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Prosthetic Thermal Management Device

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Abstract

High temperatures in lower-limb prosthetics can lead to poor user skin conditions and mechanical slippage between the user’s limb and the prosthetic. This report presents an air-cooling device for a lower-limb prosthesis. This device’s purpose is to maintain a constant skin-prosthesis interface temperature. A compact heat sink and small fan were used to transfer the bio-heat to the ambient surroundings. By changing the power of the fan, the thermal resistance of the whole system can be adjusted to match various thermal loads and environmental temperatures. Heat pads were used to mimic the heat generation of a residual limb, and cooling performance was assessed through a relationship between the thermal resistance of the heat sink and the fan power. Experiments show that the cooling capacity of the prototype device ranges from 0W to 6.7W, at an ambient temperature of 23°C. The system response time is less than three minutes. Under an automatic control mode, the controlled temperature error is less than ±0.3°C by setting a desired skin temperature of 31.2°C. For further development towards a commercial product, material considerations were also made. Pyrolytic graphite was found to be an optimal material for performance, environmental and economic reasons. Slip casting would be optimal for short manufacturing runs and die pressing and sintering would be optimal for longer manufacturing runs.
Introduction

The User
For reasons that do not concern this report, patients sometimes require amputation of some part of their lower limb (leg). These patients then normally require a prosthetic to carry on daily life. Figure 1 describes the different types of amputations. While this report only considers the specific cases of transtibial and transfemoral prosthetic designs, the ideas developed in later sections could be applied to other prosthetic cases.

The thermal management of the interior socket of a lower-limb prosthetic is important for many reasons. Poor thermal conditions can cause excess sweating and lead to a harmful environment for the user’s skin, which can cause irritation and blisters [1-5]. Furthermore, excess sweating reduces the grip of the prosthetic on the user’s limb thus causing the prosthetic to become loose and cause skin wear or even causes the prosthetic to slip off in some cases [2,3]. In order to combat the condition of
excess sweat, the skin must be kept below a critical temperature. This critical slightly varies from person to person, but is generally referenced between 32-33 degrees Celsius [6,10].

**The Device**
The prosthesis’s liner and socket material have poor thermal conductivities and prevents evaporative cooling from sweating, thus limiting heat transfer to the surrounding environment and creating non-ideal thermal conditions for the user [9]. As a system, the thermal environment inside of prosthesis is affected by heat generation of the limb (thermal load), thermal resistance of the prosthesis and ambient temperature. The heat generation in the limb varies drastically over a wide range of activities from sitting to running. Therefore, thermal management of a prosthesis requires an adaptive solution. One such solution involves adjusting the thermal resistance of a cooling system, which can utilize air cooling or liquid cooling methods.

**Previous Work**
Traditionally, both air-cooling and liquid-cooling have been used for personal thermoregulation. Air cooling systems based on forced convection remove metabolic heat by fan driven airflow within a suit. [1-3] While limited by the contact area and low heat capacity of air, heat transfer is ineffective and therefore the cooling capacity is low. The difference between thermal load and air cooling system power is large and proven to be unacceptable [4]. Instead, liquid cooling [5,7-10], has found a wide range of applications for personal cooling in space [4], deep ocean [12], fire fighting and other hazardous environments. This type of cooling system has a high coefficient of convective heat transfer that reduces the thermal resistance between the liner and environment. Additionally, it has an easily adjustable cooling capacity controlled by the liquid’s flow rate. However, comfortably using a liquid cooling system requires small diameter tubing, which translates to high power consumption for liquid circulation. Due to the relatively bulky and power intensive equipment needed for this
type of liquid cooling system, it is not viable for both a comfortable and functional design.

Traditional cooling methods rely on cumbersome external systems, which are not ideal. New personal cooling systems have been developed that are lightweight, compact and power efficient. PCM (phase change materials) are a great heat storage media that can be integrated into garments where they absorb excess metabolic heat [13]. For example, the large temperature difference between dry ice and the skin significantly enhances the heat transfer rate. An alternative to PCM cooling is thermoelectric device based cooling which offers more control and user comfort [14-18]. While limited by its working principle, the system is also relatively inefficient and costly to manufacture.

