If and only if the subjects feel able to do so, the previous two tests will be repeated with 10-30 minute breaks between them.
- The order of testing device on versus device off will be randomized
- Subjects will wear a heart rate monitor and a V02 mask
- Resting heart rate and resting V02 rate will be collected before each of the 4 trials. This resting V02 rate will set the baseline for each trial.

The subject will then have the opportunity to rest a minimum of half an hour up to an hour and then we will go to either the campus athletic track or the SRC, depending on availability, to begin over ground testing. Again, the trials as presented are not randomized but will be when the subject performs them. There will be the same 4 tests performed.

- Test subjects will first walk 800 meters with the device turned off and a 22lb payload (to account for the weight of the device). They will then be allowed to rest 10-30 minutes depending on subject's stamina.
- Test subjects will then walk 800 meters with the device turned on and a 30lb payload. They will then be allowed to rest 10-30 minutes depending on stamina.
- If and only if the subjects feel able to do so, the previous two tests will be repeated with 10-30 minute breaks between them.
- For each test, a heart rate monitor and a GPS watch will be worn to measure heart rate, speed,

and time during the test.

While performing all tests, the subjects will be monitored for their heart rate via a wireless Bluetooth heart rate wrist watch. For over ground testing, the watch will also track subjects speed and distance walked. If the subject is comfortable and able, we will repeat the tests to get more iterations. The subject can stop any test at any time if they do not wish to continue.

8 Withdrawal of Participants

Describe anticipated circumstances under which participants will be withdrawn from the research without their consent.

Describe procedures that will be followed when participants withdraw from the research, including partial withdrawal from procedures with continued data collection.

Taking part in this research study is strictly voluntary. A subject may choose not to take part in this research study or may withdraw their consent at any time. The commitment of the research staff is to provide help and assistance and will not at any time be affected by an individual's choice not to participate. If subjects decide to end their participation in the study, they will not complete any additional testing nor will they be asked to continue testing. There will be no penalty or loss of benefits if the subjects decide to end testing prematurely.

If the participant is tired and does not want to continue, they can withdrawal at any time.

If their heart rate goes above the maximum level, the heart rate monitor will beep and you will be asked to stop.

From CDC, "This maximum rate is based on the person's age. An estimate of a person's maximum age-related heart rate can be obtained by subtracting the person's age from 220. For example, for a 50-year-old person, the estimated maximum age-related heart rate would be calculated as 220 - 50 years = 170 beats per minute (bpm)."

9 Risks to Participants

List the reasonably foreseeable risks, discomforts, hazards, or inconveniences to the participants related the participants' participation in the research. Include as may be useful for the IRB's consideration, the probability, magnitude, duration, and reversibility of the risks. Consider physical, psychological, social, legal, and economic risks. Reference this information when appropriate.

- **If applicable, indicate which procedures may have risks to an embryo or fetus should the participant be or become pregnant.**
- **If applicable, describe risks to others who are not subjects.**

1. Physical risks associated with walking with a 35-45lb pack such as tripping and falling either due to the motion of the device causing the subject to lose balance.
2. Physical risks associated with carrying a 35-45lb pack such as fatigue in legs, and lower back.

3. There is a chance for the battery to overheat and catch fire.
4. There is a chance of tripping and falling and breaking a bone.

To minimize potential risks, the subject will have a training session to familiarize themselves with the device that is closely supervised by a member of the team which will allow them to feel how the device will affect their walking. Before testing begins, the subject will be asked to stretch to reduce the possibility of strained or pulled muscles. The battery will be placed in a fireproof bag, seen in Figure 2, which will contain any fire that may occur.
The subject will be asked to wear a heart rate monitor. If their heart rate goes above the maximum level, the heart rate monitor will beep and you will be asked to stop.

From CDC, "This maximum rate is based on the person's age. An estimate of a person's maximum age-related heart rate can be obtained by subtracting the person's age from 220. For example, for a 50-year-old person, the estimated maximum age-related heart rate would be calculated as 220 - 50 years = 170 beats per minute (bpm)."

