Propulsion Ankle Prosthetic

Awab Umar Khan[1] [Brad Stout[2]]

Abstract – Muscle atrophy is a major problem for the less fortunate amputees. Mercer on Mission is a program that goes annually to Vietnam to fit patients that cannot afford a genuine prosthetic; patients with muscle atrophy cannot be fit. For this reason a propulsion ankle prosthetic was designed. The purpose of this prosthetic is to give patients assistive force during the gait cycle. The energy of the reaction force created by the amputee during heel strike is delivered back to the amputee through the spring and it propels them forward which aids in ambulation. The prosthetic was manufactured and tested through Tekscan F-Scan® and Logger Pro using a real patient! The results obtained showed an improvement in gait and added force in the termination phase of the gait cycle. The use of such a prosthetic would rehabilitate the amputee's muscles over time; eventually helping them transition to the universal design prosthetic.

Keywords: Prosthetic, Ankle, Spring, Mercer, Vietnam

BACKGROUND

The Biomedical Engineering department at Mercer University has been manufacturing and refining above and below knee prosthetics for several years. Using Dr. Vo's universal socket design all amputees can be fit; however, in fitting these amputees there is a specific criterion that has to be met by the patient in order to receive a prosthetic. Inevitably every year patients are turned away due to several complications. Muscle strength plays a prominent role in the decision process; the amputee must have less than 40% muscle atrophy in their residual stump. This is a regrettable reality to turn away amputees, and for this reason Dr. Vo has requested the development and construction of a propulsion ankle prosthetic. This new prosthetic design will accommodate a greater range of amputees with muscle atrophy difficulties, and aid in their aptitude to achieve mobility once again.

Half way around the world is the country of Vietnam, located in Southeast Asia. Roughly 2,000 people are injured in Vietnam each year due to land mines as a byproduct of the Vietnamese war. The country as a whole contains around 100,000 amputees [1]; since it is an underdeveloped country, many of the amputees cannot afford customized prosthetics, often times going without one. The prosthetics owned by the amputees in Vietnam are generic, and most of them harm the patient instead of help. Without a stable government, the citizens are left to find ways to cope and treat their own injuries. Past amputees have spent up to a week's salary in travel expenses, just to be seen by the Mercer medical team. The importance of the medical mission truly has everlasting ramifications on the people aided.

This program couples service learning with study abroad, allowing for some cultural immersion to take place. These projects are targeted to help improve the quality of life of the people affected, utilizing the education and skills acquired over the student's academic careers. One of the missions in particular grants people the capability to walk, in so allowing them to live the life they once had! This selfless act does not only touch the hearts of those who are directly affected, but instills hope in the individuals as well. This medical mission is much more than a few summer classes to the students who participate. It is the chance to positively impact the lives of thousands, and inspire the world!

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INTRODUCTION

Muscle atrophy is related to the decrease in muscle mass. The worse the muscle atrophies the weaker the muscle becomes. Amputees, specifically, develop muscle atrophy due to the lack of use of their muscles shown below in *Figure 1*. This disuse overtime causes the muscle to weaken and lose mass. Eventually, this condition leads to the complete waste of the muscle to the point where it cannot be rebuilt. This, however, does not hold true if the amputees are consistent with exercising their muscles any way they can. The use of prosthetics is a good way to keep the muscle strength required to operate them. Muscles are used during ambulation and helps with strengthening and increasing the muscle mass.

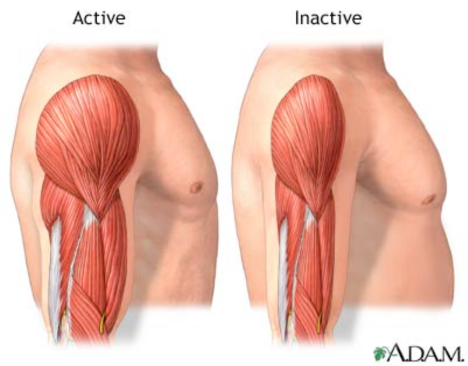

Figure 1: Healthy Muscle (Left); Atrophied Muscle (Right) [2]

