TESTING OF AN ELECTRONIC CONTROLLED PROSTHETIC SYSTEM TO REDUCE VOLUME LIMB LOSS

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ABSTRACT

Residual limb shrinkage is a major concern for prosthetic users with below the knee amputations. The remaining limb will shrink as the fluid is squeezed out as an amputee walks and applies forces to the remaining limb throughout the day. This shrinkage can lead to a loss of orientation control, uncomfortable socket fit and possibly limb tissue damage. Vacuum control is the leading method for dealing with the limb shrinkage but lacks fine control.

The system proposed uses electromagnets to add regional control while also being used to help with suspension of the limb. The rest of the system consists of pressure sensors, a microcontroller, and additional circuits to amplify the sensor outputs and control the amount of power to the magnets. The microcontroller reads the decreased pressure and sends additional power to the magnets of that region and vice versa.

A prototype system had already been devised and initial tests were done on it. However the component used to drive the electromagnets was overly complex and limited in the number of magnets that it could drive. To replace this component a simple driving circuit was devised and as many as 12 of these circuits would be able to fit onto the prototyping breadboard. The controllers coding had also been started but it too was more complicated than it needed to be. The arduino control code was simplified and expanded to control 8 magnet/sensor pairs.

To tests if our proposed system could work as a suspension system, we conducted two tests. The first was a tension test that would see if the magnets could suspend the weight of the limb and test the control system within the socket. The second was a pressure test to check the responses of the control system.

Both test showed that the control system was working properly and that the magnets would be enough to act as a suspension system for the prosthetic limb. However, while building and testing the prototype it was concluded that while the control system and the electromagnets work as proposed, the electromagnets are large and cumbersome. Future work using the newer technology of electrostatic adhesion was proposed. It would use the same control idea of this system, to achieve a less bulky design.
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CHAPTER 1
INTRODUCTION

Transtibial or below the knee amputation is the most common amputation in the United States. It is estimated that there are 185,000 new lower extremity amputations each year[1]. When asked, “lower-limb amputees rated socket fit as the most important issue they face in using a prosthesis [2].” Currently the leading method for suspension and comfort in prosthetics for amputees is the vacuum assisted system (VAS) which was developed over a decade ago. With more advanced technologies available, our goal is to expand on the recent research done on transtibial electromagnetic suspension systems. We hypothesize that an electronically controlled electromagnetic suspension system for below the knee prosthetics will allow for regionally controlled application of negative pressures.

1.1 Amputee Statistics

The Advanced Amputee Solutions’ website says [1]:

- Among those living with limb loss, the main causes are vascular disease (54%) including diabetes and peripheral arterial disease, trauma(45%), and cancer (less than 2%).
- The number of amputations caused by diabetes increased by 24% from 1988 to 2009.
- Below-knee amputations are the most common amputations, representing 71% of dysvascular amputations; there is a 47% expected increase in below knee amputations from 1995-2020.
- The Amputee Coalition of America estimates that there are 185,000 new lower extremity amputations each year just within the United States and an estimated population of 2 million American amputees.
- It is projected that the amputee population will more than double by the year 2050 to 3.6 million.

The data above correlates with Ziegler et al’s paper on “Estimating the Prevalence of Limb Loss in the United States”[3]. Additionally, they attribute the large increases of lower limb amputations to “the aging population and the the high rates of dysvascular conditions among older adults[3]” which correlates with diabetes.
1.2 Socket Fit

The prosthetic socket is designed to comfortably support the body’s weight and should be comfortable and snug. To have a good fit, a prosthetic socket must effectively transfer the forces from the socket to the residual limb in a way that allows for daily activities without damaging the tissues or causing pain. Achieving the proper fit is difficult because it requires previously non-weight bearing tissues to adapt and accept the new high pressures while walking. When an amputation of a lower limb occurs, the individual no longer has support structures that can absorb the shock when walking; forcing the remaining soft tissues of the limb to absorb these forces. Because the soft tissues in the limb are not meant to absorb great amounts of force, injuries and discomfort can occur. In order to protect the tissues within the amputated limb, it is necessary for the prosthetic socket to maintain the forces generated within safe limits. As the socket is worn over time, the forces can compress the limb tissues and cause the limb to reduce in size, thus making the socket loose and uncomfortable. “Loss of limb volume can cause bony prominences to accept more of the load during weight bearing and allow greater pistoning of the socket during ambulation”[2].

The basic principles for socket design vary from distributing most of the load over specific load-bearing areas or by distributing the load more uniformly over the entire limb. The pressures between the socket and liner vary among sites, individuals, and clinical conditions. See Figure 1.1 the pateller-tendon-bearing socket’s design centers on the idea of using specific pressure-tolerant and intolerant areas of the residual limb for transfered force distribution.[4, 5]

1.2.1 Friction

An important factor in socket fit is the way the residual limb and the socket are joined. This will affect the slippage between the skin, the prosthetic socket and the deformative residual limb tissues. The sockets shape also influences the tightness of fit and can change the pressure distribution. “A loose fit may allow slippage, which may compromise stability, while a very tight fit may offer a more stable connection, but increase the interface pressures [5].”

Friction between the residual limb and the prosthetic socket produces shear action on the skin which leads to tissue distortion. If this distortion becomes too large damage can occur. The shear forces caused by friction on the skin’s surface distributes the user’s weight onto the prosthetic or conversely the weight of the prosthetic onto the user’s limb when walking.
A proper balance in the coefficient of friction needs to balance high local stresses and tissue distortion while being able to support loads and prevent undesirable slippage.[5]

If there is slippage while walking, areas of the limb will see repetitive rubbing. This repetitive rubbing produces heat, “which may cause uncomfortable and detrimental consequence[5].” There are two skin reactions to repeated rubbing: The first is skin thickening when the abrasive force is small but rubbing is frequent and repeated. The other involves the formation of blisters when the abrasive force is large.[5] These reactions can be removed or minimized with a properly fitted socket.
1.2.2 Tissue Responses to Pressures

The socket transfers the forces of walking to the limb and must be designed to help protect the limb’s soft tissues. The skin and the underlying soft tissues of the residual limb are not particularly adapted to the high pressures, shear stress, abrasive relative motions, and the other physical irritations. Because of this it is not uncommon to develop skin problems such as blisters, cysts, edema, skin irritations and dermatitis. “Discomfort and skin problems are usually attributed to a poor socket fit [5].”

It is understood that good skin condition must be maintained, or else the prosthesis can no longer be worn. Mak et al states that the soft tissues of the residual limb within a prosthetic socket are subjected to a special environment:[5]

- The residual limb has to deal with dynamic and repetitive pressures and shear forces that are applied by the snugly fitted socket.

- Skin rubbing against the socket can result in intermittent skin deformation and biomechanical irritations. If it is excessive enough tissue abrasion can occur and heat will be generated.

- The socket fit restricts air circulation to the residual limb. This results in the collection of sweat in a high humidity environment.

- The residual limb tissues may suffer from possible chemical and mechanical irritations or allergic reactions to various socket or interface materials.

