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# NUMERICAL SIMULATION OF THE TEMPERATURE DISTRIBUTION OF THE HUMAN KNEE JOINT IN NEUTRAL THERMAL CONDITIONS

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**Abstract.** *The understanding of body temperature distribution and the comprehension of the effect of therapeutic heat treatment on the body temperature behavior represent major advancements in healthcare. However, obtaining experimental data on the topic has been proven difficult because it is an invasive procedure, restricted to only a few points in the living human body. These setbacks are overcome using numerical simulation, which is seeing increasing applications in healthcare. This study aimed to obtain a 3D geometric model of the human knee joint and the temperature profile on this model in neutral thermal conditions and steady state based on the bioheat equation published by Pennes. The geometric model was built based on cross sectional photos from a human body obtained from the Visible Human Project dataset and developed in a Computer Aided Design. A Computational Fluid Dynamics analysis was performed based on the finite volume method. Each tissue presented in the model was characterized by its thermodynamic and physical properties such as: heat conductivity, specific heat and density. The numerical results determined in simulations were within the expected range of temperature for the human knee and similar to the results reported in the literature for similar conditions to those that were used in this study.*

**Keywords:** *bioheat equation, finite volume method, CFD analysis, human knee joint, temperature profile.*

## 1. INTRODUCTION

Currently, the thermal procedures have gained prominence in several health applications that include the evaluation and prediction of thermal damage in tissues (Gašperin and Juričić, 2009), hyperthermia for the treatment of cancer (Huang *et al.*, 2012), the hypothermia (Vanlandingham *et al.*, 2015), cryopreservation (Rubinsky *et al.*, 1987) and therapeutic treatments to assist in rehabilitation (Silva *et al.*, 2011, Trobec *et al.*, 2008, Araújo, 2009). However, experimental measurements of temperature profile in the human body present great difficulties because of its invasive nature, the limited positioning of sensors, the imprecision of the data obtained and ethical issues linked to in vivo experiments (Trobec *et al.*, 2008). Yet, the studies investigating temperature behavior in living tissues (Trobec *et al.*, 2008; Xiao *et al.*, 2010; Silva, 2011; Trobec and Depolli, 2011; Narasimhan and Jha, 2012) have grown steadily since 1948 when Harry Pennes proposed the first model of bio-transfer heat that related the temperature of biological tissues to blood perfusion and the generation of metabolic heat based on his experiments (Pennes, 1948). This model is known as the Pennes bio-transfer heat equation. Although many later studies have made new approaches to this equation, it remains to this day as a basis for understanding body heat exchanges with the environment due to its simplicity (Incropera and Dewitt, 2008).

The human body is composed of irregular three-dimensional geometries with contacts, making the analytical solution of the Pennes equation unfeasible (Rashkovska *et al.*, 2012). Nowadays, the use of computational tools presents itself as an efficient method to analyse heat transfer problems and has a wide branch of application in both the industry and the academic environment such as aerodynamics, chemical processes, meteorology and medicine (Versteeg and Malalasekera, 2007). The numerical simulation for the solution of the Pennes equation has been used in the analysis of the temperature behavior in the different parts of the human body (Rashkovska *et al.*, 2012). Among the

methods of numerical solution, the finite volume method (MVF) stands out because it is a conservative method and easy to apply in unstructured meshes (Versteeg and Malalasekera, 2007).

According to Trobec *et al.* (2008), the temperature of the human knee joint is dependent of the muscle metabolism and blood perfusion. In this context, this work aimed to describe a 3D geometric model construction of the human knee joint and perform a numerical simulation to obtain the temperature profile in the steady state condition and thermal neutrality. The generation of metabolic heat and the term of blood perfusion was kept constant using the Computational Fluid Dynamics (CFD) analysis. The tissues considered in the present study are: subcutaneous, adipose, muscular and bone. Physical and thermal properties such as density, thermal conductivity and specific heat of each tissue were applied to the model. The numerical results were compared with data obtained from the literature for studies performed in similar conditions.