Participation in this study may cause all or some of the side effects listed above. There is in addition always the risk of developing previously unknown side effects.

If mild side effects or discomforts do occur, the research staff will attempt to minimize these effects by asking you to rest. If any serious side effects occur, the research staff will attempt to minimize these by directing you to the emergency room.

If there are any major side effects, the research staff will call 911 immediately. The investigator is willing to discuss any questions you might have about these risks and discomforts.

As stated in the protocol, the battery will be placed in a fireproof bag for safety.

All participants will wear shoes (not sandals).

10 Potential Benefits to Participants

Realistically describe the potential benefits that individual subjects may experience from taking part in the research. Include the probability, magnitude, and duration of the potential benefits. Indicate if there is no direct benefit. Do not include benefits to society or others.

Although we know of no known benefits to you, we anticipate that this research will assist in developing a useful product that may have several military applications.

Your participation will be of no direct benefit to you and you have the right to refuse to participate in this study.

11 Vulnerable Populations

If the research involves individuals who are vulnerable to coercion or undue influence, describe additional safeguards included to protect their rights and welfare.

- If the research involves pregnant women, review "CHECKLIST: Pregnant Women (HRP-412)" to ensure that you have provided sufficient information.
- If the research involves persons who have not attained the legal age for consent to treatments or procedures involved in the research ("children"), review the "CHECKLIST: Children (HRP-416)" to ensure that you have provided sufficient information.
- If the research involves cognitively impaired adults, review "CHECKLIST: Cognitively Impaired Adults (HRP-417)" to ensure that you have provided sufficient information.

NA

12 Setting

Describe the sites or locations where your research team will conduct the research.

- Identify where research procedures will be performed.
- For research conducted outside of the ASU describe:
  - Site-specific regulations or customs affecting the research.
  - Local scientific and ethical review structures in place.

All trials will be conducted on the Polytechnic Campus of Arizona State University within the robotics research lab, in the Student Recreational Center in a designated area, or on the campus sports track located outside the Student Recreational Center

13 Multi-Site Research

If this is a multi-site study where you are the lead investigator, describe the processes you will use to ensure communication among sites, such as:

- Each site has the most current version of the protocol, consent document, and HIPAA authorization.
- Required approvals have been obtained at each site (including approval by the site's IRB of record).
- Describe processes you will use to communicate with participating sites.
- Participating sites will safeguard data as required by local information security policies.
- Local site investigators conduct the study appropriately.

NA

14 Sharing of Results with Participants

Describe whether results (study results or individual participant results, such as results of genetic tests or research findings) will be shared with participants or others (e.g., the participant's primary care physicians) and if so, describe how it will be shared.

Data will only be shared with individuals once the study has been completed.

15 Resources Available

Describe the qualifications (e.g., training, experience, oversight) of you and your staff as required to perform your roles. When applicable describe knowledge of the local study sites, culture, and society. Provide enough information to convince the IRB that you have qualified staff for the proposed research.
Describe other resources available to conduct the research: For example, as appropriate:

- Describe your facilities.
- Describe the availability of medical or psychological resources that participants might need as a result of any anticipated consequences of the human research.
- Describe your process to ensure that all persons assisting with the research are adequately informed about the protocol, the research procedures, and their duties and functions.

There is the Gilbert Hospital next to campus
56 South Power Road
Gilbert, AZ 85295
(480) 984-2000

16 Prior Approvals

Describe any approvals that will be obtained prior to commencing the research. (E.g., school, external site, funding agency, laboratory, radiation safety, or biosafety approval.)

NA

17 Privacy

Describe the steps that will be taken to protect subjects' privacy interests. "Privacy interest" refers to a person's ability to place limits on who they interact or who can have access to personal information they provide.

Describe what steps you will take to make the subjects feel at ease with the research situation in terms of the nature of questions being asked and the procedures being performed. "At ease" does not refer to physical discomfort, but the sense of intrusiveness a subject might experience in response to questions, examinations, and procedures.