Normally, physiological forces will not disrupt tissue functions, but there are instances where it may occur. One such instance is the improper application of a large force. Another instance is if the force is prolonged or repetitive. “Mechanically, forces applied to skin surface will produce stresses and strain within the skin and the underlying tissues. Those stresses and deformation affect cellular functions and other biophysical processes in the tissues.” [5]

“Although a moderate force may not cause direct and immediate damage to the tissues, repeated applications day after day could initiate an inflammation reaction, and even result in tissue necrosis. When the applied load is within certain ranges, tissue adaptation may occur by changing tissue composition and architecture.” [5]

To avoid further tissue damage paying attention to pain is important because it is an immediate indicator for when something is wrong. A problem occurs when neuropathy develops resulting in the user’s pain being dulled or not even sensed. “Normal sensory
functions of a human body can often help to avoid a mechanical injury and the subsequent
tissue damage. Such sensory feedback can prompt the subject to stop or avoid further
application of the loads [5].” When the symptoms are ignored the tissues and the systems
within the tissues are affected.

When moderate static forces are applied to the skin, the underlying blood vessels and
lymphatic drainage can be stopped, resulting in oxygen and other nutrients no longer being
delivered at a rate sufficient to satisfy the metabolic requirements of the tissues. “Without a
sufficient circulation, the break-down products of metabolism would accumulate within the
tissues. If such a condition continues, cellular functions would be compromised and could
ultimately fail.[5]”

All living things require an inflow of nutrients and the ability to expel wastes. When
pressure is applied to the limb these flows are interrupted; the vessels can be pinched closed
and the nutrients are cut off to the tissues. “It is generally believed that ischemia is related
to the formation of pressure sores and can lead to local malnutrition” of the tissues. It was
noted that blood flow was reduced with the increased application of force.[5] The removal
of the tissue waste is handled by the lymphatic system. “The lymphatic system consists of
a complex network of vessels, and presents a drainage route for transport of excess fluid,
protein, and metabolic wastes from the tissue of origin into the circulatory system. Exter-
nal loads may interfere with the normal function of the system. With tissue edema, poor
lymphatic function was associated with sore formation.[5]” Edema decreases wound healing
by limiting capillary blood supply.[6] External forces and its effects on these two flows are
instrumental in understanding volume limb loss.

1.3 **Limb Shrinkage**

The residual limb of transtibial amputees goes through significant changes in shape and
volume throughout the day. Therefore the socket must be adjusted constantly due to the
frequency in changes so problems with socket fit, gait instability and skin breakdown is
minimized.[6]

Limb shrinkage depends on the balance between the hydrostatic and osmotic pressures
within the blood vessels and pressures in the surrounding tissue (interstitial pressures). See
Figure 1.2. Within the vessel, the primary hydrostatic force is the heart as it pumps. This
pressure is usually stronger than any other acting on the vessel walls, so the result is for
fluid to have net movement out of the vessels. The osmotic pressure, is the force that tends
to draw fluids back into the vessel. Specifically oncotic pressure, or colloid osmotic pressure, is created by proteins that normally cannot leak out through the vessel membrane and thus create a consistent pressure promoting fluid movement into the vessels.[7]

![Capillary Microcirculation](https://upload.wikimedia.org/wikipedia/commons/0/03/Illu_capillary_microcirculation.jpg)

Figure 1.2: Illustration of fluid interaction Source: <https://upload.wikimedia.org/wikipedia/commons/0/03/Illu_capillary_microcirculation.jpg>

Interstitial fluid is a solution that bathes and surrounds the tissue cells. “It provides a means of delivering materials to the cells and removes metabolic waste.[8]” See Figure 1.3 for a diagram of interstitial fluid and what it reacts with.

Blood and interstitial fluid are not the same. While interstitial fluid is a component of blood, “red blood cells, platelets, and plasma proteins cannot pass through the walls of the capillaries where interstitial fluid can. Interstitial fluid consists of water solvent containing sugars, salts, fatty acids, amino acids, coenzymes, hormones, neurotransmitters, as well as waste products from cells.[8]” Interstitial fluid also contains white blood cells, which help combat infection.

Due to the increased pressures from the transtibial socket on the soft tissues, there is an increase in the hydrostatic pressure within the interstitial spaces. “This forces the interstitial fluids into the venous and lymphatic systems. Both of these systems have one-way valves and serve to return fluids to the central circulation where they are recirculated by the heart. Fluids that leave the vascular system from the arterial side can only re-enter on the venous side.”[7]
It is the interstitial fluid that is so important to prosthetic fit. “When the volume of interstitial fluid that moves from the arteries into the interstitial space is out of balance with that from the interstitial space into the veins, the residual limb will change volume."[6]” As long as the prosthesis continues to apply pressure to the soft tissue, the hydrostatic pressure within the interstitial spaces of the limb will remain elevated. During ambulation the fluid is pushed out of the limb faster than the tissues can recover and at some point an equilibrium is reached where the tissue cannot be compressed further.

It is because sustaining proper circulation and fluid exchange in the soft tissue is imperative for maintaining a healthy residual limb, that systems are being developed to counter limb shrinkage.

### 1.4 Vacuum Assisted Suspension (VAS) Systems

Vacuum assisted suspension systems are the current leading technology for comfort and countering volume limb loss. It indirectly holds the residual limb’s soft tissues against the hard residual limb socket. Its purpose is to retard limb volume reduction by improving fluid inflow into the residual limb so that it better balances with fluid outflow.[6]

Positive pressures decrease the volume of the limb by driving fluid out (i.e. during stance), while negative pressures increase limb volume (swing phase of gait). Vacuum suspension
helps to control the prosthesis by preventing the limb from losing volume during the day. “Unlike other designs of suspension where the socket fit becomes sloppy as the limb loses volume each day, the limb stays hydrated and set to the socket.” [9]

“Traditional forms of suspension are mechanically static. The user dons the prosthesis and a mechanism holds it onto the residual limb preventing detachment. Once the user is fully engaged in the interface, the suspension mechanism becomes static in that it does not further or actively draw the patient’s residual limb into the prosthesis. In a vacuum-assisted suspension (VAS) environment, either an electronic or a mechanical vacuum pump[10]” actively draws air out of the area between the liner and the prosthetic interface creating an area of negative pressure. Because VAS socket minimize separation of the liner and socket better than other traditional suspension methods, the residual limb within the socket itself undergoes significantly less volume reduction throughout the day. Not allowing the residual limb to reduce in size allows blood vessels to maintain a more consistent size, lessening the inhibition of blood flow which is commonplace with traditional socket designs. “The advantages of this type of dynamic suspension could improve total contact between the residual limb and the interface. Improved total contact could help distribute weight-bearing forces, whereas dynamic suspension could assist in reducing motion between the residual limb and the socket. This would secure the prosthesis onto the residual limb while reducing friction on the skin. VAS offers the amputee a dynamic form of suspension that may provide a more positive link to the prosthesis and can reduce prosthetic interface movement during gait and other activities such as sitting. Reduced motion could increase control in swing and stance by establishing a more stable and healthy environment for the residual limb.[10]” The combination of reduced movement of the residual limb within the socket and better maintenance of the residual limb volume typically results in a more consistent and symmetrical gait. A more consistent and symmetrical gait lessens the tendency to fall.

