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Controls for an Exoskeletal Hip Actuator

[1]William Watson and [2]Michael Kushnak
[1]Department of Electrical Engineering and Computer Science
[2]Department of Civil and Mechanical Engineering
United States Military Academy
West Point, New York 10997 USA

Faculty Advisor: Dr. John Rogers

Abstract

In an effort to improve a soldier’s ability to move over difficult terrain at higher speeds with minimal fatigue and ensure that he/she arrives at his/her destination ready to fight, this project has developed a hip actuating exoskeleton prototype. In the future, the system could be used for running rehabilitation purposes. Attached to the user’s anterior legs and waist, this single degree of actuation system will apply torque at the hip joint to assist runners over long distances. In order to have this system work seamlessly with the runner, a large emphasis has been placed on the research and development of an adaptive control systems based on feedback from the runner’s gait collected from sensors on the system.

Keywords: Controls, Exoskeleton, Running, Human Augmentation

1. Introduction

In today’s combat zones, soldiers are required to move through harsh terrain such as mountains, sand and swamps in a short amount of time and are expected to arrive ready to fight. Unfortunately, simply moving to an objective can be exhausting and the fatigue that results can reduce a soldier’s awareness and ability to accomplish the mission. In an effort to mitigate these issues, this project is working to improve running endurance so soldiers may maintain higher running speeds for longer. To solve this problem, the team is working to create a hip actuating exoskeleton to assist the runner and reduce metabolic rates to allow a sprinting speed to be maintained for longer. An important aspect of this solution is to create an algorithm to control the timing of torque applied by the motor using the runner’s gait as a feedback mechanism. The problem space this project involves is human augmentation and, more specifically, running assistance. The solution required can be broken down into the aspects of mechanics, power, and control. The purpose of this project is to provide soldiers with greater running endurance so they may maintain higher speeds for longer, therefore improving mobility and range.

The concept of the control solution for a hip actuating exoskeleton is to first gather data about the human running gait using an angular rate gyroscopic sensor (”gyro”). With this data and the patterns it reveals, we hope to create a “map” of a walking and running gait which, when implemented in a control solution, would allow for seamless interaction between the human and exoskeleton. The feedback mechanism is using input from the same gyro sensor to determine the point at which the individual is in their gait. From here, proper inputs can be used to amplify movements throughout the gait cycle, therefore increasing rate and decreasing metabolic requirements.

The goal for this project was to gather and analyze data from a gyroscopic sensor for an individual running at various speeds to map an individual’s gait cycle and develop a look-up table or implementation for a control algorithm. In order to be successful, certain identified individual tasks needed to be accomplished: (1) conduct benchtop testing of our gyroscopic sensor, (2) conduct running tests with the gyroscopic sensor to gather and analyze hip angular rate data, (3) research and implement various analysis techniques on data to map gait and (4) create a look-up table from data for use in a control algorithm. Thus far, the team has created a working prototype and, with this research, will be able to implement an adaptive control system in the near future.

2. Controls Research

2.1. Background Research

There has been much prior research done on adaptive control systems for human augmentation. The inspiration for the closed-loop approach to solving the problem presented comes from a tibia controller for a prosthetic leg created by Matthew Holgate, Thomas Sugar and Alexander Bohler at the Human Machine Integration Laboratory at Arizona State University.[1] In their work, they mapped an individual's gait while they moved, allowing for adaptations to movement and seamless interaction with the user. In order to accomplish this task, they took angle data of the person's tibia as they walked and produced a look-up table of a percent gait equivalent. This look-up table was then used to reduce torque error to zero so the wearer would feel the benefits of the motion without fighting the prosthetic.[2] The calculations required are as follows:

1) Take angle data compared to percentage of gait (time interval).
2) Take derivative of angle, giving velocity. Plot these values against each other in a polar plot.
3) Measure the polar angle between the x-axis and the plotted point (ϕ) using an inverse tangent function as seen in equation 1.

$$\phi = tan^{-1}\left(\frac{velocity}{angle}\right) \qquad (1)$$

4) Using polar angle, determine progress through gait to know where the leg should be. The resulting graphs are seen in figure 1.

