Team 05: TEC-Pro
Design Report

Engineering 340 Senior Design Project
May 11, 2016

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Executive Summary

The Calvin College Engineering Program’s senior capstone course is divided into two semester-long classes. The first semester’s focus is on researching the feasibility of a design project of the team’s choice. One of the main deliverables of this course is the project proposal and feasibility study (PPFS), which has been completed. The second semester course is focused on the further development, prototyping, and implementation of the project. The final deliverable for this course is this design report.

This report details the research and design of the TEC-Pro, the design project chosen by Team 05. TEC-Pro is short for thermoelectrically cooled prosthetic. The goal of Team 05 was to design a prosthetic socket with thermal regulation in order to provide the user with unparalleled comfort in a daily-use prosthetic socket. The TEC-Pro incorporates battery-operated thermoelectric elements and a microcontroller in order to move heat from the user’s leg outward to a heat sink and employs a fan to help send excess heat from the heat sink into the environment. The rest of the prosthesis development, including the foot, ankle, and shaft are outside the scope of this project. The TEC-Pro will meet the need for a lightweight, cooled socket for Stephen Lander, one of the members of Team 05 and a transtibial amputee.

The final product is a functional prototype created by Team 05. This final prototype is the result of development work spanning three other prototypes, and incorporates the lessons the team learned through the incremental development performed throughout the second semester. We believe that our final prototype accomplishes the goals we set out to achieve at the project outset, and thus consider this project to be a success.
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1 Introduction

1.1 The Class
The Calvin College Engineering Program’s senior capstone project is composed of two courses. ENGR-339 and ENGR-340 combine to create a six credit-hour course that all graduating seniors must complete. The first semester course, ENGR-339, is focused on team formation, project identification and definition, a feasibility study, and the beginnings of the design work. The second semester course, ENGR-340, focuses on more in-depth design and analysis, often times accompanied by the production of a prototype. At the end of the year, senior design teams deliver their final design reports, prototypes, and a presentation to family, friends, and engineering department staff at Senior Design Night in May. These courses are also accompanied by lectures focused on transitioning students from the world of academia into the world of industry and full-time engineering careers.

1.2 Context
There are currently approximately 2 million amputees in North America alone, with that number expected to grow to 3.6 million amputees by 2050 [3]. The majority of these amputees are transtibial (below the knee) amputees. One common challenge faced by amputees is the problem of excess heat inside the socket portion of prosthetic legs. Amputees commonly wear a silicone liner, multiple socks, and a plastic socket around their residual limb. All of these elements trap heat, leading to multiple problems such as sweating and discomfort. Sweat trapped inside of the silicone liner can lead to sores, rashes, and skin breakdown, which causes the prosthetic leg user to not be able to wear their leg or to suffer through serious discomfort. Sweat can also lead to loss of function of the leg as the liner and socket slide out of place more easily, occasionally even leading to prosthetic legs falling off during vigorous exercise. According to multiple studies and surveys of amputees [4], over half of all amputees report heat and perspiration discomfort inside their prosthetic devices.

1.3 The Project
In order to combat this problem of thermal discomfort and sweat buildup at the interface of residual limb and socket, Team 05 worked to develop a thermally regulated prosthetic socket called the TEC-Pro, short for thermoelectrically cooled prosthetic. Team 05 has developed a thermal regulation system for the socket portion of the prosthesis using thermoelectric coolers, heat sinks, and fans molded in an innovative fashion. Power, weight, cost, manufacturability, and durability were all considered throughout the design process in order to produce an optimal design for the TEC-Pro.

1.4 Reason for Selection
When searching for a project, Team 05 brainstormed many possible project topics, from vehicles to animal capture systems to a folding bike. While there were many projects that sounded like they would be interesting or would make for cool prototypes, Team 05 did not initially find any projects that utilized the abilities and interests of all team members. Towards the end of the brainstorming and topic selection process, Stephen Lander made some suggestions having to do with his prosthetic leg, including a pressure-sensing socket and a socket with a cooling element in it. Team 05 zeroed in on the idea of a cooling socket for multiple reasons, including the ability to use the mechanical engineers’ expertise in thermal system design and heat transfer along with Nathan Slager’s expertise with electronics and controls. Team 05 was also drawn to the project because it allowed the team to work on a project with larger implications for people outside of the team. The potential to tackle a real problem that was faced
by many disabled or disadvantaged people while also potentially providing renewed comfort and function for a teammate also gave the team a sense of purpose.

1.5 Team Members

![Image: Left to right: Stephen Lander, Andrew Bouma, Nathan Slager, Lance Jensen]

Team 5 consists of Andrew Bouma, Lance Jensen, Stephen Lander, and Nathan Slager. All team members are senior engineering students at Calvin College. Nathan Slager is pursuing a degree in the electrical and computer concentration, while the other three team members are pursuing degrees in the mechanical concentration. Stephen Lander is pursuing a double major in both the mechanical engineering and biochemistry degree programs. The team's collective passion for helping those in need and curiosity for the intersection of biology and engineering steered them towards choosing TEC-Pro as their senior design project.

**Stephen Lander:** A Denver native, Stephen brings biological expertise to the team with his medical research experience and dual major in biochemistry and mechanical engineering. Stephen is looking forward to attending medical school and becoming a doctor. He had his lower left leg amputated in 2014 after an unfortunate incident with a forklift, and his experience as an amputee has provided the team with invaluable insights and feedback throughout the design process.

**Andrew Bouma:** Growing up in Grandville, Michigan, Andrew began his engineering career at Gentex Corporation and acquired a strong foundation in CAD and computational simulations. This background was refined and expanded on during a summer research internship at Carnegie Mellon University where he gained experience in tribology, powder flows, and metal 3D printing.
Nathan Slager: From Elmhurst, Illinois, Nathan brings expertise and skills relating to all things electronic to the team. Having experiences in industry with Epiq Solutions and research experience at Carnegie Mellon University, Nathan brings superior coding and programming skills, along with knowledge of electronic hardware and adept research skills to the team. Nathan’s experience with app development in his free time has also contributed to his analytical problem-solving skills.

Lance Jensen: Originally from Tiskilwa, Illinois, Lance has acquired many skills and valuable engineering experiences from growing up on a farm. His multiple international experiences, including studying engineering in China and working on brakes at ZF TRW in Germany, have made him a culturally conscious teammate with exceptional problem solving skills. His hands-on experience and analytical mind also bring spectacular value to the team.

1.6 Design Norms
In light of our shared Christian faith and our desire to incorporate our love for God and for others into everything we do, our group has chosen to incorporate three design norms into our project. These design norms guided our decisions and choices throughout the design process.

1.6.1 Caring
We strive to care for those who are marginalized by society. One way we can do this is by providing a product that allows a disadvantaged person, such as an amputee, with comfort and performance in their prosthetic socket. Although this product may not be accessible to everyone, we believe that the fact it exists shows that we care for its potential customers.

1.6.2 Trust
We strive to develop and design our product in such a way that its users can trust the socket to perform flawlessly all the time. With any manufactured product, there is the potential for problems, malfunctions, and failures. By rigorously testing our product, considering all possible failure modes, and designing for longevity, durability, and quality, we can gain the trust of our product users and build rapport with our customer base.

1.6.3 Integrity
We strive to develop a product that is complete in both form and function. We want to develop a product that is easy and intuitive to use. The controls should be simple and the operation should be consistent and repeatable. It is also important to us that the design of the product is complete, beautiful, and does not add additional hassle or complexity to the user.

2 Project Management

2.1 Project Breakdown
Before beginning research and design work, the project was broken down into more manageable focus areas. Each team member was placed in charge of one aspect of the project having to do with the physical project itself and at least one aspect of the project having to do with the operational aspects of the team. A visual representation of the project breakdown can be seen in Figure 1. Andrew Bouma took on team leader responsibilities as well as tackling thermal modelling and heat transfer. Nathan Slager, the team’s electrical engineer, used his expertise to design electrical systems, while also taking responsibility for the team’s finances and materials and parts acquisition duties. Lance Jensen research
materials and fabrication. He also took control of the team’s website and publicity as he took the role of the website developer. Finally, Stephen Lander used his contacts and connections with doctors and prosthetists as our customer and industrial contact liaison. He also used his knowledge as a pre-medical student to handle biological systems.

2.2 Schedule
It was important to the team to keep on or ahead of the schedule. For this reason, the schedule was kept using a Gantt chart, which was updated weekly by Lance. By using a Gantt chart, the tasks for each week were laid out in an easy-to-read way. When schedule issues arose, such as falling behind, the issues were resolved by bringing the team together and fixing it as soon as possible. This involved staying late on campus to get the work done.

