NDSU MECHANICAL ENGINEERING

Mechatronics Enhancements to Exoskeleton - Robotic Foot Structures - Phase 2

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Design Project I & II
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Table of Contents

List of Figures

List of Tables

1. Executive Summary

This report provides a detailed overview of the progress completed on the Mechatronic Enhancements to Exoskeleton-Robotic Foot Structures Phase 2 Senior Design project. The overall purpose of this project is to improve upon a testing apparatus that was built to accurately represent the human gait cycle in order to measure the effects of the unique Kingetics mechanical orthotic system and gather data to compare this orthotic to that of standard foam shoes. Another objective was to create a device that utilized an Arduino to create a supplementary data collection device that could be used for human study with the Kingetics mechanical orthotic system. This report contains some background information and introduction to the project as a whole, detailed design documentation for both the improvements to the testing apparatus along with the Arduino Supplementary Data Collection Device, the testing plan, the results and discussion from testing and finally the logistical side of the project: Bill of Materials, Project Plan, Budget, etc. Force sensors were used on the testing apparatus, in the form of a force plate, and Arduino, in the form of piezoresistive sensors, in order to gather accurate comparable force vs time data for both the Kingetics orthotic as well as normal shoes. Through this testing, it can be concluded that work is being done on the ground by the Kingetics orthotic. This provides further validation that the Kingetics orthotic does make walking more efficient compared to a regular foam soled shoe. The Arduino Supplementary Data Collection Device also shows promising data, but further improvements to that system may still need to be made.

2. Design Problem and Objectives

2.1. Background

The previous phase of this project had the goal of developing a testing apparatus for the Kingetics orthotic. An orthotic device aids in correcting the misalignment of feet due to their tendency to pronate or supinate. Pronation is when the ankle rolls inward and supination is when the ankle rolls outward. Orthotic devices are widely used in the medical industry and during physical therapy. Currently orthotic devices are used to absorb the impact shock of a normal gait walking cycle.

The idea for this orthotic came when Dr. Stephen King fractured his foot while competing with his USTA tennis and ultimate frisbee teams. He fractured his fifth metatarsal also known as a Jones fracture and is fairly common. To assist the healing process he was recommended to wear a shoe with a hard insole to support the foot during recovery. However, Dr. King was unable to find a shoe or boot that fit his needs so he decided to do some of his own experimentation. He created the double lever orthotic, seen in Figure 1, and his foot was able to heal adequately. The Kingetics orthotic is a new form of composite orthotic device that utilizes a carbon-fiber stabilizer plate along with a carbon pivot plate to aid in the motion of the foot. One of the biggest issues with foam inserts in footwear is that the impact of walking or running is absorbed by the foam. This energy is completely lost. However, if an insert was developed that would return the energy of a heel strike to the movement, the net result would be a more efficient stride.Theoretically, the energy from the heel strike of the foot is returned to help propel the foot off the ground during the toe off phase of the gait cycle. Thus increasing the efficiency of the users gait. The Kingetics orthotic requires a harder surface than other more common orthotics. If the shoe base is to soft then the orthotic is unable to use the energy from the heel strike as effectively and unable to spring up and propel the foot forward.

Figure 1. The Kingetics Orthotic

2.2. Project Description

Due to the unique nature of the Kingetics orthotic it cannot be tested like a normal orthotic. The Kingetics orthotic device is tested by a testing apparatus equipped with a load cell to measure forces on the ground. Phase 2 of this project utilized the apparatus as well as a human study with the Arduino Supplementary Data Collection device which allowed the gathering of force vs. time data while a subject walks around wearing the Kingetics orthotic.

Over the course of the 2017-2018 academic year, an ME 461/462 group, under the mentorship of Dr. Chad Ulven, developed a test fixture, as seen in Figure 2, to perform data collection and analysis on the efficacy of the orthotic device. Their final product was a usable, but unfinished apparatus that suffered from reliability and safety issues. In terms of data collection, the initial oscillation of the apparatus caused the frequency and damping calculations to lack certainty. However, the data showed a positive trend in the impact force and oscillatory amplitude. This means that the concept and efficacy of this orthotic was substantiated, but not proven. One of the biggest shortcomings of Phase 1 is that the test fixture designed was not safe or reliable. Safety is the number one concern with design revisions. The second concern is repeatability, for the test to be repeatable the fixture must be able to finish the gait cycle without causing unnecessary noise in the data. Phase 1 was unable to constrain the leg as it walked through the gait cycle and thus the leg is able to swing left or right instead of staying on course. It was also observed that a slight heel strike bounce is experienced at the beginning of the test motion.

Figure 2. The Completed Phase 1 Test Fixture

2.3. Objective

The objective of this senior design project was to design and implement improvements to the test fixture. Improvements should impact operational safety, reliability of test fixture, and accuracy of collected data. The second objective was to substantiate the experimental data by collecting supplementary data from a human-use study of the orthotic. The real life application will also help identify potential improvements for the mathematical model.

2.4. Constraints

The purpose of Phase 2 of this senior design project was to improve upon the testing system previously created, create a baseline data set of force output at the end of the gait cycle versus the force input at the beginning of the gait cycle with the testing system and integrate sensors to the orthotic system for data collection. Any improvements made should increase the safety, reliability and accuracy of the testing apparatus.

The current apparatus allowed the shoe to roll forward from heel-to-toe movement in what is known as a closed-chain gait cycle while retaining contact with the ground throughout the motion. It also allowed for variation in the angle of initial impact with the ground as well as a method for catching the system as a whole. All additions made must not interfere with any of the constraints set by phase one and must be able to be implemented to the testing apparatus without significantly negatively impacting the motion of the test sled. The collected data must be accurate and usable after the improvements are made, there can be no foam inserts below or above the orthotic. Additionally, there should exist some way to validate the experimental results against benchmark data.

3. Detailed Design Documentation

3.1. Ankle Joint

3.1.1. Constraints

When designing an ankle joint based off of the human ankle, most constraints revolve around the biomechanics of the ankle joint as well as the biomechanics of terrestrial locomotion. The ankle joint while walking can be mimicked by a simple hinge joint. The ankle joint should have an average dorsiflexion movement of 18° and an average plantarflexion movement of 22°. As well, the ankle joint had to be able to be easily inserted into the current test sled.

3.1.2. Design

When Phase 1 constructed the leg portion of their test apparatus, it was designed so that there was no ankle joint. The introduction of an ankle joint, shown in Figure 3, is a simple hinge that allows for the same angle of movement of the human ankle while walking. This would be beneficial to the accuracy of the data. This ankle joint design allows for 18° of movement in dorsiflexion and 22° in plantarflexion. Adding in an artificial ankle joint would be a cost-efficient and overall effective way of reducing the bounce of the test fixture when it is released from its held position. It would also allow the test fixture to roll over with more ease and be more accurate to the actual movement of a human step. Another point to note is the fact that the top plate of the ankle joint addition attaches directly to the current system, just under the load transducer, and no other modifications would be made.

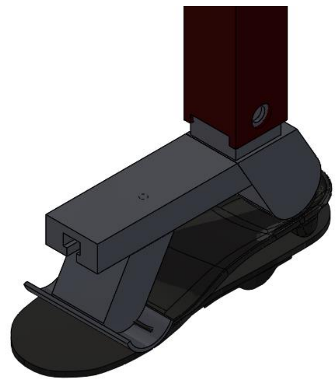

Figure 3. A CAD model of the ankle joint addition as it will appear in the finalized test apparatus.

3.1.3. Analysis

Some analysis was completed on the ankle joint. Mainly, calculations were completed that would show how much in the front and back of the joint would have to be cut away in order for the ankle joint to function properly. As well, shear stress on the pin used was also calculated, however, due to the small distance and relatively low weight being exerted on the pin, this was of little concern.

3.1.4. Manufacturing

The manufacturing for this was relatively simple. The current foot was taken off, and the 2" steel pipe that attached the foot to the load transducer was cut off, and the smaller 1.5" pipe was added. The larger piece of pipe was attached to the plate that attaches the foot to the load transducer and the slots to allow for plantarflexion and dorsiflexion were cut away. Holes were drilled through both the larger and smaller pipes so that a ⅜" pin could comfortably fit through and act as the pivot for the ankle joint.