**Design Criteria**
Thus a superior personal cooling system should be outstanding in the following aspects: 1) Fit all range of the thermal loads, 2) be compact and lightweight, 3) be quiet and easy to maintain 4) be economically producible

This report presents an air-cooling device that can regulate the inner prosthesis temperature. The cooling device uses an adjustable thermal resistance to adapt to various activity patterns and environments in a short amount of time. To make the device portable and more efficient, heat pipes are used to concentrate heat flux from the residual limb into a small region on the outside of the socket. A compact heat sink and a compact fan/air duct were placed on this region to enhance the heat transfer. After design and testing, further considerations on material choice and manufacturing processes were made for an end-user product.
Experiment Overview

Device Design
The design of the prototype cooling device is shown in Figure 2. It consists of 1) heat pipes with rectangular cross sections (10.2mm×4.0mm) placed in contact with the liner surface to collect heat flux and transfer it to a small cooling region outside of the socket, 2) a compact fin heat sink with a large surface area placed on the cooling region to remove the heat, and 3) a lightweight, low power fan with a directed air duct to further enhance the heat removal.

Figure 2: Cooling Device Design

The use of heat pipes significantly reduces the thermal resistance of the socket-prosthesis system. The heat pipes have a negligible thermal resistance (0.08°C/W, provided by the manufacturer) when compared with the large thermal resistance of a socket [9]. The thermal resistance of the heat sink is inversely proportional to the convection heat transfer coefficient and the surface area as seen in Equation 1. While the heat sink has a fixed surface area, the convection heat transfer coefficient can be adjusted by the fan power. Hence, the heat sink can be used to adjust the thermal resistance for various cooling needs under different ambient temperatures and wearer
activity patterns. Therefore, the thermoregulation of the limb inside the prosthesis is possible.

**Experiment Design**
The cooling device prototype and the measurement setup is shown in Figure 3.

![Figure 3: Measurement Setup](image)

**Residual Limb**
The stainless steel bucket used to model a residual limb is 160.0mm in length, 135.0mm in diameter and 1.0mm in thickness. Five heat pipes are wound around the bucket. Each rectangular heat pipe is 550.0mm in length, 10.2mm in width and 4.0mm in height. The outer surface of the bucket represents the interface between the skin and the socket. For comfort, a liner is normally inserted at this interface, however we did not insert a liner in the prototype system because the liner can be modeled as a constant thermal resistance. Since the device’s temperature regulation is based on a variable thermal resistance of the heat sink, the liner is unnecessary to include in this experiment. However, the effect of the liner on heat transfer was considered in our thermal resistance analysis. The thermal resistance of each heat pipe is 0.08°C/W.
(provided by the manufacturer). Heating pads attached to the bucket were used to mimic the heat generation of a residual limb. Eight self-constructed heating pads (Made with resistance wire, 34GA Kanthal A-1, TEMCo, USA) were attached on the inner surface of the bucket to provide thermal loads. The electrical resistances of the heating pads are $437\pm10\,\Omega$. The bucket and heat pipes are covered by a thermal insulation layer of polyurethane spray foam (Touch n Foam, thermal conductivity of 0.026W/m·K) to prevent heat dissipation to the environment without first passing through the heat sink, and to mimic the insulation of a socket.

**Heat Sink**
The heat sink (75mm×70mm×20mm), consisting of 477 copper fins welded onto one side of an aluminum plate, was constructed in our lab. Each fin is 20.7mm in length, 7.2mm in width and 0.2mm in thickness. The combined surface area of the fins is 0.142m$^2$. The opposite side of the aluminum plate is in contact with the ends of the heat pipes. This location can be seen in the upper right of Figure 3. Thermal compound (IceFusion, cooler master, thermal conductivity- 1.22W/m·K), is applied at two main contact areas. The first contact area is between the heat pipes and the aluminum plate. The second contact area is between the bucket and the heat pipes. The fan and flow duct is a VGA cooler (Vortexx Neo, Akasa), which is modified to fit the self-constructed heat sink and aluminum plate heat collector. To complete the external cooling unit, the heat sink, heat collector, fan and flow duct were then assembled and attached to the ends of the heat pipes.