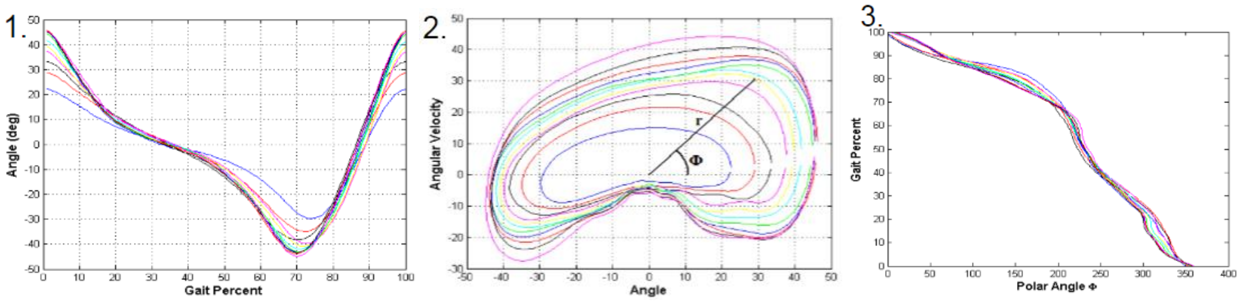

Figure 1: Calculations done with ASU control system.[3]

2.2. Simulation Data

In order to prove the validity of applying the ASU research to a femur at a run rather than to a tibia at a walk, OpenSim software was utilized to simulate a running motion and gather simulated sensory data. The result was similar data using the same calculations, as well as a plot of the ground reaction forces experienced by the foot as it strikes which can be used as a detectable peak point. The plots of this data are seen in figure 2.

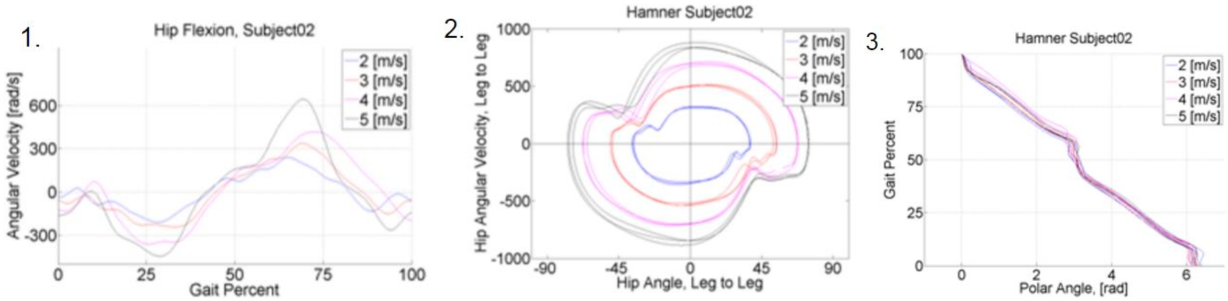

Figure 2: Simulated running data from OpenSim.

3. System Prototype

3.1. Hardware

The capstone team has developed a prototype wearable hip actuating exoskeleton. It is a single powered degree of freedom system with a single actuator (DC motor) attached at the waist by a belt with two rigid poles serving to assist leg movement.

The input to the system comes from three sensors, the first of which is a gyroscopic sensor. The sensor reads angular rate of the leg about a mediolateral axis, and this information can be used to map the runner's gait as positive and negative velocity. The system also uses a strain gauge on the poles to measure the torqueing forces between the pole and runner, therefore indicating a shift in movement. When there is more torque, the system is designed to move in order to reduce the strain read by the gauge, and therefore the net torque, to zero so the runner and exoskeleton are not fighting each other. The system's microcontroller is capable of sampling the gauges at 800 Hz. Based on initial gait analysis, a typical gait cycle has a period of between 0.68 and 0.78 seconds, which allows for between 544 and 624 samples per gait cycle. The sample rate will allow for smooth interfacing between the system and the user. Finally, a Hall Effect sensor mounted on the motor joint allows us to measure the angular position of the femur to the hip. This is information that can be used as feedback through the control system as well as provides a reliable data point that can be used to reduce drift of the gyroscopic data. All of this sensor data is read multiple times per stride by a microcontroller, which then computes the error through the control loop and outputs a signal to the motor.

