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Load Carrying Assistance Device Pogo Suit

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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. 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 different users, each with their own different and distinct gait. The results of experimental testing validated the corresponding models.

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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 back. 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 like 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.

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. 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 the 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 used a phase oscillator controller and pneumatic actuators to add torque to the user's hips [12]. Rate gyros were placed on the thighs which measured angular velocity which could be integrated to get angle. A phase angle, described in detail in section 3, was used to trigger actuators, which added torque to the user's hips. This device was taken to the Army Research Laboratory where two subjects wore the device. The device 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 effort.

This device is the basis for the mechanical design of the PogoSuit developed in this paper. The researchers have applied 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 PogoSuit 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 were able to extract estimates of the fundamental frequency, amplitude and phase shift from the elbow motion. These were the inputs to a system loop which estimates the elbow's current state and added a corresponding assistive torque (see Figure 1). The results on two subjects showed that the exoskeleton was able to get in phase with the user in approximately 10 cycles [14]. The approach described in this research added 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 as discussed in next section.

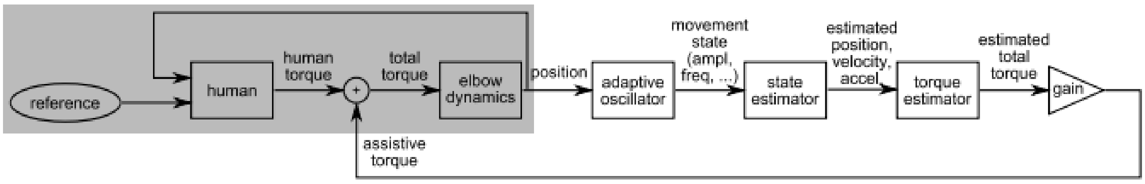

Figure 1. Block diagram of human and exoskeleton system developed by Rinderknecht et al. [14]

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.

$$m\ddot{x} + b\dot{x} + kx = 0 \tag{1}$$

$$x = -A\cos\omega t \tag{2}$$

$$\dot{x} = A\omega\sin\omega t \tag{3}$$

$$\ddot{x} = A\omega^2\cos\omega t \tag{4}$$

The natural 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. The "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 2.

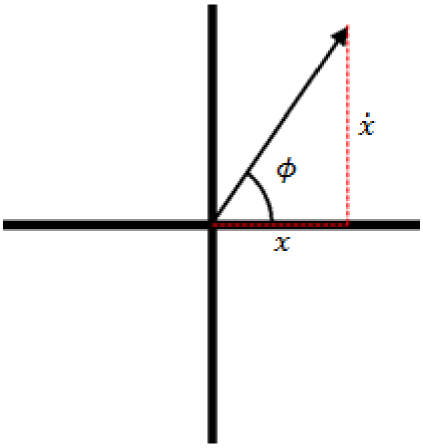

Figure 2. Phase angle is defined as $atan2\ (\dot{x}, x)$

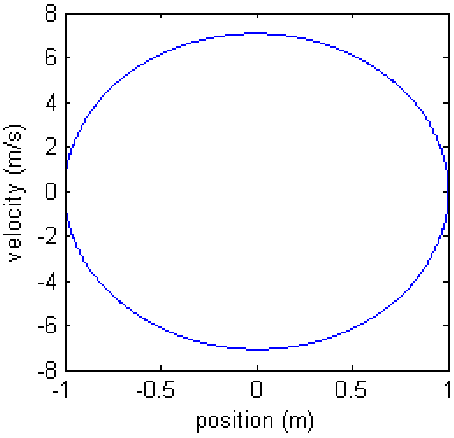

Figure 3. Phase plot of an oscillating system with no damping. $m = 1$ kg, $k = 50$ N/m, $b = 0$ Ns/m, initial position = 1 m, initial velocity = 0 m

The phase angle can be used to determine when to add energy to the system and how much energy to add. Figure 3 shows the phase plot for the case where b = 0, and Figure 4 shows the phase angle over time.