3.2. Damping Catch System

3.2.1. Constraints

Because the previous catch system was deemed unsafe, a new one had to be designed and created. The damping catch system involves a Y-shaped steel beam where the arms of the test sled would fall into upon completing the gait cycle. The air cylinders inside the Y-shaped steel beam would then allow the impact that the sled has to be lessened. The main constraints of this were that the catch system had to attach to the current catch system, it had to have dimensions capable of catching the arms of the sled, and it had to support that impact as well.

3.2.2. Design

The damping catch system is designed to help slow and catch the leg after it completes the gait cycle. Currently as the leg completes the gait cycle, the momentum keeps it moving forward as it impacts a pair of ratchet straps. After the initial impact on the ratchet straps the leg oscillates and then comes to a stop, this is not an ideal nor safe stopping mechanism. The damper catch design, Figure 4, consists of a Y-shaped catch that leads to a button shock damper. This design is meant to be used in tandem with an additional damping catch system unit. With the addition of the damping catch system, a wooden box is required to raise the sliding rail system above the edge of the Y-shaped catch. This extra height allows for optimal use of the Y-shaped catch.

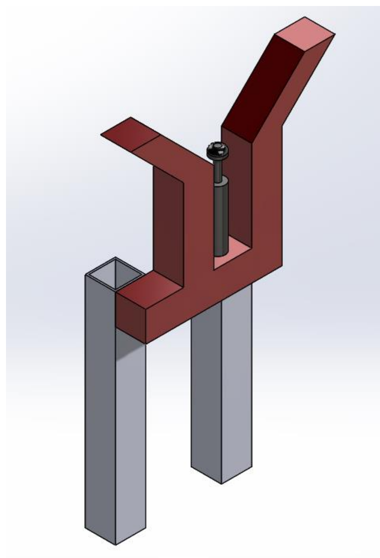

Figure 4. A CAD model of a singular damper catch addition.

3.2.3. Manufacturing

The manufacturing for this damping catch system was all done in-house in NDSU's Mechanical Engineering Shop. The steel beams were all cut and welded first. Then holes were drilled to accommodate the air cylinders that were to be used as dampers. The air cylinders were already available from the NDSU Mechanical Engineering Shop as well. Once that was completed, the Y-shaped catch system was attached to the current catch system. Finally, the dampers were added to the system so that it could be tested for use.

3.3. Arduino

3.3.1. Constraints

Development of a separate device to further substantiate the test results gathered from the biomechanics force plate was proposed in the form of an Arduino based data acquisition system (DAQ). The constraints associated with such a prototype device were broken down into two categories based on the needs of the project. The first category referred to the user-friendliness of the device, and the second to the data collection and transmission method.

User-friendliness was a top priority for this portion of the project, so the prototype was designed to allow a non-technical operator to set-up and run the device without accessing internal components or running a remote code. Additionally, the device should be easily accessible should any internal issue occur. Should any issue arise with the function of the prototype, a stand-alone document should contain relevant troubleshooting information.

Another constraint to the design included using force sensors that could be connected or disconnected at will to allow for the device to be secured around the operator's ankle without damaging any connecting wires. To compliment the usefulness of the device, the power source must be wireless and inexpensive. The use of rechargeable lithium ion batteries was precluded due to hazardous shipping considerations: it would be too expensive to ship to Dr. King.

In hopes of using this device as a means of live data collection, transmission of collected results during testing was to be automatic and wireless. This meant designing a WiFi enabled prototype that could be remotely accessed with a computer. Another constraint related to data collection was that the device must store data internally even if it is not connected to a remote device, so it may be accessed by the operator at a later date. Furthermore, the data that is collected should include force information related to the ground reaction as it correlates with strike velocity.

3.3.2. Design

The supplementary data acquisition device, also referenced to as "the Arduino" is shown in Figure 5. A set of piezoresistive force sensors were to collect information about the forces throughout the entirety of the orthotic-assisted gait cycle, and output the results to an Arduino controller where the data was to be compared against positional information collected by the tri-axial accelerometer. The data was then to be exported to a data collection and storage device such as a cell phone or laptop via the integrated WiFi chip: a Pi Zero W. The power supply was selected to be a 9v batteries because the Arduino requires relatively little power to function and using 9v batteries eliminated the need for recharging more expensive nonoptimal power sources like lithium ion batteries. To keep the Arduino from getting damaged, a housing was designed and 3D printed such that it attaches around the ankle of the subject via elastic bands. The manufacturing of this housing was handled at NDSU on a PLA filament 3D printer.

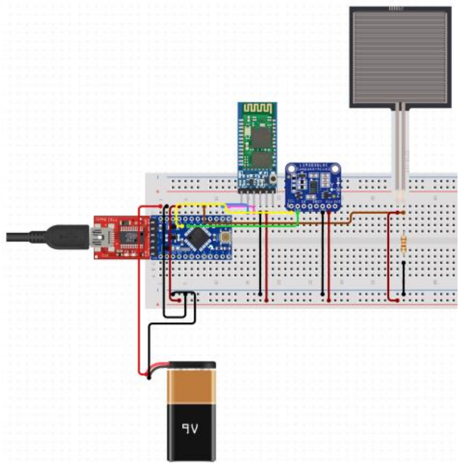

Figure 5. A graphical circuit diagram of the Arduino and sensor array (as originally designed).

The design process for the Arduino system was iterative, and required several additions that were not originally present in the design. Some of these additions included an OLED screen and amplifier chip. This extra hardware was either purchased with the contingency portion of the budget or recycled from previous projects. This iterative approach to the design ultimately yielded a suitable prototype design. Unfortunately, due to the constraints on the design of this device manufacturing was complex and the instability inherent in the construction of the device imposed some limitations.

3.3.3. Manufacturing

Manufacturing for the Arduino presented some unique challenges. The first of which was that of circuit architecture. The parts as specified from the graphical circuit diagram were purchased and assembled together, but lacked the processing power and sensing range for the proposed application. To overcome this challenge, additional hardware was specified with the assistance of a computer science and robotics expert.

A small 3D printable design for a housing generated in SolidWorks, and iterated several times to fulfill the constraints of the prototype. All components of the Arduino were connected and placed inside or attached to the housing (See “Bill of Materials” section). The force sensors were integrated into the base of the orthotic in the shoe being tested so that data could be collected. Additional detailed information can be found in the separate document titled “Kingetics Arduino Ankle Monitor and Data Acquisition System Set-Up and Operation Guide”. The finalized product can be seen in **Figure 6**.

Figure 6. The finished Arduino Supplementary Data Acquisition Device (alone and in-use)

Other challenges present in the construction included calibrating the force sensors, and adjusting the placement on the spring plate such that there is minimal interference with the general function of the orthotic device. Each challenge was eventually overcome to fit the scope of the project. Due to the prototypical nature of this device however, it cannot be applied to a shoe without an orthotic insert, and the device may be damaged by exhaustive testing.

Overall, this data collection device proved useful, and has several areas for improvement for this application. This device showed potential to be applied to running mechanics, and even - with enough enhancement - athletic injury recovery. This device could allow for real-time capture of forces during clinical trials of prosthetics or new athletic gear. It was concluded that this contribution, although still in the early prototype phase, should not be overlooked as a relevant invention.

4. Laboratory Tests and Results

4.1. Test Fixture

4.1.1. Testing Procedure

Once improvements to the test fixture were implemented, similar testing to that of Phase 1 was performed. Two different force sensors were to be used in order to obtain leg and ground reaction forces. One data set from the integrated load cell was to be compared to the Using the load cell that is attached to the testing sled in conjunction with a data acquisition system (DAQ) the forces transmitted throughout the foot apparatus will be measured. A force plate will also be used to measure the impact forces of the foot with respect to the ground. The force plate will be connected to a computer running Accupower Solutions in order to obtain force and time data.