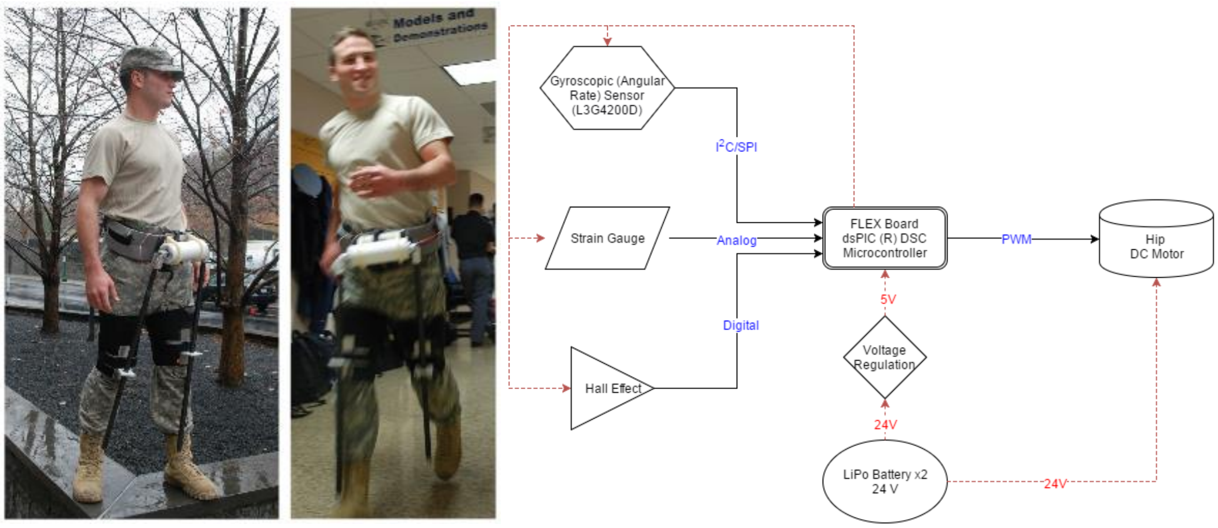

Figure 3: Prototype system as worn (left) and a hardware block diagram (right).

3.2. Software

The software for the system will be an adaptive control feedback loop that compares input from all sensors and filters them through an Extended Kalman Filter (EKF). Currently, each sensor is being independently tested to ensure proper function prior to integrating it. A concept for the control system using only the gyroscope and strain gauges to reduce torque error can be seen in figure 4. Angular velocity data from the gyroscopic sensor is integrated and the polar angle between position and velocity is determined using an arc tangent function. This polar angle is sent to a look-up table to find the percent gait equivalent, which is used in another look-up table to find what torque should be applied to the hip. This torque is compared to torque actually read from the strain gauges and the resulting error is amplified and passed as a pulse width modulation (PWM) signal to the motor dictation torque and direction.

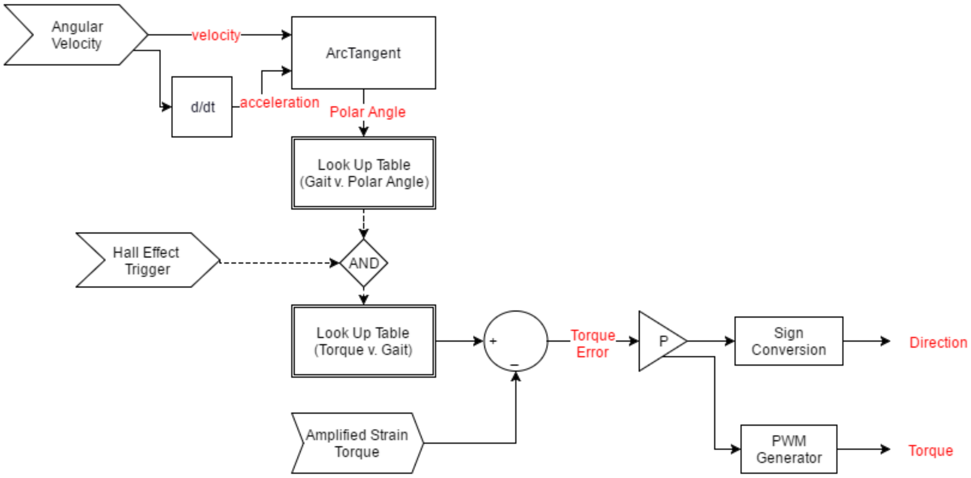

Figure 4: Explorer16 board used in testing (top) and software block diagram (bottom).

4. Gait Capture

4.1. Equipment Used

In order to gather angular rate data of an individual running the capture and analysis program was loaded onto a Microchip Explorer 16, a simple development board with the ability to swap the microcontroller via plug-in modules (PIM). In this test, we used a dsPIC 33FJ256GP710 microcontroller PIM. The gyroscopic sensor used is the L3G4200D on a SparkFun shield. This sensor is a MEMS three-axis gyroscope and is connected to the board through a 6-pin cable and header. In this test, we are only using one axis of the gyroscope. The board is connected to the computer for information storage in MATLAB via a VGA to micro USB converter using a UART protocol. The board and sensor setup can be seen in figure 5.

