Modeling Post-Surgical Cryo-Cuff Effectiveness

BEE 4530 Final Project

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Executive Summary

The knee joint is the largest joint in the human body and is necessary for normal, everyday functioning. It is estimated that 581,000 total knee replacements are performed and approximately 200,000 anterior cruciate ligament (ACL) injuries occur each year [1,2]. Total knee replacement surgery results in the implantation of a pegged metal device on both surfaces of the knee joint; whereas ACL repair involves the replacement of the torn ligament with a tendon taken from elsewhere in the body or a donor cadaver. The surgical procedures differ drastically, but recovery time and effective healing of the damaged joint relies heavily on post-surgical therapy in both cases. An easy and at-home treatment following knee surgery is application of ice to the joint in order to manage the body's inflammatory response by reducing blood flow to the area and decreasing metabolic demand of the injured cells [3]. A particularly efficient method for icing the damaged joint, and one we seek to investigate, is the use of a Cryo-Cuff, which provides a constant cold temperature to the knee for hours at a time.

Both of these surgeries result in the need for physical therapy through the use of cold treatment. However it is clear that with the addition of the metal implant, the conductivity of the area changes and therefore cold temperatures can have a magnified effect on the surrounding tissue. We aimed to compare the tissue temperature in the skin and muscle in the knee joint after icing with the Cryo-Cuff for both the total knee replacement and ACL repair surgery. We did this by constructing 2D axisymmetric geometries of the leg with and without a metal implant in COMSOL and modeling the cooling of the tissue due to the applied Cryo-Cuff. And while Cryo-Cuffs offer ease and temperature control to the patient, they are also much more expensive than another more common method of cooling, the ice pack. Therefore we also created a separate geometry in COMSOL with a layer representing the ice pack and modeled tissue cooling for this modality as well. In addition to simply modeling the cooling effects of the Cryo-Cuff, we also optimized the temperature and application time, taking into account methods in which the Cryo-Cuff was applied continuously and also taken on and off.

First considering the geometry for the post-operative knee with the non-metal implant, we found that the optimized temperature and duration time was 8°C for 20 minutes on and 10 minutes off. Most importantly, this would only be an effective method of treatment if left on for over 5000 seconds or nearly 84 minutes. For the knee joint with the metal implant the results differed for the application duration. For times less than 2.8 hours, the Cryo-Cuff should be used in a piecewise fashion similar to the non-metal implant model at 8°C except for 30 minutes on and 10 minutes off. If the Cryo-Cuff is to be used for times longer than 2.8 hours, it should be used continuously at 8°C. The ice pack had an initial temperature of 0°C and for realistic application, was only left on for an hour. The ice pack was not a feasible method of therapy as the temperature in the skin immediately dropped below the pain threshold and the temperature in the muscle never met the temperature constraint in the therapeutic region as well. Ultimately this means it is worthwhile to invest in a Cryo-Cuff. The Cryo-Cuff provides control over temperature settings meaning it can be optimized according to time and temperature. Furthermore, this cold temperature can be maintained constantly and for hours at a time.

Introduction

Background

Cryotherapy, or the use of ice and other cooling devices, has been established as a popular method for reducing post-operative pain and swelling in various parts of the body. Ice packs are the cheapest and most widely used form, but their intrinsic flaw is the rising of the pack's temperature over time during use. This problem was addressed with the invention of the Cryo-Cuff, which can be purchased for around $160. This device maintains a constant external temperature by circulating cooled liquid inside. The actual therapeutic advantages of the Cryo-Cuff over the ice pack remain unclear, however, and there remains skepticism of the Cryo-Cuff's cost-effectiveness.

Not only is there debate about the most effective mode of post-surgical topical cooling, there are also differences in the prescribed “standard” icing protocol among health professionals. Several aspects may impact the therapeutic effectiveness of cryotherapy. These include use of continuous versus intermittent application, the duration of icing, and the optimal cooling temperature. There have been a handful of previous attempts to find optimal conditions for these variables. One systematic literature review determined that the intermittent application of iced water (10 minutes on, 10 minutes off) was the safest and most effective method [4], and others have confirmed the efficacy of intermittent as opposed to continuous icing for pain relief within one week of acute soft tissue injury [5]. However, opposing views also exist in the literature, including a proposed “standard” protocol of 20 minutes of continuous icing every two hours, which has been commonly used in clinical settings [6, 7]. Thus, it is apparent that there is generally no widely accepted protocol for cryotherapy, and further investigation into this topic is required.

Although the aforementioned studies have all produced significant results, there are many limitations to their methods, namely because of their experimental nature. Clinical experiments are very time consuming, and there is often a lack of control over all parameters [8]. There is much variation between human subjects that cannot be controlled for, such as anatomical differences and activities undergone by patients during the healing process. Additionally, there is often difficulty in finding enough subjects who have had directly comparable injuries or surgeries, especially when controlling for age and gender. Thus, it seems that a better method for solving problems in science and medicine would be numerically with computer modeling.

Computer simulation provides the resources to accomplish many things that experiment alone cannot, in a much shorter time frame. For instance, computers are able to calculate and display temperature changes in any part of the domain at any or all points in time. This type of analysis would be practically impossible in a clinical setting. Likewise, there is more control over the system, which helps determine the importance of various parameters, especially if a sensitivity analysis is performed. Therefore, although experimental procedures have their time and place, computer modeling is beneficial for understanding the intricacies of many problems in medicine.

With the use of computer modeling, it is also easier to compare two models which may not be reasonably comparable otherwise. For instance, there is some question about the use of cryotherapy for surgeries involving metal implants, such as total knee replacement, because the added metal increases the internal thermal conductivity, which may cause the temperature to drop to dangerously low levels. This controversy can be resolved more accurately using a computer by modeling two knee joints that differ only in that one has a metal implant and one does not. This controls for all other variables and can produce highly reliable results.

Design Objectives

In this study we hope to find solutions for the problems presented above by modeling a knee joint using COMSOL Multiphysics. The project goals are as follows:

1. Find the optimal duration and temperature of cooling under the constraints that skin temperatures must remain above pain and tissue damage levels and muscle temperatures must remain within a therapeutic temperature range.

2. Examine the differences between a post-surgical knee with a metal implant, such as after total knee replacement surgery, and a non-metal implant, such as after ACL repair.

3. Determine the effectiveness of an ice pack versus a Cryo-Cuff device, in order to determine whether the Cryo-Cuff is cost-effective.

Likewise, there are also other, broader implications of this study. We hope the information in this report can help validate Cryo-Cuff use as a conventional therapy tool in post-surgical settings. Also, we expect the optimized protocol and temperatures can be used to streamline the use of the device. Lastly, we aim to help protect patients against tissue necrosis from improper use of the Cryo-Cuff.

Problem Schematic and Assumptions

In order to most effectively accomplish our goals, we created a model of a human knee in COMSOL Multiphysics. We implemented several assumptions to simplify the complex knee geometry in our model. First, we modeled the knee as a series of cylinders, of varying heights and diameters. To further simply our model, we decided to combine the multiple layers of the skin, including the epidermis, dermis, and subcutaneous fat layer, into one layer of "skin". We also assumed axisymmetry, thereby negating any discrepancies between dorsal/ventral and medial/lateral. Making this assumption forced us to ignore the effects of the knee cap and patellar tendon. Likewise, the knee joint was modeled as a circular bone segment, without ligaments running through it and with no meniscus or joint mechanisms. For the cases involving a metal implant, the most prominent total knee replacement implant was modeled: a cylindrical shaft insertion into the tibia and fibula with metal coatings on both interior surfaces of the knee. We modeled this implant as a metal cylinder within the center of the knee joint.

In terms of material properties, we assumed that the muscle, bone and skin were one homogeneous material with consistent thermal conductivities, heat capacities and density. In order to determine the material properties of this "skin" layer, we took a weighted average of the material properties of the epidermis, dermis, and subcutaneous fat layer.

Cryo-Cuff Models

The Cryo-Cuff was modeled as a constant temperature boundary condition because it maintains a constant temperature throughout the cooling process. The Cryo-Cuff schematics can be seen in Figure 1.