The test fixture will be assembled around the force plate and the DAQ will be connected to the load cell. Weights were added to the test fixture, with more weight being added to the front load bar in order to propel the sled forward. For these tests, 15lbs was added to both sides of the front load bar. Two different tests were run: one with a regular shoe foam insert and another with the Kingetics orthotic insert. A pair of wrestling shoes provided by the sponsor were used for the inserts, and the shoe was attached to the foot of the sled. Multiple tests were performed for both inserts at the same sled inclination angle. Impact force and force vs. time data were to be gathered from the load cell and force plate so that the data could be analyzed, and compared directly. Unfortunately, due to some hardware malfunctions, data was unable to be collected via the integrated load cell. Therefore, the data from the biomechanics force plate will be analyzed alone as well as compared to that of the Arduino to demonstrate the resultant decrease in required ambulation energy.

4.1.2. Results

After multiple trials were conducted under several different sets of experimental conditions, force vs. time graphs were generated to illustrate the differences between data sets. The control data was gathered using two team members of known weight (approximately 1040N and 780N). This control set was averaged between three trials and outlying data points were automatically excluded by the DAQ to get a relatively accurate representation of a “normal” or unassisted step. **Figure 7** shows a control dataset graph as force in newtons vs number of samples at 1250Hz sampling rate.

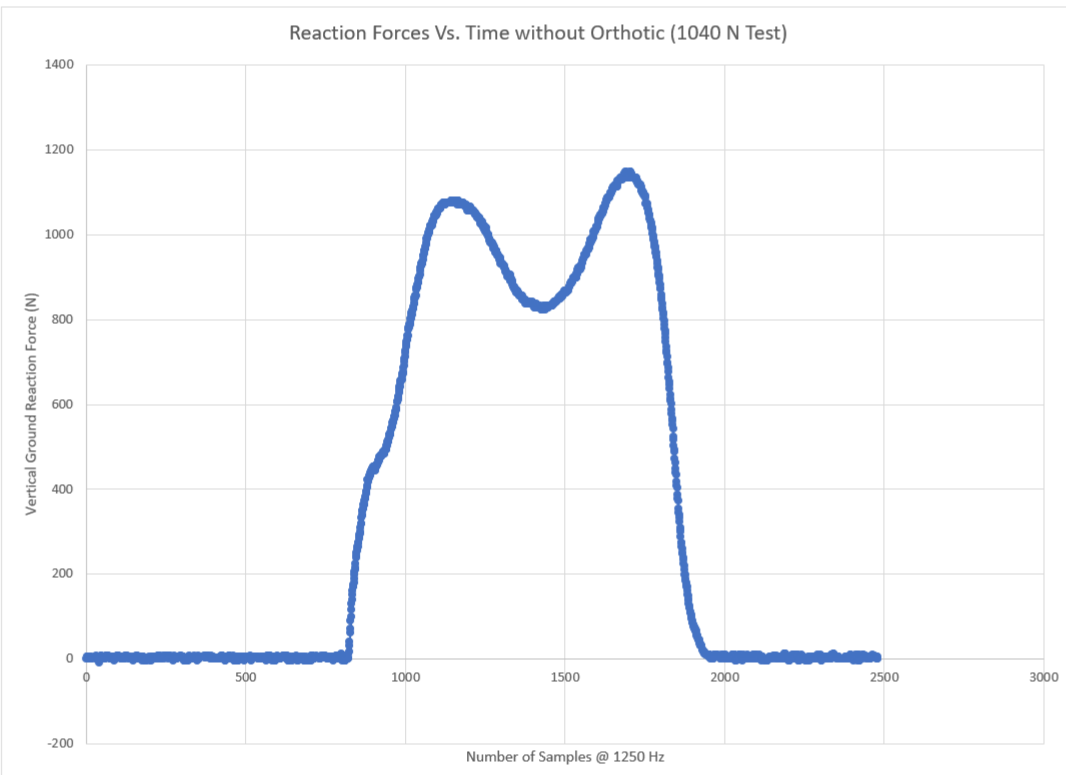

Figure 7. Force (N) over the sample period for 1040N subject (averaged control dataset)

After the control datasets were established for both subjects, the next step was to gather data with each of the three spring plates. It appeared as though each plate was made of different materials, but the exact composition was not able to be determined from the given information. That being the case, the three spring plates are classified by their coloration: white, red, and yellow.

Each spring plate has a different stiffness, the yellow being the highest, and the white being the lowest.

Using the same shoe and foam insole for every sample was vital to achieving a meaningful result. Therefore, the only independent variable between each data set was the composition of the orthotic. Walking speed was kept as consistent as possible, but some errors may be present due to fluctuations in testing conditions.

The process of averaging three trials for each experimental group remained constant for every experimental group. **Figures 8 & 9** shows the results for the White Orthotic trials for each test subject. It is evident from the graph that the initial loading rates at the heel strike were much faster than that of the control for both groups. This is likely due to the heel portion of the spring plate deforming as the load is instantaneously applied.

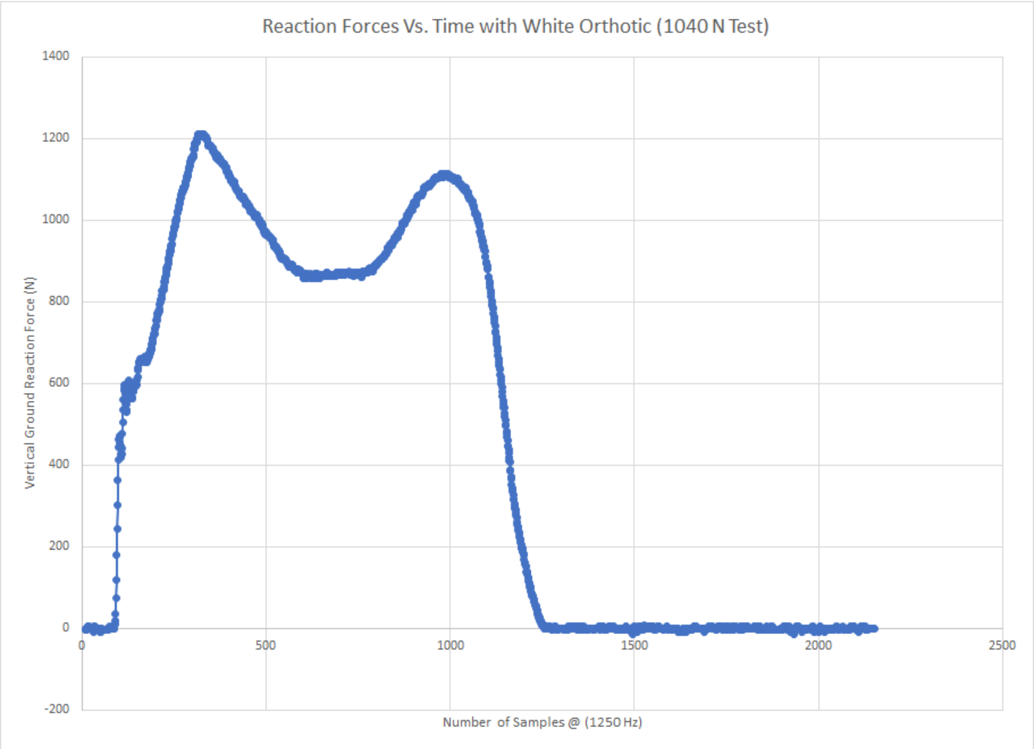

Figure 8. Force (N) over the sample period for 1040N subject (White Orthotic Group)