**Temperature Measurement**
During testing, 10 thermistors (MA100, NTC Thermistors, GE Sensing) were used to measure temperatures at various locations on the inner wall of the socket, as shown in Figure 2. Six were attached on the inner surface of the socket. Each thermistor was located in the middle of two heat pipes. Two were used to measure the temperature at the bottom and top of the heat sink. The final two were used to measure the inlet and outlet air temperature of the cooling device. According to the product specification,
the thermistors have a tolerance of ±0.1°C in a temperature range from 20°C to 35°C. Each thermistor was calibrated before use to ensure its accuracy.

**Experimental Method**

The experiment setup used to test the prototype device is shown in Figure 2. Ten thermistors were used to measure the temperature distribution in the cooling system and each thermistor has a resistance of 10kΩ. A constant 100mV voltage was applied to each thermistor by a function generator (33120A, Agilent). The thermistors themselves generated heat at 1μW due to current flow, which is negligible when compared with thermal loads of the heating pads. These heating pads are attached to the inner surface of the bucket and were used to generate 0W to 12W of heat. A power supplier (E3631A, Agilent) controlled the input voltage of the heating pads to obtain the required thermal loads. Another power supplier (E3644A, Agilent) was used to control the fan power to change the thermal resistance of the heat sink. The voltage response was recorded using a 16-channel data acquisition card (NI USB 6210, National Instruments) at sampling rate of 10Hz.
Results

Thermal Resistance

The equivalent thermal resistance model of the cooling system is shown in Figure 4. The objective of the prosthetic cooling device is to maintain a constant skin temperature of 31.4°C [10] at various thermal loads, i.e., heat generated by the residual limb. To date, little experimental data exists to estimate the thermal load of a residual limb. Here, the residual limb is modeled as a multi layer cylinder, including skin, fat, muscle and bone [15]. Parameters of these body elements are shown in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Radius (cm)</th>
<th>Volumetric Heat Generation (W/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>2.20</td>
<td>0</td>
</tr>
<tr>
<td>Muscle</td>
<td>4.80</td>
<td>684</td>
</tr>
<tr>
<td>Fat</td>
<td>5.33</td>
<td>58</td>
</tr>
<tr>
<td>Skin</td>
<td>5.33</td>
<td>368</td>
</tr>
</tbody>
</table>

Table 1: Body Tissue Parameters

We assumed the portion of the residual-limb covered by the socket is a 300mm long cylinder. The basal metabolic rate is 1.3W. For activity patterns from “Seated, relaxed” to “Standing, medium activity”, the metabolic heat generation of the muscle tissue ranges from 1.38W/kg to 5.07W/kg [S23]. This leads to an estimated range for the residual-limb thermal load of 2.7W to 9.5W.
As shown in Figure 4, the overall thermal resistance between the residual limb and the environment is affected by thermal resistance of the following 1) heat sink, 2) heat pipes, 3) liner, and 4) insulation layer. Because convection heat transfer is dominant for the heat sink, radiation can be neglected and the thermal resistance of the heat sink (convection heat transfer) can be expressed as:

$$R_{\text{heat sink}} = \frac{1}{h \ast A}$$

\textit{Equation 1: Heat sink Thermal Resistance}

Where \( h \) is the convection heat transfer coefficient (W/m²·K), and \( A \) is the surface area where convection takes place (m²). Hence, changing the fan power and surface area can vary the thermal resistance of a chosen heat sink.

Each of the heat pipes has a thermal resistance of 0.08°C/W. Thus, the total thermal resistance of the five heat pipes in parallel, \( R_{hp} \), is 0.016°C/W. Note that the small gap between each heat pipe and the bucket surface is filled with a thermal adhesive. This causes additional thermal resistances, and leads to a slight temperature variation on the bucket surface.