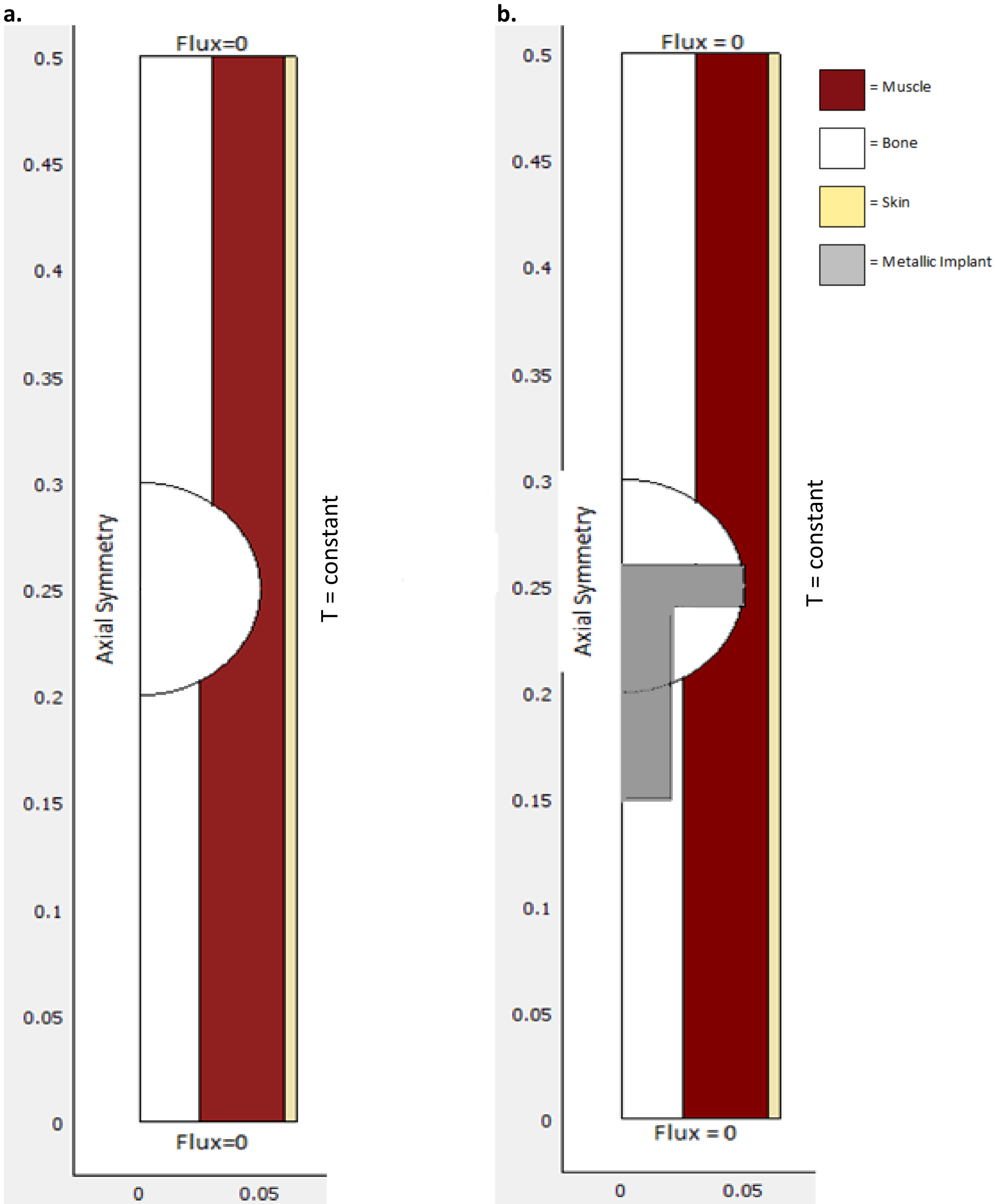

Figure 1. COMSOL geometry for use of a Cryo-Cuff on a post-operative knee joint with no metal implant (a) and with a metal implant (b).

Ice Pack Models

For the modeling of the ice pack, the problem was formulated similarly, but a few changes had to be made. An extra sub-domain had to be added against the skin, corresponding to the ice pack. The ice pack could not be modeled as a boundary condition due to its melting and thus changing material properties during use. We assumed the ice melted between 0°C and 2°C. Finally, a boundary condition corresponding to natural convection was added at the outermost boundary of the ice pack. The ice pack schematics can be seen in Figure 2.

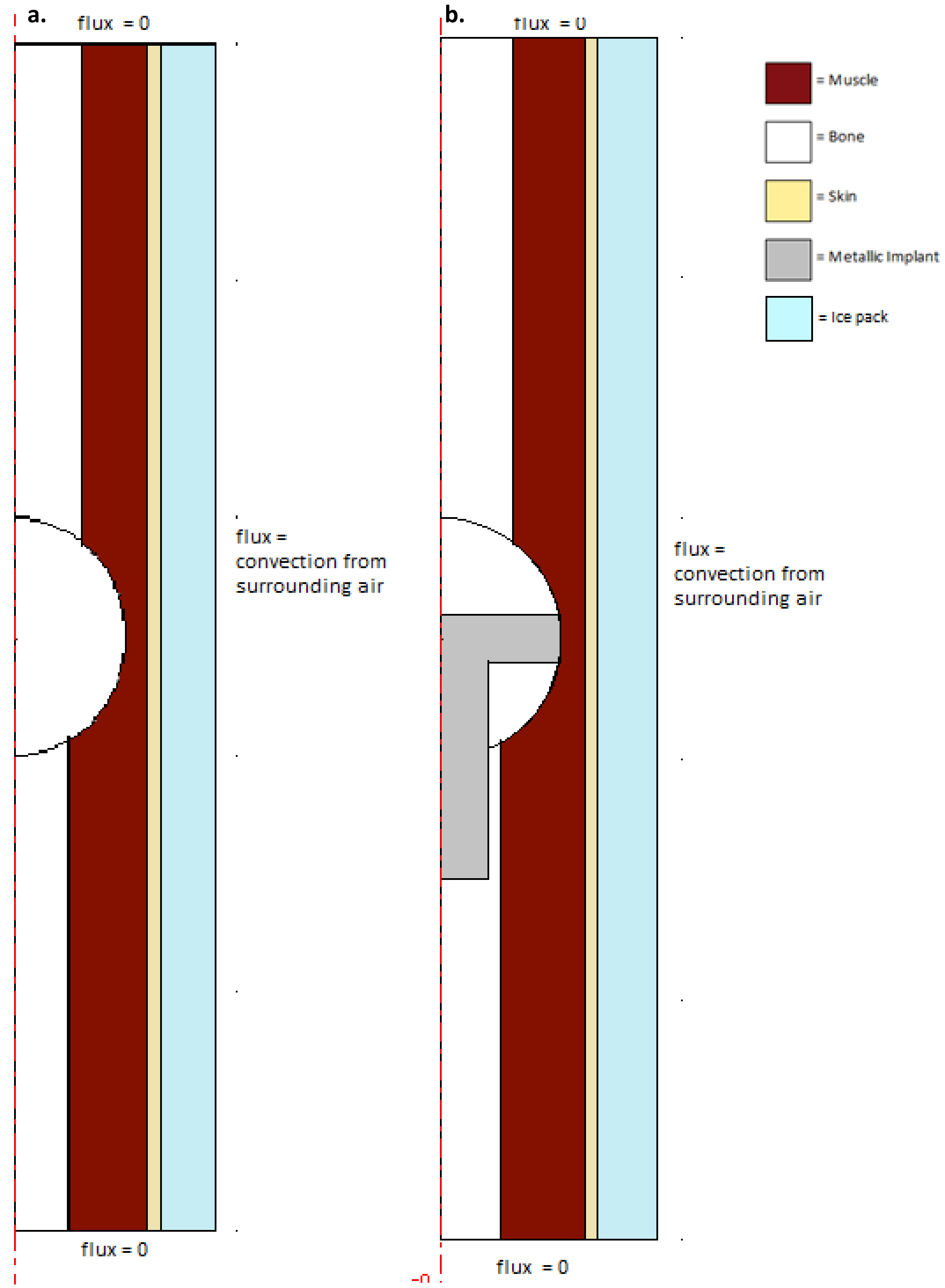

Figure 2. COMSOL geometry for use of an ice pack on a post-operative knee joint with no metal implant (a) and with a metal implant (b).

Governing Equation, Boundary Conditions and Initial Conditions

The governing equation used in this model included transient, conduction, and heat generation terms. Mathematically, COMSOL implemented the following equation:

$$\rho C_p \frac{dT}{dt} = -k\left(\frac{dT}{dr} + \frac{dT}{dz}\right) + Q$$

__Boundary Conditions__

Boundary conditions were implemented at each of the outer boundaries. At the axis of symmetry, a symmetric boundary condition was used, indicating that flux is zero. For the top and bottom boundaries of the domain, zero flux was also modeled due to a semi-infinite approximation.

Cryo-Cuff: At the surface of the skin, a constant temperature was implemented for modeling of the Cryo-Cuff, as this device utilizes a flow of cool liquid and is maintained at a certain temperature. This boundary condition is described mathematically in the following manner:

$$T_{skin\,surface} = T_{cryo-cuff}$$

To model intermittent cooling, we manually alternated between the Cryo-Cuff boundary and a room temperature boundary (22°C) to simulate taking the Cryo-Cuff on and off.

Ice Pack: The boundary at the outside edge of the ice pack accounts for convection where

$$-k\frac{\delta T}{\delta x} = h[T(x=0) - T(x=\infty)]$$

$$h = 11\ \frac{W}{m^2 K}$$

$$T(x=\infty) = 293.15$$

__Initial Condition__

The initial temperature condition implemented throughout the domain was body temperature, or 310.15 K.

$$T_{tissue} = 310.15\ K$$

Determination of Apparent Specific Heat for Melting Ice

In order to model the ice pack's melting, we had to create an apparent specific heat. We assumed the ice would be melting between 0°C and 2°C. The latent heat of fusion for water is 335 J g^{-1} K^{-1}, which is equal to the energy released during melting. We used this knowledge to create a function for apparent specific heat based on temperature, as seen on the graph below.