Indicate how the research team is authorized to access any sources of information about the participants.

We will collect data on the age, height, weight of the individual and record their heart rates and duration of the tests and VO2 results.
Andrew and Chase will sign the privacy statement attached.

18 Data Management and Confidentiality

Describe the data analysis plan, including procedures for statistical analysis.

Describe the steps that will be taken to secure the data during storage, use, and transmission.

- Training, authorization of access, password protection, encryption, physical controls, certificates of confidentiality, and separation of identifiers and data

Describe how data and any specimens will be handled:

- What personal identifiers will be included in that data or associated with the specimens?
- Where and how data or specimens will be stored?
- How long the data or specimens will be stored?
- Who will have access to the data or specimens?
- Who is responsible for receipt or transmission of the data or specimens?
- How will data and specimens be transported?
- If data or specimens will be banked for future use, describe where the specimens will be stored, how long they will be stored, how the specimens will be accessed, and who will have access to the specimens.
- Describe the procedures to release data or specimens, including: the process to request a release, approvals required for release, who can obtain data or specimens, and the data to be provided with specimens.

All data, videos, and photographs will be modified as to not contain any information relating to the subjects identity. All data, video, and photographs and will be kept in a locked storage cabinet and all unused data, video, and photographs will be destroyed two years after testing is concluded. It is estimated that the documents will be destroyed January 1, 2015. All data about the subjects will not include any names, addresses, or other identifying information.

19 **Safety Monitoring**

This is required when research involves more than Minimal Risk to participants. The plan might include establishing a data monitoring committee and a plan for reporting data monitoring committee findings to the IRB and the sponsor. Describe:

- The plan to periodically evaluate the data collected regarding both harms and benefits to determine whether participants remain safe.
- What data are reviewed, including safety data, untoward events, and efficacy data?
- How the safety information will be collected (e.g., with case report forms, at study visits, by telephone calls with participants).
- Who will review the data?

NA

20 **Compensation and Costs**

Describe the available compensation (monetary or credit that will be provided to research participants).

Describe any costs that participants may be responsible for because of participation in the research.

No compensation will be given

21 **Consent Process**

Indicate how you will be obtaining consent. Describe:

- Where will the consent process will take place
- Any waiting period available between informing the prospective participant and obtaining the consent.
- Any process to ensure ongoing consent.
- Whether you will be following "SOP: Informed Consent Process for Research (HRP-090)." If not, describe:
    - The role of the individuals listed in the application as being involved in the consent process.
    - The time that will be devoted to the consent discussion.
    - Steps that will be taken to minimize the possibility of coercion or undue influence.
    - Steps that will be taken to ensure the participants' understanding.

Non-English Speaking Participants

- Indicate what language(s) other than English are understood by prospective participants or representatives.
- If participants who do not speak English will be enrolled, describe the process to ensure that the oral and written information provided to those participants will be in their language. Indicate the language that will be used by those obtaining consent.

Waiver or Alteration of Consent Process (consent will not be obtained, required information will not be disclosed, or the research involves deception)

- Review the "CHECKLIST: Waiver or Alteration of Consent Process (HRP-410)" to ensure you have provided sufficient information for the IRB to make these determinations.

Participants who are not yet adults (infants, children, teenagers)

- Describe the criteria that will be used to determine whether a prospective participant has not attained the legal age for consent to treatments or procedures involved in the research under the applicable law of the jurisdiction in which the research will be conducted. (E.g., individuals under the age of 18 years.)
- Describe whether parental permission will be obtained from:
    - Both parents unless one parent is deceased, unknown, incompetent, or not reasonably available, or when only one parent has legal responsibility for the care and custody of the child.
    - One parent even if the other parent is alive, known, competent, reasonably available, and shares legal responsibility for the care and custody of the child.
- Describe whether permission will be obtained from individuals other than parents, and if so, who will be allowed to provide permission. Describe the process used to determine these individuals' authority to consent to each child's general medical care.
- Indicate whether assent will be obtained from all, some, or none of the children. If assent will be obtained from some children, indicate which children will be required to assent.
- When assent of children is obtained describe whether and how it will be documented.