Figure 1.4 below shows how a vacuum-assisted system works. As the limb and the socket move in opposite directions the limb and liner will want to pull out of the socket, the vacuum system will keep the liner against the sides of the socket for as long as the seal holds. The tissues of the limb within the liner will try and pull away from the liner. However because of the interaction between the skin and the gel liner the skin will stick to the gel lining and the tissues within the limb will be pulled outwards decompressing and drawing the interstitial fluids back into the soft tissues.

Vacuum suspension systems actively prevents separation between the liner and the socket (other modes of suspension begin to separate from the socket when force is applied). As
stated before the residual limb is not directly affected by the vacuum. Because of this the connection between the skin and the liner is important in the success of VAS systems. “All forms of VAS will have some type of proximal seal to block the air outside and form a vacuum environment with a distal vacuum. The more proximal the seal, the larger the area affected by VAS. Additionally, a positive residual effect of this sealing gasket is that it forms a coefficient of friction between the liner and the hard prosthetic socket. This coefficient of friction can minimize movement between the liner and the hard socket and ultimately the residual limb. Achieving and maintaining vacuum is contingent upon the effectiveness of the proximal seal. The location, size, and shape of the sealing gasket play a role in the seal’s effectiveness.” [10]
1.5 VAS Effects

“VAS is credited with helping to regulate volume fluctuations in the residual limb, making suspension more secure and reducing shear forces on the limb[6].” According to Biel et al. [2] with the use of VAS systems, thirty minutes of walking resulted in an average gain of 3.7 percent of limb volume as compared to losing 5.6 percent of the limb volume when walking in a total-surface weight-bearing socket without vacuum-assist.

Kahle et al.[10] did a literature review to determine if the commonly held view about the benefits of vacuum-assisted suspension (VAS) are supported by literature. His conclusions are as follows:

Enhanced suspension can be a contributory factor to optimizing stability. A more solid connection to the interface would potentially create less motion during swing, likely resulting in greater stability for the amputee. ... The advantages of this type of dynamic suspension could improve total contact between the residual limb and the interface. Improved total contact could help distribute weight-bearing forces, whereas dynamic suspension could assist in reducing motion between the RL and the socket. This would secure the prosthesis onto the residual limb while reducing friction on the skin. ... Reduced motion could increase control in swing and stance by establishing a more stable and healthy environment for the residual limb.

Kahle et al’s research found the following about VAS effects versus other forms of sockets: [10]

- Two studies with evidence that VAS sockets increase volume, whereas non-VAS sockets reduce the volume of the residual limb during prosthetic use.
- Pistoning was significantly less in the VAS sockets compared with pin system sockets
- Tibial displacement was less.
- Liners of VAS sockets displaced less than the suction sockets.
- A significant reduction of medial proximal pressure was observed while utilizing a VAS interface.
- Two studies with evidence that VAS sockets favorably affect the pressure distribution of the residual limb.
“These findings would have clinical significance, as the pressures an amputee experiences are significantly higher than those that can cause skin breakdown[10].”

They found two studies on the VAS wound healing topic. “One reported an improvement on the Locomotor Capability Index (LCI) time to fitting and time to taking first steps when using VAS compared to a non-VAS socket design. The other showed that VAS was equivalent in wound healing as compared to a standard soft wound dressing. No evidence exists to support the notion that a prosthesis can assist in healing wounds, with or without VAS.[10]” What this means is that while VAS will not help in wound healing it will not impede the tissues from healing themselves. And because of this users can don their prosthetics earlier both initially and when a wound of the limb occurs.

1.6 Problems with VAS and Proposed Solution

Vacuum assisted suspension systems are intended to hold residual limb soft tissues against the hard residual limb socket[6]. As air is expelled from the socket, the limb is pulled toward the socket wall and held in place by the force of the negative air pressure as the vacuum effect is created. From this two problems became apparent.

The first problem is the loss of the seal between the liner and the socket. “The benefits of vacuum suspension are only realized by the amputee if the limb and liner are in total contact with the socket [9].” If the seal is not intact, the results could be catastrophic. Losing the seal means the loss of the suspension and control of the socket.

The second problem occurs after the system loses its seal. The entire socket will then need to be re-evacuated and this is a time consuming endeavor. In addition, prosthetic users have complained that during this phase the pump can be loud and annoying.

We hope to counter the aforementioned problems by using sensors and electromagnets. Because multiple sensor and magnet pairings will be used, regional support could be achieved. This regional attraction would allow the same effect as the vacuum assisted systems while decreasing the chances of a catastrophic failure.

Should any of the magnets fail, the remaining electromagnets could instantly turn on preventing the socket from falling off or becoming misaligned. This would allow for quick and immediate reseating of the limb. Through the use of multiple magnets, the single point of failure is minimized or eliminated. In addition to the added speed, since the magnets have no moving parts the process of reseating the limb is silent.
1.7 Research Motivation

There are so many transtibial amputees in the United States. Many of them are suffering on a daily basis due to misfitted and uncomfortable prosthetics. Some opt not to wear their prosthetic limb at all because it is bulky and uncomfortable.

Amputated tissues are not adapted to take the forces when walking. When using a socket the tissues often see pressures far greater than they would normally. However under the right conditions and with the right socket fitting it is possible for the tissues to evolve and adapt to be able to withstand these higher pressures. Sockets are designed to distribute the forces over wide areas and over tissues and structures that can take the large forces seen during gait.

Throughout the day static and repetitive pressures compress the tissues of the residual limb, causing volume limb loss. This loss of volume makes the interaction loose; therefore, loss of control of the socket occurs. This loosening also increases friction and rubbing which leads to sore development and tissue damage.

To combat this volume limb loss, vacuum assisted suspension systems use the idea of total socket contact and attempt to achieve this using negative pressures. These systems have seen much success to this end. However, they still have their flaws. With the implementation of more advanced technologies such as electromagnets and sensors, we hope to advance on this technique used by the VAS systems.

1.8 Research Issues

1.8.1 Smart Suspension System Design

There was a need to develop a design that could automatically adjust for volume limb loss. To make it a smart system it would require some sort of control system and sensors. Additionally determinations had to be made as to what kind of technologies could be used to externally control the residual limb’s volume.

1.8.2 Smart System

Once the components are selected, figuring out how to get the different parts of the system to work together would be the next step. This will include the required circuitry. For our particular sensors, to get them to interact with a microcontroller (arduino in our case) they
required a signal amplification circuit. Then some sort of circuitry is needed that would allow
the microcontroller to control the components that are managing the volume of the limb.
Once the hardware and circuitry is figured out, the microcontroller has to be programmed
to effectively and efficiently manage the entirety of the system.

1.8.3 Prototype

Once the smart control system is setup, a concept for what the final prototype of the whole
system should be designed. Things such as the number of sensor/magnet pairs, where these
pairs would be placed, how they would be mounted or integrated into the various parts of a
prosthetic, and how the sensors and magnets would be connected to the control system, etc.
CHAPTER 2
PREVIOUS WORK

2.1 ME 696 group

This originally started as a ME696 graduate project course. They called their prototype MAGNOLEV, which was described as “a revolutionary prosthetic suspension system that utilizes magnets to generate negative pressure around the residual limb to prevent volume reduction and even promote wound healing.”[11] Using their prototype they found that negative pressures between 1.955-3.325 kPa were sufficient to prevent residual limb volume loss. The key relevant thing they found was that their tests validated that magnets can generate sufficient force to prevent volume limb loss.