The specific heat became a piecewise function where

$$C_p = (-167.5 * T + 46067) * 1000 \qquad 273\ K \le T \le 275\ K$$

$$C_p = 4210 \frac{J}{kg\ K} \qquad T \ge 275$$

Similarly, the thermal conductivity of the melting ice was a piecewise function where,

$$k = 2.1 \qquad 273\ K \le T \le 275\ K$$

$$k = .58 \qquad T \ge 275$$

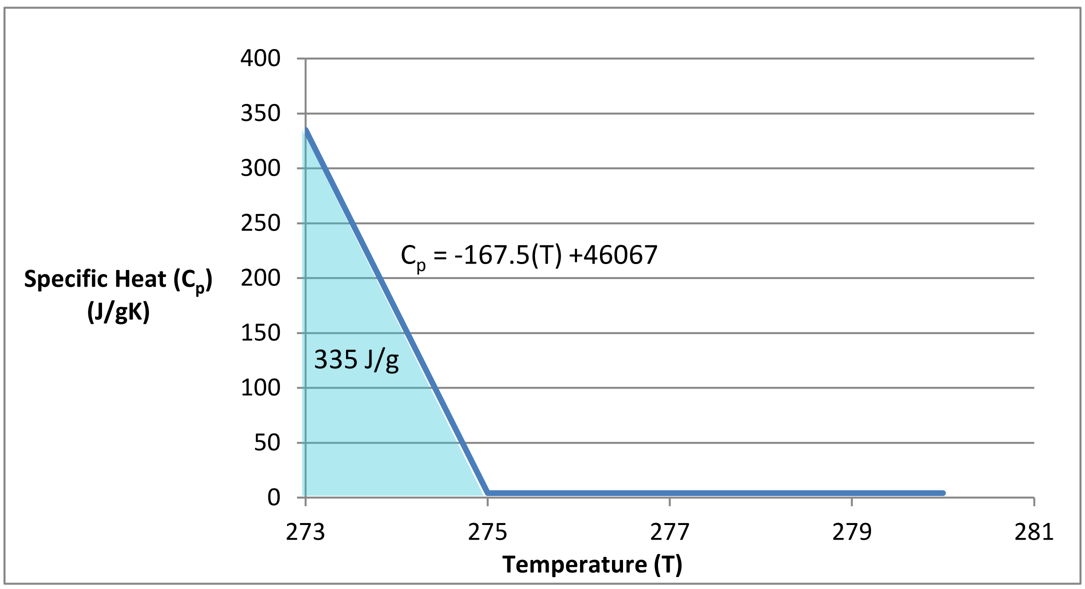

Figure 3. Apparent specific heat of melting ice as a function of temperature.

Convergence Graphs

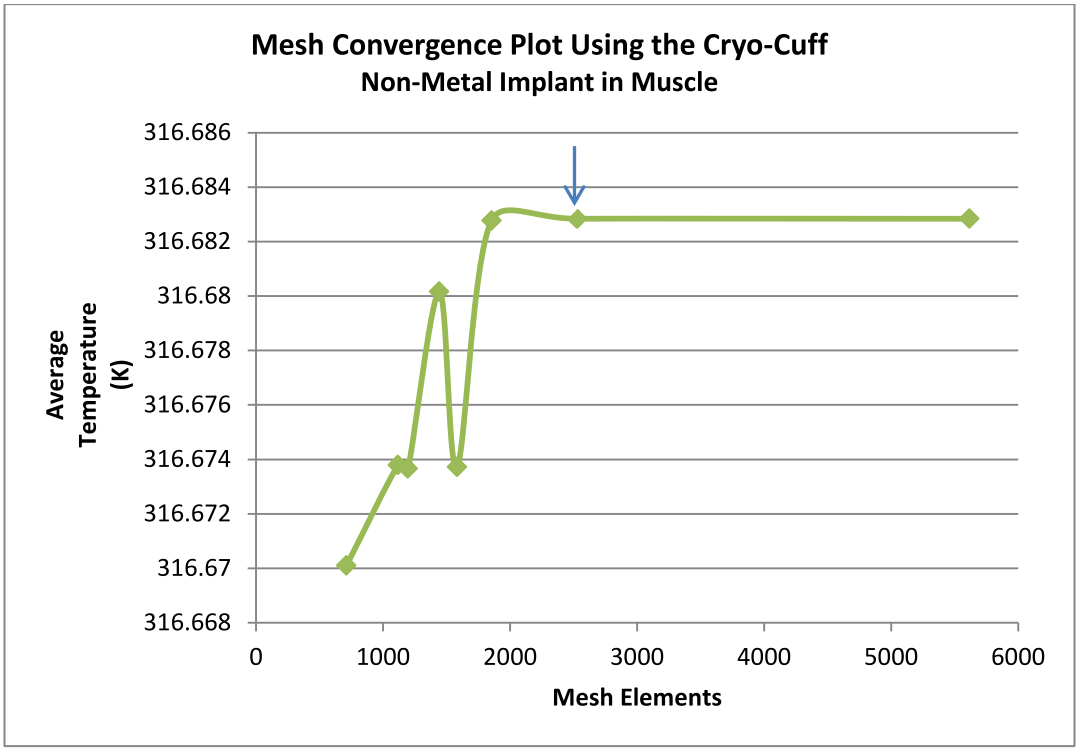

Figure 4. Mesh convergence for the case of no implant using the Cryo-Cuff. Temperatures were measured as an average temperature in the muscle domain.

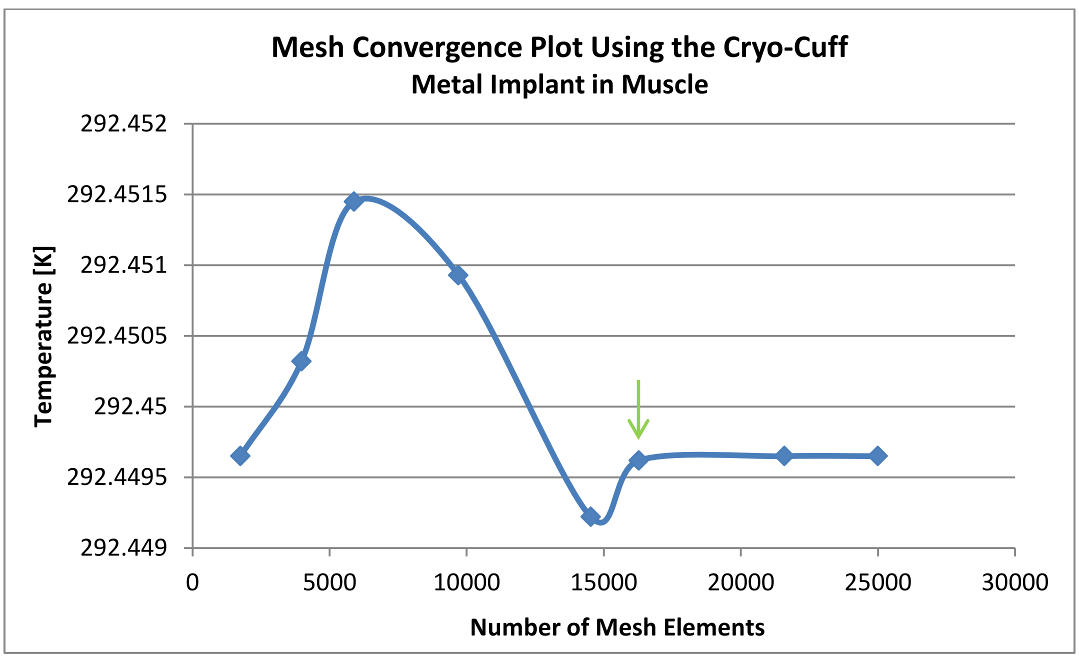

Figure 5. Mesh convergence for the case of a metal implant using the Cryo-Cuff. Temperatures were measured at the point in the muscle domain.

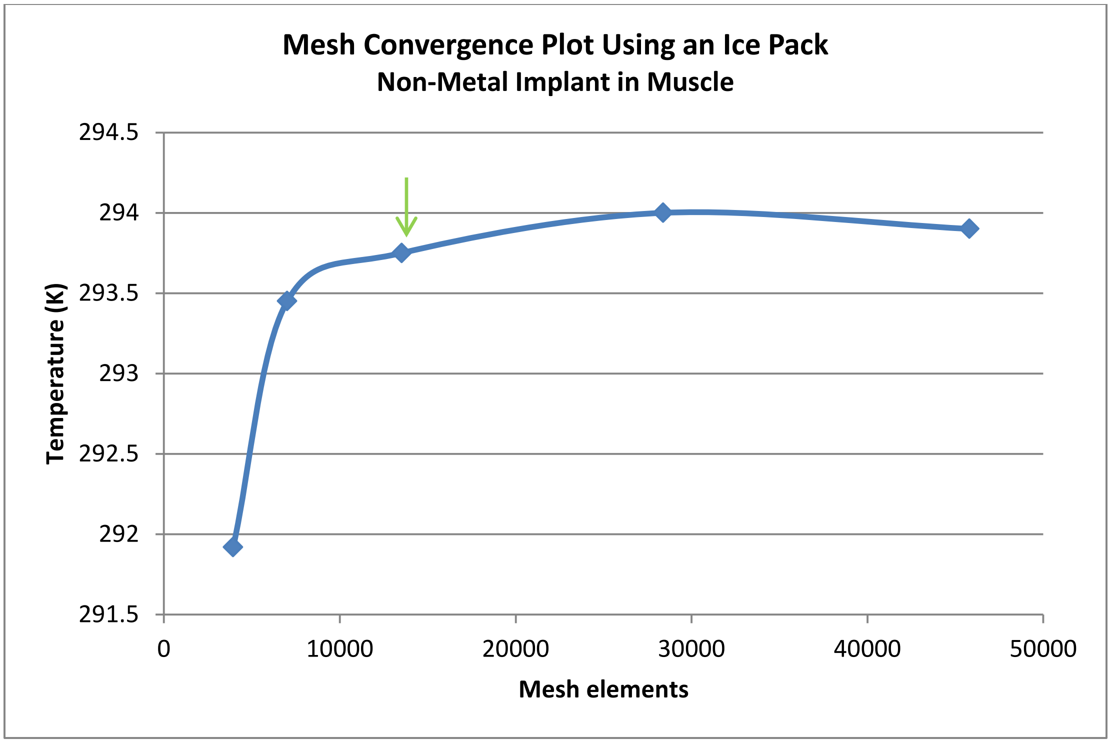

Figure 6. Mesh convergence for the case of no implant using the ice pack. Temperatures were measured at the point in the muscle domain.