2.3 Budget
Team 05 was able to apply for additional funding beyond the original $500 budget cap, which allowed the team to improve on the initial design as the prototype process was carried out. The final budget for
the TEC-Pro development and prototypes was $792.27. Nathan Slager was assigned to manage the budget. Whenever the team required more parts, he would file the order forms and update a Google document, which was shared with the entire team. Several parts were ordered by the team members themselves. For these components, the costs were accounted for and the team was reimbursed for them by the school. The parts are found in Table 1.
Table 1: Product cost breakdown

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<th>Vendor</th>
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To be stewards for the Lord, the Christian team did their best to use the provided budget without wasting money. Some initial ideas that required some investment did not work out, but this reduced the cost of the final product to a minimal, since the final product does work. The team has learned the wisdom that those who can be trusted with very little can also be trusted with very much. We look forward to taking this wisdom with us to our future work.

2.4 Task List

For the fall and spring semesters, several deadlines were created to keep the team on track to ensure the final project was completed by May. A task list was created using the Method of Approach to give the team a schedule to follow. The estimated hours are shown next to each task as this is important later for the cost analysis.

- **Determine Project (16):** Narrow down project ideas and decide on final choice
  - Brainstorm Project Ideas (8)
  - Brainstorm Project Solutions (8)
- **Budgeting (6):** Determine money available and cost of the project, tracking costs
- **Research (116):** Learning about the project and determining what needs to be done
  - Electrical Components (20)
  - Patent Search (6)
  - Thermoelectrics (20)
  - Batteries (20)
  - Socket Fit (8)
  - Materials (16)
  - Merging Electrical Components with Construction (15)
  - Academic Papers Research (10)
  - Meeting with Glenn Remelts (1)
- **Design (61):** Thermal Design of the Socket
  - Create Thermal Model: Model the Heat Flow of the Leg and Socket (50)
    - Measure Leg and Existing Socket (4)
    - Drawing in Inventor (6)
    - Inventor Simulation Drawing and Analysis (40)
  - Selection of Materials (5): Selecting the Materials for Each Component
  - Selection of Parts (6): Choosing the Correct Size for Each Part
- **Presentables (35)**
  - Presentation I (4)
  - Fridays at Calvin Student Presentation (1)
  - Poster (2)
  - PPFS Draft (23)
  - Presentation II (5)

A task list was created for the spring semester in a similar fashion. Most of these tasks involved experimentation through prototyping and testing. The estimated hours are displayed after each task.

- **Research (122)**
  - Thermoelectrics (25)
Batteries (27)
Materials (30)
Manufacturing Process (40)

**Prototypes (132)**

- **Prototype 1 (25)**
  - Manufacturing using fiberglass (15)
  - Testing: heat transfer capability of single thermoelectric (10)
- **Prototype 2 (52)**
  - Manufacturing using fiberglass (18)
  - Electrical Adjustments to prototype (10)
  - Testing: multiple thermoelectric modules and electronics (24)
- **Prototype 3 (55)**
  - Manufacturing using existing carbon fiber prosthesis (20)
  - Testing: integration of modules with socket and placement of TE’s (35)

**Presentables (76)**

- **Presentation III (8)**
- **CEAC Summary (4)**
- **CEAC Presentation (12)**
- **Presentation IV (12)**
- **Design Report (30)**
- **Senior Design Night Presentation and Slideshow (10)**

**Final Product (330)**

- **Research on manufacturing process (30)**
- **Safety training and research (15)**
- **Obtaining required materials (25)**
  - Carbon fiber weave
  - Epoxy
  - Hardener
  - Personal Protective Equipment (PPE)
- **Creating leg positives (27)**
  - Making the plaster molds (12)
  - Sanding down to adjust for leg changes (15)
- **Final socket manufacturing (233)**
  - Creating inner carbon fiber layers (8)
  - Inner layer cleanup and adjustment (10)
  - Machining aluminum plates, heat sinks, fans (25)
  - Integrating thermoelectric modules (20)
  - Outer layer carbon fiber manufacturing (15)
  - Outer layer cleanup (20)
  - Final assembly with heat sinks and fans (30)
  - Designing and machining the 3D printed battery and electronics cases (30)
  - Final electronics wiring and coding (70)
  - Foot and ankle adjustments (5)
3 Requirements

Stephen Lander served as an invaluable resource at the beginning of the project when Team 05 began to work through defining the problem at hand and developing the product requirements that would help us meet the needs of amputees while keeping our product safe, effective, user-friendly, and environmentally friendly. The product requirements described below are split into the categories of product operation, safety, environmental, and cost requirements.

3.1 Product Operation Requirements

3.1.1 Thermal Control Targets

Residual limb skin temperatures located on different areas of the limb were recorded in a study of amputees [7]. The temperatures were measured before donning of the silicon liner, during resting with the prosthesis attached, the initial transition to walking, and the steady state temperature during walking after fifteen minutes. The resulting temperatures are summarized below in Table 2 [7].

<table>
<thead>
<tr>
<th>Activity Level</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Donning</td>
<td>31.4 ± 1.3</td>
</tr>
<tr>
<td>Steady-State Resting</td>
<td>32.2 ± 1.7</td>
</tr>
<tr>
<td>Initial Walking</td>
<td>32.3 ± 1.7</td>
</tr>
<tr>
<td>Steady-State Walking</td>
<td>33.1 ± 1.8</td>
</tr>
</tbody>
</table>

As seen in Table 2, the temperature of the residual limb climbed 1.7 C from resting to walking [7]. Although this appears to be a very small increase in temperature, this temperature change is enough to trigger temperature response mechanisms by the body to work to compensate for this change. One mechanism used by the body to compensate for this change is perspiration. Any addition of moisture into the prosthetic liner remains trapped and can lead to skin breakdown or decreasing performance of the prosthesis.

The target skin temperature was chosen to be the same as the donning skin temperature of 31.4°C. By keeping the residual limb at the resting temperature outside of a prosthetic liner, perspiration and heat buildup within the socket will be minimized. The dynamic addition of heat by muscles contractions, depending on activity level, as well as blood flow from the body will need to be removed by the cooling system to keep the skin at the desired temperature.

The cold side of the thermoelectric will need to be at a temperature low enough to draw the heat generation from muscles and addition from the blood away from the residual limb and ultimately release the heat into the environment. The prosthetic cooling system was designed to remove the extra heat from the residual limb to maintain a skin temperature of 31.4°C with environmental temperatures up to 37°C.

3.1.2 Fit and Comfort

Fit and comfort of a prosthetic socket are imperative for good function. The most common reason for amputees to not wear their prosthesis is poor fit of the socket. The cooling system must not disrupt the fit of the socket. The necessary componentry for the cooling system must be able to be added without adding pressure points or lack of adaptation to the uniqueness of individuals’ residual limbs shape.
Newly fabricated prosthetic sockets are adjusted for pressure points felt within the socket. The cooling system must allow for small variations from the initial model so a proper fit can be obtained between the residual limb and prosthetic socket. A well-fitting prosthetic socket is one of the most critical aspects of a prosthesis so the comfort and fit of the socket was analyzed in every aspect of design of the cooling system.

3.1.3 Aesthetics
It was important for us to design our prosthetic socket to be aesthetically pleasing and look similar to other prosthetic legs. One initial goal was to create our prosthetic socket in such a way that the ability of the end user to wear their prosthesis with a variety of clothing options was not impeded. This goal was set while the team was under the impression that the final socket design would not require the use of fans on the exterior surface. However, with a design that required fans to help dissipate heat, the team relaxed its goal of the user being able to wear pants with the socket. The scope of the project changed slightly, and the TEC-Pro was developed more targeted for use during rigorous activities. The team decided that most people wear shorts during these activities, so the user will most likely be wearing shorts if they wanted to use the TEC-Pro anyways.

We also wanted to design the prosthesis in such a way that the socket can be worn without attracting unwanted attention to the prosthetic leg. Since we have heat sinks and fans protruding from of the socket, this was a challenge. In order to accomplish this, the team manufactured the socket in a very similar manner to how prosthetists manufacture sockets for their patients, using carbon fiber and a positive of the residual leg. We also hid the wires between layers of carbon fiber to make the socket look more pleasing.

3.1.4 User Interface
The user interface of the system is easy to use and learn. If the customer were to accidentally over-cool the leg they might possibly never wear the prosthesis again. Therefore it was crucial that we established a system where the set point and leg temperature are clearly communicated to the user, with obvious physical controls for changing the set point and shutting down the system.

3.1.5 Durability
Another important aspect of the socket performance was its durability. Most transtibial prostheses have a working life 3-5 years. It was important to our team that the TEC-Pro be able to last and function properly for at least that amount of time. The prosthesis will have to endure a number of challenges such as constant rubbing and contact with clothing, impact and drops, being splashed, and general dirt, dust, and mud contamination from everyday use. By using carbon fiber and high quality resin mixed with hardener, the team believes the socket is a highly durable alternative to similar sockets available.