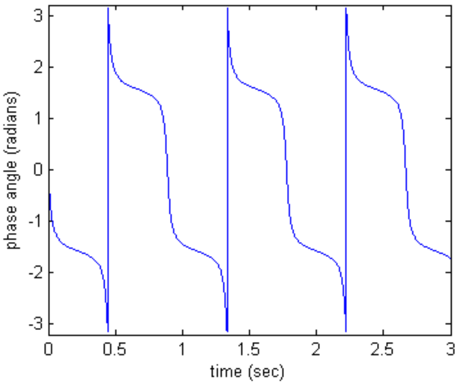

Figure 4. Phase angle of an oscillating system with no damping

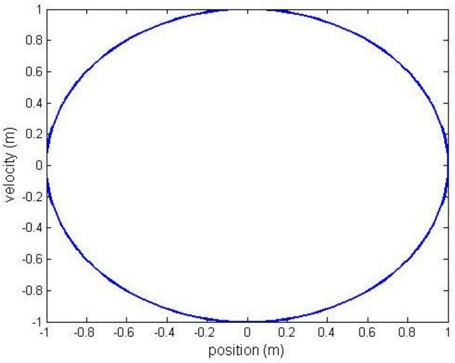

Figure 5. Phase plot of an oscillating system with the velocity divided by the natural frequency

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 5 and 6.

$$\omega = \sqrt{\frac{k}{m}} \tag{5}$$

$$\phi = atan2\left(\frac{\dot{x}}{\omega}, x\right) \tag{6}$$

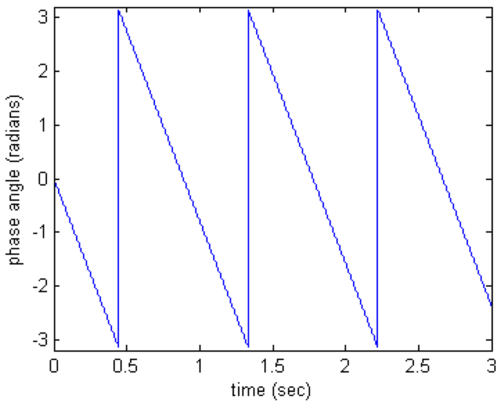

Figure 6. Phase angle when velocity is divided by the natural frequency

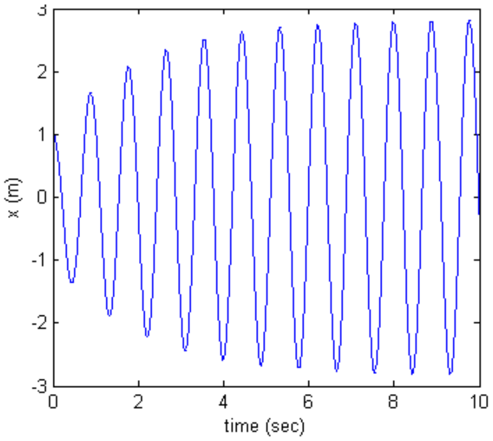

Figure 7. Spring response with phase oscillator. $m = 1$ kg, $b = 1$ Ns/m, $k = 50$ N/m, c = 20, initial position = 1 m, initial velocity = 0 m/s

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.

$$m\ddot{x} + b\dot{x} + kx = c\sin\phi \tag{7}$$

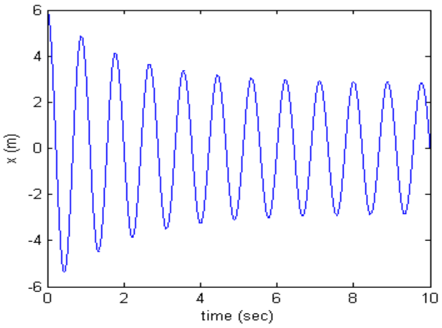

Figure 8. Spring response with phase oscillator. $m = 1$ kg, $b = 1$ Ns/m, $k = 50$ N/m, c = 20, initial position = 6 m, initial velocity = 0 m/s

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 in an actual system. When oscillatory behavior is achieved experimentally, it is highly dependent on initial conditions. Figures 7 and 8 show that using the phase oscillator controller the system will achieve steady state independent of the initial conditions [15]. 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.

$$\sin\phi = \frac{\left(\frac{\dot{x}}{\omega}\right)}{\sqrt{\left(\frac{\dot{x}}{\omega}\right)^2 + x^2}} \tag{8}$$

$$x(t) = A\sin(\omega t) \tag{9}$$

$$A = \frac{c}{b\omega} = \frac{c\sqrt{m}}{b\sqrt{k}} \tag{10}$$

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

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 9 [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.