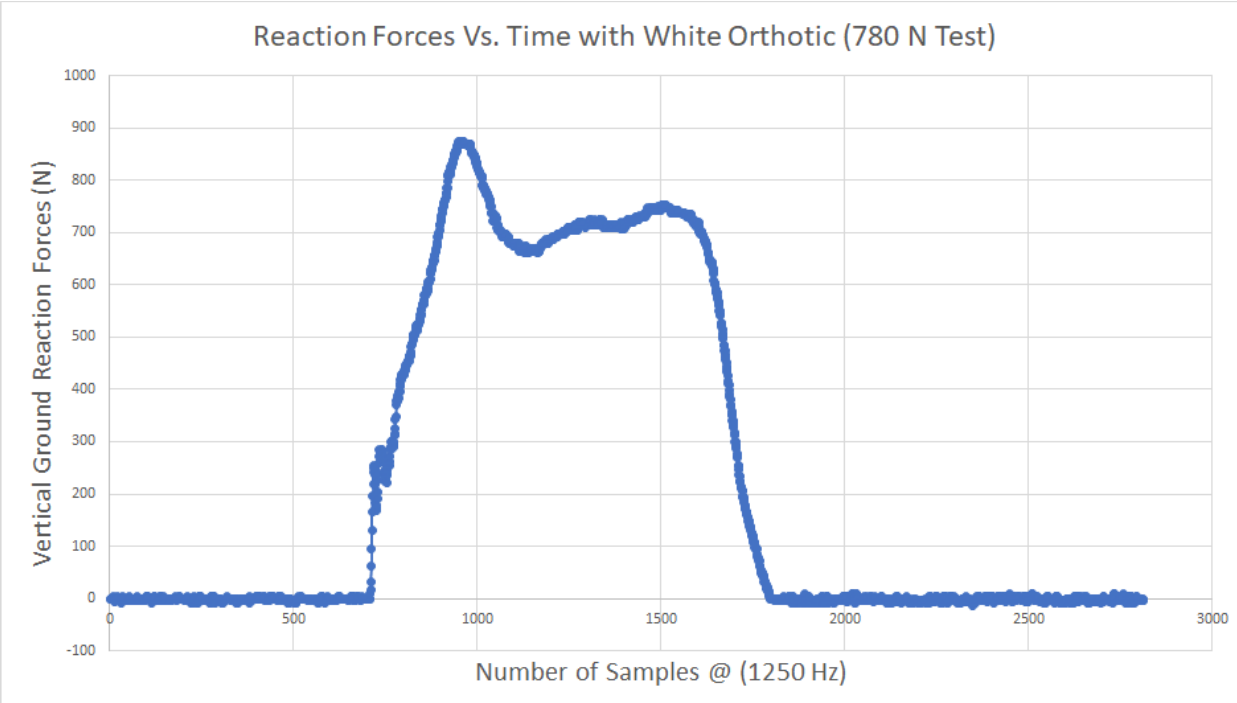

Figure 9. Force (N) over the sample period for 780N subject (White Orthotic Group)

In general, the White Orthotic data sets demonstrated an increased amount of work done to the ground as compared to the control data sets. This evidenced the hypothesis that less work is wasted during the gait cycle. **Figure 9** also shows a deeper valley between the initial peak and active peak for the 780N subject as compared to **Figure 8** of the 1040N subject under the same experimental conditions. This change in apparent effectiveness is primarily due to the change in harmonic response of the orthotic system as it supports different masses. To optimize the efficacy of the orthotic device, it is speculated that the stiffness should be higher for higher masses.

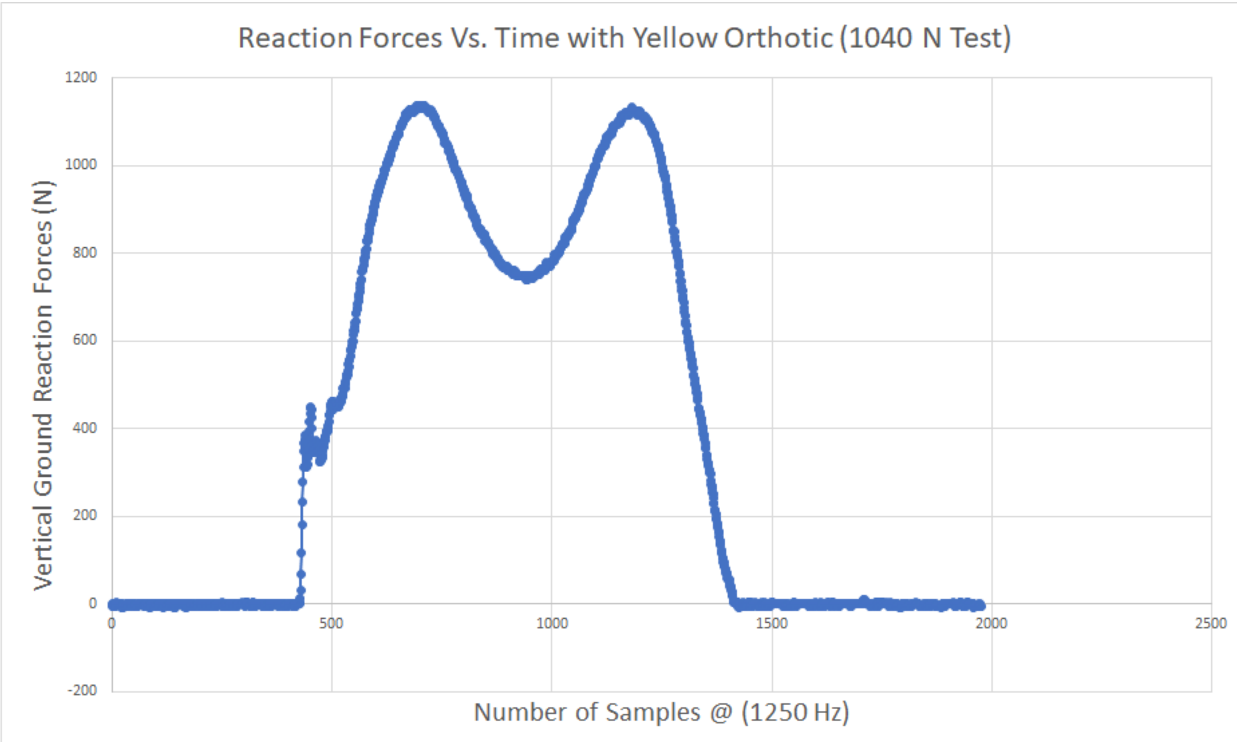

Figure 10. Force (N) over the sample period for 1040N subject (Yellow Orthotic Group)