3.1.6 Sound
The sound of the prosthesis and cooling system should be kept to a minimum and if possible, completely unnoticeable during normal walking. Although some amputees will sacrifice quiet for an added benefit such as powered propulsion with a BIOM foot, many would rather have a quiet leg than one with an added feature. Therefore, to allow the cooling system to be targeted for a broad customer base, a quiet cooling system is necessary. The initial fan-less design was ideal for sound management. However, even though the design now incorporates many fans, the socket is still very quiet, which was very pleasing to the team and the customer. By incorporating low-noise computer fans, the team was able to minimize any annoyance due to sound.
3.1.7 Weight
The weight of a prosthesis is critical for performance. The lower the overall weight of the leg, the less energy the amputee has to expend for walking or running, and ultimately, the farther the amputee can travel without becoming exhausted. The weight of the cooling system should add no more than three pounds to the overall weight of the prosthesis. However, the less weight added to the prosthesis by the cooling system, the better. The weight addition will be minimized in all possible ways, with a total weight not to exceed three pounds. The final product, including the socket, leg, cases, batteries, and electronics, weighed in at 6.05 lbs. Since the average prosthetic leg weighs approximately 5 lbs, the added weight is just over 1 lb. The team hit their weight requirement target.

3.2 Safety Requirements

3.2.1 Water Resistant
One of the main purposes of cooling a prosthetic leg was to prevent the buildup of moisture between the leg and the inside of the prosthesis. Therefore, it was especially important to keep the product resistant to water in order to avoid water penetrating into the leg and into the electronics. This was accomplished by covering all of the electronics with 3-D printed enclosures and protecting the wires within carbon fiber layers.

3.2.2 Shock Protection
In order to maintain a safe product, all electronics were sufficiently covered so that no wires were exposed. In the case that the housing for the electronics falls apart and someone comes into contact with a live wire, the highest voltages seen will be no more than 12.6 Volts. The resistance of the human skin ranges from 10,000 Ohms to 1,000 Ohms, depending on whether or not the skin is dry or wet, respectively [8]. A quick calculation of the worst case scenario gives:

\[
\frac{12.6 \text{ [V]}}{1000 \text{ [Ohms]}} = 0.0126 \text{ [A]} \text{ or } 12.6 \text{ [mA]} \quad \text{Eq. 1}
\]

which is less than the “let go” current of 15 mA. This calculation doesn’t take into account the extra resistance of the inside of the human body, which depends on the path of the electricity through the body. This extra resistance may vary from 100 to 1000 extra Ohms and the result would only decrease the current. There is extra protection from the silicone liner as well. Due to these factors, the team is confident that the final prototype is shock proof.

3.2.3 Sharp Edges and Abrasive Surfaces
Prostheses are in close proximity to other body parts and commonly rub against the other leg and various surfaces such as normal clothes or couches. The cooling system componentry does not have sharp edges or abrasive surfaces that could damage the other body parts or objects such as couches or clothing. This was especially important once the team decided to use square heat sinks to dissipate heat from the residual limb. The placement and design of all surfaces were safe for the amputee and surfaces that might come into contact with the prosthesis. In addition, the heat sink edges were rounded off, producing less scrapes and snags to the user. The thermoelectric modules were placed on the back side and outside surface of the socket because these were the areas with the most heat production. In addition, placing the modules away from his other leg removed the need for Stephen to worry about his right leg rubbing against any of the modules sticking off of the socket.
3.2.4 Frostbite
Thermoelectrics are capable of developing a temperature difference of 70°C. Therefore, they are capable of dropping well below the temperature needed to cause frostbite. Depending on the temperature, frostbite takes various amount of time to develop, with the general rule, the colder the temperature the less time it takes to develop. For a given limb, frostbite development time for is 36 minutes for 4°C, 27 minutes for 0°C, and 15 minutes for -5°C [9]. The temperature of the skin must not drop below 15°C to remain above the temperature where frostbite can occur. The cooling system must have the ability to have a safety shut-off if the temperature drops below 15°C in order to avoid frostbite.

3.2.5 Burns
The temperature difference generated by thermoelectrics could also cause burns to develop on the skin. Skin temperature must remain below 40°C. Depending on the temperature of the skin, burns develop more quickly for higher temperatures. For 45°C, burns develop in 2 hours, for 49°C, burns develop in 8 minutes, and for 55°C, burns develop in 17 seconds [10]. Therefore, the cooling system is equipped with the ability to sense if the socket temperature rises above 40°C and shut off the thermoelectrics if this does occur. This requirement will protect the amputee from developing any burns due to high temperatures created within the socket. In addition, the battery must be properly charged and discharged at the proper rating in order to avoid any explosions and or fires.

3.2.6 Cost Requirements
The cost of the project initially intended not to exceed the budget of $500. However, extra expenditures were necessary in order to complete the project to specifications and complete our development process, and so the team requested for extra funding from the Engineering Department Senior Design Fund. The cost of the final prototype itself was $423.42, and the cost of extra components and development costs was $368.85, coming to a grand total of $792.27, exceeding the budget by $292.27.

3.2.7 Contingent Goals
If we had more time and a bigger budget, the team would have liked to include some additional features on the TEC-Pro, such as a smartphone interface, complete thermal regulation (heating as well as cooling), and an LED indicator (red for heating, blue for cooling, green for reaching set point temperature). Due to time and budget constraints, the team has left these features for the next prototype.

4 Project Specifications
Once the team had identified the requirements for a thermally regulated prosthetic leg socket, the team brainstormed different methods of attacking the problem, ultimately coming up with five possible solutions to the problem. These methods were researched and evaluated with different design criteria. In the end, Team 05 chose thermoelectric cooling as the best method for this application.

4.1 Design Alternatives
4.1.1 Evaporative Cooling
One of the first methods of cooling a socket evaluated was evaporative cooling. In this method, a liquid such as water, acetone, or alcohol would be applied around the socket or the surface of the leg and allowed to evaporate, thus cooling the leg. The positive qualities of this method are that it is simple and
does not require many components. The downsides are that the system could potentially require a large liquid storage system and could easily go above the maximum weight requirement in order to have a satisfactory operating time.

4.1.2 Refrigeration Cycle
Another method evaluated was a standard refrigeration cycle with a compressor, condenser, evaporator, and expansion valve. The positives for this system were that the technology is mature and the system is well understood by the mechanical engineers on the team. The downsides are that the system would potentially be very large and bulky, have many moving parts, and be very heavy.

4.1.3 Air Cooling
The next system evaluated was an air cooled solution. For this system, we proposed a pump that would be operated by the weight of the user as their foot strikes the ground during the walking motion. This pump would shoot air through a series of vents near the user’s leg, increasing the prosthesis’ ability to evacuate heat and moisture from the leg. The benefits of this system are that it is simple, durable, and has the potential to be very lightweight. The downsides are that the system would not be operable when the user is not running or walking, and would provide no benefits when the user is stationary.

4.1.4 Helical Piping
A study was performed to model the effects of incorporating a helical cooling channel into a prosthetic socket [11]. The study used 3-D printed socket with a normal socket as a control, and another with a helical cooling channel. The study found incorporating a helical cooling channel increased the temperature difference across the socket from 4.55°C for a computer model, 5.9°C for the benchtop simulation, to 8.2°C for a computer model, and 6.5°C for the benchtop simulation [11]. There is a thermodynamic benefit to adding a helical cooling channel in a prosthetic socket. However, there would need to be additional components to create the fluid flow throughout the helical coils that were not analyzed. The downside to this model is there would be moving componentry such as a pump and fluid flow, and added weight by each component as well as a power source needed for the flow.

4.1.5 Thermoelectric Cooling
The final system evaluated by Team 05 was a thermoelectric cooling system. Thermoelectric coolers operate on the thermoelectric effect, an effect observed in some materials (Bismuth Telluride for instance) where a temperature gradient across the device generates an electrical voltage, and vice versa [12]. This is the principle behind the operation of both thermocouples and thermoelectric heaters and coolers. By applying a voltage across a thermoelectric element, the element develops a hot side and a cold side. The cold side can be placed nearer to the user’s skin to draw heat away from the leg, and the hot side can be connected to a heat sink to dissipate the heat into the atmosphere. Although thermoelectric coolers are a relatively new and immature technology, they have the benefit of having no moving parts, being lightweight, and being relatively inexpensive. The negative qualities of thermoelectrics are that they require significant electrical power to operate, which translates to a large and heavy battery. Thermoelectrics are also thermally inefficient, requiring 2 to 3 times as much heat to be dissipated from the hot side as is drawn away from the leg.