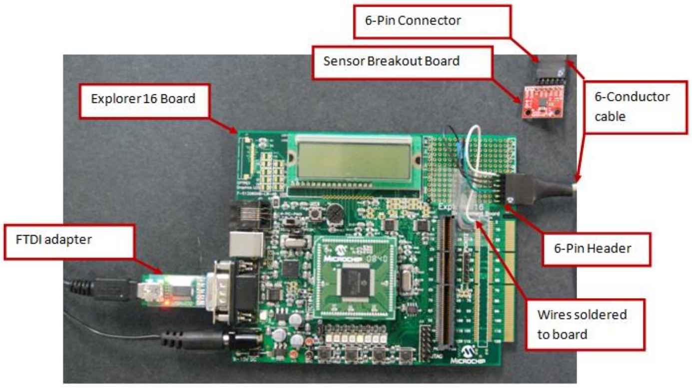

Figure 5: Board and sensor setup: Microchip Explorer 16 and L3G4200D.[4]

4.2. Benchtop Validation

In order to ensure the gyroscope worked as expected, we first conducted a benchtop test using a metal ruler as a free moving arm. Setting up the system as we would on an individual, we moved the ruler in a periodic motion to simulate running. With the gyroscopic sensor moving, we created a live plot of both the velocity and acceleration (figure 6). From here, we could clearly see the phase difference between velocity and acceleration, which we plotted as a polar plot. We were also able to break down the gait cycle into a percentage complete relative to time.

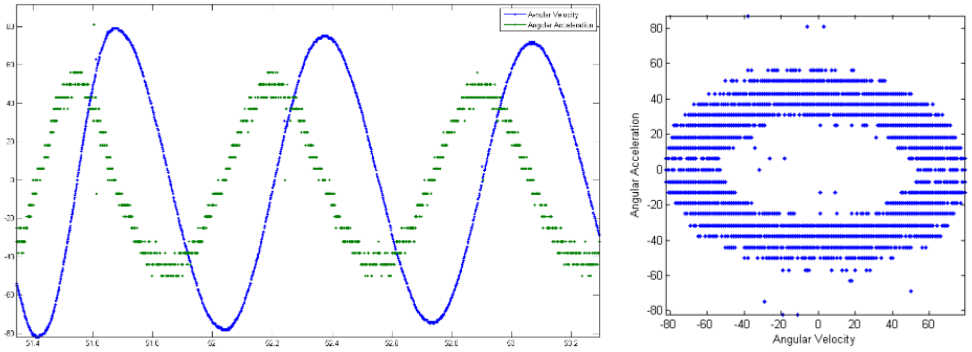

Figure 6: (a) Phase difference between velocity (blue) and acceleration (green). (b) Polar plot of acceleration v. velocity.

In addition to conducting a benchtop test of the gyroscope, we also put together similar tests for the leg rod strain gauges. Initial benchtop testing of the carbon fiber leg rods with strain gauges affixed yielded a linear relationship between the load placed on the rod and the strain readout from the gauges. This will allow for a simple relationship between the load applied, the strain experienced by the strain gauges, and the torque the motor should output in order to bring the system back to equilibrium.

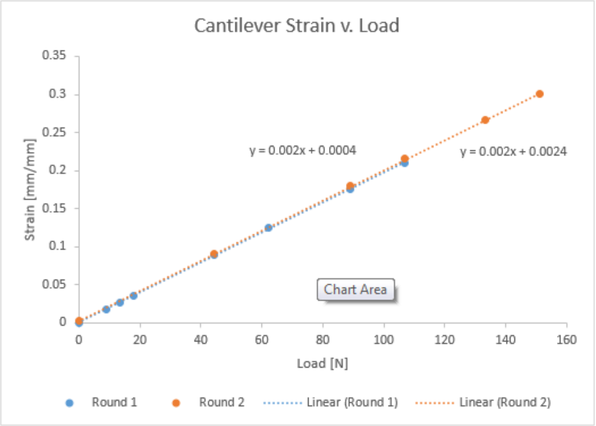

Figure 7: Results from benchtop testing of the strain gauges.

4.3. Testing Setup And Procedure

Using the above board and sensor assembly, we gathered data at running speeds of 2 m/s, 3 m/s, 4 m/s, and 5 m/s. In order to do so, our test subject ran in Army Combat Uniform (with no blouse) on a platform treadmill with accurate speed control. The gyroscopic sensor was strapped with a Velcro leg strap to the outside of the runner's left leg, oriented so the positive z-axis was pointed to the runner's right and normal to the sagittal plane (plane of movement). The six pin cable extended from the sensor to the board and computer, which were placed next to the treadmill, and the cable allowed enough slack to run without disturbing the board or computer.

At the beginning of the test, the runner was placed on the treadmill with the sensor strapped to the left leg. The treadmill was then gradually accelerated until it reached the desired running speed. After settling into the running speed, the recorder began data capture from the sensor in MATLAB for approximately 10-15 seconds of recording. Upon completion, the data capture would be stopped and the runner would slow to a halt.