Cognitively Impaired Adults

- Describe the process to determine whether an individual is capable of consent. The IRB allows the person obtaining assent to document assent on the consent document and does not routinely require assent documents and does not routinely require children to sign assent documents.

Adults Unable to Consent

- List the individuals from whom permission will be obtained in order of priority. (E.g., durable power of attorney for health care, court appointed guardian for health care decisions, spouse, and adult child.)
    - For research conducted in the state, review "SOP: Legally Authorized Representatives, Children, and Guardians (HRP-013)" to be aware of which individuals in the state meet the definition of "legally authorized representative."
    - For research conducted outside of the state, provide information that describes which individuals are authorized under applicable law to consent on behalf of a prospective participant to their participation in the procedure(s) involved in this research. One method of obtaining this information is to have a legal counsel or authority review your protocol along the definition of "legally authorized representative" in "SOP: Legally Authorized Representatives, Children, and Guardians (HRP-013)."
- Describe the process for assent of the participants. Indicate whether:
    - Assent will be required of all, some, or none of the participants. If some, indicated, which participants will be required to assent and which will not.
    - If assent will not be obtained from some or all participants, an explanation of why not.
    - Describe whether assent of the participants will be documented and the process to document assent. The IRB allows the person obtaining assent to document assent on the consent document and does not routinely require assent documents and does not routinely require participants to sign assent documents.

The research staff will provide a consent form for each subject. The subjects will be required to read, understand, and sign the consent form. All known risks and benefits will be discussed with the subject verbally and also included on consent form. An unsigned copy of the consent form may be mailed to the potential subject prior to testing so they may have the time to study it and discuss it with their family or friends before making the decision.

Dr Sugar will get informed consent from the individuals

A consent form has been attached.

22 Process to Document Consent in Writing

Describe whether you will be following "SOP: Written Documentation of Consent (HRP-091)." If not, describe whether and how consent of the participant will be documented.

If your research presents no more than minimal risk of harm to participants and involves no procedures for which written documentation of consent is normally required outside of the research context, the IRB will generally waive the requirement to obtain written documentation of consent.

(If you will document consent in writing, attach a consent document. If you will obtain consent, but not document consent in writing, attach a consent script. Review "CHECKLIST: Waiver of Written Documentation of Consent (HRP-411)" to ensure that you have provided sufficient information. You may use "TEMPLATE CONSENT DOCUMENT (HRP-502b)"to create the consent document or script.)

Dr Sugar will get informed consent from the individuals

A consent form has been attached.

23 Sharing of Results with Participants

If the drug is investigational (has an IND) or the device has an IDE or a claim of abbreviated IDE (non-significant risk device), include the following information:

- Identify the hold of the IND/IDE/Abbreviated IDE.
- Explain procedures followed to comply with FDA sponsor requirements for the following:

	Applicable to:		
FDA Regulation	**IND Studies**	**IDE studies**	**Abbreviated IDE studies**
21 CFR 11	X	X	
21 CFR 54	X	X	
21 CFR 210	X		
21 CFR 211	X		
21 CFR 312	X		
21 CFR 812		X	X
21 CFR 820		X	

NA

24 CITI

Provide the date that the members of the research team have taken the CITI training for human participants. This training must be taken within the last 3 years. Additional information can be found at: http://researchintegrity.asu.edu/training/humans

Dr. Thomas Sugar – completion 3/8/2011

Consent Form: Bioscience

Title of research study: Wearable Robot for Load Carrying Assistance

Investigator: Dr. Thomas Sugar

Why am I being invited to take part in a research study?
We invite you to take part in a research study because we are determining the effectiveness of a load carrying assistance device.

Why is this research being done?
Dr. Thomas G. Sugar and his student are designing a load carrying assistance device which has the potential to significantly reduce the energy needed to carry heavy loads long distances. A device such as this could have potential benefit to the military where soldiers are required to carry 90lb+ rucksacks.