Their prototype consisted of two parts: a liner and socket. The final liner design was made by coating a thermoplastic sheet with seven coats of magnetic paint and also infusing it with two layers of iron filings. This sheet was then rolled into a cylinder. To the bottom section of the cylinder, a metal disk was attached and left uncovered so an electromagnet could attach to it. See figure 2.1.

The final socket prototype used a cylindrical plastic design with both permanent and electromagnets embedded within it. See figure 2.2. The magnets were spaced 1.5 inches apart from each other. The intention was for the permanent magnets to provide the necessary negative forces while the electromagnets would provide additional negative force if needed. An additional electromagnet located at the very bottom of the socket is used for suspension of the prosthesis. This magnet was wired to a switch so that is will either only be on or off.

The key things that they determined that will carry over are as follows. Magnets can provide enough force to prevent volume limb loss. A magnets ability to hold onto an object is greatly affected even by placing thin fabric between it and what it is trying to attach to.
Figure 2.1: MAGNOLEV Liner design

Assembled Prototype Socket – Side View

A – Embedded permanent magnets
B – Attached electromagnets for negative pressure
C – Electronic component housing (batteries and holding force electromagnet)
D – Metal plate to connect socket with prosthetic foot

Electromagnet and Casing Assembly – Cross-sectional Side View

Figure 2.2: MAGNOLEV Socket
2.2 Previous Master’s Student

MAGNOLEV proved that magnets could be used as a feasible suspension technique. However, permanent magnets are constantly “on”, making them unadjustable.

She hoped to advance on the group’s design by removing the permanent magnets. By using only electromagnets, she hoped to make the system “smart.” “Electromagnets and pressure sensors were strategically positioned throughout the socket where the limb is expected to shrink with the ability to vary the attractive force between the liner and socket.[7]”

The same electromagnets were used as the group before. From initial tests, it was found that the force required to separate the electromagnet from a steel bar was approximately 11.7N [7]. It was also verified that physical contact with the steel was necessary for good hold. To accommodate these findings she mounted the steel plates directly to the surface of the liner, see figure 2.3.

![Figure 2.3: Final Prototype Liner from previous work](image)

To make the system smart she had created an arduino program that would read the resistance of the pressure sensors and create a signal to send the appropriate amount of power to the electromagnets.

Her code used the command digitalWrite() to control the motor driver board. However this command only has two states “on” or “off”. This did not allow for analog control of the magnets, which forced her to create her own pulse cycles. The code that follows shows the important parts of how her control code works.
// read the analog in value:
sensorValue = analogRead(analogInPin);
// map it to the range of the analog out:
outputValue = map(sensorValue, 0, 500, 0, 100);
// change the analog out value:
digitalWrite(9, HIGH);
delay(100 - outputValue);
digitalWrite(9, LOW);
delay(outputValue);

To control the power going to the electro-magnets the above code was being sent to a 4 channel motor control board, figure 2.4. This board is essentially what would be used in a radio controlled car or quad-copter.

![Motor Controller Board](image)

Figure 2.4: Motor Controller Board

Her final socket design reused the socket from the MAGNOLEV team but made some modifications. These included removing the exterior permanent magnets, removing the bottom of the socket and replacing it with a PVC end cap with 6 electromagnets mounted around its circumference, and adding a ring of 6 electromagnets around the top edge of the socket.
Figure 2.5: Bautista’s Socket Design

(a) Side  (b) top-down  (c) bottom
CHAPTER 3
SYSTEM

The prosthetic system consists of three main parts: The sleeve, the socket, and the control system. The pressure sensors and metal plates are attached to the sleeve using KISS quick bonding adhesive and selectively sewn down using polyester thread. The electromagnets are mounted in the molded socket using clear silicone. Finally, the control system consists of the microcontroller, sensor circuit board, magnet control circuit board, and the battery pack.

Figure 3.1: Main Parts
3.1 Sleeve

We decided to use a sleeve that was already widely used, the Iceross Comfort Liner (figure 3.2). The outer cover of the sleeve is made of ultra-strong and stretchable nylon that is “built for exceptional durability.” Within the liner, there is a “reinforced fabric integrated into the distal end of the liner that eliminates longitudinal stretching of soft tissue.” This stabilizing matrix is supposed to do three things: eliminate longitudinal stretching and pistoning, protect sensitive distal tissue, and accept circumferential stretch. The inside of the sleeve is made of a silky gel like inner layer.[12]

![Figure 3.2: Stock Iceross Comfort Liner Source: http://assets.ossur.com/library/16862/proc/6](http://assets.ossur.com/library/16862/proc/6)

3.1.1 Sensors

Two models of Tekscan Flexiforce 25 lb force sensors were used: models A201 (long 7.5 in.) and A301 (short 1 in.). The sensors are shown below. The sensors’ circular areas are the same size, the A301 is just a shorter version of the A201 sensor. The “active sensing area” is a 0.375 inches diameter circle. The A201 also comes in 2, 4, and 6 inch lengths.

“The FlexiForce sensor is an ultra-thin and flexible printed circuit, which can be easily integrated into most applications. With its paper-thin construction, flexibility and force measurement ability, the FlexiForce force sensor can measure force between almost any two surfaces and is durable enough to stand up to most environments.”

The sensors are constructed of two layers of substrate. This substrate is composed of polyester film. On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. Adhesive is then used to laminate the two layers of substrate together to form the sensor. The silver circle on top of the pressure-sensitive ink defines the “active sensing area.” Silver extends from the sensing area to the connectors at the other end of the sensor, forming the conductive leads.[13]
Figure 3.3: Tekscan FlexiForce Sensors

Figure 3.4: Construction of Tekscan FlexiForce Sensors
3.1.2 Plates

Previous work done on this project found that the electromagnets worked best with steel plates. The final prototype created from previous work is shown in figure 2.3. The problem with using such thin plates is that they are not rigid or dense enough for the magnets to retain a good connection. Although the magnets are strong lifting magnets, its ability to hold onto something is extremely weak if acted upon in a peeling fashion. The plates were also so thin that the magnet could not generate a substantial hold upon it. After trying several different materials the electromagnets were found to hold best to black steel plate. In addition the black steel plates have not shown noticeable corrosion in the two years of testing this system. The plates were 1/16 inch in thickness and were cut into 1.25 inch squares. See figure 3.5a.

The plates had a tendency to get caught on the magnets when inserting the sleeve and silicone limb into the socket. So the bottom edges of these plates were ground into an angle to assist getting the plates to slide past the magnets (see figure 3.5b).

![Black Steel Plate](image1.png)
![Plate with holes and edge](image2.png)
![Plate with thread](image3.png)

Figure 3.5: Black Steel Plates

3.1.3 Sensor and Plate Mounting

Industrial grade KISS (Keep It Simple Suspension) flexible quick bonding adhesive (Figure 3.6a) was originally the only thing used to mount the sensors and the plates to the sleeve. The adhesive was “specially formulated, flexible, ultra quick drying.[14]” However, after a
short time the plates were found to peel away from the sleeve and the adhesive. To remedy this, holes were drilled into the corners of the plates. They were then sewn down (Figure 3.5c) using polyester thread (Figure 3.6b) and a curved needle (Figure 3.6c).