4.4. Results And Analysis

The gyroscope used outputs data as angular rate in degrees per second and has a sensitivity of about 70 mdps/digit when collecting data at 800 Hz. Once the matrix data had been created, we graphed it by angular velocity on the y-axis and time on the x-axis (see figure 8). It is very apparent that there is a clear pattern of velocity throughout the running gait. If we look particularly at 2 m/s compared to 4 m/s, we can see some consistent patterns and differences. There are several peaks which represent a change in direction of movement, such as the foot strike or resetting of the leg for the next stride. The signal is very consistent and predictable, which will be essential for the creation of an effective control unit and real-time analysis of an individual's stride. Also very important is the comparison of the various speeds to each other. While the amplitude of the signal increases by about 100% as running speed increases to twice as fast, the pattern remains essentially the same. For the creation of a control unit, this will be very useful as it will decrease the complexity of changing speeds. Furthermore, the time period decreases by 20% as running speed doubles. Using these cues, we can begin to identify the differences in running speed and adjust the motor output as necessary.

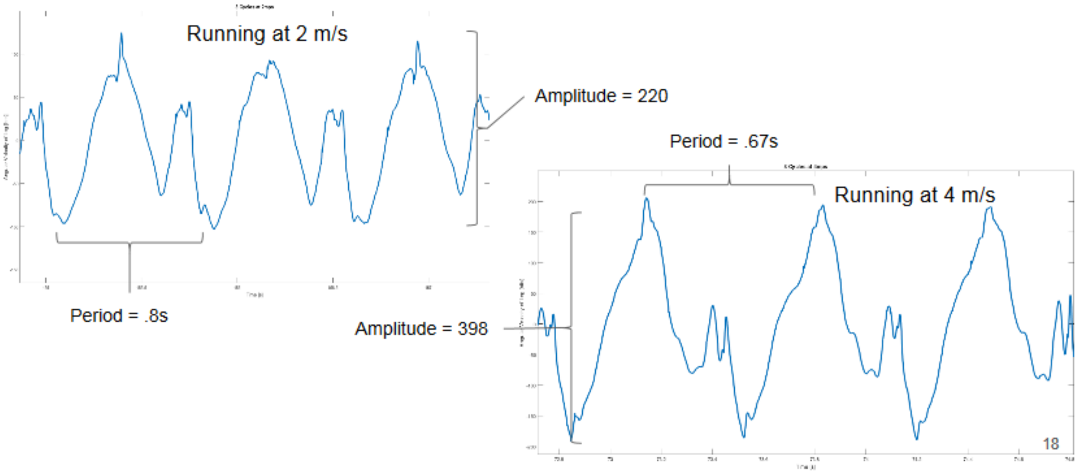

Figure 8: Running at 2 m/s compared to running at 4 m/s.

Furthermore, comparing these actual results to simulated results for the averages of all cycles at various speeds (as seen in figure 9), it becomes apparent that our results were very accurate to simulation. This data is very promising as it shows that although individuals may run differently, there is a consistent pattern that the system should be able to easily adapt to. Most importantly, this validates using the gyroscopic sensor as a data collection method and proves that one algorithm can be used for many runners due to the consistency in gait pattern.

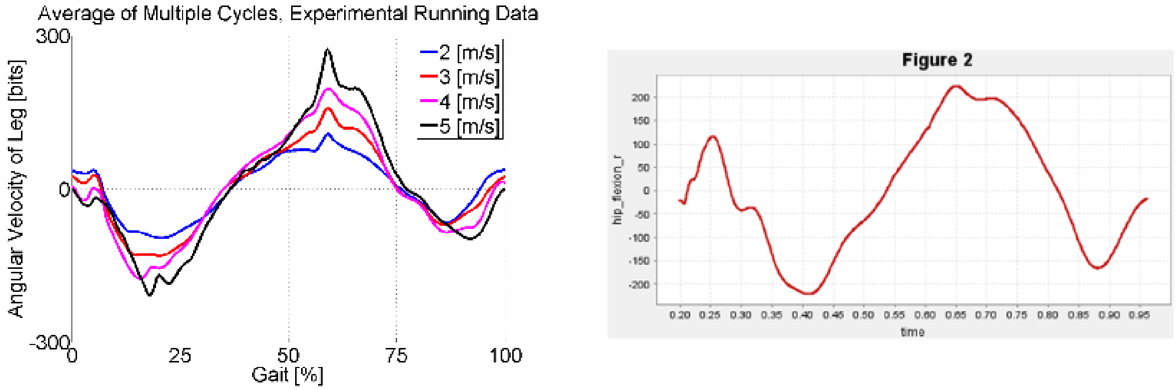

Figure 9: Averages of actual angular velocity data at various speeds (left) compared to simulation (right).

