Computational Fluids Dynamics Analysis of the Thermal Conditions in a Lower Limb Prosthesis Socket

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Abstract
A The challenge of achieving optimal thermal comfort for individuals using prostheses persists, notwithstanding significant progress in prosthetic technology. Consequently, there is a critical need to investigate the thermal conditions within the prosthetic socket. Understanding the thermal environment inside the prosthetic socket has been investigated using both numerical and experimental methods. This knowledge can aid in the resolution of design and thermal issues associated with lower limb prostheses. In this study, the temperature distribution on a transtibial residual limb enclosed in the prosthetic socket was estimated via a computational fluid dynamics (CFD) technique employing the ANSYS Fluent software; this software has the capability to calculate heat transfer through conduction, convection, and fluid mass transport, thereby making it suitable for simulating the heat transfer processes in the human body. The findings of the research

indicated that the temperature of the skin adjacent to the bone was lower than that above the muscular region. Results showed that at basal conditions, the region of higher metabolism, which tallies with the muscular area, had a maximum temperature of 33.5^0C compared to the lower metabolism region with a temperature of 30.2^0C. This supports the position that when comparing the anterior region to the posterior region, the former is usually cooler than the latter. The walking condition, which is a light activity or exercise showed that the temperature change when compared to the basal condition was small with the most significant difference being less than 2^0C.
Keywords: prosthesis, metabolism, prosthetic socket, CFD, ANSYS Fluent, transtibial residual limb

Nomenclature

Symbols	Description
C	Specific heat capacity (J/kgK)
H	Heat transfer coefficient (W/mm^2.K)
K	Thermal conductivity (W/mK)
N	Number of data points
P	Density (kg/m^3)
T	Temperature (°C or K)
Q	Heat generation (W/m^3)
ω	Perfusion rate (ml/ml.s)
∇	Gradient operator
γ_{pred}	Predicted values of temperature (°C)
γ_{exp}	Experimental values of temperature (°C)
Γ	Convergence criterion
$\sum$	Summation symbol
Subscripts	
bas	Basal
bl	Blood
m	Metabolism
ti	Tissue
work	Work/ Work factor

1. Introduction

Prosthetic technology has advanced significantly; the development of smart liners, active prostheses, and the integration of sensors in the design of prostheses are only a few of these areas of advancement. Nevertheless, it is still a challenging issue to attain the ultimate thermal comfort in a prosthetic socket. This is because factors like fit, alignment, socket design, and material selection are just a few of the variables that must be carefully balanced in order to ensure that the thermal comfort within the prosthesis is established, as research has shown that about 54% of people with prosthesis complain of thermal related challenges (Edwards et al., 2025). Additionally, unique elements, including the wearer's level of activity, the state of the residual limb, and the comfort and psychological preferences of the user, are crucial factors that need to be considered (Williams, 2020).

The prosthetic socket is one of the key components of the prosthesis as it houses and protects the residual limb. The thermal environment within the prosthetic socket plays a crucial role in the function of the residual limb because a conducive thermal environment within the prosthesis ensures that its user maximizes its use (Diment, 2019). Nontheless, sweating and heat accumulation are common side effects of enclosed socket design and weight-bearing limbs, particularly during physical activity. This may cause pain, rashes or infection on the skin. The control of moisture and heat in the prosthetic socket is vital for thermal comfort since any other scenario might result in skin issues, and decreased wear duration and general discontentment with the prosthetic device (Williams et al., 2018).

To ensure a conducive thermal environment within the prosthesis socket, some researchers have focused on socket and liner material properties (Rezvanifer et al., 2020; Klute et al., 2007), like the design of a personalized liner that work based on the thermal needs of the user (Rodríguez-Morales et al., 2024). In a related investigation, Mathur et al. (2014) employed the Gaussian process technique to estimate skin temperature in lower limb prostheses. Rather than using a conventional approach of placing the sensor directly on the skin surface, thermocouples were instead used on a location different from the skin. The thermocouples were placed at the interface of the liner and socket and the study's findings demonstrated that the temperature of the stump is affected by both the wearer's activity level and the surrounding air temperature Furthermore, Mathur et al. (2016) did a study using the Gaussian process method to track the residual limb's temperature, and the study's findings demonstrated that the subject's activity level and the surrounding temperature affected the residual limb temperature. Furthermore, adding the thermal time constant to the model improved its accuracy and made the forecasts more trustworthy. The model designed to track an amputee's residual limb temperature non-invasively was refined in terms of accuracy. Other researchers compared a digital approach with conventional ways of socket liner design and favoured the digital approach method (Lee et al., 2024). In addition to studying the materials used for the socket and liner, some researchers have opted to look into the thermal condition of the residual limb located inside the prosthetic socket. Experimental methods using both invasive and non-invasive procedures can determine the thermal condition of the residual limb, which is analogous to determining the skin temperature distribution of the residual limb.

Invasive techniques include the use of sensors on sample prototypes within lab-controlled environments (Han et al., 2015; Ghoseiri et al., 2016; Ghoseiri et al., 2018a). Another invasive technique involves the use of sensors on residual limbs within lab-controlled environments (Ghoseiri et al., 2021; Peery et al., 2005). More invasive techniques include a single-subject clinical investigation, where Ghoseiri et al. (2018b) fitted a thermistors-based temperature management and control system (TM&C) on a prosthetic socket that belonged to a patient who had a transtibial amputation. The residual limb's temperatures were recorded under various conditions. The first condition was when the limb was at rest and without a prosthesis, and the next condition was when the prosthesis being worn during walking and rest. Also, according to data, the temperature readings varies and with respect to the distal and proximal sections. In a different study, Davidson et al. (2017) developed a temperature sensor that operates using the pyroelectric effect, achieving their goal of creating a device with the dual function of sensing the residual limb temperature as well as pressure within the interface.