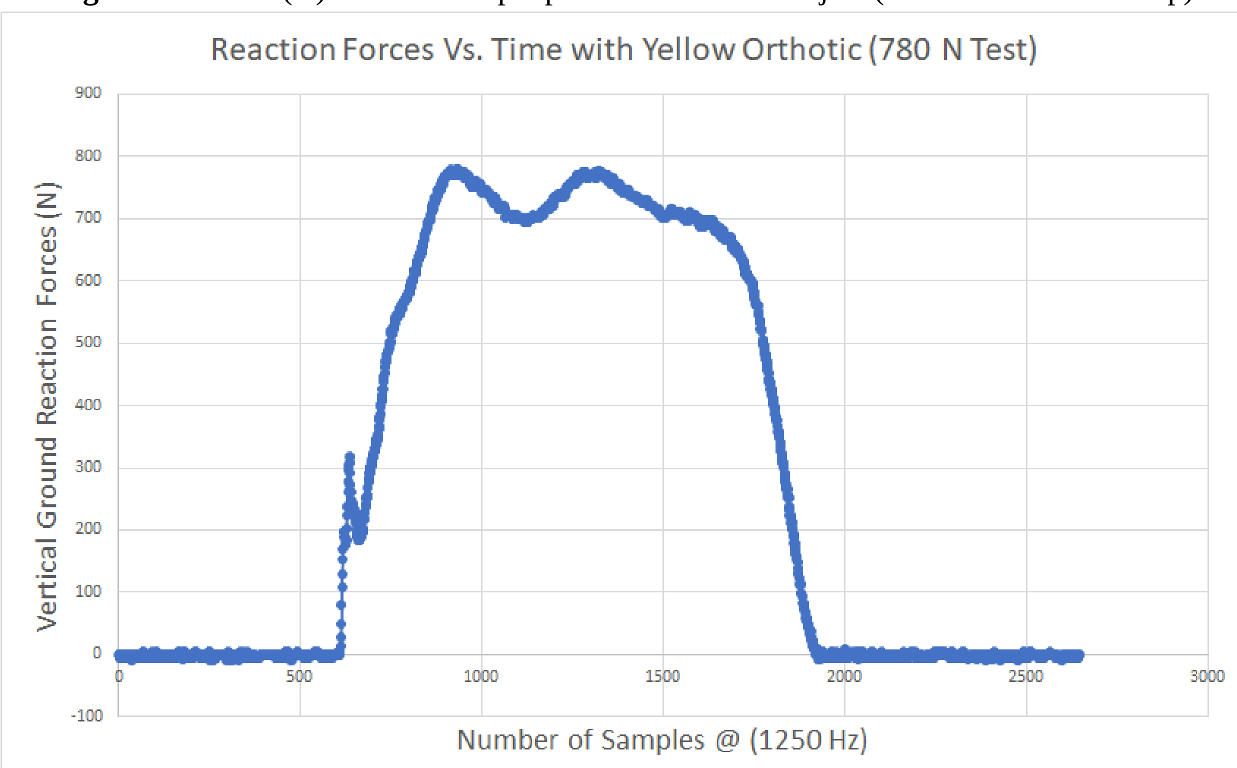

Figure 11. Force (N) over the sample period for 780N subject (Yellow Orthotic Group)

Figures 10 & 11 shows the results of the Yellow Orthotic trials for both test subjects and tends to support the idea that stiffness affects the usefulness of the orthotic to reduce the energy required to walk by demonstrating a -260N from body-weight local minimum between the initial and active peak for the 1040N subject and only a -80N from body-weight local minimum for the other subject. This means the stiffer orthotic was more than 3 times more effective for the 1040N subject. The depth of this trough is thought to represent the amount of force transferred to the toe off portion of the step, and by extension demonstrate the reduction in ambulation energy. However, additional testing and vibrational analysis of the orthotic system should be conducted to verify this conclusion.

The red orthotic was tested with both subjects on the biomechanics force plate: that data is available on the K: drive in its raw form, or see graphs in section *4.2.2*. The Red Orthotic was also applied to the sled test fixture to achieve the results shown in **Figure 12**, below.

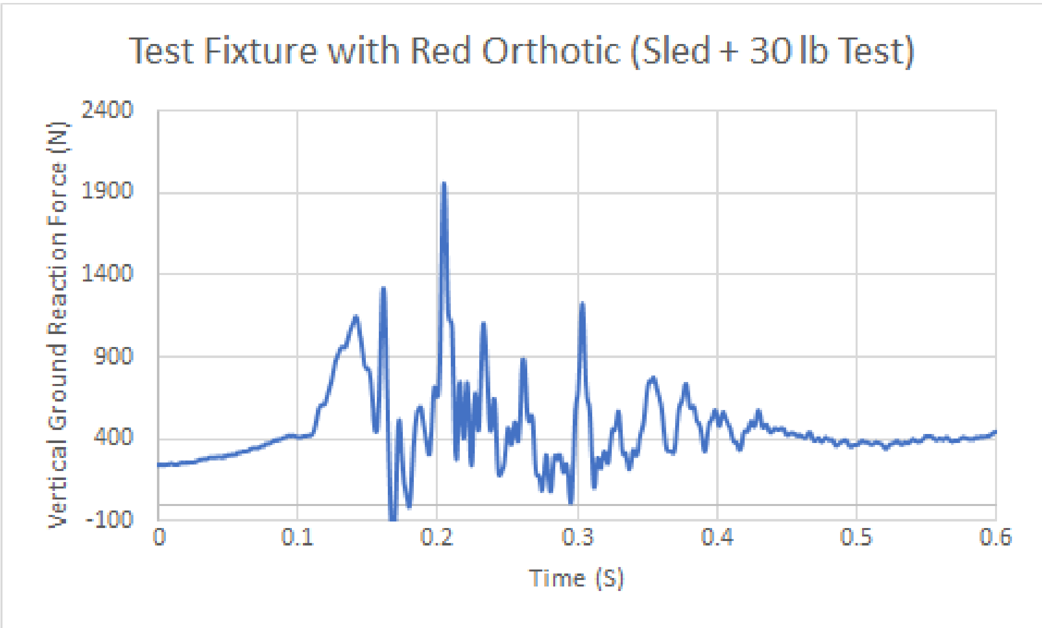

Figure 12. Sled Test Fixture with Red Orthotic

Notice two distinct peaks (Initial peak @ 0.2, and active peak @ 0.3) this means the orthotic used stored energy to exert force back to the ground. This bimodal peak is to be expected during a walking step. As shown from our control datasets, and reinforced by generally accepted biomechanical theory [1]. (See **Figure 13**)

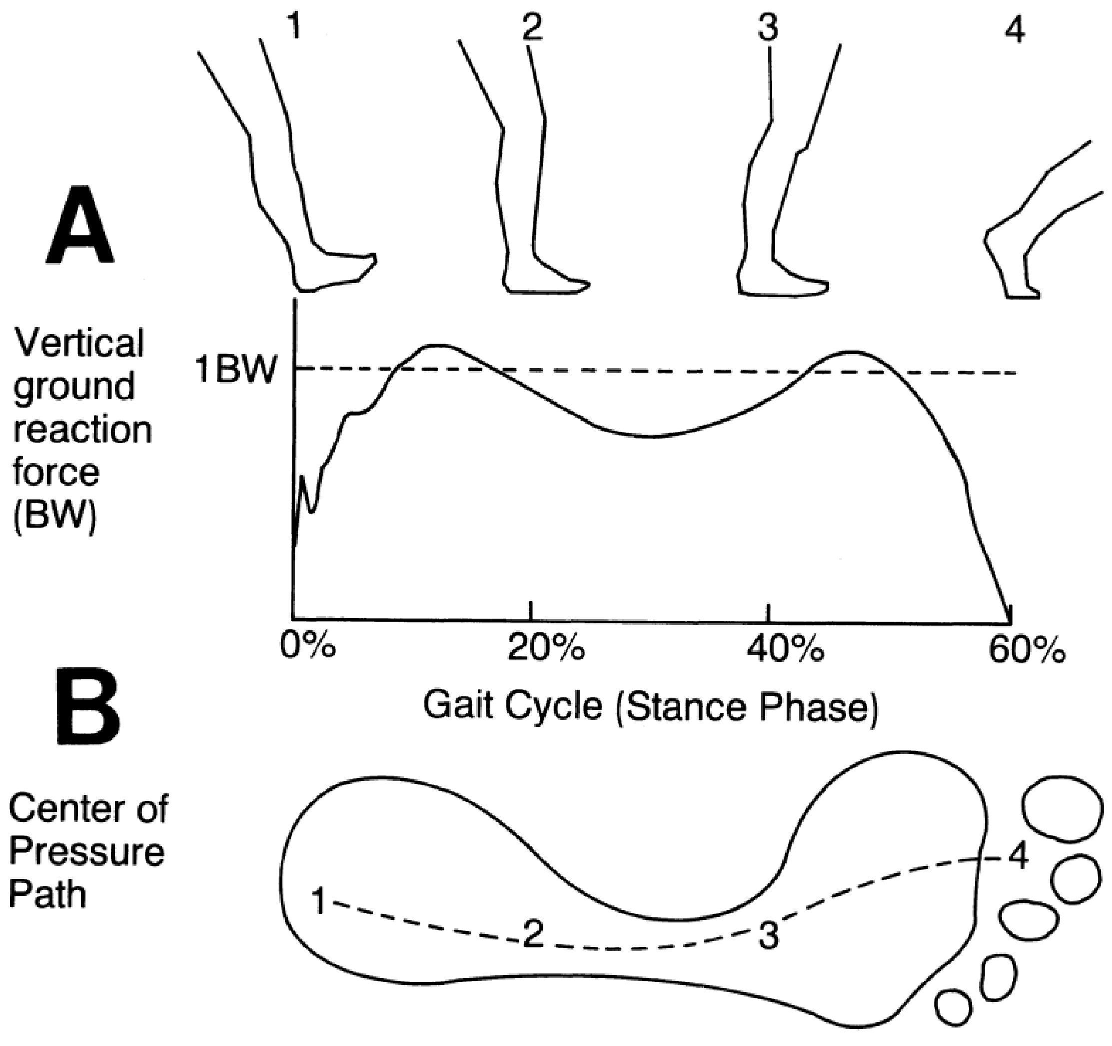

Figure 13. Accepted Biomechanical Analysis of an Arbitrary step

An active peak is clearly defined at 0.3s in **Figure 12** that is not consistent with the expected linear damping of a step without the orthotic. This fact alone evidences the functionality of the device to store and transfer energy from the heel strike (initial impact peak observed at 0.21s) to the toe off (active peak at 0.3s). If this waveform is compared to **Figure 14** - below - it is clear that there is work being done to the ground at the end of the step, and that the initial strike peak was reduced by approximately 345N.