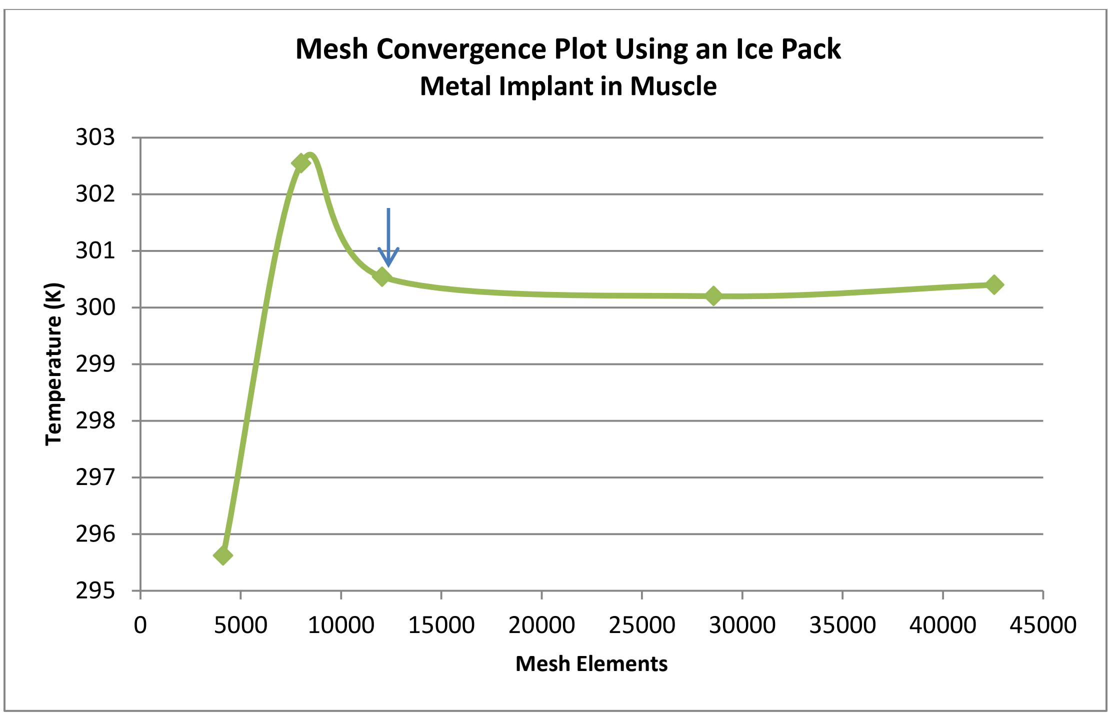

Figure 7. Mesh convergence for the case of a metal implant using the ice pack. Temperatures were measured at a point in the muscle domain.

Solution:

Optimization

One of the main goals of our project was to determine the optimal temperatures and application durations for effective cryo-therapy of post-surgical knee joints. Two sets of alternative conditions were studied: a post-surgical knee in which a metal implant was inserted versus one with no metal, and the application of the Cryo-Cuff device versus an ice pack. Thus, four scenarios were ultimately considered. We optimized the two scenarios involving Cryo-Cuff use through multiple iterations, each time varying either the temperature of the Cryo-Cuff or the length of application in order to determine the optimal values for these parameters. The constraints for our optimization were to remain within the range of optimal therapeutic temperatures for muscle (295.15K - 300.15K), while maintaining a safe temperature in the skin (pain is observed between 285.5K and 290K, while tissue damage occurs at temperatures below 285.5K.) Through optimizing the use of the Cryo-Cuff in metal and non-metal implant knee joints, we hoped to be able to distinguish how much of an impact a metal implant has on the temperatures (and thus muscle therapy and skin tissue damage or pain) of the knee, as well as to later determine whether the Cryo-Cuff is economically worthwhile as compared to the ice pack.

First, we optimized the temperatures and application time for a knee with no metal implant using a Cryo-Cuff (Appendix). Our first attempts modeled continuous use of the Cryo-Cuff. The scenario with a 13°C Cryo-Cuff only just reached the optimal cooling temperature, but also dipped into the pain threshold at the skin level. Thus, it did not appear that a continuous model would be optimal. Out next attempt was to model the Cryo-Cuff piecewise since this is the traditionally prescribed method of applying the device. We started by modeling the standard icing practice of 30 minutes on followed by 30 minutes off. This produced suboptimal condition in the muscle and skin, and more iterations were performed.

After multiple iterations, we determined that the optimal therapeutic protocol for Cryo-Cuff use on a knee with no metal implant is 8°C, with 20 minutes on and 10 minutes off. This protocol reaches therapeutic levels in the muscle almost continually without damaging the skin tissue.

Second, we optimized the temperature in the muscle and skin for a knee with a metal implant using a Cryo-Cuff (Appendix). Like in the knee without the metal implant, we tried to reach the optimal therapeutic temperature in the muscle, between 295.15K and 300.15K, while maintaining a safe temperature in the skin, greater than 285.15K. For this model, we again initially attempted to model continuous use of the Cryo-Cuff. The 13°C Cryo-Cuff barely reached the optimal cooling temperature, but also dipped into the pain threshold at the skin level. The 8°C Cryo-Cuff did not damage the skin tissue but brought muscle temperatures down into the therapeutic region, where they remained. We next attempted to model the Cryo-Cuff as a piecewise function. Both of our attempts at using a 6°C Cryo-Cuff for 30 minutes on and 10 min off and for 20 min on and 10 min off kept the muscle in the therapeutic range but brought the skin temperature down into the tissue damaging range. The attempted model of an 8°C Cryo-Cuff as a piecewise function with 30 min on and 10 min off kept the muscle in the therapeutic range and the skin out of the tissue damage range but failed after 2.8 hours to keep the muscle at an optimal therapeutic temperature. We suspect that this has to do with the increased conductivity of the metal. When the Cryo-Cuff temperature is on the warmer side, the metal collects and redistributes heat gained from the metabolic heat generation of the muscle. When the

Cryo-Cuff is too cold, the metal collects and redistributes the cold temperatures, damaging surrounding tissue.

After multiple iterations we determined that the optimal therapeutic protocol for Cryo-Cuff use in knee joints with metal implants is continuous use at 8°C for times longer than 2.8 hours and piecewise use, 30 minutes on and 10 minutes off, at 8°C for times shorter than 2.8 hours.

Our next step was to model the use of a common ice pack to compare with our optimized Cryo-Cuff protocols. Like the Cryo-Cuff, we modeled ice pack use on both a non-metal and metal implanted knee (Appendix). Common protocol for ice pack use is 20 minutes on, with up to an hour of time between applications. We modeled up to an hour use of the ice pack, to see what happen if the time was extended.

In the non-metal implant knee, at 20 minutes, the skin had reached 8°C (within the tissue damage range) but the muscle temperature had barely entered the therapeutic range. As time continued, the skin temperature remained relatively constant at 8°C the muscle temperature remained within the therapeutic range up to 45 minutes, but then dropped below the range.

In the metal implant knee, at 20 minutes, the skin had again reached 8°C but the muscle temperature hadn't reach therapeutic levels until 25 minutes. Once the temperatures had dropped into the therapeutic temperatures they stayed there indefinitely, suggesting that the metal implant has a tempering effect on the temperature.

Comparison

The surface plots for each of the four scenarios were compared (Figures 8,9).

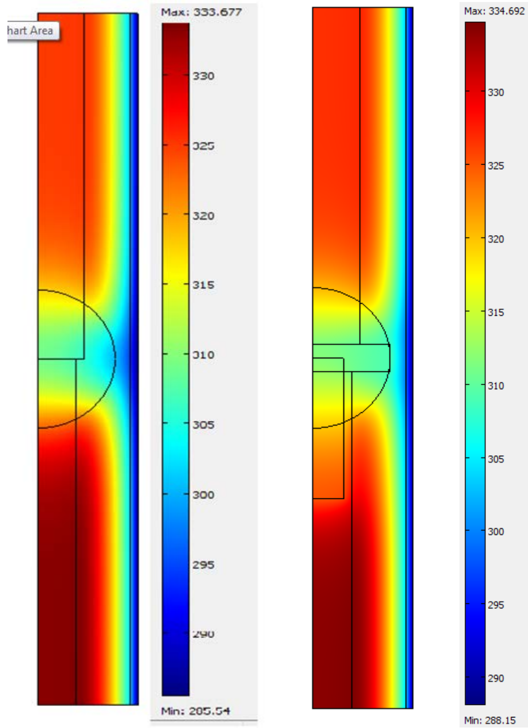

Figure 8. Surface plot of the Cryo-Cuff models at the coldest point (t=17000s) in the knee joint with a) no metal implant and b) a metal implant

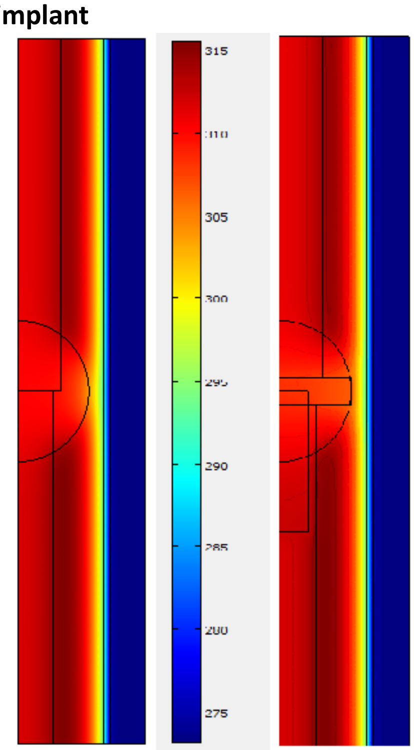

Figure 9. Surface plot of the ice pack models at the coldest point (t=1200s) in the knee joint with a) no metal implant and b) a metal implant

It is apparent that the knee joint gets significantly colder with the optimized Cryo-Cuff model than with the ice pack. Also, the skin gets extremely cold in the ice pack model. Lastly, the metal implant does seem to cause lower temperatures within the knee, which is likely due to the high conductivity of metal as compared to normal biological components.