Another invasive technique involves the use of sensors on residual limbs outside lab-controlled environments (Segal and Klute,2016; Williams et al., 2019). Segal and Klute (2016) applied the use of sensors to assess the residual limb skin temperatures of individuals with unilateral transtibial amputations while they were snowshoeing in a cold climate, also, the subjective thermal comfort experienced was also determined. Findings from the study demonstrated that physical exercise in a cold environment raised residual limb skin temperature and the results were comparable to those of trials carried out at room temperature. Even though there were only slight related drops in skin temperature, participants with amputations felt as though their skin was warming during activity and cooling during rest.

Non-invasive techniques involve the application of numerical analysis on a model geometry of a residual limb with COMSOL Multiphysics as a tool (Diment, 2019) and prediction of the temperature using the Gaussian processes (Mathur et al., 2016). More researchers that applied the non-invasive method include Harden et al. (2008), who applied an efficient and non-invasive method called infrared tele thermography (IRT) for determining the surface temperature of residual limbs, also Diment et al. (2019) conducted a thermal investigation comparing residual limbs to their contralateral counterparts, in this study, although the prosthetic socket insulated the remaining limb. Yet, the results showed the amputated limbs were cooler than the contralateral limbs. A similar postulation can be derived from Harden et al. (2008) whose results indicate that a reduction in the flow of blood to the surface of the residual limb's skin, could have led to the generation of heat that was stored in the muscle tissues. Also, Peery et al. (2006) created a model from the scanned images of a transtibial residual limb. This model was an FE model that was validated using experimental research on skin temperature distribution and to determine the skin temperature distribution inside a socket of the prosthesis without any mechanical loading. This experimental research involved multiple subjects with transtibial amputations. Aside from determining temperature of the residual limb and the thermal environment within a prosthesis, research has also shown that activities undertaken while the prosthesis is in use affect the skin temperature, unlike when the user is at rest (Abbood et al., 2017). With respect to thermal conditions within the prosthetic socket, Vieira et al. (2023) conducted a study utilizing thermographic analysis on sixteen participants with lower limb amputation. Results show that the elevated temperatures at the post-acclimatization moment point to sections of friction that lead to an uncomfortable fit between the prosthetic socket and the residual limb. Lang et al. (2023) were able to show that the temperature asymmetry that is frequently present in amputation patients disappears while wearing a neuromusculoskeletal prosthesis but returns when it is taken off.

From the literature examined above, different authors have successfully used various means to investigate the temperature distribution on a residual limb within a prosthesis socket. The irregular and complex form of a residual limb has proved to be a challenge to the application of analytical and other numerical schemes to the accurate solution of the temperature field. Therefore, there is a need for more studies to accurately predict temperature distribution on the residual limb's skin. Furthermore, the use of invasive methods, including sensors, has proven to be challenging as the placing and removing of sensors during the liner's donning and doffing procedure can be difficult. Although the use of invasive techniques in experiments to investigate the thermal state of the residual limb is common, non-invasive techniques for modeling and the analysis of the temperature distribution in the residual limb using numerical tools are also gradually making their way into the research scene. Also, the Pennes Bioheat model equation, which has been shown to be a valuable tool for simulating heat transport in the body (Essam et al., 2019; Chen et al., 2021), was employed for these numerical studies.

As far as the authors of this paper know, numerical studies involving the application of CFD in research areas of thermal and pressure distribution within the prosthetic socket (which houses the transtibial limb) are limited. Hence, this study intends to fill that gap by investigating the thermal conditions within the prosthetic socket. In this study, the non-invasive method via numerical analysis was conducted using the Finite Volume Method of ANSYS Fluent to estimate the temperature distribution within the prosthetic socket. Therefore, the difficulties in recruiting physical participants are eliminated, as are the difficulties in selecting subjects which are suitable for the experimental procedures. In addition, the residual limb's metabolism and biological characteristics can be replicated, and the procedure is non-invasive, in contrast to many other studies that involve invasive procedures that cause discomfort and cause sensors to become misaligned during the experiment. This work attempts to provide a more realistic prediction of the thermal conditions in a lower limb prosthetic socket, including the temperature distribution on the residual limb's skin, by analyzing heat conditions within a prosthetic socket.

2. Numerical methodology

2.1 Computational Model

A 3D model geometry of a transtibial residual limb is developed. as seen in Figure 1. It has overall dimensions of 300mm by 150mm by 150mm. The innermost section is the bone, which is covered and intertwined with muscle and fat. The skin is the outermost layer of the residual limb geometry. The model considered the thermophysical properties, and operating conditions of the bone, blood, muscle, fat, and skin as summarized in Table 1. The sock is introduced to the skin of the residual limb before applying a prosthetic socket which comprises of the liner and socket. The materials for the sock (2 mm), liner (5 mm), and socket (4 mm) are wool, silicone, and acrylic resin, respectively.