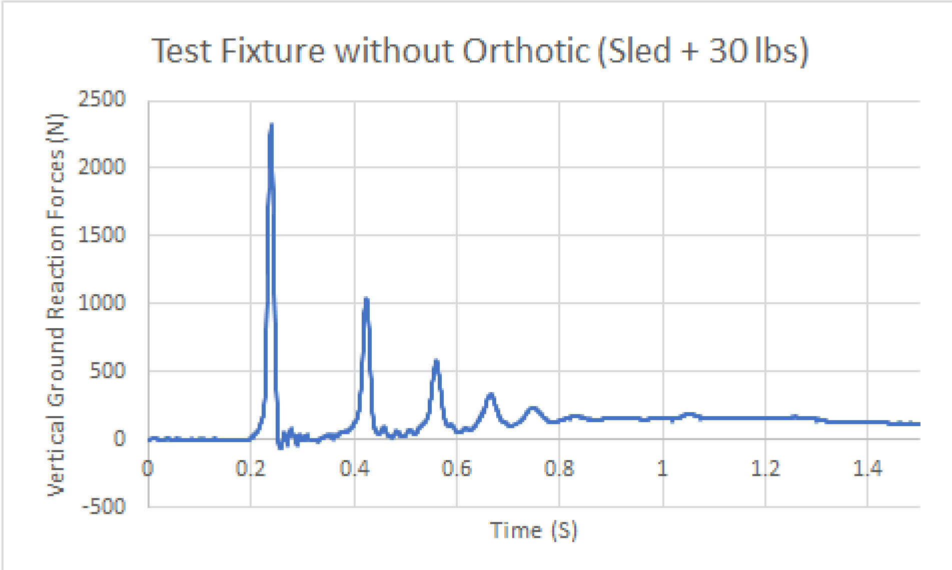

Figure 14. Sled Test Fixture without Orthotic

Again, notice the single peak at 0.23s representing the impact peak in Figure #. Coulombic damping as expected from viscous damping by a polymer sole is present in this graph because the transient vibratory response dies out at a constant rate. Damped frequency appears to have changed due to less stiffness because the time between vibrations is less than that observed when the sled test fixture incorporated the orthotic device.

One of the main contributing factors as to why this trend was not discovered in phase one is the Ankle joint addition nearly mimics anatomically correct flexion; allowing for a more accurate model by increasing the overall anatomical similitude. This addition allowed for the identification of the active peak generated by the orthotic device as it was applied to the sled test fixture, and has helped to substantiate the conceptual efficacy of the device.

4.2. Arduino

4.2.1. Data Collection and its Application

The supplementary data acquisition method used a human test subject wearing the Kingetics orthotic insert in wrestling shoes. The Kingetics orthotic had four piezoresistive force transducers integrated at high-stress points on the spring plate as described previously. Along with the transducers an accelerometer was connected to the Arduino. This sensor array exported data to an Arduino in the form of a CSV file with eight columns (acceleration components {x,y,z}, rotation components {x,y,z}, time {sec.}, and measured weight {lbs.}). The human test subject put on the shoe and tightened the strap on a housing box containing power and computer components such that it did not vibrate appreciably. The subject then walked around on a flat surface in different time intervals while the arduino recorded force vs time data from the sensors. The DAQ compiled the data obtained to a raspberry pie, which sent the data via WiFi to a laptop to be analyzed in real-time when desired, or was stored on the device for later analysis.

This supplementary data collection method was designed for non-rigorous use. An updated and improved version of this data acquisition method would allow for testing of orthotic in more versatile real-word applications such as hiking, running, jumping, etc..

4.2.2. Results

The Arduino DAQ prototype provided the ability to gather data and track peak vertical ground reaction forces for discrete steps in real time. Below in **Figure 15** is a sample graph generated from raw data (See Appendix - C) that shows 19 discrete steps as they occurred over the course of an arbitrarily long sampling period. Each data set contains 2000 samples, and the maximum sampling rate for the Arduino DAQ is 10 Hz. This needs to be improved before the waveform of each step can be scrutinized individually, but the sampling rate was sufficient to capture relevant biomechanical data for the Red Orthotic device.

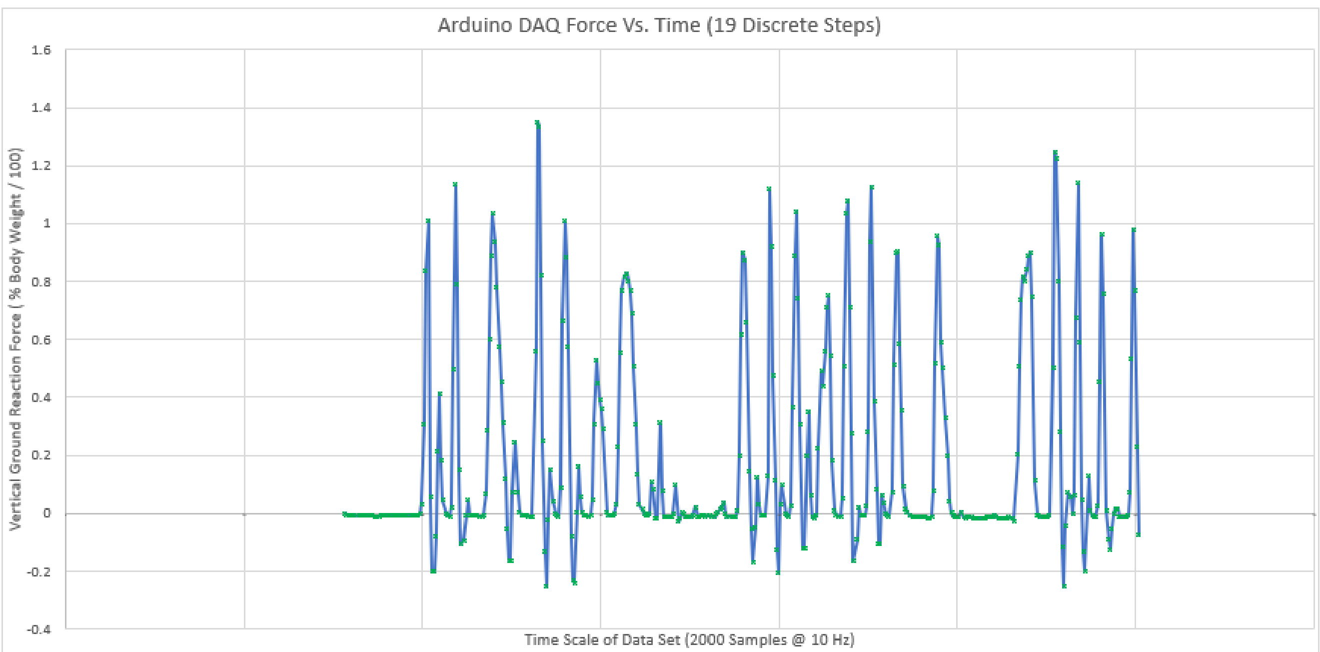

Figure 15. Arduino Results

It was evident that waveform aliasing was occuring due to the relatively high discrepancy between physical input and sensor reading: the integrated force transducers could not keep up. This is easy to improve, and may make this device a more relevant / accurate data collection device. Regardless, based on the collected data it can be observed that the load transducers output sensible data (it approximates the magnitude of ground reaction forces observed in the control tests), but some outliers exist as negative force values which may indicate that the force sensors need to be more comprehensively integrated into the spring plate as opposed to temporarily fixed in place.