In order to compare the four scenarios further, the temperatures in the skin and muscle using the optimal protocols for the four cases were plotted over time (Figure 4).

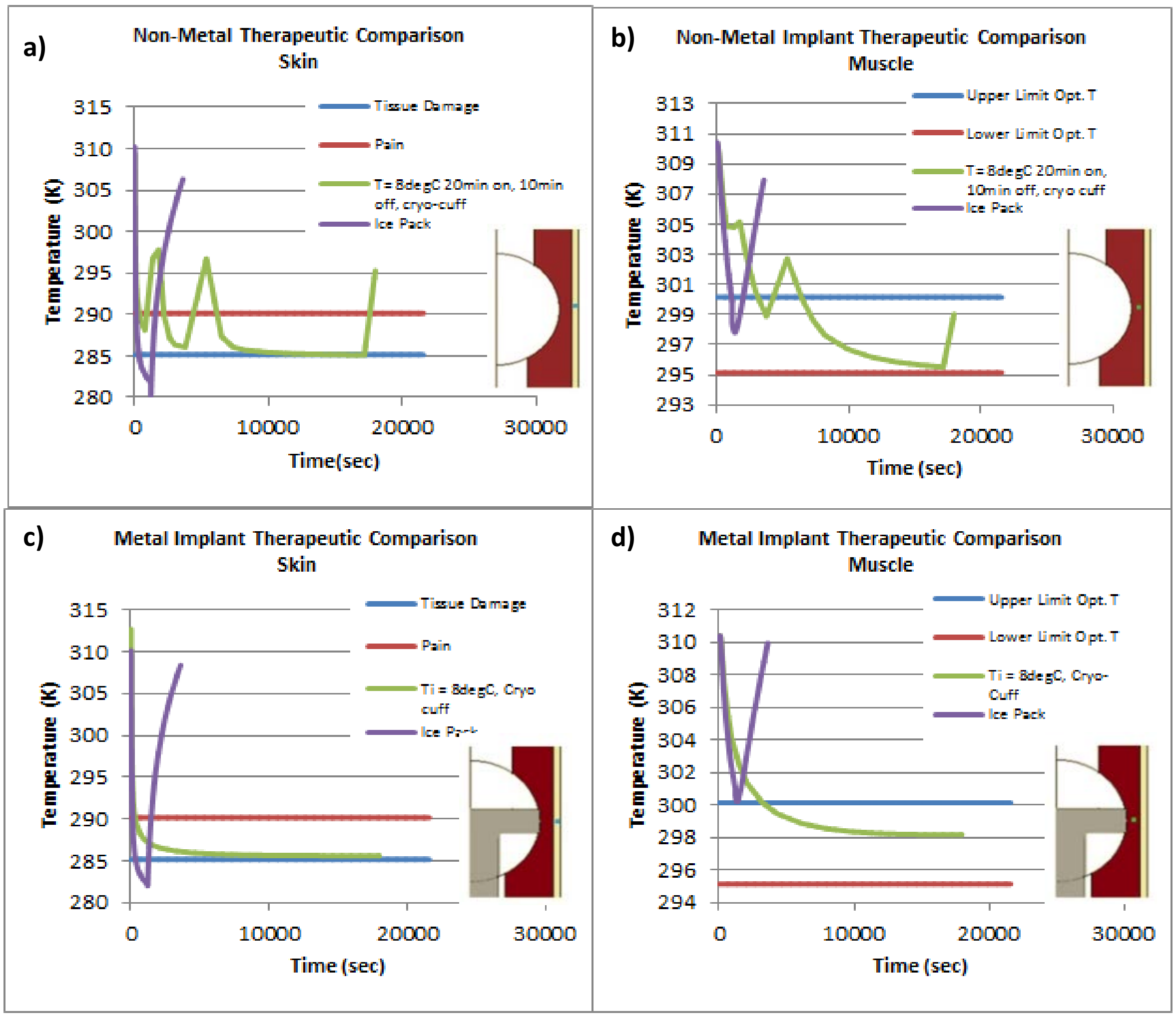

Figure 8. Comparison of the temperature effects of the optimal protocols in the skin and muscle. a) Skin temperatures with no metal implant b) muscle temperatures with no metal implant c) skin temperatures with a metal implant d) muscle temperatures with a metal implant. Schematic insets show points where temperatures were taken.

It is apparent that the control over the Cryo-Cuff yields better results in both the metal and non-metal post-operative uses. The ice is perhaps most harmful to the skin, since in both scenarios it dips below the tissue damage threshold. It should be noted that the ice does provide excellent therapeutic benefit in the muscle in the case of the metal implant, so if perhaps a towel could be placed between the ice and skin, an ice pack may work.

Ultimately, it seems that the Cryo-Cuff is worth the cost, since you can carefully control the therapy to provide the best therapeutic effect.

Sensitivity Analysis

We performed a sensitivity analysis on both the model with the metal implant and the model without. In the knee without the metal implant sensitivity analysis, we varied the thermal conductivity (k), density (ρ), and heat capacity (C_p) in the skin and muscle. The temperatures of the skin were measured at (0.063m, 0.25m) and of the muscle at (0.055m, 0.25m) at a constant time of t = 18000s, which was the time when the minimum temperature was reached. We varied the initial baseline values for thermal conductivity (k), specific heat (C_p) and the density (ρ) of the skin in muscle by $\pm$5% and $\pm$10%. These values were tabulated (Tables 1- 4, Appendix).

The parameters that were varied by ±10% were plotted against their respective for each model in the skin and in the muscle (Figure 5). These sensitivity analysis plots showed that in both the knee with and without the metal implant, neither the skin nor the muscle were sensitive to either the skin density, skin heat capacity, muscle density, or the muscle heat capacity. The sensitivity analysis also revealed that the model was most sensitive to changes in the thermal conductivity. In the knee without the metal implant, the skin was only sensitive to the skin's thermal conductivity. In the metal model, the skin was also quite sensitive to the thermal conductivity of skin and to a slight but insignificant degree the muscle thermal conductivity. In both models, the muscle was sensitive to the thermal conductivity of both the skin and muscle, with the skin thermal conductivity more highly affecting temperature in the muscle. This is most likely due to the fact that the thermal conductivity for skin is much lower than that of the muscle, therefore varying it by ±10% will have a much greater impact. Therefore, it is most important that the thermal conductivities of the skin and muscle layers be accurate.

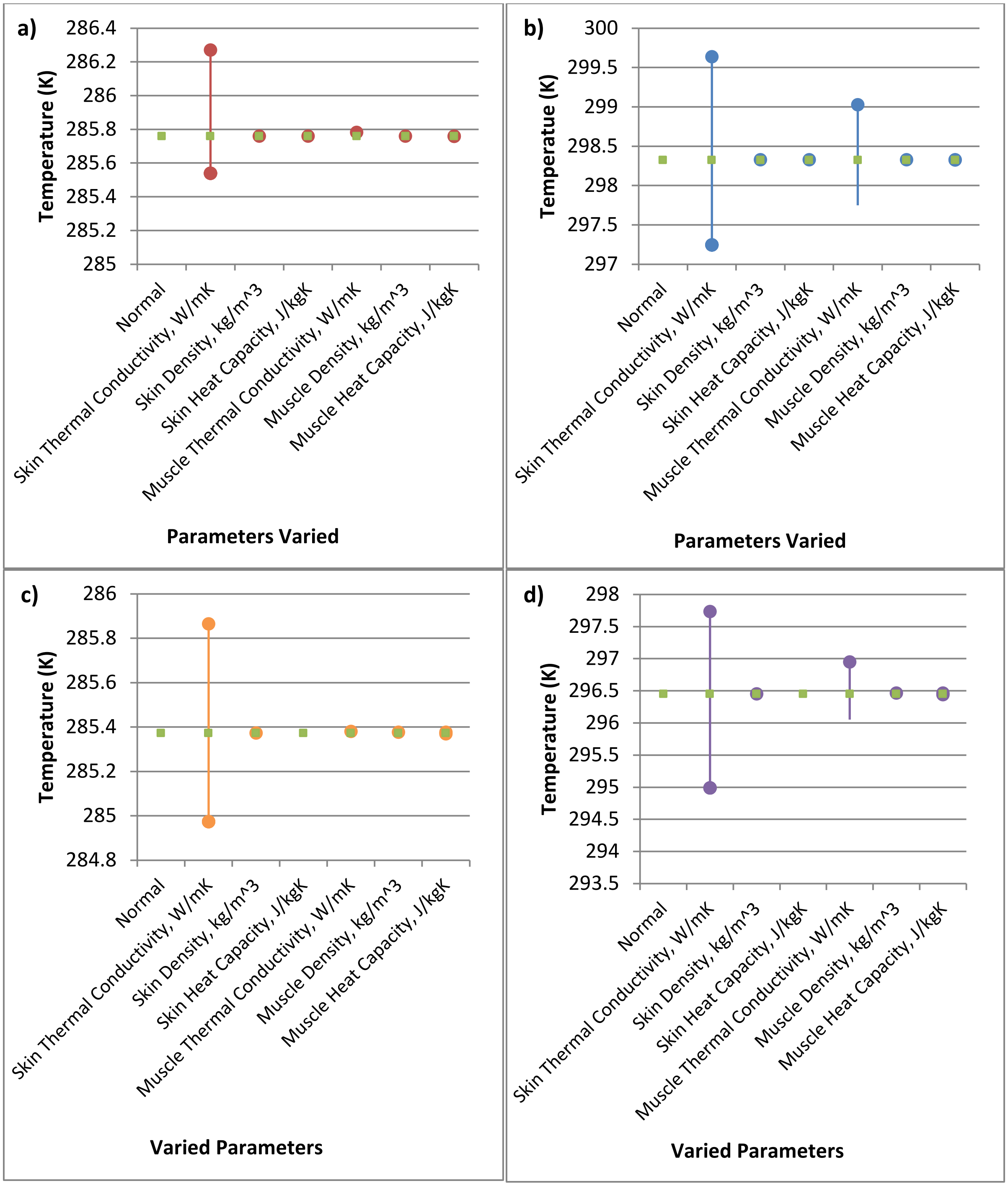

Figure 9. Sensitivity analysis results in a) skin with metal implant b) muscle with metal implant c) skin with no metal implant d) muscle with no metal implant. Square markers represent the temperatures at original standard parameters. Colored bulbs represent the temperatures found when the designated parameter was varied by ±10%.