5. Current and Future Implementation

5.1. Velocity Analysis Of Running Gait

Before creating a thorough solution in the form of an adaptive control system that would learn from the runner's gait and apply torque at precise increments, it was necessary to look at various aspects of running and sensors that could inform the system of what exactly is happening during the stride. The gyroscopic sensor was measuring the angular rate of the leg during a stride, which provided much insight into how the leg moves through its full range of motion. Taking a closer look at this data, the different parts of the stride can be broken down, as seen in figure 10, to help truly understand the velocity mechanics of running.

Based on the orientation with which the gyroscope was placed on the runner, positive velocity is based on the right hand rule about the horizontal axis to the right (i.e. clockwise if viewed from a position left of the runner). Therefore, it is logical that the hip extension phase, where the leg pulls or ”curls” back with the foot on the ground to propel the body forward, has a negative velocity opposite the body's movement. From here, there is a smooth transition into the flexion phase since the foot is off the ground and slows to a stop, which is where the zero crossing is located, then accelerates forward to recover the leg in front of the body. Finally, this is followed by a planting of the foot, or impact, and the stride restarts.

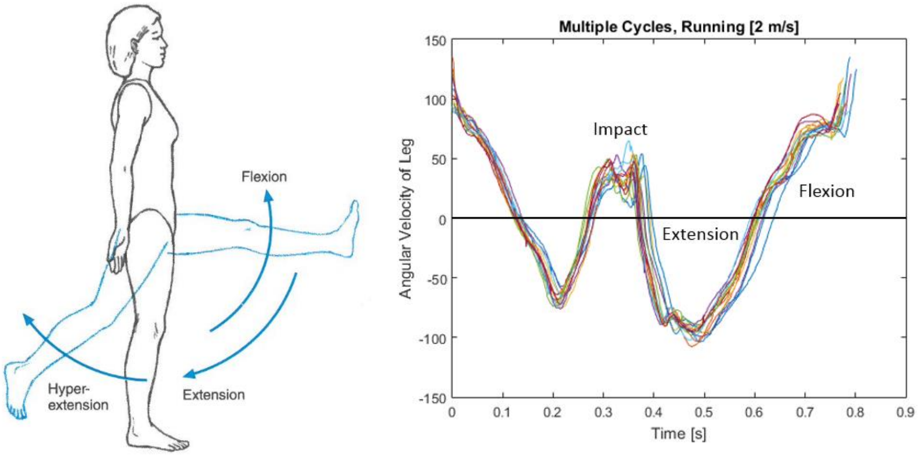

Figure 10: Leg extension v. flexion mapped at 2 m/s.[5]

5.2. Temporary Frequency Based Open-Loop Solution

In order to begin testing the validity of the exoskeleton's design and see its effect on an actual runner, the decision was made to implement an open-loop control system that could be manually controlled by the operator, similar to the cruise control on a car. Using a potentiometer as a simple control, the user could select a frequency from a range that would alter the period of the input signal to the motor. This profile consisted of two torque pulses, one positive and one negative, separated by pauses to help with flexion and extension while allowing the user to "free-wheel" in between. The frequency range required was determined using the time period of each stride from 2 m/s up to 5 m/s running speeds with some margin on either end. At the slower speeds, each stride was approximately 0.78 seconds, while at the higher speeds each was approximately 0.62 seconds. Using the conversion from period to frequency, the range of frequencies is calculated as seen in equation 2.

$$Frequency\ [Hz] = \frac{1}{Period\ [s]}$$

$$High\ Frequency = \frac{1}{0.62s} = 1.61\ Hz$$

$$Low\ Frequency = \frac{1}{0.78\ s} = 1.28\ Hz \qquad (2)$$

Based on these frequencies, the runner was able to adjust to the speed at which he was moving, however work continued towards a solution in which the runner did not have to choose, but instead where the system adjusted to his or her movement.

5.3. Velocity And Position Based Closed-Loop Solution

The challenge of creating an adaptive control system arises from the very complicated running signal. Rather than a clean, sinusoidal wave, running seems to be very sporadic and is very inconsistent from stride to stride and from person to person. To combat this, one must be able to simplify the signal into parts and create a pattern. This becomes very complicated given the shear noisiness of the impact as well as multiple peaks and valleys which a system must be able to sift through and decide what data will provide proper timing. The simplest method of timing for a stride is to look at the change in velocity, particularly at the x-intercepts or zero crossings.

As the leg reaches the extremes of its range of motion, its velocity slows to zero then changes from positive to negative or vice versa. For the transition from extension to flexion, in which the leg seamlessly changes direction while in the air, this is very simple; just look for where the x-intercept is where there is a positive slope. This becomes more difficult, however, when the extension and heel strike are also considered due to multiple zero crossings before flexion occurs again. Because of this, another method of data capture is required as reference to ensure the motor is activated at the correct time.