![Figure 3.6: Mounting Supplies](image)

(a) KISS Adhesive  
(b) Polyester Thread  
(c) Curved Needle

3.2 Socket

For observation and ease of testing, the sockets used during testing were made from custom molded acrylic and formed around a conical limb shape. These sockets were manufactured by Kai Newton.

3.2.1 Magnets

The most recent prototype uses APW Company’s EM100-12-222, a 0.78 inch by 1 inch diameter cylindrical electromagnet. These are 12 Volt 20 lb lifting magnets. APW also makes a 25 lb lifting magnet that uses 6 Volts instead of 12, which were used by the previous prototypes. A more recent search shows APW now carries a 12V 25lb version as EM100-12-222-A. This model could have been used if the power consumption was the same as the electromagnets that were already used for this project.
3.2.2 Magnet Mounting

Clear silicone and O-rings were used to mount the electromagnets within the socket. The O-rings were used to help keep the magnet in place while the silicone was applied. These were not required, but it helped. Any parts of the O-rings that weren’t encased in silicone dried out and cracked over time. To mount the magnets, a steel plate was placed within the socket and a magnet placed through the corresponding hole. Voltage was then applied to the magnet and silicone was liberally applied to the outside of the magnet and socket. Power to the magnet was left on for several minutes to allow the silicone to set before the magnet was powered down and the plate removed. The inside of the socket would then be sealed with silicone the next day, to prevent the magnet from being pushed out while the exterior silicone cured fully.
Figure 3.8: Electromagnets

(a) APW 12 Volt  
(b) APW 6 Volts

Figure 3.9: Populated Socket

(a) Full View  
(b) Close Up  
(c) Silicone
3.3 Control System

The control system allows for the reading of the pressures exerted on the sensors and then proportionally controls how much current is sent to the corresponding electromagnet. The control system consists of three main parts: The microcontroller, magnet control board, and sensor input board. This system connects to both the sensors and electromagnets. It takes the raw voltage signal from the pressure sensors and sends it through a signal amplifying circuit before the microcontroller reads the signal. The arduino then takes this signal, does some linear conversions and sends an output signal to the magnet control circuitry which controls how much power is sent to the corresponding magnet.

3.3.1 Micro Controller

The Arduino Mega 2560 was chosen to control the system over the Arduino Uno because of its larger number of analog input pins and digital PWM pins. While the board could handle up to 12 magnets, the prototypes tested only used 8. It has 54 digital input/output pins, 14 of which can be used as PWM outputs. However of these 14, only 12 are usable for controlling our magnets. This is because pins 0 and 1 are also tied to the boards usb serial tx and rx data lines.[15] These lines are used to both program the board via usb and send serial data to the connected computer over the usb cable. This board also has 16 analog input pins, which are used as inputs for the pressure sensors.

PWM “Pulse Width Modulation. or PWM, is a technique for getting analog results with digital means. Digital control is used to create a square wave, a signal switched between on and off. This on-off pattern can simulate voltages in between full on (5 Volts) and off (0 Volts) by changing the portion of the time the signal spends “on” versus the time that the signal spends “off”. The duration of “on time” is called the pulse width. To get varying analog values, you change, or modulate, that pulse width. If you repeat this on-off pattern fast enough with an LED for example, the result is as if the signal is a steady voltage between 0 and 5v, controlling the brightness of the LED.”[16]

Arduino Code

The full code can be read in Appendix A. Please see the code in the appendix for variable declarations. What follows is the sections of the main loop of the control system code.
// read the analog in value:
sensorValue = analogRead(analogInPin);
Sv2 = analogRead(Ain2);
Sv3 = analogRead(Ain3);
Sv4 = analogRead(Ain4);
Sv5 = analogRead(Ain5);
Sv6 = analogRead(Ain6);
Sv7 = analogRead(Ain7);
Sv8 = analogRead(Ain8);

The first section of the code is the analogRead() functions. This is where the values of the pressure sensors are read in. The arduino will read a voltage from 0 to 5 volts corresponding to a value range from 0 to 1023.

// Limit sensor value to range
csv = constrain(sensorValue, smin, smax);
csv2 = constrain(Sv2, smin, smax);
csv3 = constrain(Sv3, smin, smax);
csv4 = constrain(Sv4, smin, smax);
csv5 = constrain(Sv5, smin, smax);
csv6 = constrain(Sv6, smin, smax);
csv7 = constrain(Sv7, smin, smax);
csv8 = constrain(Sv8, smin, smax);
This second section limits the range of the value of the read analog input from the pressure sensors. This allows for calibration of the ranges for each sensor/magnet pair, by having a smin and smax for each of the pairs (not done in this code). During testing all sets had the same range 20 (smin) to 400 (smax); a value of 400 is about 2 volts. According to Bautista’s code she expected the input range to be 0 to 500 which is 0 to approximately 2.5 volts. Confirming what was found in my initial tests of the sensors. She used a slightly higher error margin than I did. Also, before mounting the sensors I was getting random fluctuations between 0 and 15 which is why my lower limit is 20.

```cpp
// map it to the range of the analog out:
outputValue = map(csv, smin, smax, 255, 0);
Ov2 = map(csv2, smin, smax, 255, 0);
Ov3 = map(csv3, smin, smax, 255, 0);
Ov4 = map(csv4, smin, smax, 255, 0);
Ov5 = map(csv5, smin, smax, 255, 0);
Ov6 = map(csv6, smin, smax, 255, 0);
Ov7 = map(csv7, smin, smax, 255, 0);
Ov8 = map(csv8, smin, smax, 255, 0);
```

This third section maps the constrained value of the sensor to an corresponding output value from 255 to 0 (5 to 0 volts) for the output signal to the magnet control board.

```cpp
// change the analog out value:
analogWrite(13, outputValue);
analogWrite(12, Ov2);
analogWrite(11, Ov3);
analogWrite(10, Ov4);
analogWrite(9, Ov5);
analogWrite(8, Ov6);
analogWrite(7, Ov7);
analogWrite(6, Ov8);
```

This final section has the arduino output a PWM signal to the magnet control board adjusting the power sent to the corresponding magnets. This is the last of the code that is pertinent to the system running on its own. There is a final bit of code that is used to monitor the system; it is as follows:

```cpp
// print the results to the serial monitor:
Serial.print(sensorValue); Serial.print(\"\n\");
Serial.print(outputValue); Serial.print(\"\n\");
Serial.print(Sv2); Serial.print(\"\n\"); Serial.print(Ov2); Serial.print(\"\n\");
Serial.print(Sv3); Serial.print(\"\n\"); Serial.print(Ov3); Serial.print(\"\n\");
28
```
This bit of code sends the raw values of the sensors and the resulting outputs to the magnet control board over the microcontroller's serial connection, which can be read and logged by a connected computer.

### 3.3.2 Magnet Control Board

While the motor-control board used by masters student, Diane Bautista, would have worked. It was large, only had 4 outputs, and contained unnecessary circuitry to reverse the flow across the magnet. Since the magnets only require current flow in one direction. The current controller uses a circuit that is most commonly used to control the speed of a motor in a single direction. The following circuits (Figure 3.12) shows the setup for an electric motor. The differences are that we used a 1k resistor, a 1N4004 diode, a MJE3055 npn transistor, and the electric motor is replaced with an electromagnet.