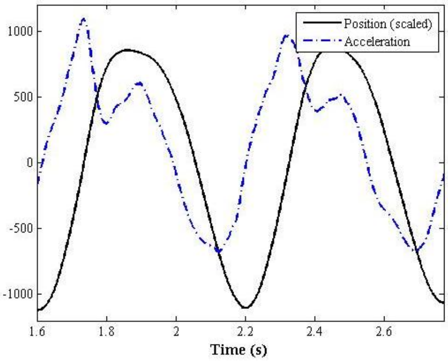

Figure 9. Acceleration and position signal of subject walking on treadmill at 3mph showing that the human's COM position can be assumed to be sinusoidal

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 [16]- [20]. A back pack can be modeled by adding a mass, m_p, pinned to the trunk, as seen in Figure 10. 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.

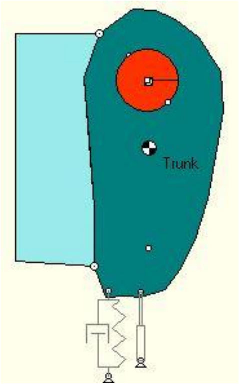

Figure 10. Working Model 2D model of human trunk with a linear actuator to simulate vertical motion

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 that is able 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.

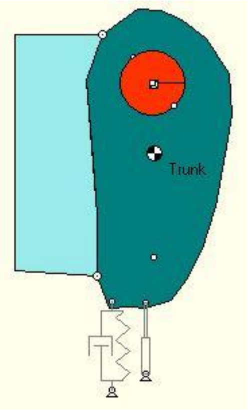

Figure 11. Working Model 2D model of human trunk with a linear actuator to simulate vertical motion and an added force

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 11. Figure 12 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.

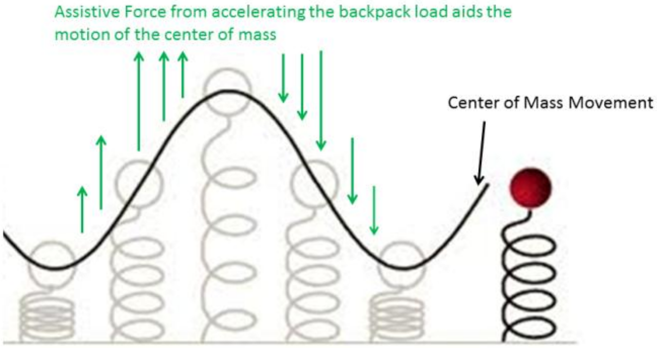

Figure 12. The forcing function based on the sine of the phase angle pushes up as the COM moves up and pushes down as the COM moves down

To validate the theory, a force based on the phase angle, $f = 100 sin\phi$, 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 13. We can see that the positive power peak is reduced but the negative power peaks are increased. The past 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.

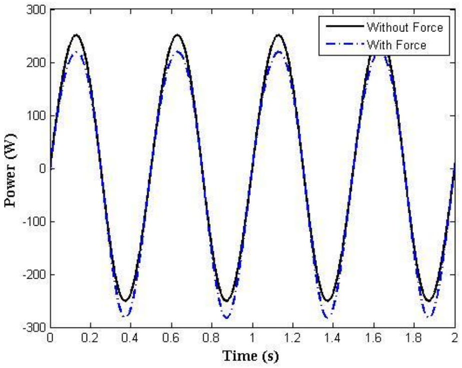

Figure 13. Positive power peaks required to oscillate the human are reduced and negative power peaks are increased

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 14.

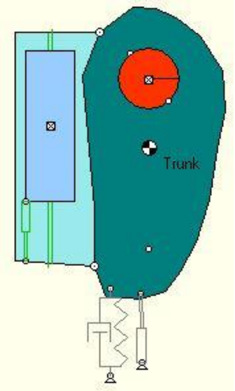

Figure 14. Working Model 2D model of human trunk with pogo suit actuator modeled in the backpack as a secondary mass on a linear actuator

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.

$$f = f_o \sin\phi \tag{11}$$

$$m_{load}\left(\ddot{x}_h + \ddot{x}_{pogo}\right) = -f_o \sin\phi \tag{12}$$

$$\ddot{x}_{pogo} = \frac{-f_o}{m_{load}} sin\phi - \ddot{x}_h \tag{13}$$

$$\ddot{x}_{pogo} = \frac{-f_o}{m_{load}} sin\phi - A\omega^2 \cos\omega t \tag{14}$$

$$x_{pogo} = \frac{f_o}{\dot{\phi}^2 m_{load}} sin\phi + A\cos\omega t \tag{15}$$

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 5.6 – 5.8. 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 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 $-cos\phi$.