5.3.1. hall effect and gyroscope in sync

At first, the system was developed to integrate velocity in real time in an attempt to recreate Holgate's results from actual running data. While this gave a position vector to compare to velocity, it itself had no hard reference as to what was a neutral position, which resulted in drift that created compounding error. To solve this issue, a button push was implemented that would reset the integration to zero. In order for the device to activate this automatically, a Hall Effect sensor seemed it would be the most effective as it would give a hard point of data with minimal alteration of the prototype.

A Hall Effect sensor is a solid state device which detects magnetic fields, or more particularly the magnetic flux density within that field. With the southern polarity end of a magnet behind the sensor, a large enough disturbance or change to the flux density will be detected by the sensor which will then produce an output voltage, or Hall Voltage. This disturbance can be caused by any conducting metal passing close enough within the field. Therefore, the Hall Effect sensor is ideal as it requires very little setup, does not wear, and is easy to replace or fix if damaged.[6]

The Hall Effect sensor was first tested by simply reading a digital HI or LO and turning on and off an LED on an Arduino Uno. Once this was proven to work, the device was implemented into the Simulink software to ensure its compatibility with the Explorer16 board.

5.3.2. closed-loop algorithm

The proposed algorithm to accomplish the task of applying torque at the proper moment in the runner's gait requires the use of the gyroscope and Hall Effect sensors in conjunction. With the Hall Effect sensor placed at a neutral position with the runner's legs parallel, which will be the reference at 0◦ , it will trigger twice a stride at that known point (see figure 11. Combining this known point with the velocity data coming from the gyroscope, particularly whether or not the velocity is positive (flexion) or negative (extension), the system can determine when to add torque. To do so, the Hall Effect sensor acts as a trigger for a latch which will store the current velocity value. When velocity reaches zero, the system will look to see if the stored velocity was positive or negative; if it was negative, torque will be applied to assist the runner with flexion. This algorithm can be seen in figure 11, and the steps include:

1) The Hall Effect sensor acts as a SET/RST trigger for a latch.
2) When the Hall Effect triggers at 0° (neutral position), a Boolean variable is stored based on the current velocity:
   a) If velocity is negative (extension), variable is TRUE.
   b) If velocity is positive (flexion), variable is FALSE.
3) When velocity is zero (x-intercept), if the Boolean variable was TRUE, then the system will apply torque. Otherwise the system will free-wheel.

Because this algorithm is relatively simple and robust, it not only can apply torque at the proper timing, but the system can easily and rapidly adjust to changes in speed or gait pattern. Furthermore, due to the reactionary force of the motor, the benefits when activated can be felt by both legs.

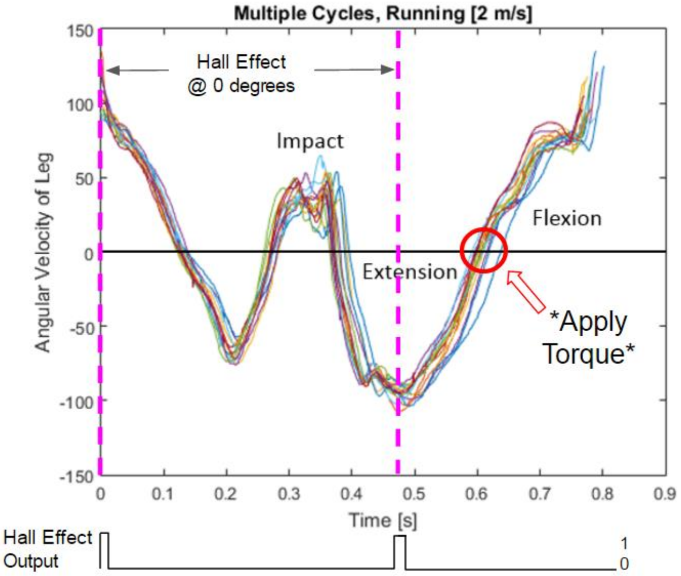

Figure 11: Hall Effect and gyroscope algorithm.