4.2 Design Criteria
The design alternatives were evaluated based on weighted design criteria. The most important criteria for our design were determined to be system weight and cooling power, with system durability and
simplicity being the second most important criteria, and system cost and size being our least important design criteria. Team 05 decided that this design criterion accurately reflected the priorities of most amputees. Of course, if the system does not have adequate cooling power, customers will not be willing to spend the extra cost and carry the extra weight of a cooling system, and so cooling power was deemed to be of utmost importance. Similarly, added weight in a prosthesis is very undesirable. Prosthesis customers already spend extra money on high-grade materials such as carbon fiber and titanium to reduce the weight of their prostheses, so adding too much extra weight was determined to be a factor that would seriously limit desirability. Only slightly less important is the durability of the socket. Prosthesis can be subjected to many forms of abuse, but are typically only in operation for 3-5 years. Product simplicity also contributes to durability, as well as limits the chances of parts breaking. The size of the product, although important to keep within a reasonable limit, was not deemed to be one of the most important factors when buying a prosthetic leg, as many users will be willing to sacrifice some aspect of beauty of form for enhanced function, although increased function and beauty of form are both desired in our product. Finally, the cost of the system was not seen as prohibitive, as many potential customers have their prostheses covered by insurance, and the added cost of our system will not be significant when compared to the already expensive nature of purchasing prosthetic legs.

4.3 Design Decisions
The criteria were ranked using the design criteria described above with the use of a decision matrix. After each design alternative was ranked, the results were added up. As shown below in Table 3, thermoelectric cooling methods excelled in nearly every design criteria. Thermoelectric cooling was the clear choice for Team 05, and thus development on a thermoelectrically cooled leg began.

<table>
<thead>
<tr>
<th>Design Criteria</th>
<th>Weight</th>
<th>Thermoelectric Cooling</th>
<th>Helical Piping</th>
<th>Air Cooling</th>
<th>Refrigeration Cycle</th>
<th>Evaporative Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>10</td>
<td>10</td>
<td>2</td>
<td>10</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Cooling Power</td>
<td>10</td>
<td>6</td>
<td>10</td>
<td>3</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Durability</td>
<td>7</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Simplicity</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>6</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Size</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Cost</td>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
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<td>Total</td>
<td>39</td>
<td>34</td>
<td>18</td>
<td>30</td>
<td>17</td>
<td>27</td>
</tr>
</tbody>
</table>

5 Project Design
The proposed thermoelectrically cooled prosthetic socket (TEC-Pro) is composed of an inner heat sink in contact with the user’s skin or silicone liner, a middle composite thermal insulation layer, an exterior heat sink and dissipation sleeve, thermoelectric cooling elements, and an electrical control and processing system. This section describes the research and design work done thus far on these systems.

5.1 Electronics System Research
The general function of the electrical system in the prosthesis is to provide power to the thermoelectrics with a battery. In addition to this, the system should appropriately control the power to the
thermoelectrics based on the temperature sensed inside the socket, hence creating a control system. In order to implement this electrical control system, the team decided that four different components within the system were necessary: batteries, thermoelectrics, temperature control circuitry, and a user interface.

5.1.1 Thermoelectrics
At max load, the thermoelectrics are expected to draw a total of 50 W of heat from the cold sides to the hot sides. In order to evenly distribute the thermal load, multiple thermoelectrics will be positioned within the socket (See Section 5.2 Heat Transfer Research for more information on this). In order to discuss the process of choosing the right thermoelectrics, one must understand a few key system parameters: $dT_{max}$, $Q_{max}$, $I_{max}$, and $U_{max}$. The term $dT_{max}$ refers to the maximum temperature possible across the thermoelectric (when $Q = 0$); $Q_{max}$ is the maximum heat being moved across the thermoelectric (when $dT = 0$); finally, $I_{max}$ and $U_{max}$ are the current and voltage necessary for the thermoelectric to achieve maximum performance. Figure 3 below depicts the relationship between these parameters.

![Figure 3: Example applications with required $dT$ and heat load [1]](image)

From Figure 3, one can observe that thermoelectrics are current regulated devices; the thermal output is proportional to the input current. In order to calculate the sufficient $Q_{max}$ needed, Eq. 2 below was used [1].

$$Q_{max} = \frac{Q}{1 - \frac{dT}{dT_{max}}}$$  \hspace{1cm} \text{Eq. 2}

Inserting the desired $Q = 50 \text{ W}$, $dT = 12 \text{ K}$, and $dT_{max} = 70 \text{ K}$ (for single stage thermoelectrics) produces a required $Q_{max}$ of 60 W. While researching thermoelectric modules, the team discovered that they run most efficiently when a DC voltage is applied. Thus, a low-pass filter should convert PWM signals into DC voltage levels. Given the inherently curved shape of a prosthetic limb, the team elected to use many thermoelectric modules distributed around the socket in order to draw heat away
uniformly. The team considered using thermoelectrics from manufacturers such as RMT, TETECH, and Mouser Electronics. Because the contacts from RMT and TETECH were unwilling to provide quotes at the quantity specified, the team decided to purchase CUI Inc. thermoelectric modules from Mouser Electronics. As stated previously, the thermoelectric modules were estimated to need a lower limit of at least 60 W of heat transfer with a temperature difference of 12 K. Each thermoelectric module purchased has the capability to move 5 W of heat at 1.2 A and 2 V of power at a temperature difference of 12 K. According to the CUI datasheet [15], twelve of these modules are capable of pulling 60 W of heat at a temperature difference of 12 K if each is supplied with 1.2 A at 2 V. Figure 4 containing the schematic for this design shows the thermoelectrics modules modeled as 2 Ohm resistors. Given this assumption, the equivalent resistance of the thermoelectric modules is 1.5 Ohms. Choosing a 7.4 V, 5200 mAh, battery gives a total current of 4.93 A (7.4 V / 1.5 Ohms). This allows each of the modules to see 1.64 A (4.93 A / 3 parallel sections) at 2.47 V (7.4 V / 3 resistors in series), which satisfies the design requirement of 1.2 A at 2 V.

Figure 4: Thermoelectric Modules Schematic

5.1.2 Batteries
The team decided to use two 7.4V 5200mAh rechargeable Lion-Ion battery packs with a max continuous discharge rate of 5A each to drive the thermoelectrics. Each battery has protection circuitry that disconnects the battery terminals when the current reaches 11 A +/- 3A. Extra protection includes a cutoff for when the voltage of either cell (two cells per pack) rises to 4.35 +/- 0.025V or falls to 2.40 +/- 0.08V. This prevents the battery from being overcharged or over-discharged [13]. With the thermoelectrics drawing nearly 4.93 A, this will give each battery a battery life of about an hour (5.2 mAh / 4.93 A = 1.05 h). In addition to this, two smaller 11.1 V batteries will power the fans. These also contain PCB protection circuits with similar characteristics as the batteries mentioned previously.
The customer theoretically can recharge one battery pack while they use the other, or they have the option to use both for double the capacity at the cost of added weight. Battery holders will be designed to allow for easy attachment and removal of the batteries.

5.1.3 Control System
In order to control the thermoelectrics, an Arduino reads the voltage level of a temperature sensor PID control on the Arduino processor. In order to drive the thermoelectrics, the output PWM signal coming from the Arduino is filtered into a DC signal using a low pass filter. This is then fed to a MOSFET which will act as a valve for the main source of power coming from the batteries. Below in Figure 5 is a top level block diagram of the control system to be implemented in the prosthesis.

![TEC-Pro Temperature Control System](image)

Figure 5: Top level representation of the temperature control system

5.1.4 User Interface
Initially, the team has elected to implement an on/off switch that will turn the control system on or off with no functionality to alter the temperature set point. However, the team has decided to include an LCD screen and buttons to allow for temperature control and display of temperature measurements.

5.2 Heat Transfer Research
One of the major problems faced in the feasibility study and design of the system was the problem of moving the excess heat from the leg and the heat generated by the thermoelectric away from the user. In order to ensure that we are able to successfully remove all excess heat and provide cooling power under extreme conditions, Team 05 attempted to create a computational thermal model. After beginning to create a thermal model based on heat transfer equations and parameters from online references, the team decided to abandon complex paper and pencil or EES models and develop an Autodesk Inventor and Autodesk Simulation Mechanical model. This model allowed for the precise calculation of heat flows throughout various components of the system and allowed for the simulation of complex geometries and heat flow regimes. The Inventor model, as shown in Figure 6, was composed of an exterior finned heat sink, a composite woven insulating shell with integrated thermoelectric coolers, an interior aluminum heat sink, a silicone liner, and the residual limb.
This model was analyzed using Autodesk Simulation Mechanical’s thermal solver. This first-order approximation was used only to confirm that we could indeed dissipate the required amount of heat while keeping the exterior heat sink at an acceptable temperature. All physical approximations were approximated and the geometry was simplified for ease of simulation and to save computation time. This model was simulated in the worst conditions we expected to face, with the user going for a run, generating approximately 45W of heat that need to be removed. Because of the inefficiencies in the thermoelectric element, in order to keep the user’s skin at a comfortable temperature in the steady state, the system was estimated to have to be capable of dissipating nearly 130W of heat. This large amount of heat generated by the thermoelectric cooler could be dissipated by a simple block heat sink, but would require a more complex heat sink with very efficient fin design. It was later determined that fans would be required as the team did not have the capabilities to manufacture the required heat sink.