The accelerometer data can be applied to determine if positive force outliers were the result of excessive loading rates, or simply electrical noise by matching the acceleration of the device to the observed peak. If the acceleration or rotation values are very high, the data may still be usable and can be analyzed. However, if the load is very high but no excessive acceleration of the leg was present in the data, the outlier may be ignored.

Some waveforms present in **Figure 15** show the characteristic bimodal shape, but lack the resolution to accurately determine the local minimum between the impact and active peaks. This can be solved by increasing the sample rate of the DAQ with better sensors. In conclusion, the Arduino DAQ is a promising and versatile prototype, but was unable to fully satisfy the data collection constraints.

4.2.3. How to use the Arduino DAQ

A separate document titled "Arduino DAQ Operation and Troubleshooting Guide." was created in order to have a comprehensive document on everything regarding the Arduino Supplementary Data Collection device.

5. Bill of Materials

A bill of materials for all components needed for this project was compiled and is shown in the table below.

Table 1. Bill of Materials

Product	Description	Quantity	Manufacturer	Supplier	Cost
Low Carbon Steel Framing	Structural Framing Steel, 5ft	8	McNeilus Steel	McNeilus	230.00
Hardware	Assorted Nuts & Bolts	Multiple	Fastenal	NDSU ME Shop	-
Air Cylinder	Dampener	2	-	NDSU ME Shop	-
3 Axis Accelerometer	Arduino Compatible	1	Arduino	Amazon	6.84
Arduino	Leonardo	1	Arduino	Amazon	15.84
Piezoresistive Force Transducers	Arduino Compatible	1	Taidacent	Amazon	24.94

Bluetooth Module	Arduino Compatible	1	Mayata	Amazon	19.99
Pi Zero W	WiFi Chip	1	Raspberry Pi	Amazon	21.99
9V to 5.5V Buck Converter	Voltage Adjustment Chip	1	LIVISN	Amazon	7.22
Micro USB to Micro USB Cable	Connection for Arduino to Pi Zero W	1	AmazonBasics	Amazon	7.99
Various Jumper Wires	For internal connections	Multiple	GenBasic	Amazon	5.99
Spiral Wrap / Misc. Hardware	For securing chips / wires in place	Multiple	-	Amazon	-
1-inch OLED Screen	Display screen for Arduino	1	Arduino	Amazon	6.99
9V Battery	N/A	Multiple	EBL	Amazon	21.99

6. Project Plan

A project plan for both semesters was created at the beginning of the project. Objectives and gantt charts were also created for both semesters in order to maintain consistent work loads throughout the entire project. The project plan for the second semester was revised after first semester progress was complete. A gantt chart can be seen in **Appendix - A.**

6.1. First Semester Progress

Project familiarization was done over the first two week. This included a meeting with all team members and the sponsor. This was done to better understand wanted deliverables for our phase of the project. Along with analysis of completed objectives from Phase 1, a project plan and rough budget were created. The next four weeks were spent constructing conceptual design improvements along with a matrix for selection of the final improvements. Within this time a bill of materials was also created of all required parts in order to finalize the budget. Two weeks were then used in order to finalize the calculations for the final design along with creating CAD models. As mapped out in the project plan the goal of first semester was to design improvements for the test sled along with developing a new testing method for real time human testing. Both goals were achieved with two weeks left in the semester. The next steps were to order parts, complete manufacturing, and start testing. With little time to complete these in this semester, they will remain to be objectives in the second semester. In the last weeks the last objective to accomplish was to write a final first semester report along with present all work completed.

6.2. Second Semester Progress

A revised project plan was worked on in order to account for changes made after the first semester, work being completed over the summer, and setting a more realistic time frame. The first objective of the second semester was to order all necessary materials to manufacture the test sled improvements and build the Arduino Supplementary Data Collection device. Because of shipping and manufacturing times this took about three weeks for all of the parts, which was one longer than expected. Manufacturing of the ankle joint, and catch system was a top priority as this required help from the ME manufacturing department, along with the IME welding shop. An anticipated four weeks was given for the test fixture manufacturing, however, the actual amount of time taken was six weeks. This pushed back the amount of time for testing, along with a smaller amount of time to analyze the data. Testing on the test fixture was set to be completed over a few days in the middle of November. The goal of these testing days were to obtain force vs time data. Throughout the month of November the supplementary testing device was built and coded, in order to meet the goal of running tests before Thanksgiving. The last three weeks of the semester were used to analyze data from the force gauges along with writing a finalized report and presenting the whole project. Although the original goal of writing a research paper was not met due to unforeseen manufacturing difficulties, all other goals of the project plan were completed on time or near the expected time.

7. Project Budget

A total budget of $789.13 was originally allocated in order to complete the necessary improvements to the phase 1 test fixture, and $800 was granted by the NDSU Mechanical Engineering Department. The cost of all items required for this project can be seen above in **Table 1**, the bill of materials. Previous year's materials and components were also utilized and taken into consideration when determining the final budget. As described further, the project came in at ~$400 under budget. This is due to the fact that the button shock dampers were obtained in house as leftover air cylinders from previous projects. Originally, the dampers were a significant portion of the original budget costing ~$300 total. The remaining difference came from some Arduino Components being recycled, therefore no cost used.

8. Safety Considerations

Safety was one of the most important considerations of this project. Since the phase one sled tended to tilt to one side or the other while moving through the gait cycle, finding a way to safely reduce the tilt and/or safely catch the sled was of utmost importance. By implementing the ankle joint, the sled tilted less while moving through the gait cycle, however, the sled still had a tendency to tilt to one side once released, but did not pose any risk to people standing nearby. In the case of the Arduino Supplementary Data Collection device, it is completely safe for the user to wear and the critical components are all within the housing.

9. Ethical Considerations

The team followed the engineering code of ethics when completing the design for both the test fixture and Arduino Supplementary Data Collection System. It was important that, since this was a phase 2 project, any changes to the project should be unique to our group as to distinguish ourselves from phase 1 while still achieving the overall goal of the project. These changes should also not hinder the use of the apparatus as a whole nor should put any of the users in danger in any way. In the case of the Arduino Supplementary Data Collection device, it is completely safe for the user to wear, and does not impede any movement or motion naturally done whilst walking.

10. Conclusions

Phase 2 of the Mechatronic Enhancements to Exoskeleton-Robotic Foot Structures Senior Design project was tasked with making improvements to an already working system that could accurately model the unique Kingetics orthotic. These improvements were planned, designed and manufactured in parallel with a small electronics package that could gather accurate force vs. time data from a walking human subject. Both the testing apparatus and the Arduino Supplementary Data Collection device were able to collect usable data that can help validate the idea that the Kingetics orthotic does make walking more efficient over a standard foam-soled shoe. It can be concluded that work is being done on the ground by the Kingetics orthotic. This provides further validation that the Kingetics orthotic does make walking more efficient. The Arduino Supplementary Data Collection Device was slightly less successful, but still shows promising data.

11. Future Work

At the forefront of the issues that Phase 2 encountered was the fact that when Phase 1 finished its project, they did not accurately lay out all of the problems that they were having or noticed throughout the year that they were working on the project. This will be alleviated in this section to streamline Phase 3's early project planning along with covering all of Phase 2's bases.

As far as the test sled goes, more data can always be collected to further validate the objective/conclusions already obtained. However, some improvements should still be made if there is to be a Phase 3 to this project.

Before being released, it is noticed that the sled already has a tilt of a few degrees. This can be seen when standing directly behind the sled, by looking at the weight-bearing arms of sled, the right arm sits a small distance below the left arm. This is a major contributor in the fact that the sled does not always fall straight forward when taking a step.

As well, Phase 1 designed adjustable feet as nuts welded to the underside of the test fixture with screws attached to a ball-and-socket foot. One of these feet has come detached through various uses of the sled.