Below the knee amputees are, as the name suggests, amputated below the knee. The muscles that are affected by such amputations include the calf muscles, which are made up of the gastrocnemius, plantaris, and soleus. Along with this, other muscles include the tibialis anterior, tibialis posterior, extensor hallicus longus, flexor hallicus longus, peroneous brevis, peroneous longus and many more relative to the location of the amputation illustrated in *Figure 2*. Two of the three calf muscles, the gastrocnemius and plantaris, function to flex the knee and plantar flex the ankle. The soleus only functions to plantar flex the ankle. Amputation causes disruption and the loss of function to these muscles along with the ones mentioned. Structure equals function and with such injuries when the structure changes, the function does as well. This sort of amputation limits the patient. The muscles they use for plantar flexion, dorsiflexion, inversion, eversion, supination, pronation, adduction, and abduction of the foot are not available to them anymore. The ankle joint has two degrees of freedom, which includes some of the motions just stated. A perfect prosthetic would provide a patient with all of these capabilities if they were amputated. However, this is not possible, and after amputation patients are limited; this limited use of the function can cause the muscles to atrophy over time. It can also change the orientation of muscles after amputation causing even more problems.

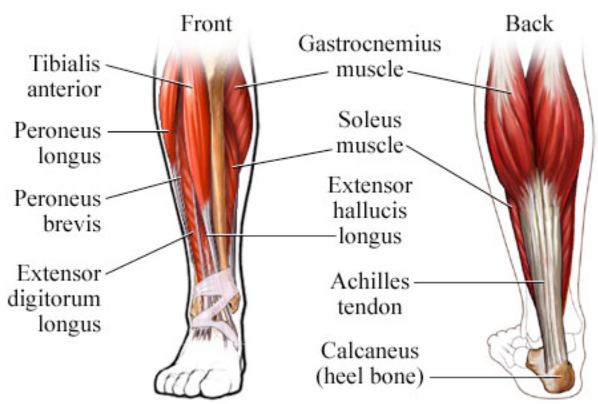

Figure 2: Lower Extremity Anatomy [3]

A tendon attaches a muscle to bone. The Achilles tendon helps insert the calf muscles into the calcaneus bone (the heel bone) and it acts like a spring in the ankle. This is so due to the compressive and tensile abilities of the tendon. The tendon converts potential to kinetic energy as it is compressed and released upon heel-strike during ambulation. The use of a spring feature for the prosthetic that was designed will take over some of this function and convert potential energy to kinetic energy just as the Achilles tendon does.

Gait Analysis

A single gait cycle consists of a stance phase and a swing phase. The stance phase includes 3 phases, heel strike, flat foot, and toe-off. The swing phase includes 2 phases, acceleration and deceleration. The following *Figure 3* goes through one normal gait cycle and shows the phases that are in action.

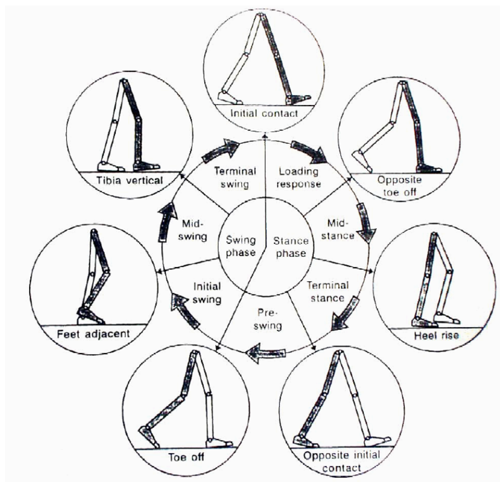

Figure 3: Single Gait Cycle [4]

As the figure illustrates, the initial contact is at heel strike, which is a part of the stance phase. From here there is a loading response when the load is shifting form heel strike to mid-stance, also known as flat foot. After this point the load shifts again towards the termination stance called the toe-off. The instance that the foot leaves the ground it is in the pre-swing phase, after which is the initial swing. From the initial swing to the mid-swing the foot is in acceleration, once the foot passes mid-swing and is in termination swing, the body is bracing for the heel strike so the foot must start decelerating. This gait cycle is integral in understanding the ankle movements during gait.