$$\sqrt{\left(\frac{\dot{x}}{\omega}\right)^2 + x^2} = \sqrt{A^2(\cos(\omega t))^2 + A^2(\sin(\omega t))^2} = A \tag{16}$$

$$cos\phi = \frac{x_h}{\sqrt{\left(\frac{\dot{x}_h}{\omega}\right)^2 + x_h^2}} = \frac{x_h}{A} = -\frac{Acos\omega t}{A} = -cos\omega t \tag{17}$$

$$\sin\phi = \frac{\frac{\dot{x}_h}{\omega}}{\sqrt{\left(\frac{\dot{x}_h}{\omega}\right)^2 + x_h^2}} = \frac{A\sin(\omega t)}{A} = \sin(\omega t) \tag{18}$$

Table 1. Each definition for the position of the COM results in the human acceleration term being equivalent to $-cos\phi$

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

Thus, 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 5.9 – 5.14. This shows that the amplitude of the force is changed by simply changing the amplitude of the secondary mass' position function.

$$x_{pogo} = \frac{f_o}{\dot{\phi}^2 m_{load}} sin\phi - A\cos\phi \tag{19}$$

$$let\ a = \frac{f_o}{\dot{\phi}^2 m_{load}}\ and\ b = A \tag{20}$$

$$asin\phi - bcos\phi \equiv Rcos\alpha sin\phi - Rsin\alpha cos\phi \equiv Rsin(\phi - \alpha) \tag{21}$$

$$tan\alpha = \frac{b}{a} \therefore \alpha = \mathrm{atan2(b, a)} \tag{22}$$

$$R = \sqrt{a^2 + b^2} \tag{23}$$

$$x_{pogo} = Rsin(\phi - \alpha) \tag{24}$$

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 15 and 16 show the simulated position of the trunk and actuator and the actuator position for $x_{pogo} = 0.0254\sin\left(\phi - \frac{pi}{4}\right)$.

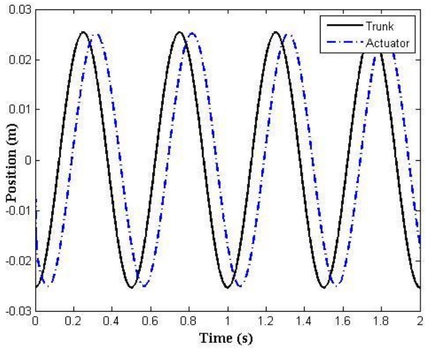

Figure 15. Working Model 2D simulation of the trunk and pogo actuator position for the derived position found in eq. 5.11

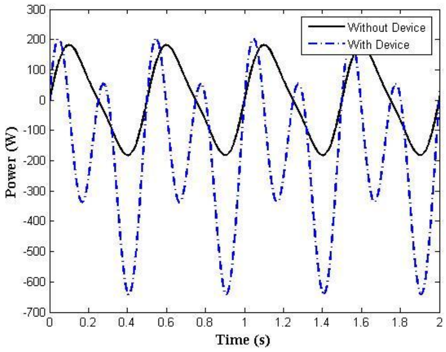

Figure 16. Simulated powers required to oscillate trunk with and without pogo suit device

Once the Working Model 2D model was created and being driven by MATLAB, it was simple to try other potential control methods. Figures 17 and 18 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.

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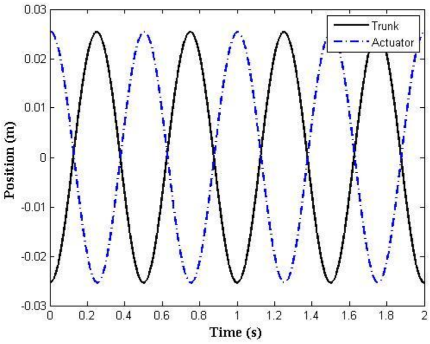


Figure 17. Working Model 2D simulation of the trunk and pogo actuator position for $x_{pogo} = cos\phi$

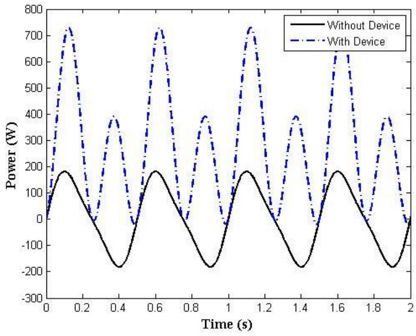


Figure 18. Simulated powers for $x_{pogo} = cos\phi$

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.