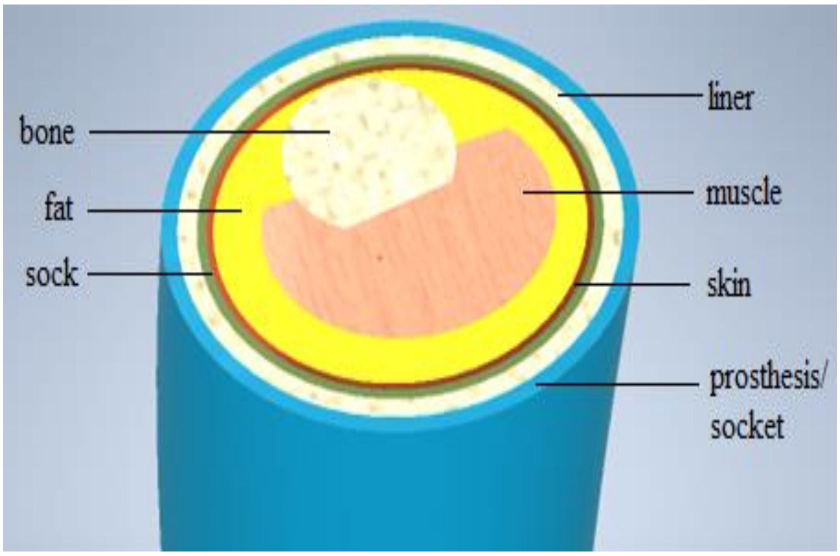


Figure 1: Geometry of transtibial residual limb enclosed within a prosthetic socket

Table 1: Material properties of biological tissues at basal state

	Heat Capacity (J/kg.K)	Density (kg/m^3)	Thermal Conductivity (W/m.K)	Basal Metabolism(W/m^3)	Basal Perfusion (cm^3/cm^3.s)
Fat	2674	928	0.219	58	0.00000472
Muscle	3800	1040	0.520	684	0.00052000
Skin	3770	1120	0.498	368	0.00037200
Blood	3840	1060	0.520		
Bone	1260	1420	0.435		

[source: Diment (2019); Peery et al. (2006); Jaime et al. (2013); Okabe et al. (2018)]

2.2 Governing Equations and Boundary Conditions

Using the Pennes bioheat equation as the bio heat model, Equation (1), the rate of thermal energy store of the tissue, based on the passive system (that is a body not undergoing exercise or activity/ basal state), is:

$$\rho_{ti} C_{ti} \frac{\partial T_{ti}}{\partial t} = \nabla(-k\nabla T_{ti}) + \omega_{bl}\rho_{bl}C_{bl}(T_{bl} - T_{ti}) + q_{ti,m,bas} \quad (1)$$

where:
ρ_{ti}=tissue density (kg/m^3)
ρ_{bl}= blood density (kg/m^3
C_{ti} = the specific heat capacity of tissue (J/kg.K)
C_{bl} = the specific heat capacity of blood (J/kg.K)
T_{ti} = tissue temperature (K)
T_{bl} = blood temperature (K)
k = thermal conductivity (W/m.K)
ω_{bl} =blood perfusion rate= volumetric rate of perfusion (ml/ml.s).
$q_{ti,m,bas}$ = basal heat generation caused by cell metabolism
∇= gradient operator
ti = tissue
bl = blood

When the body is no longer at rest (basal state) and is involved in one activity or the other, including walking, running etc., the body heats up the working muscles in proportion to the amount of work it performs.

Hence, Equation (1) is now modified to include the work factor and becomes

$$\rho_{ti} C_{ti} \frac{\partial T_{ti}}{\partial t} = \nabla(-k\nabla T_{ti}) + \omega_{bl}\rho_{bl}C_{bl}(T_{bl} - T_{ti}) + q_{ti,m,bas}\ q_{ti,m,work} \quad (2)$$

For the boundary conditions, the outside surface of a prosthesis was exposed to natural convection and ambient temperature conditions, while the proximal end was subjected to an adiabatic boundary condition. Hence,
h = heat transfer coefficient = 4×10^{-6} W/mm^2.K
T = ambient temperature = 23°C = 296K

The predefined material and thermal properties of the bone, muscle, skin and fat included in the simulation, excludes the need for specific boundary conditions at each interface. Moreover, the ‘coupled’ condition which is applied in the ANSYS Fluent boundary condition section enables the heat transfer modelling, to ensure a more accurate representation of thermal conduction across the boundaries.

3. Numerical Solution

3.1 Numerical Technique

The governing equations and the boundary conditions were numerically solved using a three-dimensional computational fluid dynamic code (ANSYS Fluent), which uses the finite volume method (Patankar, 1980). Figure 2 shows the detailed procedure in flowchart. The modeled geometry being imported into ANSYS Fluent, and parameters, including solid and fluid options like thermal conductivity, density, perfusion rate, heat capacity, and metabolism, were defined, and the boundary conditions were set. Also, boundary conditions applied and the material properties of the materials used for the prosthetic component; liner (silicone), sock (wool), and socket (carbon fibre), were obtained from Peery et al. (2006). The model imported into ANSYS CFD was applied in the process of predicting the skin temperature distribution in a residual limb. The main emphasis of this validation was the temperature distribution on the skin. The temperature of the outer prosthetic socket was not the main focus. Other relevant properties like the material and biological tissue properties, metabolism, and rate of perfusion were retrieved from existing research work, and the body core temperature was 37.7°C. All thermal properties were isotropic.

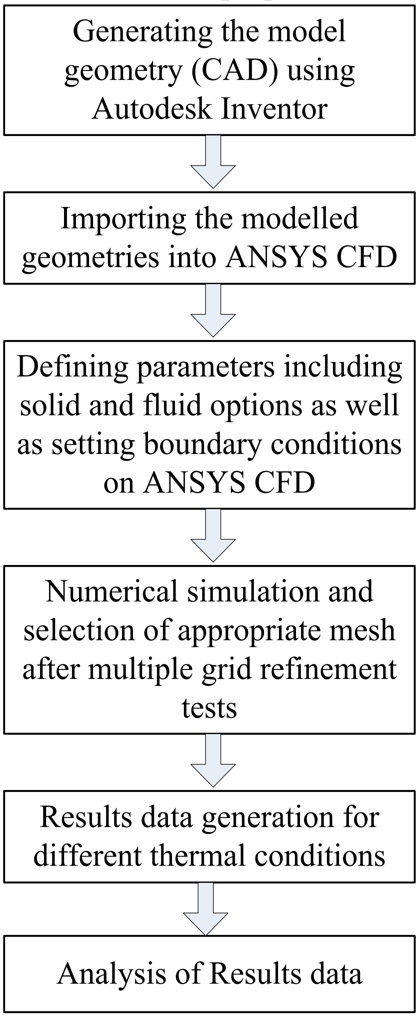
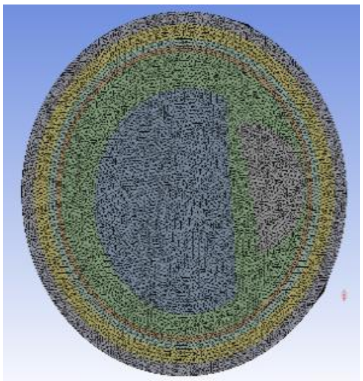