Accuracy Check

Through an extensive literature search, we found various temperature values including: the therapeutic temperature range for muscle, the pain threshold temperature for skin, and the temperature at which skin damage occurs. Therefore we know these values are accurate. We found a similar experiment done using a bag of crushed ice, a gel ice pack, and wet-ice for a knee without an implant. The temperature of the tissue was taken 1 cm and 2 cm subadipose. The graphs for these experiments look very similar to ours; both have the most heat loss in the first minute. We cannot directly compare values because they did not use a Cryo-Cuff, but our values are certainly reasonable when looking at theirs. Our optimization shows that the Cryo-Cuff should be set for 8°C and applied for 20 minutes and taken off for 10 minutes, repeating these intervals for 110 minutes. Literature again shows application times varying between 10-35 minutes, with intermittent use favored over continuous use. One systematic review of the literature found that 10 minutes on followed by 10 minutes off followed by 10 more minutes on every two hours was the most effective duration of application [4]. This study also validated the use of wet ice applied directly to the skin through a wet towel over "dry" ice, cryogen packs, and the Cryo-Cuff device. Since the results from the muscle implant are not significantly different, the values for the cases involving metal implants can also be validated with the aforementioned studies.

Cost/Benefit Analysis

Cryo-Cuffs for the knee are normally around $160.00. This cost is significantly lower than the cost of both ACL repair and total knee replacement. Bearing this in mind, it is a fairly accurate assumption that those who are undergoing such surgeries will also have the funds to afford the Cryo-Cuff, the question is whether or not it is worth the fee.

Our analysis shows that the greatest benefit of the Cryo-Cuff is the ability to optimize its use, specifically in regards to temperature. We feel that the increase in therapeutic cooling time, without damaging any tissue is beneficial enough to validate the cost of the Cryo-Cuff. Furthermore, although we did not study this aspect of the Cryo-Cuff, it also has the capability to compress the tissue. Compression also has therapeutic benefit, especially when there is significant swelling in the joint, which is the case in both surgeries.

Overall, the Cryo-Cuff's small cost is worth the added benefit of stabilized, optimized temperatures and compressive capabilities.

Conclusion and Design Recommendations:

Keeping in mind all that we aimed to accomplish within this project, our first task was to sufficiently design models in COMSOL representing the four scenarios we planned to study. Considering the most frequent injuries sustained by the knee, we made the decision to model a knee that had undergone a total knee replacement resulting in a metal implant and a knee recovering from an ACL repair. For both of these models, we also wanted to explore the effects of cooling by Cryo-Cuff and the more common bag of crushed ice. The ice pack model, unlike the Cryo-Cuff, followed standard procedures for application and offered no temperature control. As a result it could not be optimized. With these models created in COMSOL we could begin our optimization and comparison.

In order to determine if the Cryo-Cuff was a beneficial investment for a patient, we had to optimize the metal and non-metal implant scenarios with regards to application temperature and time. Ultimately, to perform the optimization for both models, we had to observe the temperature reached in the skin and muscle during the experiment. This was because we had constraints that described the temperatures at which skin damage and greatest therapy to the muscle occurred. The optimization was performed iteratively changing both of these variables in both models. The combination that resulted in the greatest therapeutic effect with minimal skin damage for the non-metal implant model was the Cryo-Cuff set for 8°C for 20 minutes on and 10 minutes off. Similarly in the metal implant model, the Cryo-Cuff should be set for 8°C, but left on continuously for at least 25 minutes, after which the temperature reached steady state. The highly conductive metal implant in the knee acted as a sink for cold temperatures and therefore temperatures in the knee joint itself became cooler. However, this helped to moderate the temperature gradient in the muscle so that it was actually warmer in comparison to the non-metal implant model. This is why we were able to continuously apply the Cryo-Cuff for extended periods of time.

These results were compared to the ice pack, which offered no temperature control or lasting effects. The ice pack was also the model most likely to cause skin damage as the skin rapidly cooled in a very short amount of time due to the freezing temperature of the ice. The Cryo-Cuff, however, could be applied for hours at a time with great control so damage did not occur and maximum therapeutic effect was achieved. Therefore, while it is an expensive piece of equipment, it is one that can be used effectively for the long healing period that follows such an operation.

Our model could be improved with a more anatomically accurate model. It is possible to use 2D scans to create incredibly detailed 3D models, but this is outside the scope of the course. This would take into account varying geometries between patients and factors like the thickness of the subadipose or muscle tissue. The governing equation could also be altered to take into account the heat brought to and taken from the site of cooling by blood flow. The ice pack model would benefit from a more robust equation for the apparent specific heat and also a layer separating the skin and bag from each other, like the way a towel would in reality. This would help to buffer the cold temperature of the ice. Our model also offered the best approximation for shorter time periods, around 3 hours or less. This is reasonable since most of the literature did not conduct experiments for such extensive amounts of time. After 3 hours factors like the heat generation in the muscle started to dominate the model and steady state was reached. Also because of the way COMSOL predicts future points during the finite element analysis, unrealistic effects were created for the final points if the time was such that the Cryo Cuff was currently removed.

Considering the damaging effects of the ice pack that offer no therapy to the region and the option of being able to continuously wear the Cryo-Cuff, the device is a wise investment. These surgeries have the potential to offer patients full functionality, but they also cost hundreds of thousands of dollars. Reasonably, a patient would want the best possible post-operative treatment in order to obtain the best possible results and make the effects of that surgery last. The Cryo-Cuff, while more expensive than an ice pack, will ultimately make sure the money placed towards a major knee operation is well worth it and therefore a wise investment

Appendix:

Material Properties:

Subdomain	Thermal Conductivity [W/mK]	Density [Kg/m^3]	Specific Heat Capacity [J/KgK]	Heat Source [W/m^3]	Initial Temperature [K]
Skin	0.236[16]	1200[15]	3431[15]	0	310.15
Muscle	0.49[15]	1179[15]	4669[15]	33800[12]	310.15
Bone	0.36[16]	1850[16]	1300[16]	0	310.15
Titanium	7.51[19]	4507[17]	540[18]	0	310.15

COMSOL Implementation:

COMSOL geometry

Our COMSOL geometry can be found in our schematic in our problem formulation section.

Mesh

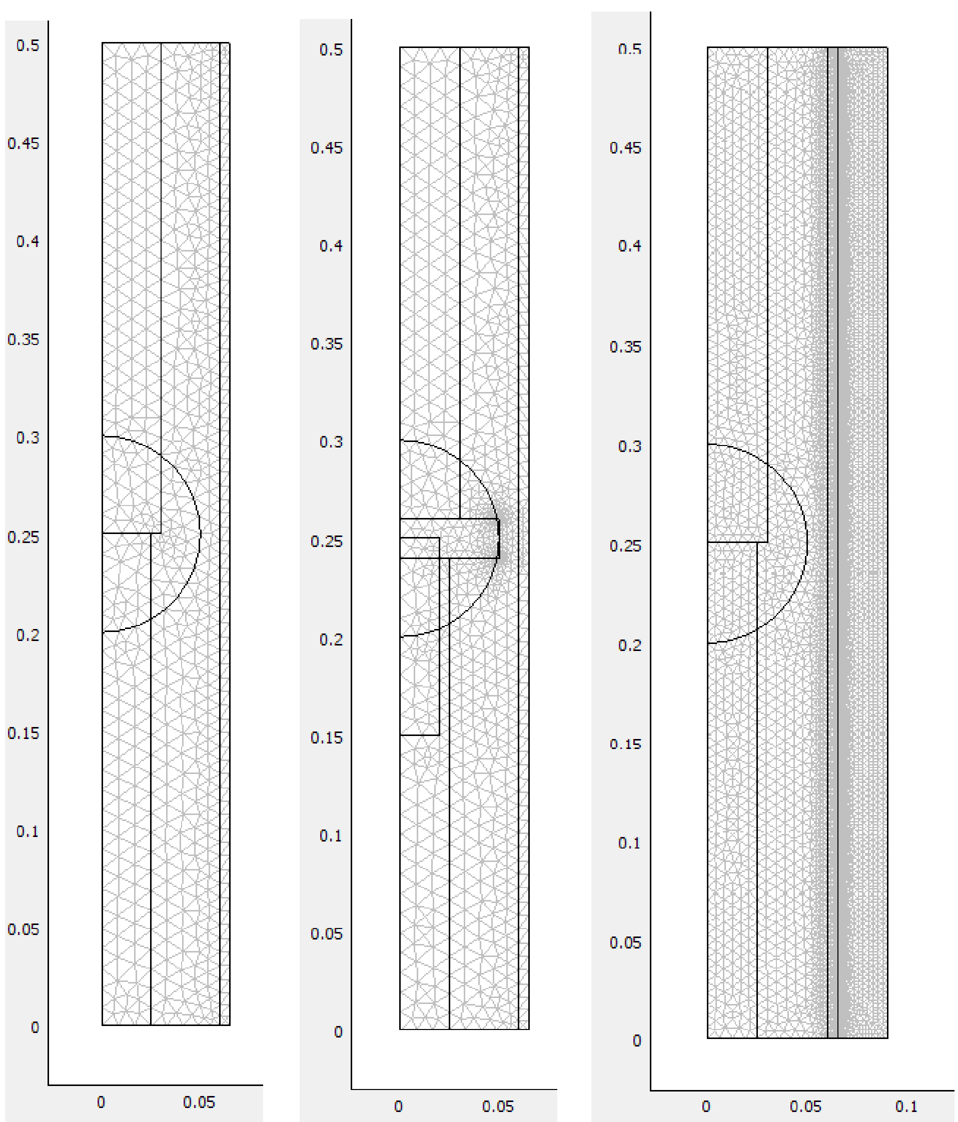

Figure i. Meshes for knee joint a) without metal implant b) with implant c) with ice pack.