At heel strike, initial contact, the ankle dorsiflexes. As the loading response shifts to mid-stance, there is gradual dorsiflexion. Once the gait cycle gets to the toe-off phase, the movement involved is plantarflexion. While the foot is in the swing phase, the foot is dorsiflexed. This is to avoid dragging the toes against the ground and also to prepare for heel strike as the cycle continues. These movements are possible because of the articulation of the tibia against the talus. The subtalar joint movements, eversion and inversion, occur simultaneously depending on what part of the gait cycle is being observed. Inversion occurs during the initial contact phase to prepare the body for contact and it occurs once again in the toe-off/termination stance to keep the ankle rigid and provide a stable platform. After the inversion at heel strike, eversion occurs during the loading response to mid-stance. This change is to allow the body to absorb the shock and adapt to the terrain. The benefit of having a rigid platform during heel strike and toe-off is to keep the ankle stable and reduce the probability of an injury occurring. This is a biomechanical mechanism that plays an important role in the gait cycle. The *Figure 4* below is a graphical representation of the ankle movement during gait.

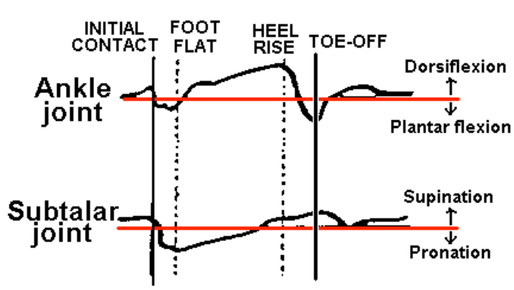

Figure 4: Ankle Movement during Gait Cycle [4]

There is a significant amount of movement and load involved at the ankle joint. The ankle has to bear up to 5 to 7 times the weight of the person walking during normal ambulation on flat ground. Therefore, if an individual were to weigh 150 lbs, the amount of load at heel strike during ambulation would be around 750 to 1050 lbs. This is a significant amount of weight coupled with the complex movements. Strong ligaments, henceforth, stabilize the ankle joint. Ideally it is desired that an amputee walk biomechanically as closely as possible with the use of a prosthetic as without [4].

MATERIALS AND METHODS

There are a numerous amount of tools and materials that were used in the construction of the prosthetic. However, due to the page limit only the construction method is highlighted. It should be cautioned that proper handling of the materials and machinery should be used. Safety is the number one priority when building the device. Supervision of experienced personnel is advised!

There are two components to the foot, the top plate and bottom plate. In order to make the top plate, a mold had to be used to make the foot portion of the prosthetic. The material that was used to make the mold is aluminum T3003 and it was bent according to the shape of the top plate that was desired. Polypropylene plastic sheets of ½" width were cut into proper dimensions and heated in the oven at 390° for a specific period of time after which they were taken out and the mold was utilized. The bottom plate was made with a flat piece of polypropylene plastic of ¾" width. The front portion of the bottom plate has the sliding mechanism, and this is the reason that the thicker plastic is used. The back portion of the bottom plate is cut in half to reduce the width and weight of the foot. The top plate is connected to the bottom plate at the sliding mechanism region. This is a special joint in that it is a revolute joint but there is also a sliding capability of the top plate on the bottom plate. This mechanism is used for the spring that is to be placed in between the top and bottom plates in line with the pylon and the rest of the prosthetic. The spring that is used is LHC 207U 01M. This spring has a free length of 2.5" and a solid length of 1.365". The rod diameter of the spring is 1.472" and it has a spring rate of 146.4 lb/in, which complies with the target rate, determined by the patient's weight that is to be tested. The spring is attached to the top plate by milling out a circle and using melted polyethylene. A hole was put in the bottom plate where the spring is to be placed and a galvanized steel pipe was measured, cut, and inserted into the hole. The bottom of the pipe is flared on the bottom plate to stabilize it to the plate. The pipe can then insert inside the spring. The superior aspect of the prosthetic is identical to the Universal Design prosthetic that is famous at Mercer University, and therefore its construction methods are not discussed. Crepe and foam are used to give the foot a more aesthetic appeal. The following *Figure 5* shows the top and bottom plate before they are assembled using a binding post, and then with the binding post inserted.