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. The Bode plot of a pseudo integration is shown in Figure 19.

$$Single\ Integrator \Rightarrow \frac{s}{(s+\tau)} \tag{25}$$

$$Double\ Integrator \Rightarrow \frac{s}{(s+\tau)^3} \tag{26}$$

Dr. Matthew Holgate used 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 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.*" [21]

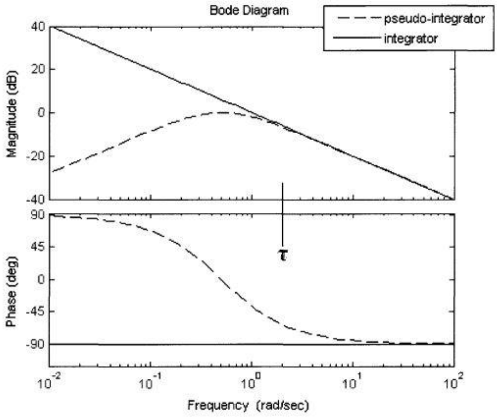


Figure 19. Bode plots for pseudo-integrator transfer function and integrator [21]

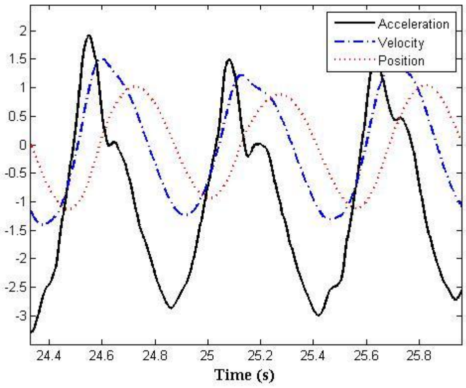


Figure 20. Human acceleration, velocity and position signals used to control the pogo suit

With position and velocity signals that center around zero, a phase plane can be developed and a phase angle extracted. Figures 20 - 22 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.

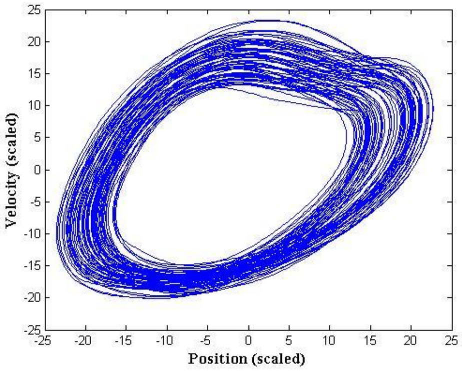


Figure 21. Phase plane of subject walking on a

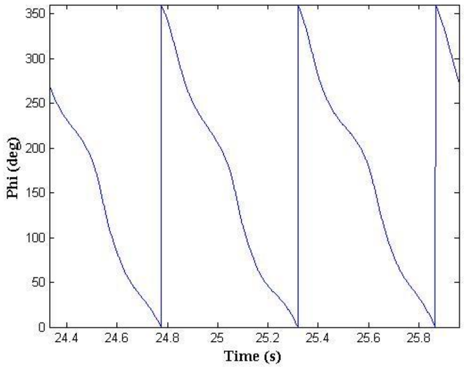


Figure 22. Phi versus time for a human subject

treadmill at 3mph walking at 3mph

The actual device (as shown in Figure 23) 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.

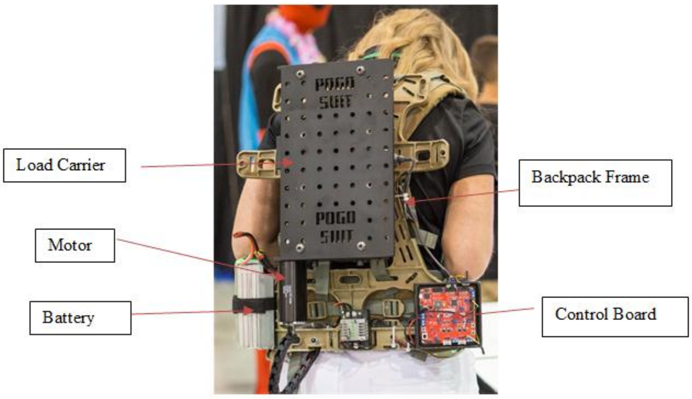


Figure 23. Pogo Suit physical devices

Figure 24 shows the derived and simulated control position of $x_{pogo} = 0.0254\sin\left(\phi\text{-}\frac{\pi}{4}\right)$. 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.