Optimization

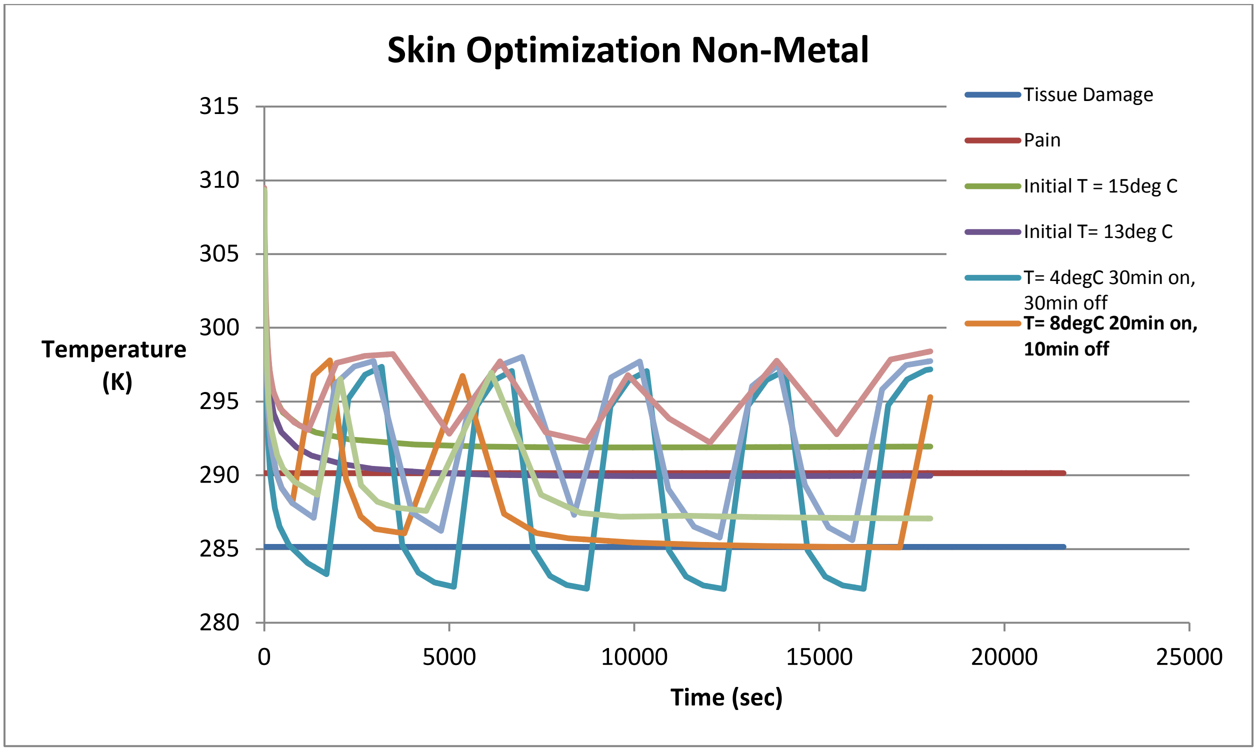

Figure ii. Optimization trials in the skin for the case of no metal implant using a Cryo-Cuff.

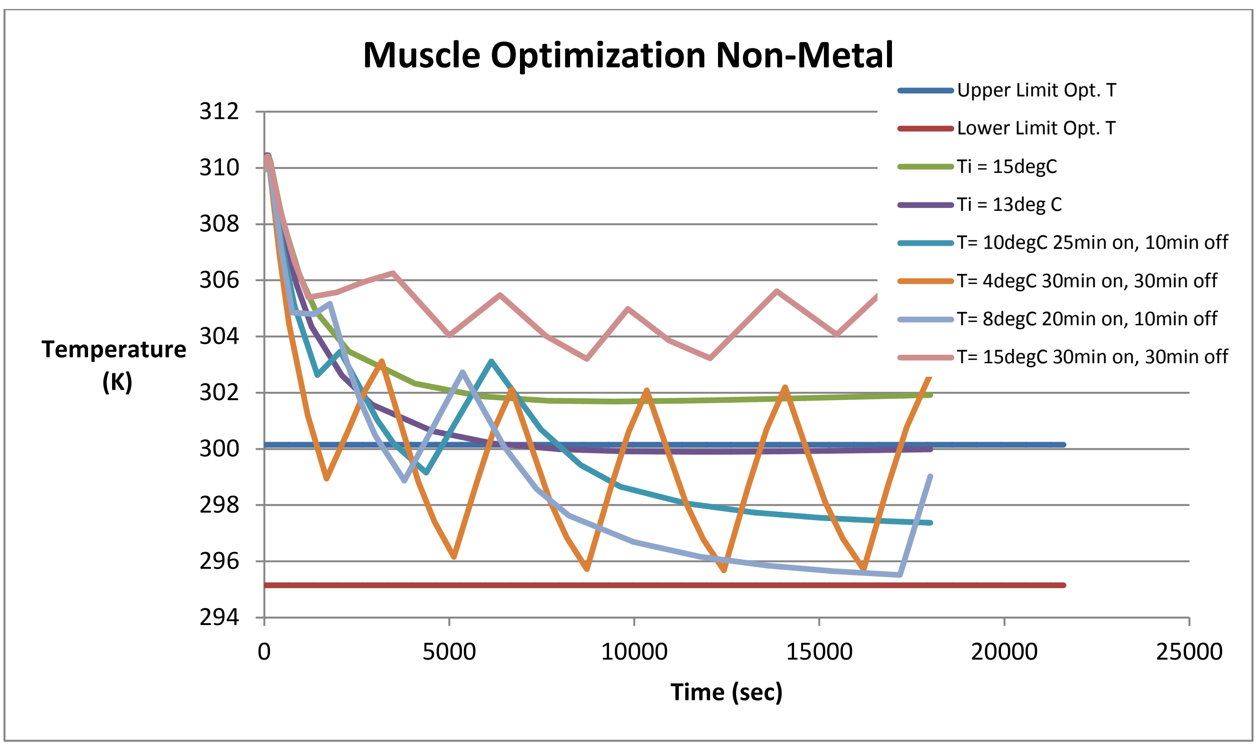

Figure i. Optimization trials in the muscle for the case of no metal implant using the Cryo-Cuff.

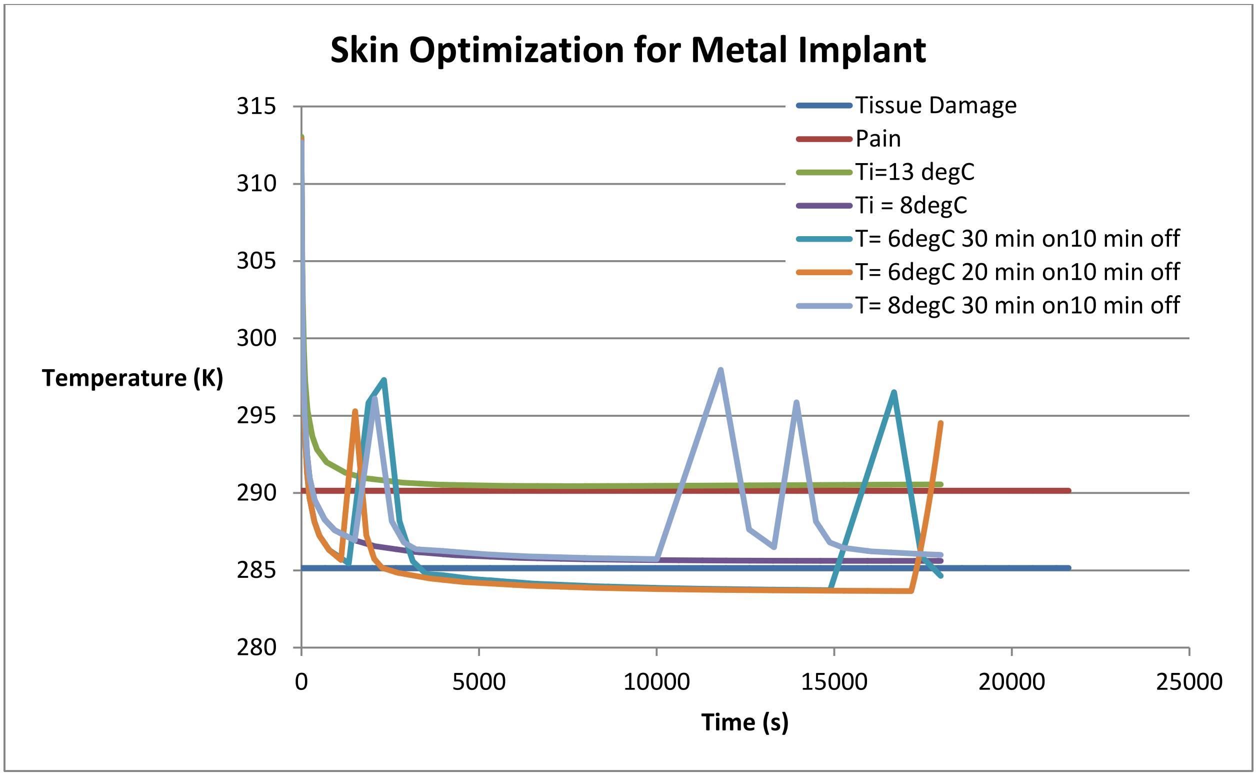

Figure iv. Optimization trials in the skin for the case of a metal implant using the Cryo-Cuff.