For the initial simulation, a heat sink with relatively inefficient fins was used as a fast first-order approximation. The amount of heat dissipated by the heat sink is a function of the surface area of the heat sink in contact with the air, the airspeed around the heat sink, and the difference in temperature between the heat sink and the surrounding air. In Figures 7 and 8, a temperature map of the exterior heat sink at steady state conditions is shown. The map is shown such that the hottest spot on the heat sink is about 120°F while the coolest spot is just under 100°F.
Figure 7: Exterior heat sink temperature map from Simulation Mechanical thermal simulation

Figure 8: Inner view of the exterior heat sink temperature map from Simulation Mechanical
These two figures showed that the temperature is very unevenly distributed to the location of the thermoelectric element. This simulation also showed the team that the exterior temperatures with only one thermoelectric element and large blocky find would not adequately dissipate the required heat. However, the simulation also showed us that the temperature of the rest of the heat sink would be adequately low. By adding more and smaller thermoelectric cooling elements, dispersing them more evenly throughout the socket, and enlarging the heat sink, the team created an improved thermal model which is shown in Figure 10.

Figure 9 shows another heat map of the initial thermal simulation, this time showing the inside of the inner heat sink for the initial simulation, which is closest to the user’s skin. In this temperature map, the lowest temperature near the skin was near -60°F, while the hottest temperature was again near 120°F. This again gave us reason to believe that by moving the thermoelectrics around, adjusting the power, and increasing the heat dissipated in the heat exchanger, we would be able to develop a system that
draws the correct amount of heat from the user’s leg. The improved model, shown in Figure 10, shows our first attempt at further spreading out the heat. We began by getting a more realistic picture of the geometry of a residual limb by taking measurements on Stephen’s leg. In order to increase model accuracy, we also added the silicone liner layer, which was not incorporated in the initial model.

![Figure 10: Heat map of improved thermal model](image)

By increasing the number and decreasing the size of the thermoelectric coolers and revising the locations and heat flux parameters, we were able to distribute the heat more evenly. Although this model was an improvement, there were still hot spots that could be uncomfortably hot and potentially dangerous on the exterior. The lessons that were learned from these simulations were mainly that we needed many thermoelectric elements in order to distribute the heat and the cooling evenly. We did not place too much value on the temperatures we observed in the simulations because of the large uncertainty in the inputs to the simulations. Any simulation is only as good as the numbers provided to the simulation, and because there were so many uncertainties in the convection coefficients for our simulations, the team determined that the proper course of action was to use incremental development during the course of the second semester in order to get experimental results and reduce the uncertainty as we developed the final product. Because of the complexities of computational modelling and the high level of uncertainty, the team also decided it would not be prudent to go into an in depth simulation of the strength of the socket where holes were being cut out. Because the team had no
experience in modelling soft bodies such as muscle and skin and their interactions with a hard carbon fiber or Kevlar socket, it was determined that overbuilding the socket was the best course of action for our situation.

5.3 Materials Research

The temperature generation within the residual limb is dependent on location [2]. The skin temperatures were elevated near muscles such as the tibialis anterior, peroneus brevis and longus, and the medial and lateral heads of the gastrocnemius [2]. The skin temperatures near bony regions, such as the anterior regions along the surface of the Tibia, and end of the residual limb were decreased [2]. This is visually shown below in Figure 11.

![Figure 11: Skin temperature contours of the left residual limb and prosthetic socket [2]](image)

Since temperatures on the surface of the skin vary with location, Aluminum was initially chosen for an internal heat sink material due to its high thermal conductivity and light weight, as well as its machinability considerations. However, due to the issues encountered in attempting to manufacture a thin and irregularly contoured internal sleeve, the idea for an internal heat sink was eventually abandoned in favor of putting the thermoelectric elements in direct contact with the silicone liner. Aluminum was still used as the heat sink material of choice for exterior heat sinks for all the reasons listed above. For the structural portion of the socket, the team considered Kevlar and carbon fiber for their high strengths, and ended up choosing to utilize carbon fiber because it was easier to acquire and was recommended by our industrial mentor.
5.4 Overall System Qualities/Parameters/Targets
After our initial feasibility study, we found that we were able to meet or exceed most of the requirements, with a few areas of our design requiring further development. The weight of the proposed model along with the weight of the batteries and electronics came to roughly 3 pounds, including some wiggle room for additional improvements. This exceeded our goal of keeping the weight below 3 pounds of added weight, as the original socket itself weighed roughly 1.5 pounds. Thermal simulations with one thermoelectric element and a small heat sink have given the team reason enough to believe that with some modifications and tweaking a system could be developed with the correct cooling power, low enough exterior temperatures, and a low enough weight.

6 Prototyping and Development
After developing the basic operating principles for the TEC-PRO during the first semester of ENGR 339/340, we moved on to the prototyping and development phase during the second semester. Throughout the first semester, we realized that there were many sources of uncertainty in our calculations. These included the uncertainty in our original estimate of the required heat flux away from the leg, the uncertainty in watts of cooling from our thermoelectric modules, uncertainty in the heat transfer coefficient on the outside of the heat sink, and uncertainty in the number of modules and optimal placement of the modules on the socket itself. The team decided that the best approach for us to take in order to produce a final product that met all our targets and goals was one of incremental development, building several prototypes, each of increasing complexity, until we arrived at a final prototype that was representative of our final product. We ended up creating three prototypes, along with a fourth, final prototype.

6.1 Prototype 1
The first prototype was created for the purpose of testing our Arduino-based control system and determining how close to expected cooling values we could get. A fiberglass bowl was created to represent the carbon fiber shell for the final design, a hole was cut into the bottom of the bowl, and a thermoelectric module and heat sink were glued and sealed into the bottom of the bowl. This bowl was filled with warm water, rigged with thermocouples, as shown in Figure 12, and tested with the thermoelectric module on and with the module off. The thermocouples were placed in the water, on the base of the heat sink, and near the end of a fin on the heat sink in order to ensure that the heat sink would not get hot enough to burn the skin of the user.
The results of these tests, as well as other prototyping tests, can be found in the Appendix. After performing this first test, the team was disappointed to discover that the thermoelectric module and heat sink had been unable to dissipate heat from the hot side as well as we had hoped, and the heat was actually flowing back into the water, resulting in the water actually heating up with the thermoelectric module on when compared to natural convection with all electronics off. This was determined to be due to the low convection coefficient between the ambient air and the heat sink. Because there was little to no air movement, heat was not dissipated from the heat sink, which resulted in the hot side of the thermoelectric increasing, and eventually the cold side of the thermoelectric increasing as well, releasing heat back into the water instead of pulling heat out. This test showed the team that we were indeed going to have to use fans to help remove the heat from the heat sink and the hot side of the thermoelectric modules. The team considered not using fans and requiring that the user be running or in a windy environment when using the full functionality of the TEC-Pro, but determined that in order to provide a comfortable and consistent experience for the user, we would have to be able to provide cooling operation when the user was not moving. The testing was repeated, this time with a fan blowing across the fins of the heat sink, and we were able to see much improved performance. The major takeaway from this testing was that fans would be required, and that our control system's function was validated.

6.2 Prototype 2
The second prototype was created for the purpose of testing the thermoelectric elements, heat sinks, and fans that we selected for our final prototype, as well as to ensure that our electronics system, batteries, and control system were capable of handling the cooling loads that we required. The second prototype, like the first, was made out of fiberglass. This prototype was made by forming fiberglass around a quasi-residual limb shaped piece of Styrofoam. Holes were cut in the fiberglass socket, and 8
thermoelectric modules, heat sinks, and fans were secured in place. Once completed, tests similar to the tests performed on prototype 1 were run. Thermocouples were attached to the heat sink, the cold side of a thermoelectric element, and a third was placed in the water. Again, warm water was poured into the socket and the thermocouples were monitored every 20 seconds to keep track of the data. The testing setup for prototype 2 is shown in Figure 13.

![Figure 13: Prototype 2 in the process of testing](image)

The data, which is shown in the Appendix, was used with specific heat equations in order to determine the amount of heat removed from the water. These tests lasted for 8 minutes each, which was long enough to understand how the thermoelectric modules would act over an extended period of time. Tests were performed with no electronics on in order to estimate the heat lost due to natural convection. Throughout testing, the team determined that running the fans and thermoelectrics both at 5 Volts was not going to produce enough cooling power to hit our targets. The settings of our power supplies were tweaked until we achieved satisfactory performance, with the fans running at 12 Volts and the thermoelectric modules running at 6.7 Volts. Although we were satisfied with the performance at these conditions, this meant that we would need a higher voltage battery to be able to power the fans when running off of battery power.