Figure 2: The flowchart of the numerical solution and procedure

3.2 Grid Independence Test

Figure 3 shows discretized domain of the model. The selection of the appropriate mesh size was done after multiple grid refinement tests. To verify the grid independence test, numerous grid tests were conducted to guarantee the simulation results' accuracy. The mesh elements were refined continuously until an acceptable mesh allowed for efficient calculation was achieved. The convergence criterion was determined using Equation (3).



(a)

(b)

Figure 3: Meshing of the model of (a) top view and (b) sectional view also showing the top and lateral views of the model

$$\gamma = \frac{T_i - T_{i-1}}{T_i} \leq 0.00040 \tag{3}$$

The element size of 6,771,491 was considered to be a suitable mesh, thereby fulfilling the convergence criterion. Also, further increase had no significant effect on the outcome as seen Table 2.

Table 2: Grid Independence Study

Element Size	T (°C)	γ
220,773	35.883	-
1,167,194	36.018	0.00044
6,771,491	36.109	0.00029
14,533,491	36.111	0.00001

3.3 Error Analysis

The experimental study and present study results were compared via the average deviation (AD) and mean average deviation (MAD) formulas as shown in the Equation (4) and Equation (5)

Average deviation (AD):

$$\boldsymbol{AD = \frac{1}{N}\sum_{1}^{N}\left[\frac{(\gamma_{pred} - \gamma_{exp})\times 100\%}{\gamma_{exp}}\right]} \tag{4}$$

Mean Absolute deviation (MAD):

$$\boldsymbol{MAD = \frac{1}{N}\sum_{1}^{N} ABS\left[\frac{(\gamma_{pred} - \gamma_{exp})\times 100\%}{\gamma_{exp}}\right]} \tag{5}$$

Where N represents the number of data points, while γ_{pred} and γ_{exp} represent the predicted and experimental values for temperature respectively.
For the present study, results show that the mean average deviation (MAD) and the average deviation (AD) estimated for the values of temperature at the four regions (anterior, medial, lateral, and posterior) had the highest value of not up to 3% (see Table 3). This is a good value since it indicates that the deviation values are small and the data points are more closely packed. When comparing the present study with the experimental study of Peery et al. (2006), it can be seen that the MAD Value is 1.72%. This is a lower value compared to the FEM values in Peery et al. (2006) versus Experimental values of Peery et al. (2006) whose MAD value is 2.09%. This lower value suggests that the data points are relatively close to the mean, indicating less variation and stability in the analysis of the present study. A higher MAD indicates increased variability, meaning the data points are more spread out from the mean. This could represent greater fluctuations or inconsistencies. Similarly, the AD values indicate small deviations, the negative value (-0.36%) in Peery FEM vs Peery Experimental represents a larger and downward deviation from the mean, whereas the positive value (0.28%) in present study vs Peery FEM represents a smaller upward deviation.

Table 3: MAD and AD of temperature distribution along all sections of the residual limb

Regions	**Location Points**	**Present Study (°C)**	**Peery (Exp) (°C)**	**Peery (FEM) (°C)**	**Present vs Peery Exp (MAD)**	**Peery FEM vs Peery Exp (MAD)**	**Present vs Peery Exp (AD)**	**Peery FEM vs Peery Exp (AD)**
Anterior	1	31.161682	31.155390	30.202460	0.000202	0.030586	0.000202	-0.030586
Anterior	2	31.638062	31.611380	31.308300	0.000844	0.009588	0.000844	-0.009588
Anterior	3	31.766205	31.993650	32.223010	0.007109	0.007169	-0.007109	0.007169
Anterior	4	32.082535	31.537660	32.261230	0.017277	0.022943	0.017277	0.022943
Lateral	5	32.849320	32.640450	32.036490	0.006399	0.018503	0.006399	-0.018503
Lateral	6	33.140030	32.376210	33.241710	0.023592	0.026733	0.023592	0.026733
Lateral	7	33.022950	32.788740	33.241710	0.007143	0.013815	0.007143	0.013815
Lateral	8	32.504807	32.750990	31.998740	0.007517	0.022969	-0.007517	-0.022969
Posterior	9	33.545258	33.015220	33.505940	0.016054	0.014863	0.016054	0.014863

Posterior	10	33.078308	32.413960	32.977480	0.020496	0.017385	0.020496	0.017385
Posterior	11	32.232828	33.241710	31.510720	0.030350	0.052073	-0.030350	-0.052073
Medial	12	31.110169	32.036490	30.944500	0.028915	0.034086	-0.028915	-0.034086
Medial	13	31.976899	32.939730	32.826490	0.029230	0.003438	-0.029230	-0.003488
Medial	14	32.429430	31.020000	31.583520	0.045436	0.018166	0.045436	0.018166
Percentage MAD AD					**0.017183**	**0.020880**	**0.002452**	**-0.003583**
					1.72%	**2.09%**	**0.25%**	**-0.36%**

3.4 CFD Model Validation

The model predictions were collected from location points comparable to the location points as seen in Peery et al. (2006). The current research is modelled in line with the Peery et al. (2006) including the use of twenty temperature point locations in each section of the single residual limb model. These location points were determined from the experimental and numerical positions Peery et al. (2006) as seen in Figure 4. Skin temperatures were measured at anterior, lateral, posterior, and medial locations on the residual limb model.