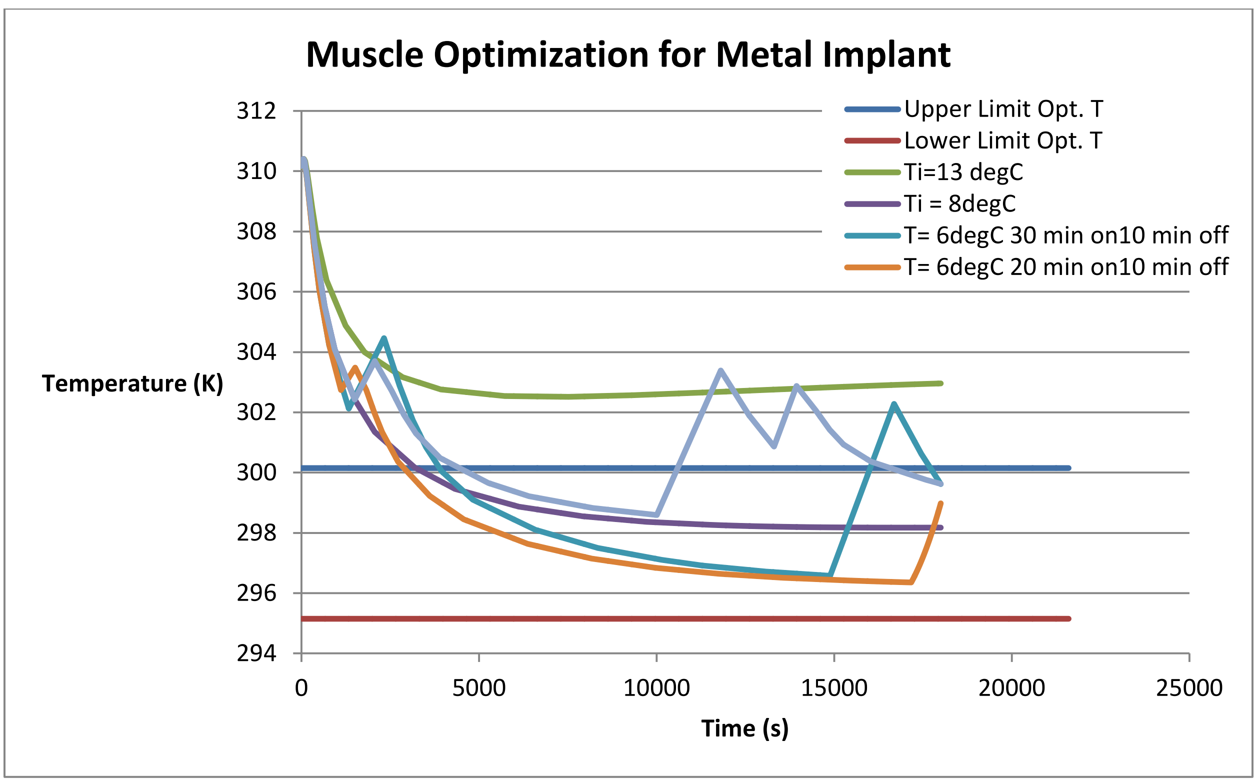

Figure v. Optimization trials in the muscle for the case of a metal implant using the Cryo-Cuff.

Sensitivity Data

Table i. Sensitivity analysis in skin when varying parameters in skin and muscle

Skin Variation	Thermal Conductivity (k) [W/mK]	Temp. [K]	% Difference	Density [kg/m^3]	Temp. [K]	% Difference	C_p [J/kg K]	Temp. [K]	% Difference
0%	.236	285.372401		1200	285.372401		3431	285.372401	
-5%	.2242	285.614702	1.57	1140	285.378685	2.15	3259.45	285.378685	2.15
+5%	.2478	285.166353	2.28	1260	285.379786	1.82	3602.55	285.379786	1.82
-10%	.2124	285.864198	1.20	1080	285.37174	1.30	3087.9	285.372581	1.30
10%	.2596	284.9704	0.13	1320	285.37302	1.47	3774.1	285.37302	1.47
Muscle Variation	Thermal Conductivity (k) [W/mK]	Temp. [K]	% Difference	Density [kg/m^3]	Temp. [K]	% Difference	C_p [J/kg K]	Temp. [K]	% Difference
0%	.49	285.372401		1179	285.372401		4669	285.372401	
-5%	.4655	285.36934	4.40	1120.05	285.374039	1.52	4435.55	285.374041	4.47
+5%	.5145	285.375677	0.00	1237.95	285.370852	1.43	4902.45	285.37085	-2.91
-10%	.441	285.36645	1.51	1061.1	285.375604	1.49	4202.1	285.375604	1.49
10%	.539	285.379188	1.43	1296.9	285.369396	1.39	5135.9	285.369396	1.39

Table ii. Sensitivity analysis in muscle when varying parameters in skin and muscle

Skin Variation	Thermal Conductivity (k) [W/mK]	Temp. [K]	% Difference	Density [kg/m^3]	Temp. [K]	% Difference	C_p [J/kg K]	Temp. [K]	% Difference
0%	.236	295.45876		1200	295.45876		3431	295.45876	
-5%	.2242	296.664978	0.76	1140	296.04088	1.15	3259.45	296.456156	1.15
+5%	.2478	295.493136	1.11	1260	296.052039	0.91	3602.55	296.444091	-0.11
-10%	.2124	297.731205	0.68	1080	296.447437	2.13	3087.9	296.450445	2.13
10%	.2596	295.399045	-0.21	1320	296.37302	0.53	3774.1	296.452322	0.53
Muscle Variation	Thermal Conductivity (k) [W/mK]	Temp. [K]	% Difference	Density [kg/m^3]	Temp. [K]	% Difference	C_p [J/kg K]	Temp. [K]	% Difference
0%	.49	295.45876		1179	295.45876		4669	295.45876	
-5%	.4655	296.684749	1.60	1120.05	296.45615	0.56	4435.55	300.56429	1.73
+5%	.5145	296.239402	-0.07	1237.95	296.444097	0.50	4902.45	296.92395	0.50
-10%	.441	296.947562	0.69	1061.1	296.462077	0.60	4202.1	296.462077	0.60
10%	.539	296.049903	0.39	1296.9	296.438574	0.47	5135.9	296.438574	0.47

Table iii. Sensitivity Analysis for Varying Parameters in the Skin

		Thermal Conductivity (k) [W/mK]	Temperature [K]	Density [kg/m^3]	Temperature [K]	Heat Capacity (C_p) [J/kg K]	Temperature [K]
Skin Variation	0%	.236	285.758557	1200	285.758557	3431	285.758557
	-5%	.2242	286.01128	1140	285.758856	3259.45	285.758856

	5%	.2596	285.338674	1260	285.75898	3602.55	285.75898
	-10%	.2478	285.5393	1080	285.757679	3087.9	285.757679
	10%	.2124	286.270449	1320	285.759406	3774.1	285.759406
Muscle Variation	0%	.49	285.758557	1179	285.758557	4669	285.758557
	-5%	.4655	285.77047	1120.05	285.759152	4435.55	285.759152
	5%	.5145	285.747919	1237.95	285.758878	4902.45	285.758878
	-10%	.441	285.782524	1061.1	285.759835	4202.1	285.759835
	10%	.539	285.736925	1296.9	285.75874	5135.9	285.75874
Metal Variation	0%	7.51	285.758557	4507	285.758557	540	285.758557
	-5%	7.1345	285.741571	4281.65	285.759142	513	285.759142
	5%	7.8855	285.774696	4732.35	285.757764	567	285.757764
	-10%	6.759	285.723667	4056.3	285.759013	486	285.759013
	10%	8.261	285.790774	4957.7	285.757304	594	285.7304

Table iv. Sensitivity Analysis for Varying Parameters in the Muscle

		Thermal Conductivity (k) [W/mK]	Temperature [K]	Density [kg/m^3]	Temperature [K]	Heat Capacity (C_p) [J/kg K]	Temperature [K]
skin variation	0%	.236	298.323499	1200	298.323499	3431	298.323499
	-5%	.2242	298.945612	1140	298.324447	3259.45	298.324447
	5%	.2596	297.245403	1260	298.325119	3602.55	298.325119
	-10%	.2478	297.761338	1080	298.320141	3087.9	298.320141
	10%	.2124	299.635991	1320	298.326746	3774.1	298.326746
muscle variation	0%	.49	298.323499	1179	298.323499	4669	298.323499
	-5%	.4655	298.657766	1120.05	298.326071	4435.55	298.326071
	5%	.5145	298.02275	1237.95	298.324198	4902.45	298.324198
	-10%	.441	299.026296	1061.1	298.328959	4202.1	298.328959
	10%	.539	297.74718	1296.9	298.323297	5135.9	298.323297
metal variation	0%	7.51	298.323499	4507	298.323499	540	298.323499
	-5%	7.1345	298.253369	4281.65	298.325578	513	298.325578
	5%	7.8855	298.390115	4732.35	298.320811	567	298.320811
	-10%	6.759	298.179422	4056.3	298.325127	486	298.325127
	10%	8.261	298.456045	4957.7	298.3191	594	298.3191

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Other knee joint dimensions were taken from measurements of group member Nicole Stevens' knee and were approximated.