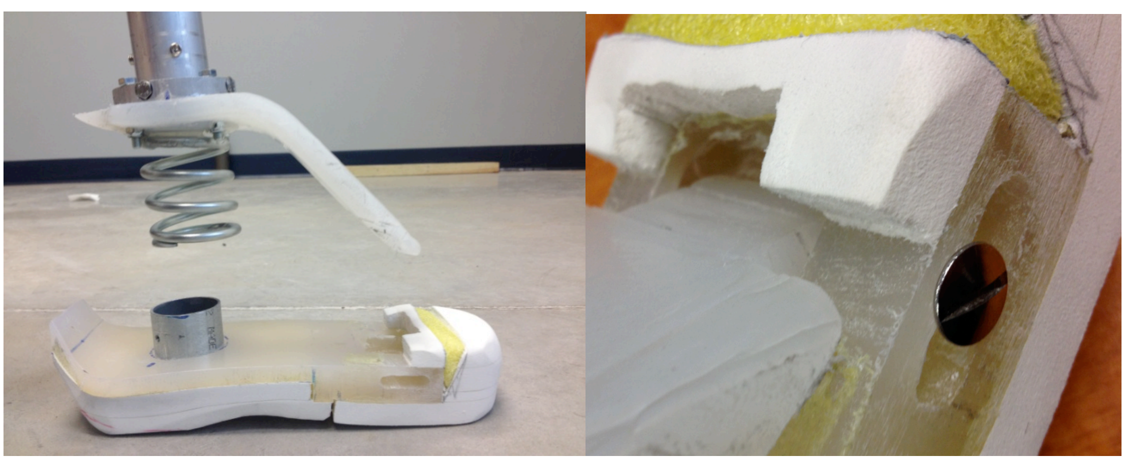

Figure 5: Pre & Post Binding Post Insertion

Patient Profile

Figure 6. Amy Talcott

Name: Amy Talcott (*Figure 6*)
DOB: 09/02/1973
Weight: 162.8 pounds
Height: 5’11”
Shoe size: Women’s 12
Cause of amputation: The patient was born with a fatty foot and the bones did not develop properly, and due to this reason her left leg had to be amputated below the knee.
Background: The patient’s current prosthetic has been in use for two years. She has had a prosthetic since she was 12 months old. The patient is highly active in sports and requires a durable prosthetic. During F-scan analysis for the patient’s personal prosthetic sandals were used to secure pressure sensors. In the operation and testing of the ankle propulsion prosthetic, due to the limitations of the prosthetic, shoes had to be used.
Cost of personal prosthetic: The patient had a college park prosthetic that was estimated to be $24,000. The cost of the patients silicone insert was approximately $1000. Mr. Paul Boland, prosthetist, fit the patient at Boland Prosthetics and Orthotics in Warner Robins, GA.

The ankle propulsion prosthetic had to be tested to ensure that it was functional. Part of the analysis was to test the mechanical components of the prosthetic to determine if there were any weak points. The prosthetic was constructed for a 150 lb. patient and its purpose was to propel the patient forward. The F-Scan® software was utilized to measure pressure variations on both of Amy’s feet. This data yields the patients peak pressures during heel strike and toe-off. The data also provides information on her peak forces during gait. The ankle propulsion prosthetic was compared and analyzed against the patients real prosthetic to determine differences, similarities, advantages, and disadvantages.

This prosthetic was constructed for the purpose of aiding those amputees that have atrophied muscles. Unfortunately, for this research such a patient could not be found. Mrs. Talcott was wonderful enough to volunteer as the test subject. Though the tests would have been more beneficial if tested on a patient that had muscle atrophy, significant conclusions can still be drawn from the testing that was done. It can still be used to prove that the prosthetic works and compare it to the patient’s gait with her prosthetic to determine if she is assisted during ambulation. The patient was healthy and active and was therefore included in this research.

RESULTS AND DISCUSSION

Testing

After the prosthetic was constructed it was tested with the use of a real patient. Tekscan F-Scan® is used to accomplish this. The F-Scan® system is a gait analysis tool that is used at Mercer University to collect plantar pressure data. The patient had to be F-scanned to assess her pressure variations as she walks during their natural gait cycle with the new prosthetic. F-scan® is composed of two sensors that are connected to two hubs. The sensors detect pressure variations shown below in *Figure 7*. The data is then wirelessly transmitted to the computer and the corresponding graphs and charts are formulated. This system has been used to evaluate amputee prosthetic fittings and to also conduct research on limb length discrepancy. The software has the capability to chart center of force trajectory, step averaging as a graph showing force versus percentage of step, and multistep force versus time analysis. Calibration of the F-Scan® allows for force and pressure measurements to be taken with respect to the subject’s weight, therefore calibration is used prior to evaluation of every new patient.