6.3 Prototype 3

The third prototype was the last one before our final iteration. This prototype was a complete carbon fiber socket with a pin-lock attachment mechanism built by professionals. This socket was an old one that was no longer in use by Stephen, and was donated to our team in order to do fit testing. The goal of this prototype was to ensure that our cooling power estimates would be satisfactory to cool off an actual amputee and to determine the number of thermoelectric modules required, as well as the optimal placement for the thermal and physical comfort of the user. This prototype, shown in Figure 14,
was built by cutting holes in the existing socket and sealing in thermoelectric modules, heat sinks, and fans.

Instead of using thermocouples and water to test this prototype, testing was performed by Stephen. He wore a silicone liner similar to the one he would be wearing with our final product. He then donned the prototype socket, and gave us feedback to help us improve the design. Throughout the course of this testing, we found that our design had adequate cooling power to keep Stephen cool. Although there was a lag of about 30 seconds right when the thermoelectric modules turned on before cooling could be
felt through the liner, there was enough cooling power that the skin on the back of the leg, where many of the return veins are, was significantly cooler to the touch than skin on the front of the leg, where much of the blood flowing to the leg is. The team also learned that two of the modules that were originally placed on the inside and front of the leg would not be necessary for the final design, as the muscle mass in Stephen’s leg in that location was less than that of other transtibial amputees. This lower muscle mass led to lower heat generation and less cooling requirements. We concluded from this testing that the best places for us to place thermoelectric modules were on the calf and on the lateral side of the socket. Using the lessons learned from three rounds of prototyping, the team then moved on to developing the final product.

7 Final Design

7.1 Socket Creation
The beginning of the lamination process was completed through the normal fabrication techniques. A positive mold was created using a check socket from a previous prosthesis. The positive mold, shown in Figure 15, was poured using plaster and a metal rod was inserted into the plaster to act as a stand for the future lamination steps. After the plaster had hardened, measurements were made around the current residual limb and prosthetic liner, and modification were made using a sander to form the positive model into a shape, which would allow a tight fit to the current volume and shape of the residual limb.

Figure 15: Positive of a fitted socket that was used to create the final socket
The adjusted plaster mold was then laminated using a braided carbon biaxial sleeve, generously provided by A&P technologies, and Ear1 acrylic epoxy resin as well as 617P37 hardening powder. The lamination process was performed using an interior close-topped poly vinyl alcohol (PVA) lamination bag slid over the positive model. Two layers of carbon fiber sleeve laid over the positive, as shown in Figure 16, followed by an open ended PVA lamination bag. The resin and hardener were mixed and poured into the top of the open PVA and drawn into the carbon weave under 20-25 psi of vacuum. The resin was messaged into the weave and wetted out, using a cord, to remove any unneeded weight that extra epoxy would add to the socket. The socket was allowed to harden in the PVA bags for three hours. After the epoxy was determined to be set, the plaster was broken out of the socket using pneumatic air tools. The top of the socket was cut appropriately around the knee line and sanded to a smooth surface.

After this step, the regular process for socket preparation was complete. The final components of the socket included a pyramidal adapter, height adjusting shims, and a prosthetic foot. The components were attached to the socket through hexagonal set screws. The alignment of the socket was then adjusted to allow for a correct ambulation. With the alignment correct, the fit of the socket was tested and modifications were done on any hot-spots by sanding down those spots. Once a good fit was obtained, the electronic components were introduced through a novel lamination technique.
The novel lamination method started with careful placement of eight thermoelectric elements within the two layers of carbon fiber. An expandable foam was poured into the socket, after Vaseline had been applied to prevent bonding. The foam held the shape of the limb within the socket. Eight squares were cut out of the prosthetic socket, with two horizontal rows of three thermoelectric modules in the back, and two thermoelectric modules placed vertically over the tibialis anterior muscles in the front of the leg. The placement of these thermoelectrics mimicked the natural heat generation within a residual limb as shown above in Figure 11. Care was taken to avoid the fibular head as well as the front of the tibia so if future adjustments were necessary, modifications to relieve these typical hot spots could be made.

Once the squares were cut from the carbon fiber to accommodate the placement of thermoelectrics, the thermoelectrics were epoxied in place using the same mixture as for the carbon lamination, shown in Figure 17. Thin aluminum spacers were machined to allow direct heat transfer from the thermoelectrics to the heat sinks without the heat passing through any carbon, which can be seen in Figure 18. The aluminum spacers had a thinner edge that protruded past the needed area of the thermoelectrics. This edge allowed for the third and fourth layers of carbon fiber, applied in the second lamination step, to hold the aluminum spacers and thermoelectrics in place. The aluminum spaces also contained threaded hole locations in each of the four corners for screws to hold in the heat sinks and fans in the future. The aluminum spacers were super glued along the sides to hold them in place until the final carbon fiber layers were laminated to provide the final securing of the components.

Figure 17: First two layers of the final socket with the thermoelectrics wired
The thermoelectrics were wired, as well as a wire to power the fans on the back of the leg and a wire for the fans on the front. The wires were taped in place on the socket and a long rubber tubing was placed over the end leading from the socket to the leg. Two additional layers of carbon fiber were laid over the electrical components and the aluminum spacers. Vaseline was applied to the exterior of the aluminum spacers to allow the carbon to be easily removed from the spacers after the lamination step was complete. The wires were fed through the carbon fiber at the appropriate locations, at the very bottom for run to the battery and control system, and to one location for the fans on the back of the socket, in addition to one location for the fans on the front. Vaseline was applied to the threads and tops of 32 screws to hold keep epoxy from entering the screw holes in the aluminum spacers. The tops of the screws were fed through the carbon fiber at the appropriate locations to hold the carbon in place, and give reference points after the carbon had been hardened with the epoxy. Vaseline was applied to four screws and placed in the bottom of the socket to hold the spots for attachment of the baseplate of the socket to the foot.

![Figure 18: Final socket with the aluminum plates where the heat sinks and fans were attached](image-url)
Before the epoxy was poured, an outer PVA lamination bag was placed over the carbon fiber, and vacuum was applied to pull the epoxy through the carbon. The rubber tubing which held all of the wire components was fed out the top of the PVA lamination bag and past the funnel where the epoxy was poured. Extra care was taken feeding the lamination bag over the head of the screws to prevent the bag from ripping. The same epoxy and hardener were used as in the first lamination process. Once the epoxy set, the socket was broken out with the same process as the first two layers of carbon. However, additional care was taken to avoid cutting the tubing which contained the wires. Squares were cut out of the carbon fiber over the aluminum spacers, using a dremel, to make sure heat would not be passed through the carbon. A rotary sander was used to sand the carbon flat over the exposed aluminum squares so the heat sinks would sit flush with the aluminum.

The wires to each of the fans were connected to the wire feed in the front and the back of the socket, with minimal exposure of the wires to the fans by feeding the wires through the heat sinks. The fans and heat sinks were attached to the aluminum spacers by four screws in each corner. The rubber tubing was cut away to allow the correct wires to attach to the control system, located on the foot, and the batteries to run the fans and thermoelectrics, attached the pylon of the leg. The torque lock and height adjusting pylons were bolted together to allow for the correct height of the leg. Adjustments were then made to orient the foot accurately for normal ambulation. The final product is shown in Figure 19.

![Image](image_url)

Figure 19: Final product with the LCD displaying power level and socket temperature
7.2 Electrical System
A perforated board, Arduino, switches, buttons, and LCD display were placed within a plastic and aluminum (for heat dissipation) water-resistant case. The perforated board contained the electronics necessary to facilitate control of the thermoelectrics and fans, while the Arduino handled all of the sensor input and data output (temperature sensors, LCD display, MOSFETS control voltage). The team decided to use only one 7.4 V 5200 mAh battery at a time on the leg to limit the total weight of the battery case. In addition, an 800 mAh 11.1V battery was added in order to power the fans. The outside of the electronics case features an LCD display, an ON/OFF switch, temperature increase and decrease buttons, as well as a menu button to control the display.

The final rendition of the prosthesis features 8 thermoelectric modules, instead of 12, as explained earlier. Despite having fewer thermoelectric modules, using less increased the power delivered to each thermoelectric. The devices were configured into three parallel sections. One section contained two modules in series, while the other two sections had three modules in parallel, as seen below in Figure 20.