## 2. METHODOLOGY

### 2.1 Computacional domain

In this paper, a 3D geometric model of the human knee joint was built based on real images of the human body that are available from the Visible Human Project® (VHP) licensed to the Bioengineering Research Laboratory (LABBIO) of the Universidade Federal de Minas Gerais (UFMG). Visible Human is a project developed by the National Library of Medicine (NLM) in the United States of America and consists of three-dimensional representations of the bodies of two corpses anatomically detailed, one male and the other female (U.S. National Library of Medicine, 2015). The male cadaver was sectioned transversally at 1 mm intervals. Anatomical axial images, approximately 7.50 megabytes each, have a resolution of 2048 pixels by 1216 pixels. To elaborate the 3D model of the knee joint, the transversal sections corresponding to this segment were identified among the images available in the VHP database, using 150 sections of the transversal images (images 2230 to 2380). Figure 1 shows one of the cross-sectional images used for the construction of the 3D model and Table 1 shows the identification of tissues.

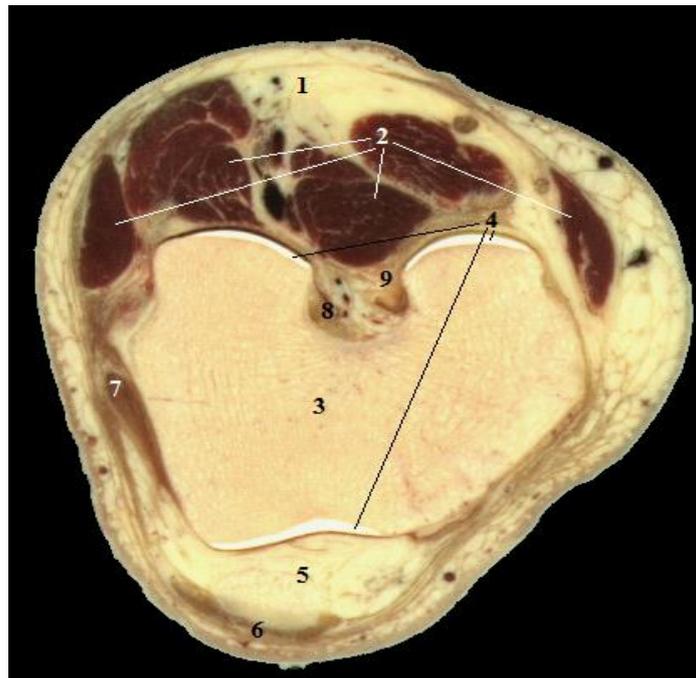


Figure 1 – Cross-sectional photo of the knee joint  
 Source: U.S. National Library of Medicine, 2015

Table 1 – Human tissues in the knee joint

Number	Tissue
1 and 5	Adipose tissue
2	Muscles: Sartorius, Gastrocnemius (lateral and medial head), Plantaris, Biceps
3	Femur
4	Cartilage

6	Patellar ligament
7	Collateral fibular ligament
8	Anterior cruciate ligament
9	Posterior cruciate ligament

Source: (Bergman *et al.*, 1991)

The 3D model considered has a height of 0.15 m. The SolidWorks 2012® program was used to perform the contours of the target tissues and structures of the study and align the cross-sections along the vertical axis. The contours were united to form solids. The human tissues geometry obtained were: subcutaneous tissue, adipose tissue, muscles and bones. Figure 2 shows the construction of the Femur. Figure 3 shows the geometry model considered to perform the numerical simulation.