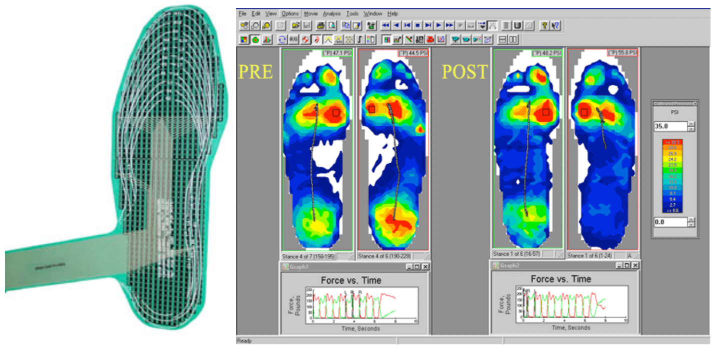

Figure 7: Sensor (left), pressure variations (right) [5 & 6]

After the patient is fitted with the prosthetic, the F-scan® software is used to acquire gait data by recording pressure/force distribution over a specified distance. The patient is required to walk a straight path while wearing the F-Scan® sensors. This data is saved and used to analyze the patient and compare the individual legs of the patient. This helps compare the patient's real leg with their prosthetic leg. On-site analysis of this data provides near real-time feedback on the patient's gait. The operator, using a trained eye, can view the color gradient display (2-dimensional) to determine if varus/valgus adjustments are needed. Analysis of the force versus time and force versus percentage graphs can provide information on phase times, degree of force applied in each phase and comparison data between the two legs. Looking at the center of force trajectory will inform the operator of any discrepancies in the rotational alignment of the prosthetic foot, allowing the fitter to make necessary adjustments to abduction/adduction.

The first step in collection of data is cutting the sensors to fit the shape and size of the patient. When complete, the sensors are securely placed in shoes that are the appropriate size for the patient. This ensures that the sensors do not move and crinkle inside of the shoes (Note: wrinkles in the sensor will cause pre-loaded values to be recorded, this appears as providing initial offset to the recording and should be avoided). Straps are used to secure the handles to each leg. Ethernet cables are connected from the handles to the F-scan® hub to bring the pressure data from the sensors to the F-Scan® software in the computer wirelessly. After this is done, the patient's first walk is used to calibrate the sensors; the patient's weight is recorded to ensure accuracy in calibration. A second recording is collected that is used as post calibration data for analysis. All of the data is then analyzed as mentioned earlier for discrepancies and to make comparisons between the prosthetic leg steps and the natural leg steps.

Amy's Personal Prosthetic F-Scan Data and Analysis

Figure 8 below gives the pressure distributions for the forces that are at the end of the patient's feet during ambulation. The calibrated pressure legend gives the colors that correspond to the amount of pressure applied. The peak stance pressures are seen in this image. The patient wears a left leg below knee prosthetic and applies more force to this leg copmared to her actual leg. During the gait cycle, progressing from heel strike to mid-stance to toe-off, the peak pressures that were applied were higher for the left foot compared to the right foot. This shows that the patient truly trusts her prosthetic to support her during ambulation. Another reasoning behind this pressure distribution could be due to the manufacturing of her personal prosthetic. It was noted, that the patient liked the prosthetic leg pylon to be slightly longer than her actual leg. This would, overtime, cause the pressure that is applied to that limb to be greater.

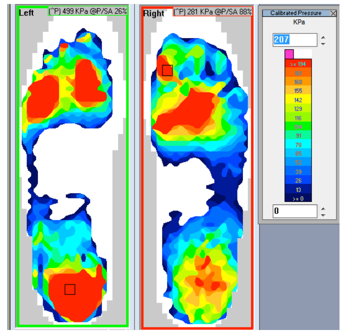

Figure 6: Peak Stance Average (Personal Prosthetic Trial 1).