How long will the research last?
We expect that individuals will spend about 4 hours on a single day participating in the proposed activities.

How many people will be studied?
We expect 5-10 people to participate in this research study.

What happens if I say yes, I want to be in this research?
It is up to you to decide whether or not to participate.
If you decide to participate, as a study participant you will join a study involving research of a powered wearable robot device to assist load carrying.
Your participation will last for one day at the Human and Machine Integration Laboratory at the Polytechnic Campus of Arizona State University in Mesa, Arizona.
You will interact with three people involved in the research study, Dr. Thomas Sugar, Mr. Chase Wheeler and Mr. Andrew Bates.
You will be asked to come to the Polytechnic Campus of Arizona State University to perform the tests. The testing day will last for 4 hours which includes a 10 minute training session, a 10 minute period of familiarization with the device, followed by 8 tests with resting time between the tests. The schedule is as follows:

1. You will go through a 10 minute training demonstration of how the device works and how to use it.
2. You will then have the opportunity to wear the device for 5-10 minutes to familiarize yourself with the controls and how the device affects how you walk.
3. We will then commence testing on the treadmill. You will be allowed to rest 10-30 minutes and we will perform four tests on a treadmill.
4. You will put on a heart rate monitor and mask that measures VO2 and first walk 800 meters at approximately 3mph with the device turned off and a 22lb payload. You will then be allowed to rest 10-30 minutes depending on your stamina and how you feel.

5. You will put on a heart rate monitor and mask that measures VO2 . Test subjects will then walk 800 meters at approximately 3mph with the device turned on and a 30lb payload and then be allowed to rest 10-30 minutes depending on stamina.
6. If and only if you feel able to do so, we will repeat the previous two tests with 10-30 minute breaks in between.
7. We will then walk to the Student Recreation Center or campus sports track, depending on availability, and you will first walk 800 meters with the device turned off and a 22lb payload. You will then be allowed to rest 10-30 minutes depending on your stamina and how you feel. A heart rate monitor will be worn and walking speed and time will be recorded.
8. You will then walk 800 meters with the device turned on and a 30lb payload. You will then be allowed to rest 10-30 minutes depending on your stamina and how you feel. A heart rate monitor will be worn and walking speed and time will be recorded.
9. If and only if you feel able to do so, we will repeat the previous two tests with 10-30 minute breaks in between.
10. After completing the tests you will be asked to give your feedback on the device.

Some people will walk with the device turned on first and some will walk with the device turned off first. A random order will be generated by the team.
Before each test begins, a resting heart rate and a resting metabolic rate will be measured.

What happens if I say yes, but I change my mind later?
You can leave the research at any time and it will not be held against you.
If you decide to leave the research there will be no adverse consequences, and no one will try to convince you otherwise or change your mind. If you decide to leave the research, contact the investigator so that the investigator can prepare for another candidate.

Is there any way being in this study could be bad for me?
There are certain risks and discomforts that may be associated with this research. They include but are not limited to:
1. Physical risks associated with walking with a 35-45lb pack such as tripping and falling either due to the motion of the device causing the subject to lose balance.
2. Physical risks associated with carrying a 35-45lb pack such as fatigue in legs, and lower back.
3. There is a chance for the battery to overheat and catch fire.
4. There is a chance of tripping and falling and breaking a bone.

To minimize potential risks, the subject will have a training session to familiarize themselves with the device that is closely supervised by a member of the team which will allow them to feel how the device will affect their walking. Before testing begins, the subject will be asked to stretch to reduce the possibility of strained or pulled muscles. The battery will be placed in a fireproof bag which will contain any fire that may occur.
The subject will be asked to wear a heart rate monitor. If their heart rate goes above the maximum level, the heart rate monitor will beep and you will be asked to stop.

From CDC, “This maximum rate is based on the person's age. An estimate of a person's maximum age-related heart rate can be obtained by subtracting the person's age from 220. For example, for a 50-year-old person, the estimated maximum age-related heart rate would be calculated as 220 - 50 years = 170 beats per minute (bpm).”