Next, we estimated the thermal resistance of the liner layer, which is usually applied between a socket and a residual-limb for comfort. Here the thermal resistance, \( R_l \), is estimated based on a commonly used liner, “Ottobock, Silicone Liner” with a thermal conductivity of 0.228W/m²·K and a thickness of 3mm [9]. Using Equation 2 below, the thermal resistance of a cylindrical liner attached to the residual limb is about 0.13°C/W. Note that although we did not use a liner in our experiment, theoretical analysis was conducted to show the cooling device has the capability to maintain a constant surface temperature while wearing a liner.

The thermal resistance of the cylindrical spray foam (thermal insulation layer) is calculated by:

$$R_{\text{ins}} = \frac{\ln \left( \frac{R^2}{2L} \right)}{k \ast L}$$

\textit{Equation 2: Thermal Resistance of Insulation Layer and Liner Layer}
where k is the thermal conductivity of spray foam; r1 and r2 are the inner diameter and outer diameter of the insulation layer. The thermal resistance of the spray foam insulation, $R_{\text{ins}}$, was calculated to be $17.6^\circ\text{C}/\text{W}$, which is much larger than the combined thermal resistance of the liner, heat pipes and heat sink (ranging from $0.17^\circ\text{C}/\text{W}$ to $0.42^\circ\text{C}/\text{W}$). Thus the heat flux dissipated through the thermal insulation layer is miniscule. This ensures that for the following experiments, the majority of heat was transferred by heat conduction through the liner, the heat pipe and the heat sink.

### Determining Performance Characteristics

![Figure 5: Varying Thermal Load](image)

Figure 5 shows typical temperature response curves at a fixed fan power of 2.3W. Note that the variation in bucket surface temperatures (red curves) is due to the variation of thermal contact resistances caused by uneven application of thermal grease. We used the average bucket temperature for the thermal resistance analysis. From Figure 5, the temperature difference between the bucket surface and the environment (T1-T10) and between the heat sink and the environment (T8-T10) were calculated and plotted in Figure 6.
Similar experiments were conducted at various fan powers and the results are seen in Figure 7.

It can be seen in Figure 7 that when the fan power reached 2.3W, the thermal resistance remained nearly constant ($0.97^\circ\text{C}/\text{W}$). This represents a saturation of the convection constant in Equation 1.
Cooling Capacity Simulation

Experiments were conducted to demonstrate that the cooling device can maintain a nearly constant skin-socket interface temperature during different thermal loads. To obtain Figure 8, the testing procedure was as follows: the thermal load was set to 3.9W via the heating pads to simulate “Sedentary Activity” for 30min; a fan power of 0.24W was used. For the next 30 minutes, the thermal load was set to 6.7W, and the fan power was set to 1.96W. After the first hour, the thermal load and fan power were set back to the initial “Sedentary Activity” settings for an additional 30 minutes. Figure 8 shows the temperature response curve of the bucket surface, the heat sink (both top and bottom surfaces) and the environment. The bucket surface temperature was kept nearly constant (31.0°C) during “sedentary activity” with a fan power of 0.24W. After switching the system to the “standing, light activity” mode (thermal load of 6.7W, fan power of 1.96W), the surface temperature stabilized at 31.3°C; the response time was approximately three minutes. Subsequently, after returning to the “sedentary activity” mode, the surface temperature changed to 31.1°C within three minutes. The results show that the cooling system is capable of maintaining a constant surface temperature by using appropriate fan powers. For comparison, we also conducted an experiment using a constant fan power (0.24W) for both sedentary and standing modes; as shown in Figure 9, the surface temperature increased to 33.2 °C at the end of the 30-minute “standing activity” mode. Even when the thermal load was switched back to “sedentary”, it took nearly 30 minutes for the temperature to drop from 33.2°C to 31.6°C.
Figure 8: Temperature Response of Changing Thermal Load with Active Fan Power Switching

Figure 9: Temperature Response of Changing Thermal Load with Constant Fan Power
Further Development

Material Optimization and Selection
After displaying the device’s capabilities in earlier sections, it would be useful to make considerations concerning socket material, which could increase the rate of heat transfer from the residual limb to the environment. While we used insulation foam to insulate the model residual limb for analysis purposes, we would not want to insulate the limb in actual use. Using optimization theory from Material Selection in Mechanical Design (4th Ed) by Michael Ashby, objectives and constraints are developed and used to analyze different material options in Granta CES EduPack software.