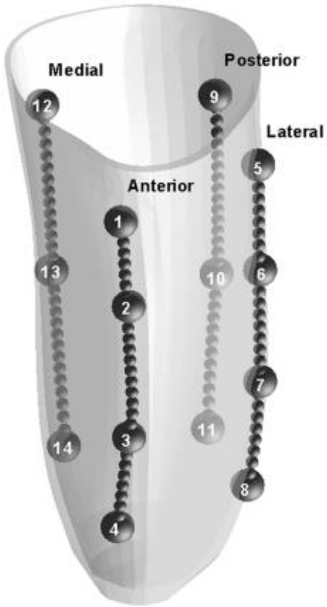


Figure 4: Locations of temperature data acquired experimentally (large spheres) and extracted from the numerical model (small spheres) of a residual limb (source Peery et al. 2006

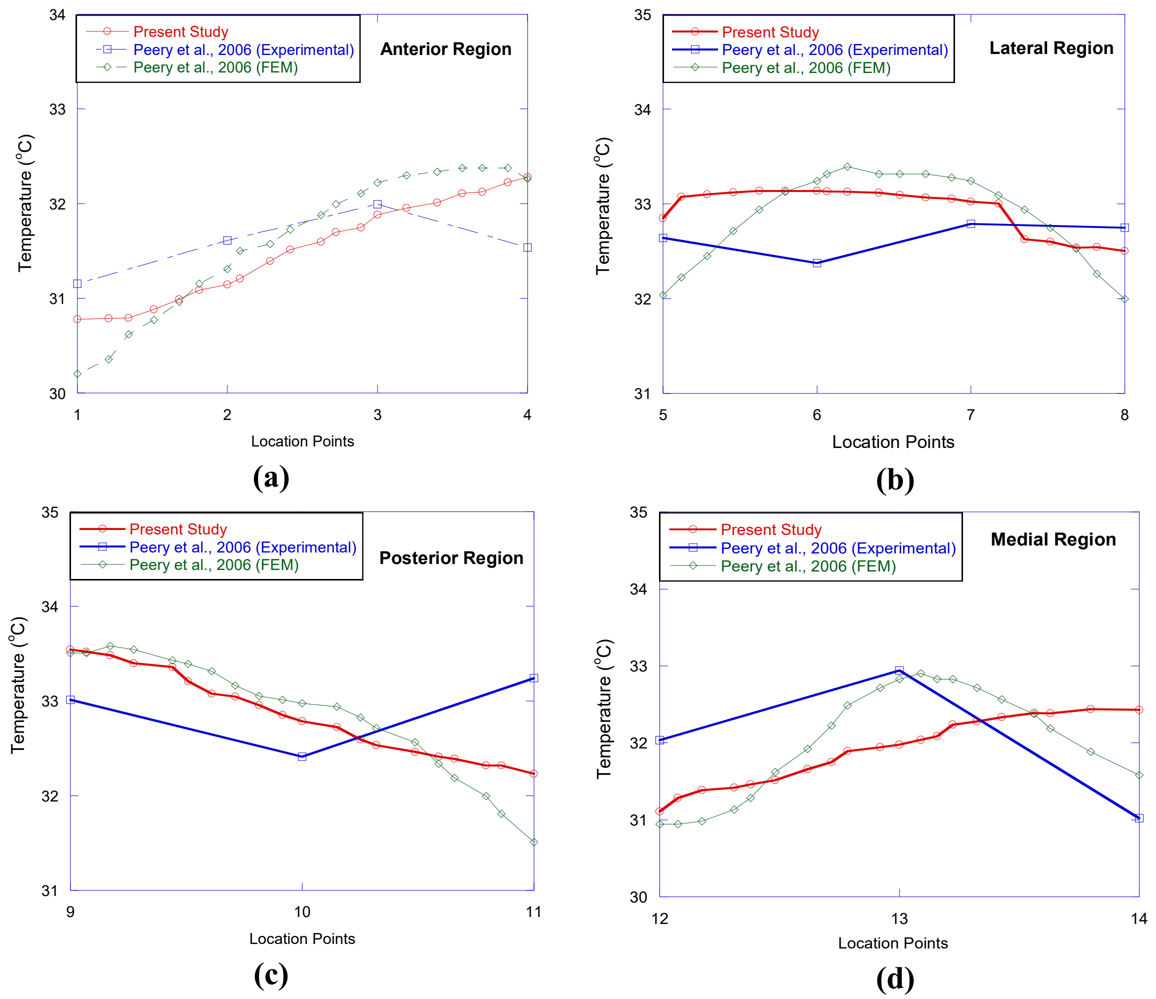


Figure 5: Comparative analysis of skin temperature at basal (rest) condition in present study versus Peery et al. (2006) at (a) Anterior (b) Lateral (c) Posterior and (d) Medial Regions

Figure 5(a-d) compared the present study with existing experimental and numerical studies of Peery et al. (2006) with respect to the temperature distribution of the residual limb's skin at basal condition. In the section of the anterior region (Figure 5a), the experimental locations consist of four points, for which temperature increased from an initial value of 31.16°C with a steady increase till it dropped to a value of 31.54°C at the fourth point which is still higher than the initial starting temperature. Consequently, it can be observed that there was a steady increase in temperature for the present study and FEM study. A larger range of temperature distribution occurred in the FEM study as the first point has a temperature value of 30.20°C, thereafter there was a steady increase in temperature across the twenty numerical points on the skin before it finally dropped to 32.30°C. The temperature values of the present study were more at par with the temperature values of the experimental study. The present study analyzed twenty points on the skin starting with a temperature value of 31.20°C including slightly varying temperature values across the twenty thermal points until it reached a value of 32.08°C. From this graph, the present study aligns more with the experimental values than FEM values. Results also show that the anterior region has a lower range of temperature values when compared to the other regions of the residual limb.