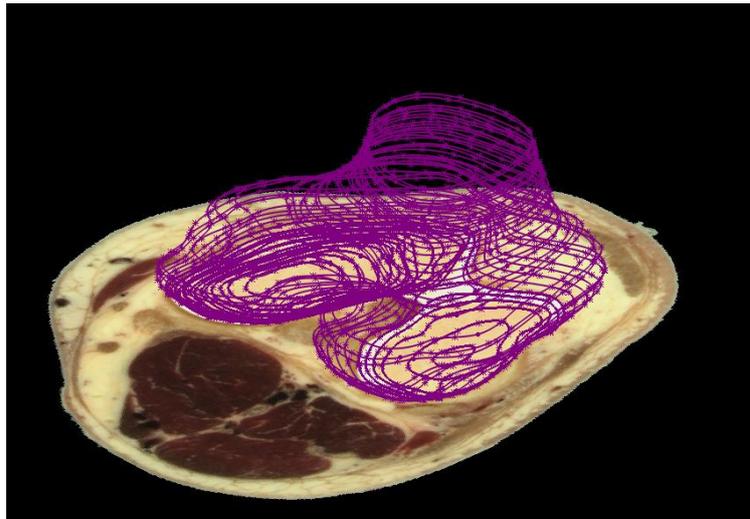


Figure 2 - Construction of the Femur from the photos 19-110.  
Source: Author

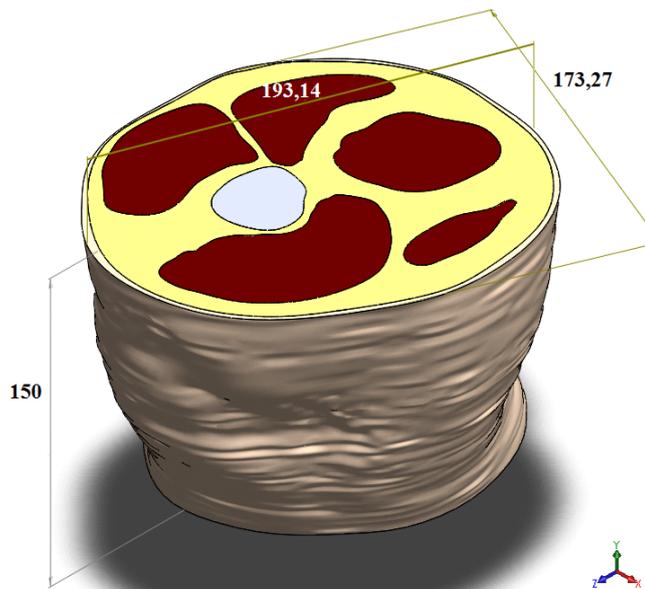


Figure 3 – Dimensions of the 3D geometric model  
Source: Author

Figure 4 presents the computational subdomains considered for the numerical analysis.