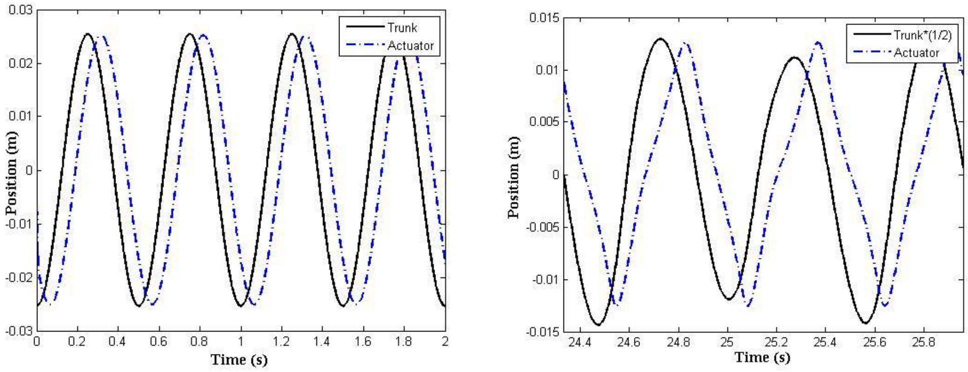


Figure 24. Simulated(left) versus actual (right) human and pogo suit position for

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

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.

7. RESULTS AND CONCLUSION

The testing was performed at ASU polytechnic HMI lab. 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 provided 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 commenced 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.

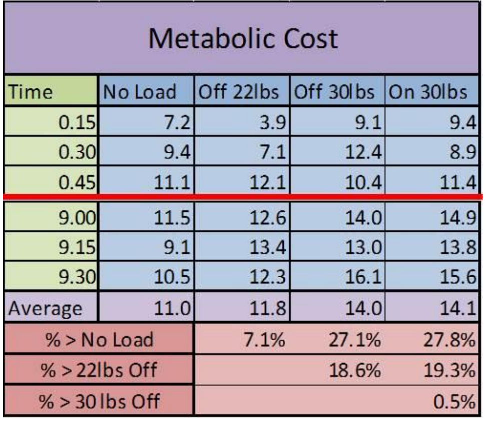
- Test subjects first walked 800 meters at 3mph with the device turned off with a 22lb payload (to account for the weight of the device) and then were allowed to rest 10-30 minutes depending on subject's stamina.
- Test subjects then walked 800 meters at 3mph with the device turned on with a 30lb payload 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 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.

- 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 being monitored for their heart rate via a wireless Bluetooth heart rate wrist watch. The average metabolic cost (VO2) results from the test shown in Table 2.

Table 2. Metabolic results for one subject with no load, 22 lbs, 30 lbs and 30 lbs oscillating based on the phase angle



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%

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. In this testing the phase delay was set to be zero.

In order to study the effect of phase delay another experiment was performed. In this test subject was asked to walk on the treadmill at 3 miles/hr for 10 mins with device on and device off and a phase delay was added and metabolic data was recorded. In between device on and off 20 mins. Break was provided.

Table 3. Effect of phase shift.

Case	VO2 Pogo Suit Off	VO2 Pogo Suit On	Phase Delay
1	15.34	15.12	110 Deg. Phase Shift
2	15.34	15.07	170 Deg Phase Shift

It can be seen from Table 3, that for by adding phase shift to the phase oscillator aprroximately 1.5% of improvement was achieved. It was also noted that by increasing phase shift beyond 180 Deg. The metabolic cost actually increased. At more than 180 Deg phase shift, the pogosuit was out of walking phase and actually exerting load on the human.

Thus, some metabolic augementation cab is expected by pumping energy in the walking gait. The phase oscillator approach is an adaptive oscillator that can tune itself to walking frequency. However, in real life there could be group delay, controller lag, friction and inertia effects in transmission that may decrease the net energy pumped in the walking cycle. One can add a phase delay to phse oscillator controller to compensate for unmodelled dynamics. Currenlty, the researchers are working on improving the pumping efficiency of the pogosuit and tuning the adaptive oscillators for improved performance.

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Chase Wheeler complted his MS at Arizona State University working in Human Machine Integration Lab. His research interests are robotics, dynamics and control

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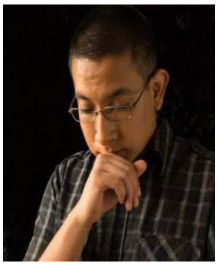

Eddie concentrates on the design and build of all our projects. Known for working long hours well into the early morning his marathon style of work leads to quick, high quality results. This allows us to run through many revisions before committing to a final design. Eddie has his Mechanical Engineering degree. He is now working on his Master Degree in the same field. He is a full time research technician for the HMI Lab.

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