6. Results and Discussion

To validate the prototype for feasibility as well as assess the benefits to the runner, the open-loop, adjustable frequency circuit was placed on a runner for testing outdoors. After initial validation runs to ensure no discomfort to the runner and safe operations, a metabolic rate sensor, which simply measures the volume of oxygen (VO2) consumed while running, provided an objective metric for the quantity of metabolic rate reduction. In the initial testing phase, three tests were conducted: one on gentle, rolling hills, one on a steep incline, and one on flat ground. Each test consisted of two iterations: one running with the system and one running without the system. The same test subject was used for each test so a clear improvement or degradation could be seen, in which an improvement is defined as a lower VO2 consumption and therefore increased efficiency (less energy expenditure for the same amount of work). Results from the three tests are inconclusive as to the benefits of the open-loop prototype. The testing showed slight improvement to VO2 consumption (between 2% and 5%) on the rolling hills, slight degradation over flat ground (about 8%) and a greatly increased degradation when running up or down a slope (about 30%). The degradation seen is due to a variety of factors from the weight of the system to how it fits on the body, as well as the system not being perfectly in sync with the runner. The ergonomics of the system can be greatly improved by utilizing a more rigid belt that allows the reactionary forces to be more efficiently transferred to the hips and pelvis. The current, open-loop system caused a number of issues as well. The variable frequency, while allowing the runner to manually select a speed, does not consider the period of the runner’s stride after it applies torque. Therefore, since the torque application is constant, the runner will occasionally feel as if he or she is working against the system to back-drive the motor. The implementation of a closed-loop control system with torque feedback will fix this issue in the future and will hopefully yield more benefits over longer periods of running.

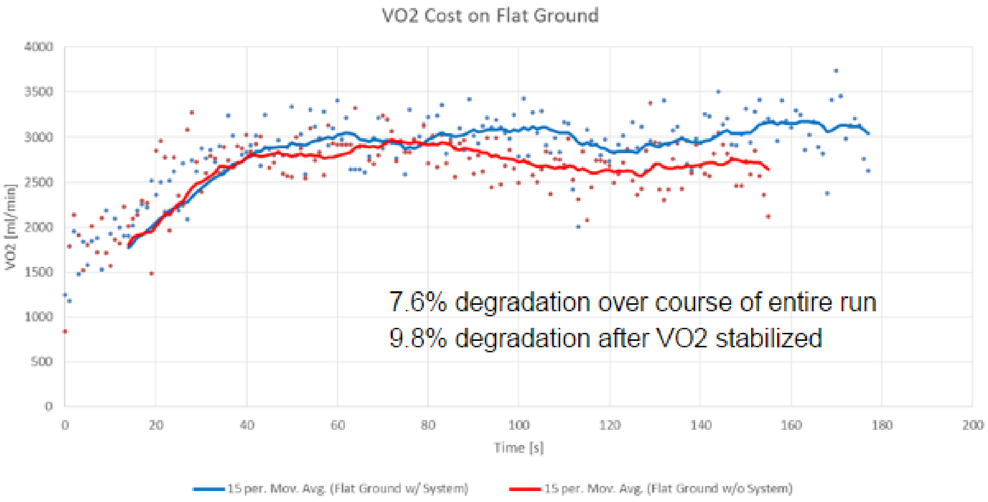

Figure 12: Comparison of running with (blue) and without (red) system over flat ground.

7. Conclusions

Human augmentation has become a priority of research due to its applications for improving soldiers' abilities in combat as well as many other potential uses such as rehabilitation. In an effort to improve a soldier's ability to move over difficult terrain at higher speeds with minimal fatigue to ensure he/she arrives to his/her destination ready to fight, this hip actuating exoskeleton hopes to reduce metabolic rates while running in a small, easy to put on and take off package. The testing has begun on the initial prototype controlled by an open-loop frequency control, and although our results thus far are not ideal, an improved closed-loop control system will improve the integration of the runner with the system. As many research teams work to make human augmentation with exoskeletons practical, this research will hopefully guide others in their efforts towards improving human abilities. This solution is one of many, and there is still much work to be done in the realm of human augmentation.

8. Acknowledgements

The authors would like to acknowledge the Hip Actuator Capstone Group, consisting of CDTs John Bellet, Katie Holder and Michael Kushnak. This group designed, built and tested the hip actuating exoskeleton discussed in this paper. The authors would also like to acknowledge CDTs Gabriela Barrera and Cameron McDonald, both previous independent study cadets who contributed to the mechanics and electronics of the exoskeleton. Finally, the authors would like to recognize the advisor of the capstone group and this study, Dr. John Rogers. Dr. Rogers has lead this project for several years and plans to continue the project in the coming years. His efforts and determination have made this all possible.

9. References

1. M. A. Holgate, T. G. Sugar, and A. W. Bohler, "A novel control algorithm for wearable robotics using phase plane invariants," IEEE International Conference on Robotics and Automation, 2009.
2. Ibid.
3. Ibid.
4. G. Barrera, "Me389 individual report," 2015.
5. P. M. McGinnis, Biomechanics of Sport and Exercise, 3rd ed., 2013.
6. E. Tutorials. (2016) Hall effect sensor. [Online].
   Available: http://www.electronics-tutorials.ws/electromagnetism/hall-effect.html