Looking at Figure 3.11, the wires running out the top of the board runs to a 9-pin D-sub connector that connects to the magnets. The 2 sets of ribbon wires are the leads from the magnets running to the NPN transistors. The single white wire running behind the wires is the common 12 volts running to the magnets. The two sets of ribbon cables running down connect the arduino to the transistors’ base pins. The 4 black and white wires coming out from the bottom left of the board are power lines and are connected to the battery pack and the arduino, see figure 3.1c.

### 3.3.3 Sensor Board

The sensor board is based around the circuit shown in Figure 3.14 for the FlexiForce sensors. The board uses 100k reference resistors x8 (one for each sensor), MCP6004 quad op-amp x2(1 chip for every 4 sensors), and a muRata NME0505 (dc-dc converter). The muRata NME0505 (little black block at the bottom of the board) converts the positive 5 volts from the arduino to the -5 volts for the sensors.
Figure 3.11: Magnet Control Board

Figure 3.12: Magnet Control Circuitry
Figure 3.13: Sensor Board

Figure 3.14: Pressure Sensor Circuit
CHAPTER 4
EXPERIMENTAL TESTING AND RESULTS

Two tests were done to evaluate the performance of the prototype. The first used an Instron tension testing machine allowing a shear test of the magnets to be performed. The second, was a inflatable pressure test to check the sensors reaction to increased pressures. A third test was performed to see how hot a magnet would get if it were to run under full power for an extended amount of time.

4.1 Experimental Setup

4.1.1 Instron Test

The silicone limb (Fig 4.2a) was mounted into the upper half of the machine using a friction clamp (Figures 4.1, 4.2b); and the socket was mounted to the instron using a screw that was press fit into a PVC adapter on the socket (Figure 4.2c). In figure 4.1 the control system is on the box to the left of the socket, its’ data was logged by the laptop. The Instron’s computer is to the right of the laptop.

4.1.2 Pressure Test

Pressure test was done by pressurizing an inflatable within the sleeve and socket. The bladder was inflated using a 12 Volt car pump see figure. Figure 4.3 shows two arduino mega 2560s; the top one is the prosthetics control system being read by laptop (far left of photo) and the lower one is attached to a pressure sensor reading the pressure in the bladder via tubing from the pump to the inflatable. The values from the pressure sensor are being read and recorded by a Raspberry Pi microcomputer (red light left of white keyboard). Both computers are running a linux based operating system and logging the data using a python based script (see Appendix B).
Figure 4.1: Instron 5500R tension testing machine

Figure 4.2: Components of Instron Test

(a) Silicone Limb  (b) PVC Tab  (c) Instron Screw Mount
Figure 4.3: Pressure Test Setup

(a) Air Pump  
(b) Raspberry Pi B+  
(c) Inflatable Pressure Sensor

Figure 4.4: Pressure Set Up Components
4.1.3 Temperature Test

A temperature test was performed using the temperature probe of a multimeter. Ambient temperature was taken and then the magnets were left under full power and the temperature checked every 5 minutes with both magnets reaching stable high levels at around 15 minutes. The temperatures are in Celsius. This is relevant because in one study some users noted discomfort within the socket due to interface temperature increases and perspiration.[5] Because the above mentioned discomfort was from normal use, should the magnets create additional heat the prosthetic will become uncomfortable and potentially harmful.

![Temperature Test Setup](image)

**Figure 4.5: Temperature Test Setup**

4.2 Results

Please note that the system’s circuit for sensor signal amplification was replicated based on the setup used by the previous master’s student. The pressure values are based on her calibration tests, as we had not performed a calibration test on this new system. For future tests each of the sensors will need to be individually calibrated, the time scale for all plots except for figure 4.6 have approximated time scales based on a samples per time average calculation. The prosthetic has 8 magnet/sensor pairs. On the graphs, pairs 1-4 are the lower 4 pairs and 5-8 are the upper 4 pairs. These graphs were created using MATLAB. The trend lines were created using the functions polyfit and polyval, which fit the data to a 5th
degree polynomial function. The plot of the data that is displayed with the trend lines is the data that has been passed through the medfilt1 function of MATLAB and told to apply a 4th-order one-dimensional median filter. The left axes is the sensor’s force in newtons, the bottom axis is the time in seconds, and, if there is a right axis, it is the voltage going to the magnet.

4.2.1 Instron Test

Looking at the force data with the magnets on and off, the magnets added approximately 40 N (9 lbs) of sheer resistance between the sleeve and the socket. A conceptual prototype (Figure 4.7) was weighed and found to be 6.2 lbs, meaning that the added sheer force of the magnets would be more than enough to counter the prosthetics’s weight and possible twist.
There really is no way to directly compare the results of these tests to those done in previous works for several reasons. The first reason is because of the shape of the limbs. All previous researchers did their tests using amputee volunteers with sockets that were custom fit to their residual limbs. Whereas in this research, a conical approximation for both the socket and the limb were used. This shape difference makes a difference in the way the limb is removed from the socket. In the custom fit sockets there are points that when the limb tries to be removed will add a physical resistance. In the case of our conical limb and socket there are no overhangs or depressions that will cause this same effect.

Second and third are the method and focus of test. While the method varied from source to source most relied on having the user induce a force by walking or assuming a specific pose to induce a phase of gait. The focus of the tests was to determine the normal forces and shear stress at the skin interface where at the time we were more interested in the magnets ability to counter the weight of the socket.

The Instron test was the first test of the system. Looking at the system’s sensor data, (figure 4.8), it is clear that all of the sensors see a decrease in force as the limb is removed from the socket. The peak in sensor 7 is likely from when the limb was under compression; the sensor may have gone past the magnet, which caused a lesser force on the sensor. Interestingly, sensor 8 has an unusual rising force. Our best conclusion is that this may be from the way the sensor was mounted since the bottom 4 magnets show greater force than that of the upper 4 magnets. This was expected since the Instron machine started the limb with a bit of compression. Also, the socket and limb are conical. This shape causes the upper interface to be a little looser.

Looking at the data when the magnets are powered (figure 4.9), the system clearly shows the proportionality of when the forces become less, the signal to the magnets increase. Just like before, all of the sensors show a decrease in force throughout the test with the exception of sensor/magnet pair 8. One possibility that can explain both the stability in this test and the unusual rise at the end of the sensor only test is that during the first test, a connection between the sensor and the Arduino had become loose, causing the Arduino to constantly receive a semi-stable voltage. Another possibility could be the way the sensor was mounted, as mentioned before.
Figure 4.8: Instron Sensor Data (Magnets Off)

Figure 4.9: Instron Controller Data (Magnets On)
4.2.2 Pressure Test

Table 4.1: Peak Positive Pressures

<table>
<thead>
<tr>
<th>Source</th>
<th>Peak Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goh et al. [4]</td>
<td>77 - 110</td>
</tr>
<tr>
<td>Biel et al. [2]</td>
<td>&lt;150</td>
</tr>
<tr>
<td>Kahale et al. [10]</td>
<td>80 - 83.5</td>
</tr>
</tbody>
</table>

Figure 4.10 shows that the bladder pressure got up to about 80 kPa (11.6 psi) during this test. Table 4.1 lists peak positive pressures from various sources. Even though our pressure did not get up into the ranges listed, they all noted that the average pressures were much less, so we believe that this setup was a reasonable initial one for testing the system. It does need to be refined. As the bladder would inflate to the point of expanding past the top of the socket it no longer had anything to keep the pressure up. We ended up physically trying to contain the bladder by keeping it down with our hands. Another method must be developed to alleviate this problem.