Participation in this study may cause all or some of the side effects listed above. There is in addition always the risk of developing previously unknown side effects.

If mild side effects or discomforts do occur, the research staff will attempt to minimize these effects by asking you to rest. If any serious side effects occur, the research staff will attempt to minimize these by directing you to the emergency room.

If there are any major side effects, the research staff will call 911 immediately.

The investigator is willing to discuss any questions you might have about these risks and discomforts.

What happens to the information collected for the research?
Efforts will be made to limit the use and disclosure of your personal information, including this research study, to people who have a need to review this information.

What else do I need to know?
If you agree to participate in the study, then consent does not waive any of your legal rights. However, no funds have been set aside to compensate you in the event of injury.
If mild side effects or discomforts do occur, the research staff will attempt to minimize these effects by asking you to rest. If any serious side effects occur, the research staff will attempt to minimize these by directing you to the emergency room.

Who can I talk to?
If you have questions, concerns, or complaints or think the research has hurt you, talk to the research team: Dr. Thomas Sugar at 480-727-1127.
This research has been reviewed and approved by the Bioscience IRB (“IRB”). You may talk to them at 480-965-6788 or research.integrity@asu.edu if:

- Your questions, concerns or complaints are not being answered by the research team
- You cannot reach the research team
- You want to talk to someone besides the research team
- You have questions about your rights as a research participant
- You want to get information or provide input about this research

Signature Block for Capable Adult
Your signature documents your permission to take part in this research.

_____

_____
Signature of Participant Date

_____
Printed Name of Participant

_____

_____
Signature of Person Obtaining Consent Date

_____
Printed Name of Person Obtaining Consent

Training Session

Description of Device and How the Device Works(3 min):
The device is a backpack with a linear carriage that oscillates based on the motion of the human being. There is an accelerometer in the waist belt that measures the motion of your trunk as you walk which is fed to a microcontroller that manipulates the signal and controls the position of the linear carriage. The device oscillates 0.5 inches only if the user is activating a switch on a joystick. The device is powered by a lithium polymer battery.

Demonstration of How to Put On and Adjust the Pack(2 min):
One of the team members will show the subject how to put on and adjust the pack to where it is comfortable.

Trial (5 min):
The subject will then put on the backpack, adjust it for comfort and turn the device on to feel how the device will affect how they walk.

Physical Activity Readiness Questionnaire (PAR-Q) and You

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly:

YES	NO		
☐	☐	1.	Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
☐	☐	2.	Do you feel pain in your chest when you do physical activity?
☐	☐	3.	In the past month, have you had chest pain when you were not doing physical activity?
☐	☐	4.	Do you lose your balance because of dizziness or do you ever lose consciousness?
☐	☐	5.	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
☐	☐	6.	Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
☐	☐	7.	Do you know of any other reason why you should not do physical activity?

If you answered:

YES to one or more questions

Talk to your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want – as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- Start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- Take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively.

Delay becoming much more active:

- If you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- If you are or may be pregnant – talk to your doctor before you start becoming more active.

Please note: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed use of the PAR-Q: Reprinted from ACSM's Health/Fitness Facility Standards and Guidelines, 1997 by American College of Sports Medicine