First, the working principle, or function, of the cooling device and the socket is to transfer heat with minimal time delay. The objectives functions should then be to maximize heat transfer while minimizing time delay. Next, there are many constraints to consider and many concern environmental effects. These constraints along with the full translation can be seen in Table 2.

<table>
<thead>
<tr>
<th>Function</th>
<th>Transfer heat from limb to environment with minimal time delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constraints</td>
<td>Corrosion resistant, Non-Flammable, Resistant to UV radiation, Fracture Toughness &gt; .1ksi/in², Stable between -20 to 120 degC, Hypoallergenic</td>
</tr>
<tr>
<td>Objectives</td>
<td>Maximize heat transfer, Minimize time delay and weight</td>
</tr>
<tr>
<td>Free Variables</td>
<td>Material choice, Material thickness</td>
</tr>
</tbody>
</table>

Table 2: Material Optimization Translation

Objective Function
Next we will develop an objective function to plot materials based on properties of interest. Two equations are of interest for our objective function; heat conduction and the transient heat time constant both shown below.

$$q = k_s \Delta T \frac{A}{L}$$

Equation 3: Conduction Heat Transfer Equation

$$t = \frac{c \rho V}{h A_s}$$

Equation 4: Time Constant of Transient Heat Transfer
Holding the design area, length, volume, and convection coefficient constant, we can see that conduction heat transfer, Equation 3, is directly related to the thermal conductivity of the material.

\[ q \propto k_s \]

*Equation 5: Maximum Heat Transfer Relationship*

Similar analysis will show that the time response, Equation 4, of the system is directly related to the density and specific heat capacity of the material.

\[ t \propto c_p \]

*Equation 6: Minimum Time Response Relationship*

Thus we can develop an objective function that we want to maximize as;

\[ M_1 = \frac{k_s}{c_p} \]

*Equation 7: Objective Function Performance*

Imposing the constraints in Table 3 and plotting the results we arrive at Figure 10 as a material selection plot based on performance only.
From Figure 10, two materials are shown to maximize the performance objective function, pyrolytic graphite and diamond. Obviously, from an intuitive understanding, diamond will be too costly and difficult to manufacture for normal economic use. Thus, we will develop another objective function that takes the material price into account and plot it against the performance objective function.
Using Equation 5 and material cost we develop the second objective function as Equation 8.

\[ M_2 = \frac{\$}{k_s} \]

Equation 8: Economic Objective Function

To find the optimal material with regards to both performance and cost, we plot the inverse of the economic objective function against the inverse of the performance objective function and minimize. The result can be seen in Figure 11.

As seen in Figure 11, diamond is no longer the optimal choice as the inverse of the economic objective function is too large due to the price of diamond. However, the second best option, pyrolytic graphite, is now the obvious winner.
However, while economic concerns are of great importance, the environmental impact of the device is important to consider as well. To take into account the environmental impact of the device, we will consider the energy required to manufacture it, the embodied energy $H_p$.

$$M_3 = \frac{k_s}{H_p \rho c}$$

Equation 9: Environmental Objective Function

Using methods from previous charts with an additional constraint that the material must be able to be thrown in a landfill we arrive at Figure 12.

![Figure 12: Environmental Objective Plot](image)

Again, pyrolytic graphite is shown to be the best choice with copper alloys a close second.