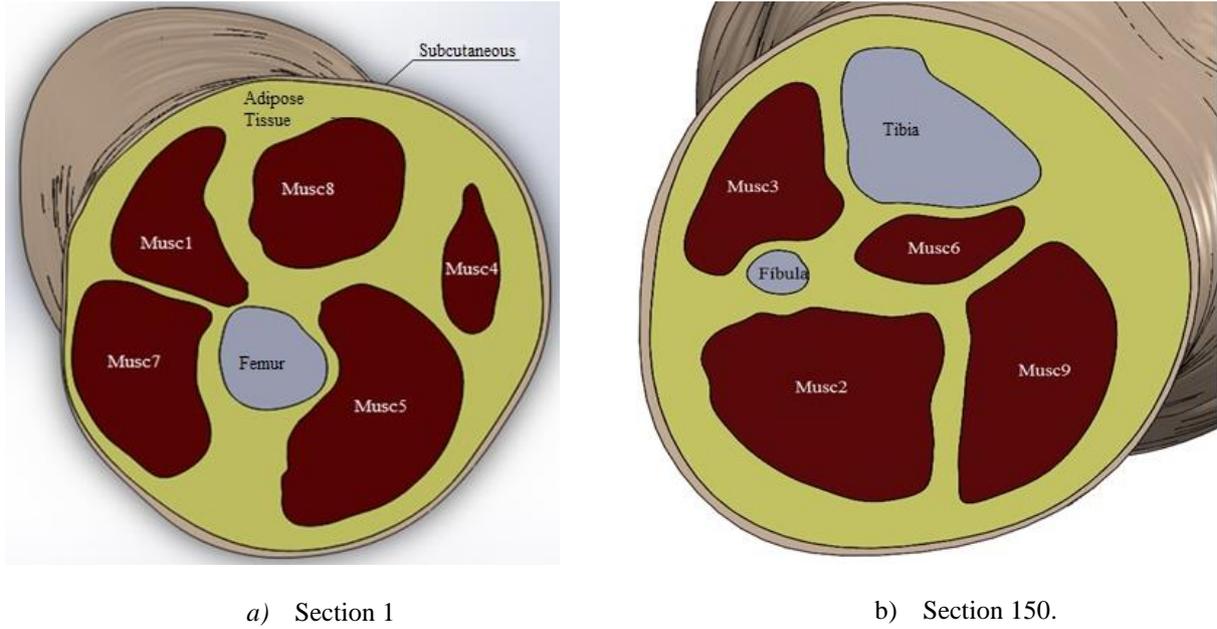


Figure 4 – Subdomains: Muscles (red); Femur (grey); Adipose Tissue (yellow); Subcutaneous (beige)  
 Source: Author

## 2.2 Mathematical model and tissues properties

The bioheat equation published by Pennes, a partial differential equation of second order, was used to model the phenomenon of heat transfer in the tissues under the condition of thermal neutrality. The problem was defined as being three-dimensional and permanent regime. This equation can be described as:

$$\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + qm + qp = 0 \quad (1)$$

Where:  $k$  represents the thermal conductivity of each tissue;  $qm$  is the metabolic heat rate;  $qp$  is the blood perfusion rate. In this study, the metabolic and blood perfusion rates were also held constant. The perfusion rate was calculated according the Eq. 2 for each computational subdomain.

$$\dot{q}_p(w) = w\rho_s c_{ps}(T_a - T_{tissue}) \quad (2)$$

Where  $w$  represents the blood perfusion [ $m^3s^{-1} m^{-3}$ ] of each tissue;  $\rho_s$  is the specific mass of blood [ $kgm^{-3}$ ];  $c_{ps}$  is the blood specific heat coefficient [ $Jkg^{-1} ^\circ C^{-1}$ ] and  $T_a$  and  $T_{tissue}$  are the arterial temperature and tissue temperature, respectively. According to Trobec *et al.* (2008), the arterial temperature is  $36,8^\circ C$  and tissue temperature  $36^\circ C$ . These values were used to calculate blood perfusion rate. The thermophysical properties of the human tissues are presented in Table 2. All properties were considered constant for the implementation of the simulations.

Table 2 – Thermophysical properties of the tissues

Tissues	$c_p$ ( $Wm^{-1}^\circ C^{-1}$ )	$\rho_s$ ( $kgm^{-3}$ )	$k$ ( $Wm^{-1}^\circ C^{-1}$ )	$q_m$ ( $Wm^{-3}$ )	$w$ ( $m^3s^{-1}m^{-3}$ )
Subcutaneous	3365	1200	$4.64 \times 10^{-1}$	200	$1.3 \times 10^{-3}$
Adipose	2678	937	$2.03 \times 10^{-1}$	3,9	$2.9 \times 10^{-4}$
Muscle	3684	1097	$5.29 \times 10^{-1}$	716	$5.8 \times 10^{-4}$
Bone	1785	1585	$7.35 \times 10^{-1}$	368,3	$4.0 \times 10^{-4}$

Source: (Eberhart and Shitzer, 2012)

The solution of equation 1 depends on the boundary conditions in the surroundings. For that the air temperature considered was  $25^\circ C$ . Considering the heat exchange between the knee joint and the surroundings occurs due to natural

convection, a convective coefficient of  $6 \text{ Wm}^{-2}\text{K}^{-1}$  (Silva, 2015) was considered for the its calculation. It was also considered no heat exchange in the sections 1 and 150 (Fig. 4) with the environment.

### 2.3 Mesh

The method chosen for numerical simulation was the Finite Volume Method due to its simplicity and good accuracy. According to (Versteeg and Malalasekera, 2007), the mesh generation for complex geometries is one of the critic aspects in numerical simulation. For the mesh generation, the 3D model generated in the Computer Aided Design (CAD) software was imported into the ANSYS ® 2015 program were tetrahedral elements was chosen for the mesh. This kind of elements are recommended for complex geometries such as the 3D model built for this study.