After the peak stance averaging is done for the pressure distributions on both feet, a graph can be plotted of Force versus Percentage. The green line is representative of the patient's left prosthetic leg and the red line is representative of the patient's right leg, her actual leg. The peaks that are labeled with a vertical line are during the heel strike phase of the gait cycle. This graph shows that during the gait cycle from heel strike to mid-stance to toe-off, there is more force applied at the heel strike on the prosthetic leg than at the patient's actual leg. This data further helps prove that even though it goes against the norm, the patient applies more pressure on her artificial limb. This difference at heel strike is 23.9 lbs higher for the left leg versus the right leg. This value was calculated after averaging all of the peak stances during gait for the left and right foot (*Figure 9*).

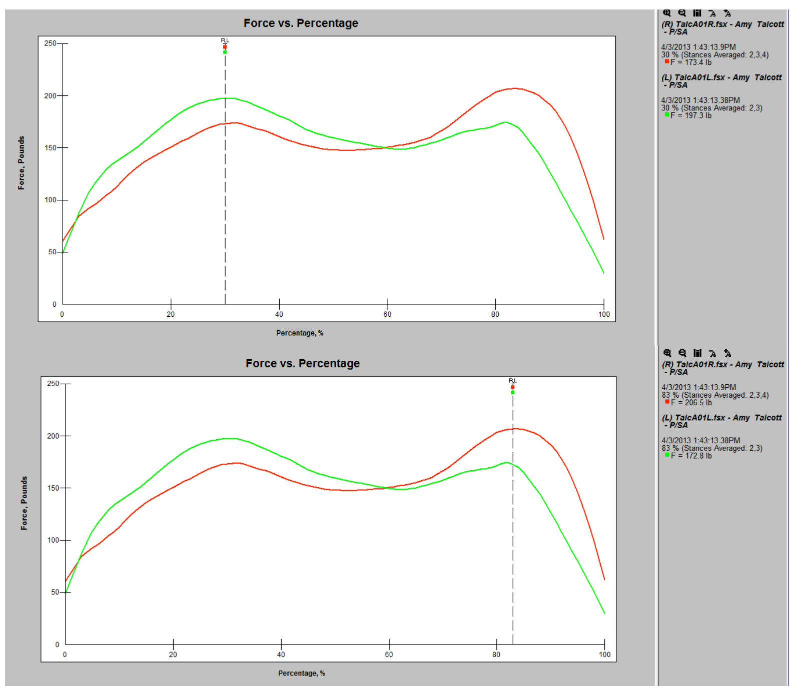

Figure 7: Force versus Percentage at Heel Strike (Top) & Toe-off (Bottom) (Personal Prosthetic Trial 1).

At the toe-off phase of the gait cycle, the left foot and right foot were compared again after having peak/stance averaged all the data. This gave a force difference of 33.7 lbs. The right foot has a greater toe-off force than the prosthetic foot. This data matches with the force versus time graph (not shown), which yielded a higher right foot toe-off force of 34.5 lbs. This is roughly around the value obtained after averaging all of the peaks/stances. The similarities in these values strengthen the conclusion that at heel strike, the left foot experiences more force, and at toe-off the right foot experiences more force. The amount of pressure and the location that it is applied fits with the peak/stance average pressure distributions shown above in *Figure 9*.

One of the features in the F-Scan® software that was also used to analyze the patient's gait was center of force (COF) trajectory. This feature is beneficial in observing the speed of pressure distribution in each foot during gait. It also shows the line that the COF trajectory follows as the patient goes from heel strike to mid-stance to toe-off. From the pressure distributions video, it was observed that the prosthetic leg (left leg) had a faster COF than the right. Also, the COF for the left foot was more linear from heel strike to toe-off. The right foot had a longer COF. This could be due to that being the patient's actual foot or it could be due to the pressure sensors that were placed in the sandals. The right foot COF trajectory had a curved pattern and this is due to the patient having an arched foot shown in *Figure 10*.