The lateral region has slightly more muscle mass than the anterior region. For this region, the experimental locations consist of four points (Figure 5b). Temperature values for the experimental values increased from an initial value of 32.64°C at location point 5 before it dropped slightly to 32.38°C at point 6 with the highest temperature of 32.79°C at point 7. When compared to the FEM study values of Peery et al. (2006), the present study's temperature values were comparable to the experimental values. The maximum temperature observed in the present study was slightly over 33°C. The study's temperature was 32.85°C at the first point, and it varied steadily during the next twenty location points, reaching a final temperature of 32.51°C. The posterior region is where the higher temperature distribution is found (Figure 5c), with temperature values as high as 33.56ºC. The residual limb's muscular regions are warmer than the regions containing the tibia and fibula. Higher skin temperatures on the residual limb are explained by the existence of the gastrocnemius muscle in the posterior region.

The medial region also possesses muscle mass but not like the posterior region. In the medial region (see Figure 5d), the experimental locations consist of just three points where the temperature rose to 32.04ºC at first and then decreased to 31.02ºC in the end. In general, the low temperature levels of the medial region are comparable to those in the anterior region. In the current investigation, its temperature readings more closely match the experimental findings of Peery et al. (2006) than the FEM study Peery et al. (2006). Overall, the results show that the skin temperatures were determined for the residual lower limb enclosed within the prosthetic socket. Furthermore, the skin temperature values were highest at the regions of larger muscle tissues.

4. Results and Discussion

In addition to the Peery et al. (2006) validation, further simulation at basal (rest) and active (walking) condition states were carried out where the temperature distribution across other sections of the residual limb regions was taken into account.

4.1 Temperature distribution within some sections of the residual limb at basal condition

This subsection outlines the results and discussion for the temperature distribution on the skin of the residual limb at basal condition, temperature distribution within some sections (fat and muscle) of the residual limb at basal condition. The bone, muscle and fat regions are represented by these sections, including parts of the prosthesis like the liner, sock and the socket (Figure 6). The temperature varies across the bone, muscle and fat regions due to the heterogeneous nature and varying thermal properties of each of the sections of the residual limb. The temperature highest at the muscle section with a temperature of 34.0°C which is due to the high metabolism occurring within the muscle. Comparable temperature ranges for muscle values have also been noted in earlier research, such as Diment (2019) and Peery et al. (2006).

Temperature variation across the residual limb varies from the highest temperature (due to metabolism) which is located at the muscle section with temperature of 34.0°C to the lowest temperature at the skin section (the skin is exposed to the outside environment) with a temperature of 32.1°C. The temperature drops across from the core to the outside skin is 1.9°C which is a 6% drop in temperature. The prosthetic socket is in direct contact with the ambient or outside temperature. This accounts for the socket having the lowest temperature with a value of 29.2°C. Hence, the variation in temperatures among bone, muscle, fat and skin within a prosthetic limb is determined by metabolic activity i.e. heat generation and dissipation, material properties of the prosthesis, blood flow dynamics, and environmental conditions. These factors should be considered crucial for optimizing prosthetic design and improving thermal comfort for amputees.