The catch system as a whole still can be an issue, and a complete redesign may be in order rather than just an improvement. When trying to catch a system as wide, heavy and prone to tilting as this, catching it at the ends of the weight-bearing arms can be very difficult. Catching the sled successfully within the damper catch system involves a lot of trial-and-error to get the system as a whole set up correctly.

Part of the reason the catch system is such a problem is because the release system has one major issue - the height adjustment is very hard to lock into place. Changing the height adjustment system to allow for quick adjustment would streamline the process by which adjustment can be made.

There is also the issue of the sled hitting the ground before the gait cycle is actually completed - this led to the addition of the small wooden box that would allow for the gait cycle to finish before the sled was caught. Figuring out a way to alleviate the issue of the sled hitting the ground before the gait cycle completes would remove the need for the box which may create extra noise in later testing.

At the time of writing this, the I/O port on the load transducer has some broken pins that prevent the usage of the load transducer. The company Tacuna Systems has been contacted about the "AmCells LPD Series Alloy Steel Disk Load Cell" to discuss possibilities on how to fix it. As well, data collection from the load transducer is difficult and will require some additional trial-and-error since no DAQ, amplifier or documentation on how to use the load transducer was passed from Phase 1 to Phase 2.

The Arduino improvements/future work is mostly discussed in the corresponding results section, discussed as limitations of the system - this mostly includes improving some equipment within the system.

Note: The Arduino limitations can all be found in its individual documentation titled "*Kingetics Arduino Ankle Monitor and Data Acquisition System Set-Up and Operation Guide*."

12. Acknowledgements

Our acknowledgements go to Dr. King with Kingetics, LLC for giving our group the opportunity to work on this project. As well, we would like to thank North Dakota State University and the Department of Mechanical Engineering for the funding to make this project happen. As well, Dr. Chad Ulven for coordinating this class and all of the planning and organization that goes along with it to make all of the senior design projects possible along with his guidance as our advisor for the duration of this project. Finally, we would also like to thank Dr. Bryan Christensen and the NDSU Department of Health, Nutrition and Exercise Science for their generosity in allowing us to use their tools and equipment throughout our data collection process.

13. Individual Contributions

Thomas Cameron contributed to the team by leading the design, fabrication and implementation on the Arduino Supplementary Data Collection device. He also acted as a team leader throughout the course of the project. He also was vital in data collection and analysis using both the test sled and Arduino. Benjamin Eichholz led the design and implementation on the ankle joint addition while doing all necessary analysis calculations to ensure its safety. He also spent a significant amount of time working in the shop manufacturing the additions needed to complete this project. Ben and Thomas both spent time putting together the troubleshooting document for the Arduino. Taylor Kray led the design and implementation of the damper catch system addition while doing all of the necessary analysis to also ensure its safety. He also was crucial in the development of the project plan and gantt chart early in the first semester as well as putting together the final video. Dallas Patton took charge of all of the 3D modeling for this project, taking care of all of the parts, assemblies and drawings. He also led the organization of the budget early in the first semester. He also assisted with the design and implementation of the damper catch system. All team members assisted equally on finishing written deliverables.

References

[1] Rodgers, M., "Dynamic Biomechanics of the Normal Foot and Ankle During Walking and Running." December 1988 https://pdfs.semanticscholar.org/358d/9523ff11992d115656034204fd75b8d47eee.pdf

Appendix A - Project Plan Gantt Chart

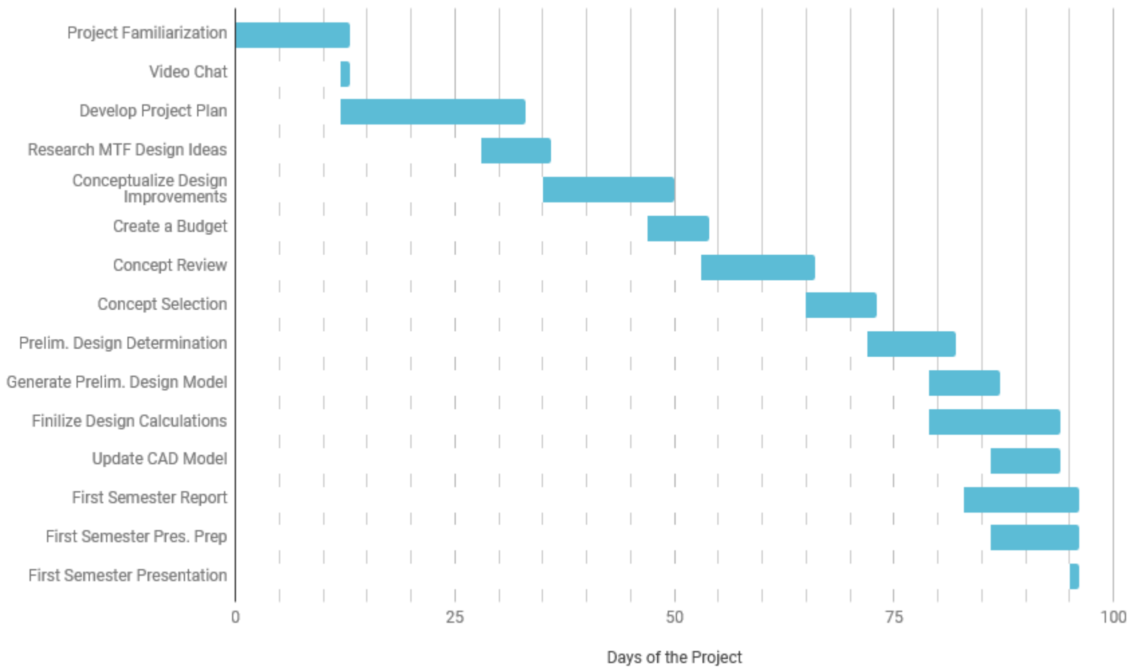

Figure 1A: A gantt chart showing ordered tasks to be completed before April 30th, 2019.

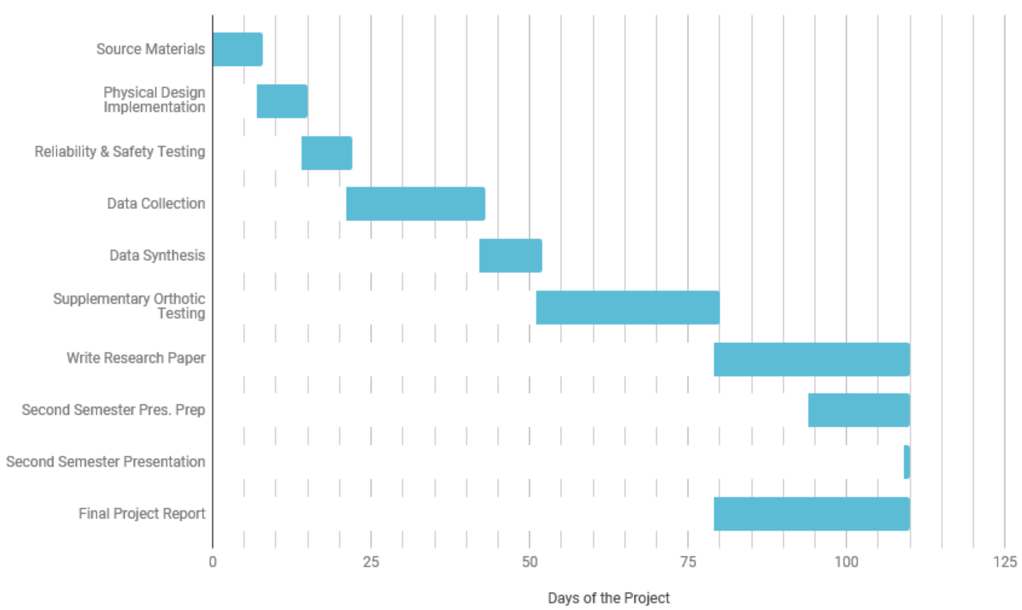

Figure 2A: A gantt chart showing ordered tasks starting on August 29th, 2019 up to the completion of phase 2 of the project.