![Figure 20: Thermoelectric Modules Configuration](image)

In order to ensure reliable operation, the components were chosen for the prosthetic socket to function within reasonable temperatures. Looking at the maximum and minimum ratings for each component below in Table 4, the overall temperature range for the socket spanned from -10 to +60 degrees Celsius, or about +14 to +140 degrees Fahrenheit. Assuming the user will not need to cool their leg at temperatures below freezing, the system’s temperature range satisfies desired temperature constraints.
Table 4: Temperature Ratings of the Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Operating Temperature Range (°C)</th>
<th>Storage Temperature Range (°C)</th>
<th>Power Rating at 70 °C (W)</th>
<th>Maximum Actual Power (W)</th>
</tr>
</thead>
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<tr>
<td>NTE2371 MOSFET</td>
<td>-55 to +175</td>
<td>-55 to +175</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>10K Resistor</td>
<td>NA</td>
<td>NA</td>
<td>0.25</td>
<td>0.016</td>
</tr>
<tr>
<td>7.4K Resistor</td>
<td>NA</td>
<td>NA</td>
<td>0.25</td>
<td>0.003</td>
</tr>
<tr>
<td>LCD Display</td>
<td>-10 to +60</td>
<td>-20 to +70</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Arduino (ATMega 2560)</td>
<td>-55 to +125</td>
<td>-65 to +150</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Li-Ion Batteries</td>
<td>-20 to +60</td>
<td>-40 to +50</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CP60233 TEs</td>
<td>No higher than +80</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Finally, high side driver circuits were used to drive the fans and thermoelectric modules as seen below in Figure 21.

![High Side Driver Circuit](image_url)

Figure 21: High Side Driver Circuit

Originally, the team designed for a low side driver circuit, which uses fewer components. However, the grounds of the fans, thermoelectric modules and temperature sensors were all accidentally connected underneath the carbon fiber during the fabrication of the socket. This also forced the team to drive the Thermoelectrics with PWM, which contradicts our previous research. Despite this, the MOSFET now
dissipates significantly less heat due to the nature of PWM allowing the MOSFET to quickly switch between its ON and OFF states.

In addition to an electronics case, a battery holder was designed to hold the two different batteries.

7.3 Performance
Although Stephen has not run with the TEC-Pro on yet, because we didn’t want something to go wrong for Senior Design night, stationary and walking testing has been completed with successful results. After putting the socket on and powering up, Stephen could feel cooled areas produced by the thermoelectric modules within 30 seconds. He also said that it was a consistent feeling – it wasn’t a quick chill and then warm again. Instead, his leg stayed cold until the socket was powered down. This also speaks to the success of the electrical system. With the flick of a switch and the push of a button, the socket can be powered up within 5 seconds, with an almost instantaneous transfer of heat on the thermoelectrics. The extra time required for Stephen to feel the temperature difference is due to the low thermal conductivity of the silicone liner he must wear on his residual limb. The LCD screen on the electrical box displays the power percentage and temperature of the socket on a readable screen. The control system has a limit on the high and low temperatures that can be experienced before the socket shuts itself down to prevent burn and frostbite risks. The electrical components are sealed in watertight cases or integrated into the carbon fiber socket, making the socket almost completely waterproof, although there is a small risk that if submerged, the fans could short, which would also power down the system. The team minimized the risk of snagging any components or accidentally cutting anyone by sanding the thermoelectrics until there were rounded edges and making the stack up of the cooling system modules as small as possible. With four layers of carbon fiber, the team believes the socket will be durable enough to last long past its expected life. The socket fit itself was better than the team could have hoped for, and provides a high level of comfort to the user with little to no disruption to the smooth interior surface from the thermoelectric cooling modules. The fan operation is also extremely quiet, and there is no disruption to the user at all. In addition to hitting all of the initial product operation and safety requirements, the team feels that the design norms are embodied in the TEC-Pro. Our product provides care for a disadvantaged and often overlooked group of people by improving the overall experience of amputees. Our product is built in such a way that it will stand the test of time, and we believe that the durability built into the socket will allow the user to trust the electrical, structural, and thermal reliability of the TEC-Pro. Finally, the simple operation and delightful harmony of the TEC-Pro speaks to the final prototype's integrity. Overall, the team feels that the TEC-Pro’s performance accomplishes the original goals, embodies several Christian design norms, and we hope that the prototype will be a blessing to the user for years to come.

8 Business Plan
8.1 Marketing Study
8.1.1 Competition
There is only one other company who makes a product similar to the one Team 05 has designed. This company is Leto Solutions, with their product called the Aquilonix™ Prosthesis Cooling System. This product “provides a thermoelectrically cooled environment within the prosthesis socket that cools the space and removes heat.” The product has some features such as being lightweight (less than 2 pounds), is powered by rechargeable batteries, and is turned on and off with a switch. The product is not
commercially available yet, so no pricing data is available [14]. A comparison between the TEC-Pro and Leto Solutions’ product is shown in Table 5.

Table 5: Comparison of the competition

<table>
<thead>
<tr>
<th>Features</th>
<th>TEC-Pro</th>
<th>Leto Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoelectrically Cooled</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Rechargeable batteries</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Lightweight</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Integrated into socket</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quiet</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Water resistant</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Self-regulating temperature</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Aesthetically pleasing</td>
<td>Yes</td>
<td>?</td>
</tr>
<tr>
<td>Temperature adjustability</td>
<td>Yes</td>
<td>?</td>
</tr>
</tbody>
</table>

8.1.2 Market Survey
There is quite a demand for the TEC-Pro. According to the United States Department of Veteran's Affairs, “The United States had nearly 1.6 million people with amputation based on 2005 reports. In the United States, it could be estimated that the population with amputation will increase to 3.6 million by 2050” [7]. Currently, there are no products available that solve the issue of discomfort inside the prostheses due to heat and/or perspiration. The team’s client, Stephen, was the main source for features desired by prospective customers, and the "customer" for our final product. These features are broken down in Section 3: Requirements.

8.2 Cost Estimate
8.2.1 Development
The cost to develop this product is seen in Section 2.3. To summarize, the development and extra parts cost $368.85. The production of the final product was $423.42. The grand total for our project was $792.27.

8.2.2 Production
For this product, mass production is not the most viable way to distribute our product. Each product would have to be specially designed for its customer because socket fit is one of the most important features for an amputee. Therefore, mass production on an assembly line is not practical. However, many components could be produced on a line separate from the parts that are custom fit. We envision producing the thermoelectric, heat sink, and fan as an integrated module as well as a control system and integrated electronics that would be proprietary. These pieces would be sold or licensed to the prosthetists who are making the sockets themselves. Our hypothetical company would also provide training to prosthetists on how to integrate our technology into their sockets. If large enough quantities were being sold, the TEC-Pro modules would be able to be integrated, streamlined, and manufactured more cheaply, leading to higher profit margins and reduced costs for the end user.
8.2.3 Fixed Costs
Fixed costs are expenses that are present no matter how many products are created and sold. Fixed costs of this project include $100/hour for design time and material for the prototypes and development including a carbon fiber socket, heat sinks, thermoelectrics, batteries, wiring, and epoxy.

8.2.4 Variable Costs
Variable costs are expenses that depend on the amount of production of a company. The amount of products that could be produced will depend on assembly time and production costs, which would have to be calculated if we were to sell our product for mass production.

8.2.5 Summary Financials
Not including parts donated to the team, the total cost of parts purchased was $792.27. If the socket were to be produced again, this cost would theoretically decrease significantly because many of the parts purchased were not included in the final socket. However, because it does not reflect the carbon fiber and other donated materials, it stands as a decent estimate of what the material costs. The engineering hours put into the project, 894 hours, would cost around $89,400 (Total hours x salary/hour).

The team will need to know the final costs of producing the TEC-Pro. With this information, it will be possible to calculate the price at which the product should be sold, which takes into account the labor, materials, production tooling, and other expenses. Since Stephen, Lance, and Nathan were in Business 357, they were able to perform an analysis of the cost of the project and apply that knowledge in the feasibility study. In addition, Andrew has taken multiple business classes so his knowledge also contributed in this business analysis.

8.3 Future Outlook
As technology advances, integration of cooling componentry to prosthetic sockets will become more seamless. Future prospects include curved thermoelectrics, which would allow for more interior surfaces of the prosthetic socket, that are from the thermoelectrics, to process the correct features to fit the patients residual limb. The final prototype featured an Arduino and perforated board to facilitate control of the thermoelectric modules and fans. Ideally these two boards would be simplified into a single board with processing, I/O, and analog circuitry to drive the fans, thermoelectric modules, and a higher resolution screen. This would reduce cost, weight, complexity and size in order to create a more aesthetically pleasing prosthesis. Battery life weight with respects to its life are areas of heavy research. Advancements in battery technology will allow for future sockets to have less additional weight for extended duration of cooling. As technology advances, the technology will allow for the heat transfer from the residual limb to the environment to become more efficient and seamless, allowing for the prosthetic sockets to support the desired functions of the patient, without many of the negative side effects of trapping heat.
9 Conclusion