Wearable Robot for Load Carrying Assistance

Date _____

Subject ID Number _____

Age: _____ Circle: Male / Female Weight _____

Resting Heart Rate _____

1. Treadmill Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds
    d. Attach COSMED Metabolics Print Out

2. Rest 10-30 minutes

3. Treadmill Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds
    d. Attach COSMED Metabolics Print Out

4. Rest 10-30 minutes

5. Treadmill Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds
    d. Attach COSMED Metabolics Print Out

6. Rest for 10-30 minutes

7. Treadmill Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds
    d. Attach COSMED Metabolics Print Out

8. Rest for 10-30 minutes

9. Over Ground Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____

b. Heart Rate at end of Test _____
c. Duration of Test (seconds) _____ seconds

10. Rest 10-30 minutes

11. Over ground Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds

12. Rest 10-30 minutes

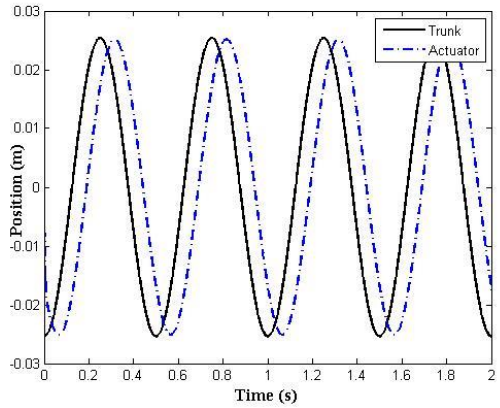
13. Over Ground Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds

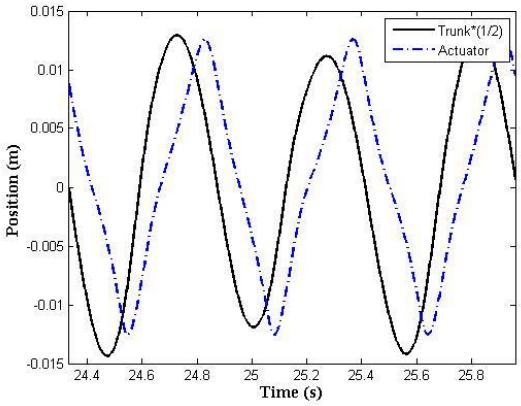
14. Rest for 10-30 minutes

15. Over Ground Test Circle: Device Off Device On
    a. Heart Rate at beginning of Test _____
    b. Heart Rate at end of Test _____
    c. Duration of Test (seconds) _____ seconds