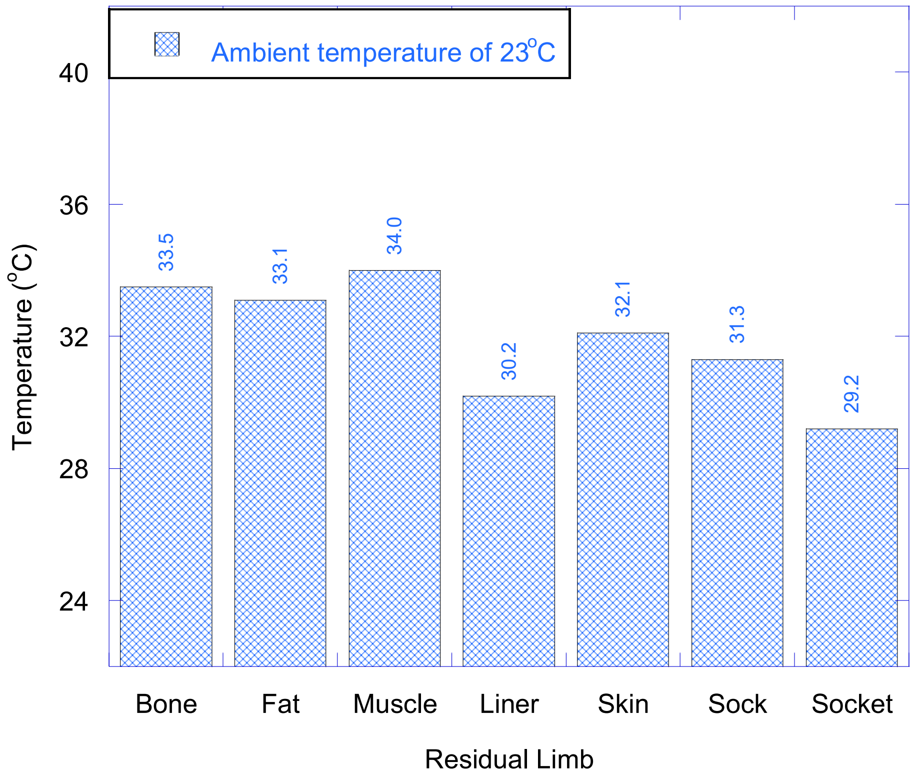
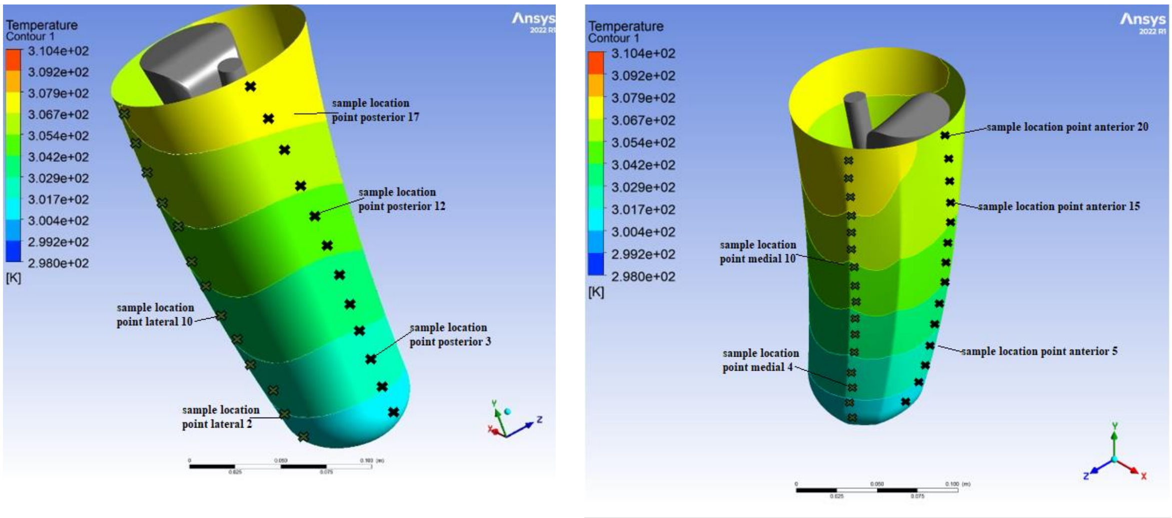


Figure 6: Temperature distribution for the fat, muscle and skin of the residual model for the present study (basal state)

4.2 Temperature distribution on the skin of the residual limb during active condition (walking)

This section outlines the results and discussion for the temperature distribution of the skin of the residual limb at active condition (walking). The production of heat in a human body in a thermoneutral environment during mental and physical rest, at least 12 hours after the last meal, is known as the basal metabolic rate (BMR). Heat is produced in tissues by blood perfusion and metabolism. The heat produced during metabolic activities, such as growth and the creation of energy in a biological system, is referred to as metabolic heat (Marcus, 2013). The body has regular flow of blood and metabolic activity when it is at rest. Nonetheless, there is aberrant blood flow and metabolic activity during exercise (i.e., walking). Low-intensity exercises like typing, cooking, and sitting have similar metabolic rates to baseline metabolic rates because there is less change in the vascular system. The simulation of the active condition (walking) is presented in Figure 7(a-b).

Figures 7(a-b) show the temperature profile on the skin of the residual limb when a light activity (walking) is being carried out. In Figure 7a, the location points are arranged along the XY and YZ planes. These points represent the values of the temperature distribution of the residual limb's skin and the figure shows the location points running across the posterior and lateral regions. Similarly in Figure 7b, the location points are arranged along the XY and YZ planes, showing the temperature points running along the anterior and medial regions of the residual limb.



(a) **(b)**

Figure 7: Temperature distribution showing a) posterior and lateral regions, b) anterior and medial regions during walking.

The simulation of the activity process of walking was conducted at the precise location points on the residual limb used in the current study at the basal state. Walking metabolism statistics were obtained from Shrestha et al. (2023) as shown in Table 4 and used in numerical simulation.

Table 4: Values of metabolic rate (Shrestha et al. (2023))

Activity Condition/ State	Metabolic Rate (W/m^3)
Basal Metabolic Rate	1114
Walking	3889.43

Figures 8 (a-d) show the skin temperature distribution of residual model for basal (rest) and active (walking) states at different regions. In the anterior region of the residual limb (see Figure 8a), observations show an intersection of temperature values, which fall close to where the bone is located. It is essential to highlight that the majority of the bone is situated in the anterior region. In the lateral region, there is only one intersecting temperature point where the basal and walk activities intersect (see Figure 8b). It should be noted that the XY Plane, which traverses the anterior and posterior regions, also intersects with the bone, resulting in the observation of location points with overlapping temperatures in the posterior region (see Figure 8c). Also, at sections where bone density is minimal, there are fewer intersecting points of temperature values like in the medial region with only two intersecting temperature points of basal and walk activities (see Figure 8d).

All the regions except the posterior region experienced a slight increase in temperature readings for the walking activity at certain location points. In these regions, there were location points where the walking exercise resulted in lower temperature readings. Due to the anterior and medial regions having less muscle mass than the other regions with greater muscle mass, these regions exhibit temperature reduction. The results then indicated that the temperature change for walking in comparison to the basal condition was minimal, with the largest difference being slightly over 1°C.