Figure 4.10: Inflatable Pressure
While the previous test tested the system under lessening pressure this one tests its response under increasing pressures. Figure 4.11 shows that the system is again working as it should; this time decreasing the signal to the magnets as the pressure increases. With the exception of sensor/magnet pair 7, which started with high pressure readings and then dropped as the pressure increased. It was assumed that this again may have had something to do with the way the sensors were mounted. Set 1 is also unusual in that it does not really change much or there is a very slight overall decrease in pressure. It is especially interesting in that during the inflation test the wires connected to sensor 1 were sheered, but still showed changes in the exact same places as the other sensors.

The effect of the coded range limits are also clearly visible. The code has an upper limit value of 400 this corresponds to a value of about 2 volts or 31 Newtons, so when the sensors reach this value or greater then the magnet power signal also drops to zero. Set 4 (right most bottom graph of figure), has the clearest example of this; where the sensed pressure steadily climbs as the magnet goes to zero. The fact that the test managed to peak the sensor means that the system needs a proper calibration and/or the pressure produced by the bladder is far greater than expected.

An interesting thing to note is that when comparing the two graphs the system sensors are far more sensitive than the pressure sensor. During the test we had repositioned one of our hands on top of the inflatable around the 42 second mark. On the pressure sensor plot all you can see is a slight discontinuity drop; whereas on the sensor data there are clear spikes when that happened.
4.2.3 Temperature Test

Table 4.2, below shows the results of the temperature test. Both magnet types get equally hot after an extended amount of time, and they rise in temperature at the same rate. If a magnet were to remain on for an extended amount of time the user would definitely feel an increase in temperature.

Table 4.2: Temperature Test Data

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>6V</th>
<th>12V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>24.0</td>
<td>26.2</td>
</tr>
<tr>
<td>5</td>
<td>38.4</td>
<td>39.2</td>
</tr>
<tr>
<td>10</td>
<td>44.0</td>
<td>44.6</td>
</tr>
<tr>
<td>15</td>
<td>45.2</td>
<td>46.4</td>
</tr>
</tbody>
</table>
CHAPTER 5
CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The prototype prosthesis that we envisioned to help prevent volume limb loss in transtibial amputees was built and tested. This system used sensors and electromagnets to achieve similar results to the vacuum assisted suspension systems' total interface contact. The control system reads the pressures between the user’s limb and socket at critical regions and a corresponding electromagnet would adjust accordingly depending on the amount of pressure being exerted. These were initial tests of a fully assembled concept.

The first test performed was putting the prosthesis into a tension testing machine to see how much shear force the prototype system would add. This test showed that the magnets added 9 lbs of resistance to the prosthesis. On the final conceptual prototype, figure 4.7, the addition of the control system and 6 magnets only added 1.7 lbs to the socket. The data from this test showed that the control system worked as it was designed to do, which was to increase the power to the magnets as the pressures became less. The data also showed that the method used to mount the sensors may have an effect on how the prosthesis worked and should be looked into. During the analysis of the data, it was thought that interference might account for some of the inconsistencies and noise in the data, because the system was built using unshielded ribbon wire.

During the second test we saw how the system performed when pressures were increased. This test the system again performed as expected, with a few problems. Most notably was pair 7 which saw a decrease in pressure during the test. The sensors also had different rates at which they responded to the pressures. This was another reason to look at the mounting method of the sensors. During this test, several of the sensors also read higher than the expected pressures for which the code was set. This was evidence that a more thorough calibration test of the system is needed.

Based on the temperature test, should a malfunction occur which results in one or all of the magnets receiving full power for an extended time, it will cause the user to become extremely uncomfortable and they may become potentially harmed.

Overall the control system worked as proposed. It sent power to the magnets only when needed. They can be adjusted to the amount needed to be powered, based on the
corresponding pressure at the region controlled by the magnet. Results also showed that the added sheer force created by the magnets was more than enough to provide suspension of the proposed prosthetic socket.

If magnets will be continued to be used, an investigation should be done to see if the generated magnetic fields have any negative effect on the body.

Several problems with the proposed prototype were discovered while building and testing this design. The first being that the magnets are large and cumbersome. With prosthetics becoming thinner and lighter, the magnets vastly increase thickness and weight of the socket. The next problem is the difficulty of using a flat metal plate in a curved socket. The flat plate provided the best interface with the magnet. If we were to use a curved plate to match the curvature of the socket and limb, it would require an additional piece of metal to be added to the magnet to increase the affected surface area between the magnet face and the curved plate. Unfortunately this would have meant adding additional weight and pushing the magnet out of the socket even further. This would be additionally more complex in an organically shaped socket. The plates would also make it hard for the user to take the sleeve on and off. The sleeve is like a second skin over the limb so the sleeve is often turned inside out and rolled onto the user’s limb. The plates make this process difficult to do. Due to the varied results from the sensors, it was concluded that these variations were likely caused by the method of mounting the sensors within a rubber matrix causing the force levels to be all over the place. Further testing and calibration of the system is necessary to confirm this or to determine if it was being caused by something else. Finally, some of the noise in the signals may have been caused from using unshielded solid-core wires. This should be tested in future work.

Additional technologies found for this project included electro-static adhesion and pressure mapping. These technologies could drastically help the design of this system by removing the weight and thickness of the magnets and plates. By eliminating the plates and using a pressure map incorporated into the sleeve itself, would make putting the sleeve on and off much easier.
5.2 Future Work

5.2.1 Electro-static Adhesion

While the prosthetic adds less than 2 lbs to the system, the less weight the limb will have to adjust to offset the better. One solution to do this is to remove the weight of the magnets and replace them with electroadhesion technology. Each magnet is about 0.14 lbs meaning that 8 of them comes out to 1.12 lbs. Electroadhesion works by creating alternating positive and negative electrostatic fields across surfaces. “When alternate positive and negative charges are induced on adjacent electrodes, the electric field sets up opposite charges on the substrate and thus causes electrostatic adhesion between the electrodes and the induced charges on the substrate.” [17] This is similar to how electromagnets work, except the surface charges being induced with this technology allows for adhering to other materials than just ferrous (iron) materials.

Grab It

Grabit, Inc. is an SRI (Stanford Research Institute) spin-off company that is commercializing the cutting-edge electroadhesion technology for manufacturing and logistics. “Electroadhesive pads are comprised of conductive electrodes that are deposited on the surface of a polymer.”[17] Figures below show GrabIt’s Each Pick line of products adhering and lifting a can and a box. Application of this technology into the socket of the prosthetic system could potentially replace the electromagnets and plates. This would work because the objective of both the electromagnets and the vacuum system in creating negative pressure is that the sleeve should not loose contact with the socket. By laying strips or patches like those used in the figure to line the inside of the socket and allowing them to all be controlled individually by the system, it will work the same as the electromagnetic system.