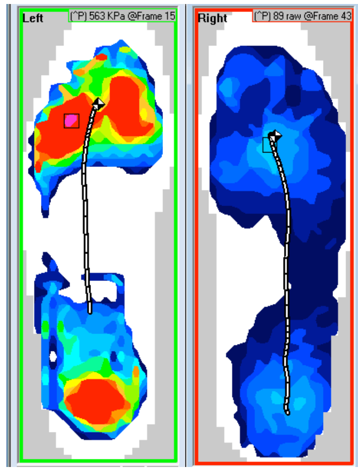

Figure 10: Center of Force (COF) Trajectory from Trial 3 (Personal Prosthetic).

Amy's Propulsion Ankle Prosthetic

Below is the pressure variation of trial four. The amount of pressure exerted on the heel portion of the propulsion ankle prosthetic was similar to that of the pressure exerted upon the patient's residual limb. One of the points that should be noted would be the average heel force for the prosthetic. The force is not exerted over the whole surface area of the heel, yet it is concentrated on the medial side. This could be attributed to both the crepe and the positioning of the spring. The following *Figure 11* shows the average force being exerted on the bottom of the prosthetic and the patient's foot. As the patient became more comfortable with the prosthetic, her gait improved vastly as did her results.

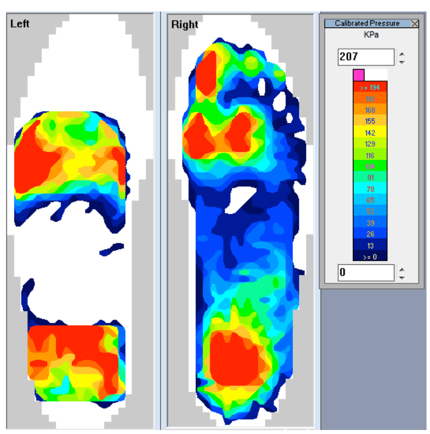

Figure 11: Trial Five Pressure Variation.

The force versus percentage is an important graph because it illustrates the difference between the patients existing limb and the prosthetic. This helps to compare the two and discriminate between force differences. This is an average of all of the steps for both the left and the right feet. The patient has a distorted heel strike overall. This is due to the right foot rolling from medial to lateral as the heel strike progresses throughout the gait. The patient's right foot heel strike has a force of 159.2 lb and a left foot heel strike of 183.8 lb. This again reinforces that the patient places more force onto the prosthetic during heel strike than her residual limb. Both the heel strikes come at around the same time, so the right and left feet are moving at the same pace shown below in *Figure 12.*

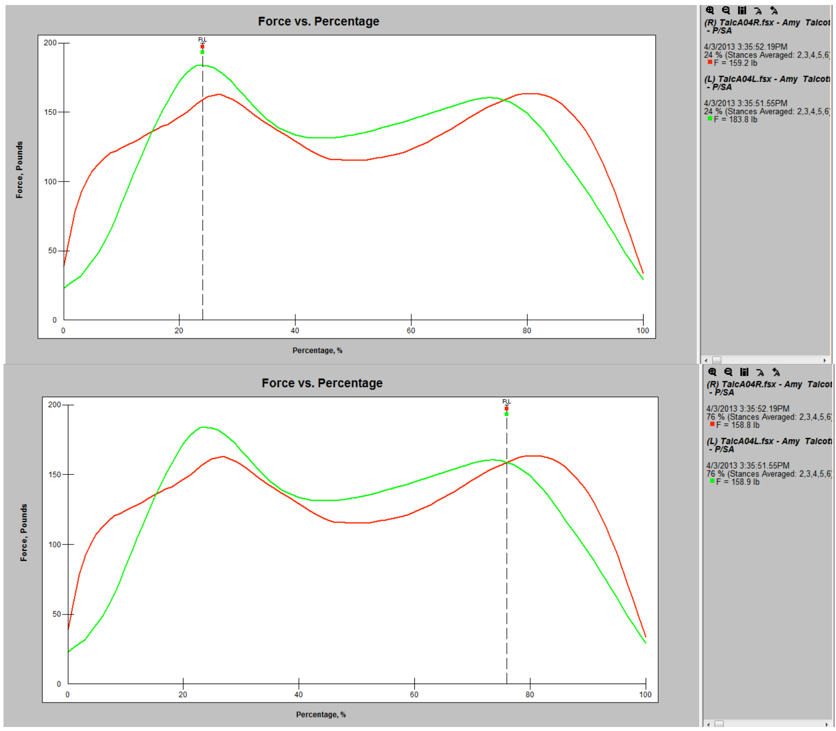

Figure 12: Heel Strike (Top) & Toe-off (Bottom) Force Difference

The patient's toes off forces were very similar between the right and left feet. The right foot had a toe off of around 158.8 lbs and the left foot had a toe off of 158.9 lb. As the figure illustrates, the left foot goes through the mid-stance portion of the gait into the toe off much faster than the right leg. This can be attributed to the spring propelling the patient's foot forward as she walked shown above in *Figure 12.*