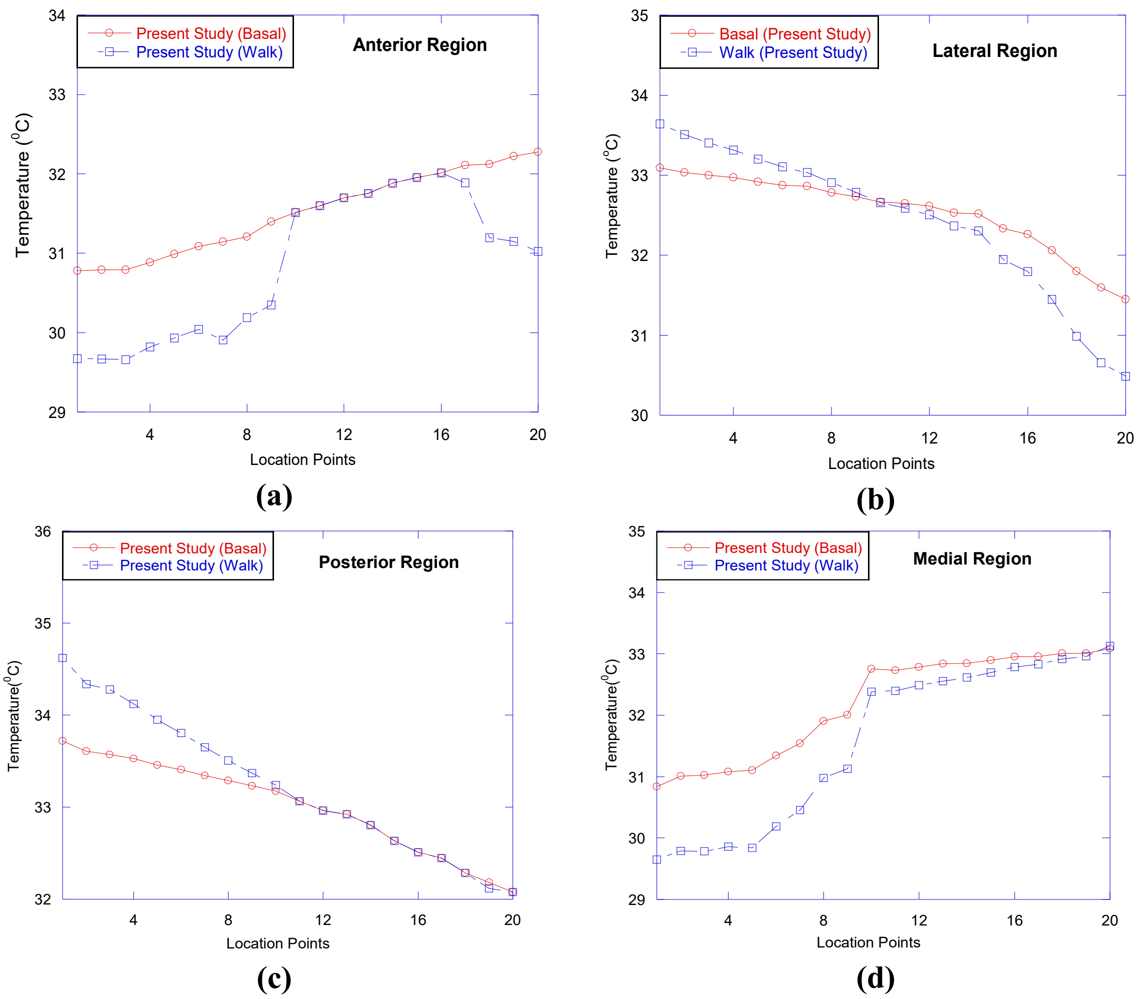


Figure 8: Skin temperature distribution of residual model for the present study comparing basal state and walking for a) Anterior, b) Lateral, c) Posterior, and d) Medial Regions

In the anterior region and medial regions there was a temperature reduction for the low intensity activity (walking). These findings are consistent with the previous study by Diment (2019) indicating that skin cooling on the residual limb can occur during a low intensity activity. This idea is confirmed by scientific study, which indicate that if the ability of the body to release heat generated in those muscles is hindered, then there is a tendency for more heat to be stored within the active muscles during activity (Shrestha et al., 2020).

In summary, the anterior, lateral, posterior and medial regions, had intersecting location points temperature values for both basal and walking conditions. This is because low-intensity exercises like typing, cooking, and sitting have similar metabolic rates to baseline metabolic rates because there is less change in the vascular system also these location points are closer to the bone where there is less musculature.

5. Conclusion

A numerical study of the temperature distribution of a residual limb in a lower limb prosthesis was conducted for basal and walking conditions. The numerical simulation was done using commercial CFD code - ANSYS Fluent. The effect of basal and active conditions (walking) was investigated on the anterior, lateral, posterior and medial regions of the residual limb. The application of ANSYS Fluent as a non-invasive method of thermal analysis in the current study with a similar model as used by existing study compares favorably with existing experimental studies that used sensors to determine temperature distribution. The following are the findings from this study:

- For the basal condition, it was observed that regions with larger muscle mass like the posterior region recorded high temperatures up to 33.5°C while the anterior region with lower muscle mass had temperatures as 30.2°C. It can be inferred from this that a region with more muscle mass retains heat energy more effectively than one with less muscle mass.
- An average deviation of 0.25% and MAD value of 1.72% was recorded when comparing the present study and Peery experimental values of residual limb model.
- Furthermore, low-impact exercises like walking did not significantly change the residual skin temperature because the highest difference in temperature when comparing basal and active conditions is less than 2°C.

Based on the above results, it is recommended that non-invasive methods like numerical analysis for the investigation of the thermal conditions in the lower limb prosthetic socket be considered by researchers and clinicians. These simulation studies offer benefits by allowing for the prediction of long-term performance and patient outcomes, the ability to explore a wider range of parameters, including user-specific models in a virtual environment, this leads to faster development cycles, cost effective and safer clinical trials as the multiple iteration tests are reduced drastically, as well as the creation of more personalized and advanced prosthetic devices.

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