However, their ability to adhere to the sleeve needs to be determined. GrabIt did allow us to do testing with their devices figures. The device we tested was barely able to lift an empty cardboard box and failed outright to adhere to a section of the sleeve. We have not been able to determine if the device itself may have been defective.
(a) Grab It Each Pick lifting a can.  
(b) Grab It Each pick adhering to a box.

Figure 5.1: Grab It Each Pick

(a)  
(b)  
(c)

Figure 5.2: Grab It Flat panel
5.2.2 Pressure Mapping

A pressure map similar to the ones shown in Figure 5.4 could be incorporated into the exterior of the sleeve. A pressure map works using the same piezo resistive technology as the force sensors with the exception that it uses a grid matrix to generate a map of pressures across an area. The setup in figure 5.3a will be able to output data that an arduino system could understand. Because the map is gridded the positions of the regions could be set in the code and used just like the sensors but it also allows for outputs that could show the prosthetics makers what is exactly happening in their sockets.

Figure 5.3: Pressure Map Technologies

5.2.3 System Calibrations

Calibration tests still need to be done on the new system. First, to see if conversions used by Bautista and for this paper are consistent. Secondly, to see how much of an effect mounting the sensors has on the numbers. Additionally, a test to see if shielded wires makes a difference should also be tested.

5.2.4 PWM Additional

There are two major effects of using the pulse width modulation signal. The first is that PWM signals have a tendency to use more power than a standard analog signal. The second is that it is likely that the high frequency noise seen on the system data is being caused by the use of PWM signals. To help compensate for these problems a low pass RC filter can be used.
This filter consists of a resistor and capacitor to turn the PWM square waves into a more analog signal. Figure 5.4a, shows a diagram for how the resistor and capacitor should be wired to create the filter. Figure 5.4b, shows an example of the difference in signal between the input and output of the filter. In it they used a pwm signal that ran 3.3 volts with a 50% duty cycle, shown by the black lines; The output signal is shown in blue. By using the filter between the Arduino and the transistor the power being sent to the magnet will be reduced as compared to using a purely PWM signal while maintaining the same functionality. In this way the magnets will receive the more stable blue signal, reducing the spikes from the pwm signals and using less power from not having to quickly switch between high and low voltage states. With the magnet signals smoothed, the induced noise on the sensors will also be reduced. An article on All About Circuits website on using low pass filters on PWM signals[18], gives a good explanation on how the filter works and how adjusting the components will adjust the output signal. The best configurations will have to be determined for the sensors and frequency outputs of the Arduino. The article showed a delayed response time of almost a millisecond, this delay would be adequate for our systems response times.

![RC Filter Diagram](image)

(a) RC Filter Diagram

![Signal Example](image)

(b) Signal Example [18]

Figure 5.4: Low-Pass RC filter graphics
// These constants won’t change. They’re used to give names
// to the pins used:
const int analogInPin = A0;
const int Ain2 = A1;
const int Ain3 = A2;
const int Ain4 = A3;
const int Ain5 = A4;
const int Ain6 = A5;
const int Ain7 = A6;
const int Ain8 = A7;

// set constrain value range
int smin = 20;
int smax = 400; // set max sensor value for constrain function

int sensorValue = 0; // value read from the pressure sensor
int outputValue = 0; // value output to the PWM (analog out)
int csv = 0; // constrained sensor value

int Sv2 = 0; int Ov2 = 0; int csv2 =0;
int Sv3 = 0; int Ov3 = 0; int csv3 =0;
int Sv4 = 0; int Ov4 = 0; int csv4 =0;
int Sv5 = 0; int Ov5 = 0; int csv5 =0;
int Sv6 = 0; int Ov6 = 0; int csv6 =0;
int Sv7 = 0; int Ov7 = 0; int csv7 =0;
int Sv8 = 0; int Ov8 = 0; int csv8 =0;

void setup() {
  // initialize serial communications at 9600 bps:
  Serial.begin(9600);
  // set output pins
  pinMode(13,OUTPUT);
  pinMode(12,OUTPUT);
  pinMode(11,OUTPUT);
  pinMode(10,OUTPUT);
  pinMode(9,OUTPUT);
  pinMode(8,OUTPUT);
}
pinMode(7, OUTPUT);
pinMode(6, OUTPUT);
}

void loop() {
  // read the analog in value:
  sensorValue = analogRead(analogInPin);
  Sv2 = analogRead(Ain2);
  Sv3 = analogRead(Ain3);
  Sv4 = analogRead(Ain4);
  Sv5 = analogRead(Ain5);
  Sv6 = analogRead(Ain6);
  Sv7 = analogRead(Ain7);
  Sv8 = analogRead(Ain8);

  // Limit sensor value to range
  csv = constrain(sensorValue, smin, smax);
  csv2 = constrain(Sv2, smin, smax);
  csv3 = constrain(Sv3, smin, smax);
  csv4 = constrain(Sv4, smin, smax);
  csv5 = constrain(Sv5, smin, smax);
  csv6 = constrain(Sv6, smin, smax);
  csv7 = constrain(Sv7, smin, smax);
  csv8 = constrain(Sv8, smin, smax);

  // map it to the range of the analog out:
  outputValue = map(csv, smin, smax, 255, 0);
  Ov2 = map(csv2, smin, smax, 255, 0);
  Ov3 = map(csv3, smin, smax, 255, 0);
  Ov4 = map(csv4, smin, smax, 255, 0);
  Ov5 = map(csv5, smin, smax, 255, 0);
  Ov6 = map(csv6, smin, smax, 255, 0);
  Ov7 = map(csv7, smin, smax, 255, 0);
  Ov8 = map(csv8, smin, smax, 255, 0);

  // change the analog out value:
  analogWrite(13, outputValue);
  analogWrite(12, Ov2);
  analogWrite(11, Ov3);
  analogWrite(10, Ov4);
  analogWrite(9, Ov5);
analogWrite(8, Ov6);
analogWrite(7, Ov7);
analogWrite(6, Ov8);

// print the results to the serial monitor:
Serial.print(sensorValue); Serial.print("\n");
Serial.print(outputValue); Serial.print('t');
Serial.print(Sv2); Serial.print('t'); Serial.print(Ov2); Serial.print('t');
Serial.print(Sv3); Serial.print('t'); Serial.print(Ov3); Serial.print('t');
Serial.print(Sv4); Serial.print('t'); Serial.print(Ov4); Serial.print('t');
Serial.print(Sv5); Serial.print('t'); Serial.print(Ov5); Serial.print('t');
Serial.print(Sv6); Serial.print('t'); Serial.print(Ov6); Serial.print('t');
Serial.print(Sv7); Serial.print('t'); Serial.print(Ov7); Serial.print('t');
Serial.print(Sv8); Serial.print('t'); Serial.println(Ov8);
}
import serial
print('connecting to /dev/ttyACM0')
ser=serial.Serial('/dev/ttyACM0', 9600)
filename=input("filename? example.txt")
f=open(filename, 'w')
d=input('display? 0:NO 1:YES')
print("logging data")
print('press ctrl c when finished')

while 1:
s=ser.readline()
f.write(s)
if d==1:
    print(s)