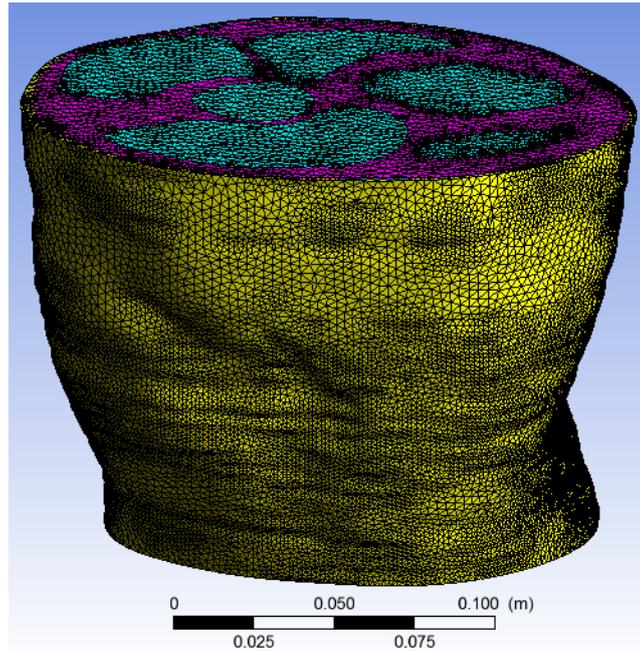


Figure 3- Mesh  
Source: Author

For the selection of the ideal mesh, the simulations were started with coarse meshes that were progressively refined homogeneously. The criterion of selection is that the numerical solution was independent of the mesh with percentage difference smaller than 1% between the results obtained for previous gross mesh and the subsequent refined mesh. As a reference, the mean temperature in the adipose tissue was monitored and the residual RMS error for final convergence in all meshes was of the order of  $10\text{e-}6$ . The mesh parameters obtained for the model can be visualized in Table 3. Among the meshes evaluated, mesh 3 fulfilled the criterion considered for the geometric models of the human knee and for this reason, it was chosen for the accomplishment of the simulations.

Table 3 - Meshes parameters analysed for the mesh test

<i>Mesh</i>	<i>Nodes</i>	<i>Elements</i>	<i>Temperature of Adipose Tissue [°C]</i>
1	75337	350542	33.1
2	95833	451938	33.1
3	169845	819299	33.3
4	245424	1367994	33.3

### 3. RESULTS AND DISCUSSION

The temperature distribution obtained from the numerical simulation is presented in Figure 4. The highest temperature was found in the central region of the knee ( $38.0 \text{ }^\circ\text{C}$ ) in adipose tissue and the minimum temperature was  $29.8 \text{ }^\circ\text{C}$  in the subcutaneous tissue. From the Fig. 4, it can be deduced that the region of the patella corresponds to the

region of lower temperature. Figure 4 presents lines indicating the positioning of the temperatures profiles demonstrated in Fig. 5.