In conclusion, Team 05 has studied the feasibility of a thermoelectrically cooled prosthetic leg socket for transtibial amputees, created a design, and executed the design by producing a functional prototype. The final design is composed of a carbon fiber socket, thermoelectric cooling elements, heat sinks, fans, batteries, an Arduino, and several other electrical and mechanical elements to support the system. After preliminary studies into the heat transfer, materials, biological considerations, and electrical controls, Team 05 has designed, developed, and created a functional prototype that was presented at Senior Design Night on May 7, 2016. The prototype has been tested by our customer and team member Stephen Lander. After about 30 seconds, Stephen could feel the cold, which means that heat buildup will take much longer and the amount of sweat produced through work will be much less. Although development of the TEC-Pro cannot move forward into mass production or further development because of patent infringement issues, Team 05 considers this project a resounding success.
10 Acknowledgements

We would like to thank the Calvin College Engineering Department for sponsoring our project, and we would also like to thank the following people who helped us in this accomplishment:

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- Professor Heun, for all his help with the thermodynamic and modelling aspects of the project we faced first semester
- Zach Harvey, board certified prosthethist, for being our industrial mentor
- Stephen Lander, for being our teammate and customer, and allowing us to use the trials he has faced with his amputation for our senior project
- Zachary Hagen, for contributing to our team’s business model and providing us with moral support
- A&P Technologies for donating the carbon fiber weave for our project and helping us to keep our costs down
- Bob DeKraker, for getting us everything we needed when we needed it
- Phil Jasperse, for helping us to find the best way to make all our components and using his years of manufacturing experience to minimize our headaches
- Chemistry Department, for allowing us to use the fume hood when laminating the socket
- Professor Tatko, for advising us on the use of the epoxy and hardener
- Jennifer Ambrose, for providing safety equipment and training
- Professor Yoon Kim, for providing electrical engineering expertise
- Professor Mark Michmerhuizen, for providing battery advice
11 References


[4] Prevalence of heat and perspiration discomfort inside prostheses: Literature review. Kamiar Ghoseiri, PhD Candidate; Mohammad Reza Safari, PhD* Department of Orthotics and Prosthetics, University of Social Welfare and Rehabilitation Sciences, Tehran, Iran


12 Appendices

Preliminary Heat Transfer Calculations

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Preliminary Heat Transfer Calculations

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### Run #2: Thermoelectric Off

![Graph showing temperature over time for Test #2 with Thermoelectric Off](image1)

### Run #1: Thermoelectric On

![Graph showing temperature over time for Test #4 with Thermoelectric Running at 5°F](image2)

Total cooling minus convection: 12.2
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Average watts of cooling, minus convection, for entire test period: 4.65
Test details
mass of water - 1.6 kg
Cp of water = 4.187 kJ/kg

POWER RAMPED UP

ROOM TEMP WATER, JUST TO SEE HOW COLD IT COULD GET

Test #1 with Thermoelectric at 6.73V, 1.73 A and Fans at 12V

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// TEC-Pro
// Nathan Slager
// Calvin College 5/7/2016
// This software provides an interface between a TEC-Pro user and their socket

// Sources:
// arduino.com
// http://www.pjrc.com/teensy/td_libs_OneWire.html

#include <LiquidCrystal.h>
#include <OneWire.h>

// Input Pin Definitions
#define BUTTON1PIN 52
#define BUTTON2PIN 51
#define BUTTON3PIN 48
#define TEMPPIN 13

LiquidCrystal lcd(2, 3, 6, 7, 10, 11); // lcd uses these pin numbers
OneWire ds(TEMPPIN);

// Output Pin Definitions
#define TEPIN 5
#define FANPIN 4

// Button Variables
int button1 = 0;
int button2 = 0;
int button3 = 0;
int button_press;
unsigned long now1;
unsigned long last_push = 0;

// Menu Variable
int menu_toggle = 0;
int total_menus = 1; // number of menus
unsigned long now3;
unsigned long last_menu = 0;

// Temperature variables
byte i;
byte data[12];
byte addr[8];
byte present = 0;
byte type_s;
unsigned long now2;
unsigned long last_read = 0;
int converting = 0;
float celsius, fahrenheit;

// TE and fan power
int power = 0;
bool emergency_off = false;

void setup() {
    // Initialize pins as off
    analogWrite(TEPIN, 0);
    analogWrite(FANPIN, 0);
    pin_setup();
    lcd_setup();
    temp_sensor_setup();
}

void loop() {
    poll_temp();
    menu();
}

void menu() {

    button_press = poll_buttons();

    if (button_press > 0) {
        set_power();
    }
    if (button_press == 3) { // Toggle menu
        menu_toggle = (menu_toggle + 1) % total_menus;
    }

    // Menu 1
    if (menu_toggle == 0) {
now3 = millis();
if (now3 - last_menu > 1000) {
  last_menu = millis();
  // Display Menu 1
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("Temp: ");
  int t = fahrenheit;
  lcd.print(t);
  lcd.write(byte(0)); // Prints degrees symbol
  lcd.print(" F");
  lcd.setCursor(0, 1);
  lcd.print("Power: ");
  for (int i = 0; i < 5; i++) {
    if (i < power) {
      lcd.write(byte(1)); // Prints block
      lcd.setCursor((8+i), 1);
    } else {
      lcd.print(" ");
    }
  }
  lcd.print(power*20);
  lcd.print("%");
}
}

void set_power() {
  if (emergency_off) {
    power = 0;
    return
  }

  }
  if (button_press == 1) {
    power = power + 1;
  } else if (button_press == 2) {
    power = power -1;
  }
  if (power > 5) { // Keep power between 0 and 5
    power = 5;
  }
  if (power <= 0) { // Fan power should be either off or higher than (170/255);
    power = 0;
    analogWrite(FANPIN, 0);
  } else {
    analogWrite(FANPIN, (power * 17 + 170));
  }
  analogWrite(TEPIN, (power * 51));
  button_press = 0;
}

int poll_buttons() {
  now1 = millis();
}
if (now1 - last_push > 500) { // At most one button press every half second
    last_push = millis();

    // Measure voltage of pins 1-3
    button1 = digitalRead(BUTTON1PIN);
    button2 = digitalRead(BUTTON2PIN);
    button3 = digitalRead(BUTTON3PIN);

    if (button1 + button2 + button3 > 1) {
        return -1;
    } else if (button1 == HIGH) {
        return 1;
    } else if (button2 == HIGH) {
        return 2;
    } else if (button3 == HIGH) {
        return 3;
    } else {
        return 0;
    }
}

void temp_sensor_setup() {
    if ( !ds.search(addr)) {
        // Display to lcd that temp sensor not found
        ds.reset_search();
        delay(500);
    }
}

void poll_temp() { // Measures the temperature of the socket, not the leg skin temperature
    if (converting == 0) { // Don't restart conversion before the previous finishes
        converting = 1;

        if (OneWire::crc8(addr, 7) != addr[7]) {
            return;
        }

        ds.reset();
        ds.select(addr);
        ds.write(0x44, 1);        // start conversion, with parasite power on at the end
    }

    now2 = millis();
    if ( now2 - last_read > 1500) {
        converting = 0;
        last_read = millis();

        present = ds.reset();
    }
ds.select(addr);
ds.write(0xBE);         // Read Scratchpad

for (i = 0; i < 9; i++) {
    data[i] = ds.read();
}

OneWire::crc8(data, 8);

// Convert the data to actual temperature
// because the result is a 16 bit signed integer, it should
// be stored to an "int16_t" type, which is always 16 bits
// even when compiled on a 32 bit processor.
int16_t raw = (data[1] << 8) | data[0];
if (type_s) {
    raw = raw << 3; // 9 bit resolution default
    if (data[7] == 0x10) {
        // "count remain" gives full 12 bit resolution
        raw = (raw & 0xFFF0) + 12 - data[6];
    }
} else {
    byte cfg = (data[4] & 0x60);
    // at lower res, the low bits are undefined, so let's zero them
    if (cfg == 0x00) raw = raw & ~7; // 9 bit resolution, 93.75 ms
    else if (cfg == 0x20) raw = raw & ~3; // 10 bit res, 187.5 ms
    else if (cfg == 0x40) raw = raw & ~1; // 11 bit res, 375 ms
    // default is 12 bit resolution, 750 ms conversion time
}

celsius = (float)raw / 16.0;
if (celsius != 85.00) { // In case conversion went awry
    fahrenheit = celsius * 1.8 + 32.0;
    fahrenheit = round(fahrenheit);
}

if (fahrenheit > 110 || fahrenheit < 20) {
    emergency_shutoff = true;
} else {
    emergency_shutoff = false;
}

void lcd_setup() {
    byte degree[8] = {14,10,14,0,0,0,0}; // Custom degree character
    lcd.createChar(0, degree);
    lcd.createChar(1, block);
    lcd.begin(16, 2); // Init lcd
    lcd.print("TEC-Pro");
}

void pin_setup() {
    // Button Pins Setup
    pinMode(BUTTON1PIN, INPUT);
    pinMode(BUTTON2PIN, INPUT);
    pinMode(BUTTON3PIN, INPUT);
    pinMode(TEPIN, OUTPUT);
    pinMode(FANPIN, OUTPUT);
}