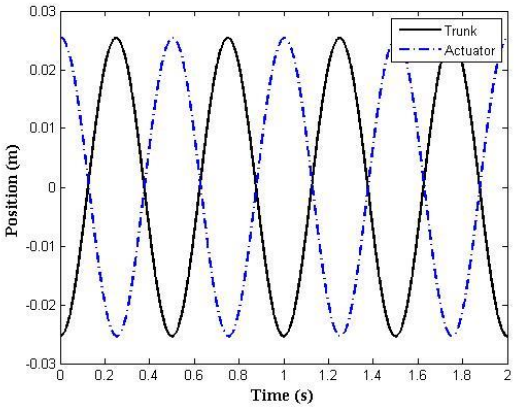
APPENDIX B

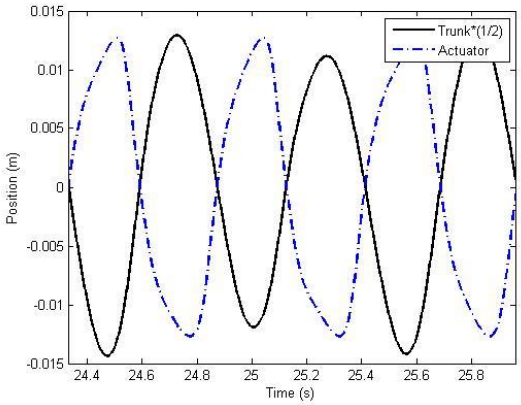
SIMULATED VERSUS ACTUAL CONTROL SIGNALS



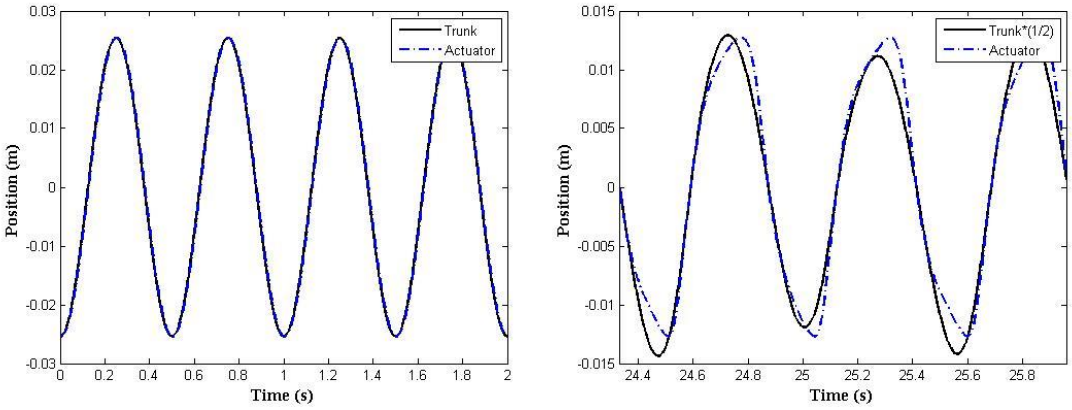


$$x_{pogo} = 0.0254 \sin\left(\phi - \frac{pi}{4}\right).$$

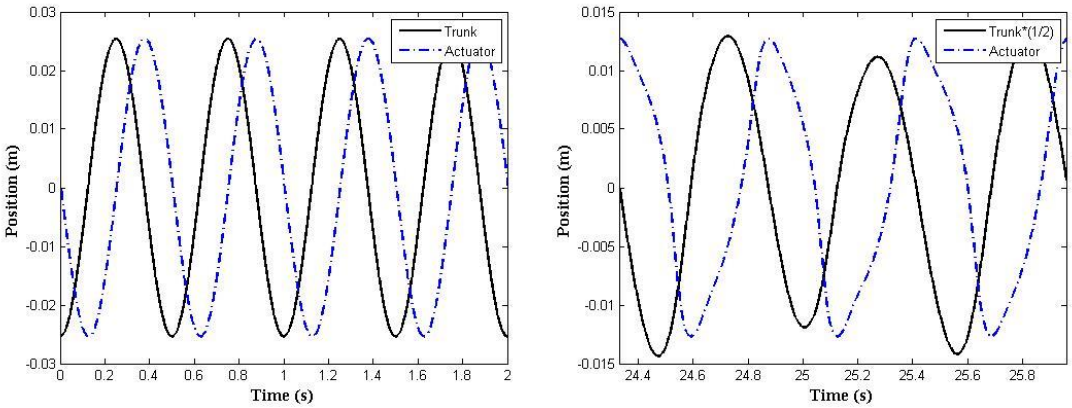




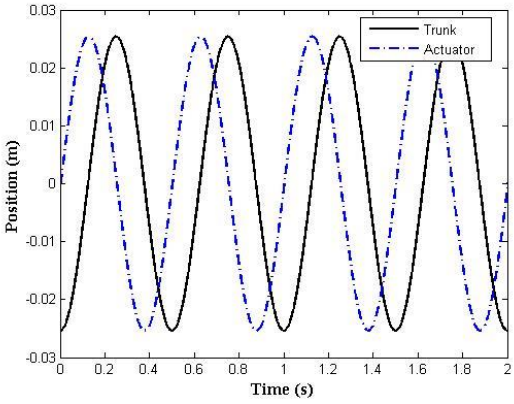
$$x_{pogo} = 0.0254 \cos \phi$$

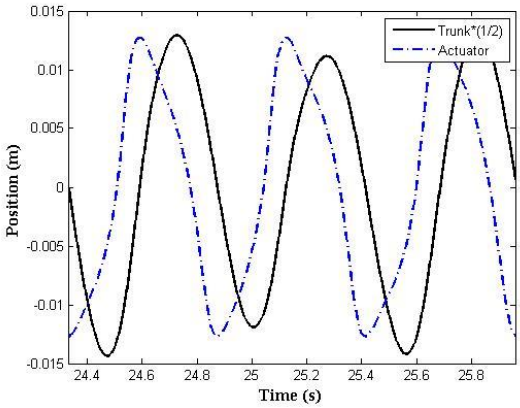


$$x_{pogo} = -0.0254\cos\phi$$



$$x_{pogo} = 0.0254sin\,\phi$$





$$x_{pogo} = -0.0254 sin\,\phi$$