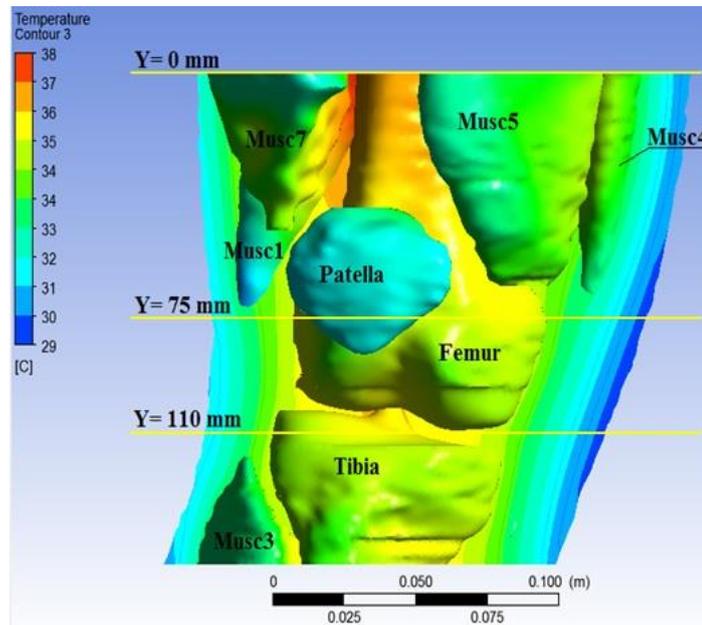


Figure 4 – Temperature distribution in the knee joint  
 Source: Author

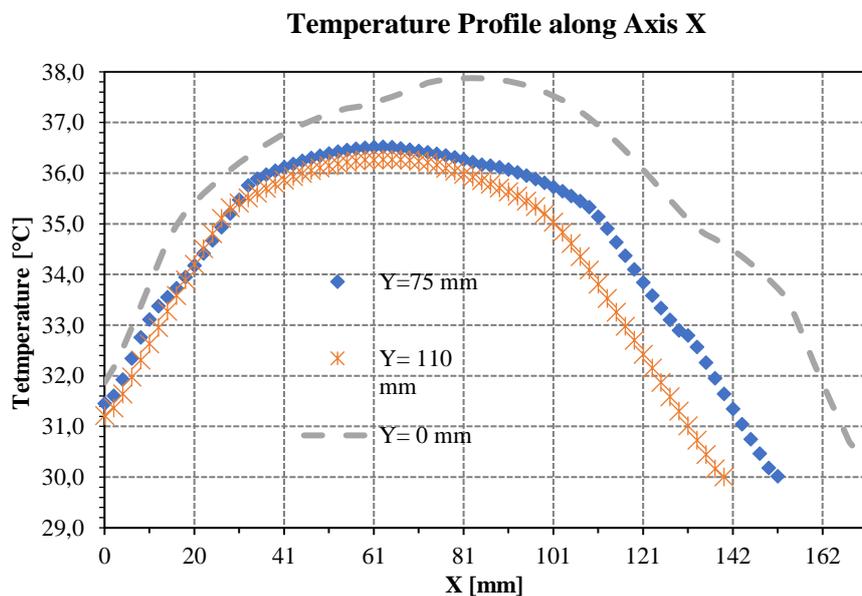


Figure 5 – Temperature profiles  
 Source: Author

Table 4 presents a comparison of these results with data obtained from the literature for similar simulation conditions. The results of the simulation are close to the values presented in the work of Trobec *et al.* (2008) for adipose, muscular and bone tissues. For the skin, there is a difference of 8.9% between the results. According to Xiao *et al.* (2010), the temperature of the skin in the condition of thermal neutrality is between 30.2 and 32.8 ° C. It does not show the temperature of the other tissues. This greater difference found between the temperatures in the skin is due to the different conditions of air temperature and convective coefficient adopted in the three studies: Trobec *et al.* (2008) considers the ambient temperature at 27 ° C and Xiao *et al.* (2010) 22 ° C with convective coefficient of 10 Wm<sup>-2</sup>K<sup>-1</sup>.

Table 4- Comparison of results

<i>Human Tissues</i>	<b>Temperature [°C]</b>		
	<i>Simulation</i>	<i>Trobec et al. (2008)</i>	<i>Xiao et al. (2010)</i>
Bone	35.8	36.0	
Muscle	36.8	36.0	
Skin	31.9	35.0	30.2 -32.8
Adipose	34.8	35.6	

#### 4. CONCLUSION

In this study, it was presented the construction of an anatomical model of human knee joint for a CFD analysis. Also, this research performed a numerical simulation analysis and compared the results of temperature distribution for the subcutaneous, adipose, muscular and bone tissues. The Finite Volume Method was applied to the numerical simulation which was performed for the condition of steady state and the numerical results were compared with numerical data obtained from literature. Although the different conditions adopted for the environment that led to a difference between the temperatures found on the surface of the model, it can be concluded from this analysis, that the results obtained were satisfactory and the application of the finite-volume method can provide adequate solutions to healthcare problems. The 3D geometric model built in this study will serve as base for further studies which topical cooling and warming conditions will be applied to the knee.

#### 5. ACKNOWLEDGEMENTS

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