Below in *Figure 13*, is the center of force for the prosthetic. This line shows the force flow from heel to toe and is important in analyzing how straight a patient walks. The propulsion ankle prosthetic maintains a very straight trajectory in comparison to the patients pre-existing prosthetic. This helped the amputee maintain a relatively consistent gait.

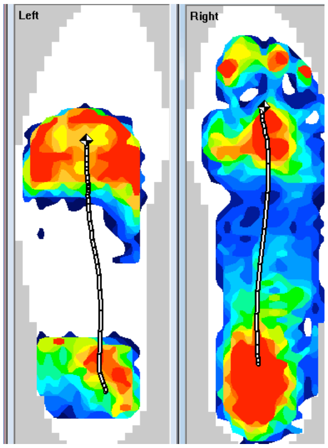

Figure 13: Center of Force (COF) Trajectory from Trial 4

CONCLUSION

The propulsion ankle prosthetic was designed to propel the patient forward to help prove that it could aid patients with muscle atrophy. The prosthetic did just what it was intended to and it propelled the amputee forward. The pressure variations between both the patient's original prosthetic and the propulsion ankle prosthetic were similar with respect to the toe-off phase. The forces applied during toe-off were a lot closer than those measured during heel-strike. The patient relies heavily upon her prosthetic, and places about 90 lbs. more force during ambulation on her left leg (prosthetic) than the right. This pattern was observed in both the patients existing college park prosthetic and the propulsion ankle prosthetic. This consistency in load distribution proves that the patient trusted the propulsion ankle prosthetic as much as her personal prosthetic, which is not often the case because patient's are apprehensive about trusting a device they are using for the first time.

The center of force between both the patients pre-existing prosthetic and the propulsion ankle prosthetic were very similar as well. The patient retained a very natural gait due to her ability to maintain a straight center of force as she walked with both prosthetics. It should be noted that the propulsion ankle prosthetic accelerated the patient's swing phase. When looking at the force versus percentage graph, the prosthetic completed swing phase much faster than the residual limb. This can be attributed to the spring converting potential to kinetic and back. This energy was delivered back to the patient via the spring. Overall, the prosthetic functioned well, and did what was required of it. The patient did not have problems walking with it, and stated, "I definitely like the spring action", referring to the regenerative energy that could be harnessed with the spring.

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BIOGRAPHICAL INFORMATION

Awab Umar Khan

I was born in Lahore, Pakistan and my family moved to the United States when I was 8 years old. My parents wanted for my brothers and I to have a better education. I have lived most of my life in Macon, GA. After middle school I attended Central High School as a part of the International Baccalaureate (IB) program. After graduation I chose to attend Mercer University also in Macon, GA and major in biomedical engineering on the pre-medical track and a minor in technical communications. I participated in Mercer on Mission to Vietnam in 2012, a well known program, where a group of students go and fit the less fortunate amputees with a prosthetic developed by Dr. Ha Van Vo, set up an orthopedic clinic, teach physical therapy, and give food and medication to those in need. I went again to Vietnam in the winter of 2012 and became a certified and licensed prosthetist.

Brad Alan Stout

Brad had the pleasure of participating in the Mercer on a Mission Vietnam trip with Dr. Vo and other students during the Summer of 2012. This trip has made him understand the gravity of the situation this proposal entails and the need for a propulsion ankle prosthetic. Brad's knowledge and firsthand experience with prosthetics will make him a great addition to the team. Additionally, Brad volunteered previous to going to Vietnam in the prosthetics lab manufacturing the above and below knee prosthetics for Dr. Vo. The experience gained from both of these will greatly help his team.