Therefore, after the multiple objective functions considered, pyrolytic graphite is clearly the most optimal material to choose. Outline the properties of this material.
Manufacturing Considerations
The Granta CES software was again used to analyze manufacturing processes for pyrolytic graphite. This analysis was performed for both short and long manufacturing runs. Slip Casting was chosen as the optimal process for short runs and Die Pressing and Sintering was chosen for longer manufacturing runs. The characteristics of these two processes can be seen in the following figures. It is important to note that 3D printing of a socket would be ideal as each person’s residual limb shape is different. This is discussed later in Conclusion and Discussion.

Economic Batch Size: **10-1000**

![Figure 13: Slip Casting Characteristics](image-url)
Die Pressing and Sintering

**Physical attributes**

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass range</td>
<td>5.71e-5 - 0.0286 lbf.s²/in</td>
</tr>
<tr>
<td>Range of section thickness</td>
<td>0.0591 - 0.315 in</td>
</tr>
<tr>
<td>Tolerance</td>
<td>0.00394 - 0.0197 in</td>
</tr>
<tr>
<td>Roughness</td>
<td>6.3e-5 - 2.48e-4 in</td>
</tr>
</tbody>
</table>

**Economic Batch Size:** 5000-5,000,000

Figure 14: Die Pressing and Sintering Characteristics

Figure 15, compares the cost of producing 10 units between the two manufacturing processes.

**Figure 15: Slip Casting and Die Pressing and Sintering Comparison**
Discussion and Conclusion
This report has developed and demonstrated an air-cooling device that maintains a constant skin temperature in a lower-limb prosthesis. The cooling system uses thermal pipes to collect heat generated from the residual limb and deliver the heat to a compact heat sink outside of the socket. A small, quiet fan was used to remove the heat from the heat sink. For a known activity, a suitable fan power can be set to maintain a constant skin temperature.

The thermal management of our device is based on the adjustable thermal resistance of the heat sink ranging from 0.77°C/W to 2.95°C/W. The thermal loads are limited by this range for this specific design. For example, with a fan power of 3.3W, the max cooling capacity is about 7.1W in an environment with a temperature of 23°C. Using a heat sink with higher surface area and higher fin efficiency can further reduce the thermal resistance of the heat sink. Finally, the metal bucket used to mimic the residual limb works as a heat collector to concentrate heat from the heat pads and transfer it to the heat pipes. In a real prosthesis, we can increase the number of heat pipes installed in the inner surface of the socket for effective heat collection.

A Li-ion battery can be used to power the cooling fan for everyday use. As an example, a cell phone battery with a capacity of 5.3Wh and a weight of 28.5g can sustain 22h and 2.7h of fan use for “Sedentary Activity” (fan=.24W) and “Standing, Light Activity” (fan=1.96W), respectively. The fan is quiet and has virtually no vibration, which makes the system convenient to wear, maintain and replace.

The resistance of the prosthesis socket is also very important in determining the overall thermal resistance and thus the steady state temperature of the skin-prosthesis interface. An analysis was performed to show that pyrolytic graphite is an optimal material to use for a socket. However, sockets usually need to be custom molded to an individual’s residual limb. Additive manufacturing methods are extremely good at manufacturing custom products, however pyrolytic graphite cannot directly be manufactured by additive methods (ie 3D Printing). There could be other mechanical
socket designs that do not require custom molding, however it is possible to additively manufacture a die or a mold and use that to manufacture the pyrolytic graphite socket. It is also possible to manufacture the socket out of another material that is able to be manufactured by additive means. During the material analysis, some of the copper alloys were shown to be viable solutions. It is possible to use to EBM (electron beam melting) or SLM (Selective Laser Melting) additive manufacturing processes to directly create a custom socket.

In summary, the present prosthesis cooling device requires lower fan power level and lower power consumption. With its compact size, quiet operation and capabilities of removing 2.7W to 6.9W heat load. However, the cooling capacity can be further improve by using a larger heat sink. Decisions can also be made about the socket material to further reduce the overall system resistance and increase heat transfer to the ambient environment. Pyrolytic graphite was shown to be an optimal material to do so.
References