ANALYSIS TO DETERMINE THE BONE TEMPERATURE DISTRIBUTION DURING THE BONE CUT IN TIBIA OSTEOTOMY SURGERY

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Abstract*. For the bones cut in orthopaedic surgeries, tools as drills and saws are used. The friction between the tool and the bone generates heat, that must be controlled. During the surgical procedure, the bone temperature must be controlled to prevent the bone necrosis due to high temperature, what makes essential the knowledge of the temperature value in the cut region, mainly if the surgery is carried out through the automation aids, such as specially designed robot and saw. To determine the temperature distribution during the bone cut, it is necessary to know the heat flux generated to during the cut process. To calculate the heat flux, some operational parameters of the automatic saw (shear speed and force) and a bone physical parameter (shear tension for both cortical and trabecular sections), must be known. The objective of this paper is to present a model to determine the temperature distribution during the bone cut. To calculate the temperature distribution, the calculated heat flux is used as boundary condition to solve the 2-D and heat conduction transient partial differential equation, in a qualitative way. Simulation results that match literatured findings are presented.*

Keywords*: Mechatronics, Bioengineering, Tibia Osteotomy, Heat Flux, Thermal Necrosis, Bone Temperature Distribution*

1. INTRODUCTION

When machining cutting tools as saws and drills are used, heat is produced, what raises the temperature of the tool and also of the material that is being cut. In orthopaedics, the drilling and cutting tools are frequently used in bone cut, and the heat produced by these procedures might result in thermal necrosis of the bone, according to Lundskog (1972). Due to the fact that the thermal necrosis has a negative impact on the result of a drilling and cutting procedure, the temperature of the bone must be kept below the threshold that results in necrosis.

Within the context of knee orthopaedic surgery, the tibia osteotomy is a surgical procedure implemented in three stages: surgery planning (image capitation and registration); surgical cut (1^{st} and 2^{nd} cut); and realignment. The focus of this paper is at the surgical cutting stage, because it is during this stage that the heat - which raises the bone temperature - is generated. The heat flux is caused by the friction between the cutting tool (saw) and the working piece (bone). And

In order to maintain the bone temperature below the threshold that results in necrosis, it is necessary to determine the temperature distribution during the cut, and, for that reason, the heat generated due to the saw/bone friction must be determined. To calculate the heat flux, some operational parameters of the robotic equipment, such as cutting speed and force of the tool as well as the bone shear tension (for both cortical and trabecular sections) must be known.

This paper presents a model to determine the temperature distribution during the bone cut. To calculate the temperature distribution, the calculated heat flux is used as boundary condition to solve the 2-D and heat conduction transient partial differential equation, in a qualitative way.

2. STRUCTURE AND PROPRIETIES OF THE BONE TISSUE

The human skeleton is composed mostly of bone tissue, the most resistant tissue of the human body that performs the following mechanics and dynamics functions in a healthy body: sustentation of the mass index, protection from the external solicitations, locomotion, besides the fact it is the repository of calcium and cells, according to Shimano (1994). The bone tissue is composed of collagen fibers and organic components. It may be distinguished basically two types of bone tissue: the trabecular or spongy and the cortical, as shown in Fig. 1.

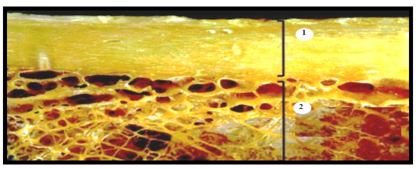

Figure 1. Components of the bone tissue where 1 – Cortical Bone and 2 – Trabecular Bone

The cortical bone composes 80% of the skeleton: it is hard, dense and is the external part of many bones and the body of long bones. According to Rodrigues (2003), it has a porosity considered low, from 5 to 30%; it is rigorous, compact and contains microscopic vascular canals connected.

The spongy bone composes 20% of the skeleton. It is a highly porous structure found in vertebral bodies and at the final end of the long bones. According to Rodrigues (2003), it has a porosity considered high, from 30 to 90%; it is composed of a net of trabeculas interconnected with empty spaces filled by the bone marrow. The bones are classified basically in four types: long, short, flat and irregular. The bone analyzed herein is the tibia, classified as long.

One of the types of tibia osteotomy surgery is done at the end of the tibia, also called epiphysis. This region has as characteristic to be composed, in its central part, with trabecular bone with a thin external layer of cortical bone. The bone presents many structural variations, what makes it more difficult to make an accurate geometrical analysis. For that reason, in this paper, the bone was considered as being a non porous cylinder, with 0.05m of diameter, composed of a trabecular region with a diameter of 0.047m and a cortical region with thickness of 0.0015m, as shown in Fig. 2.

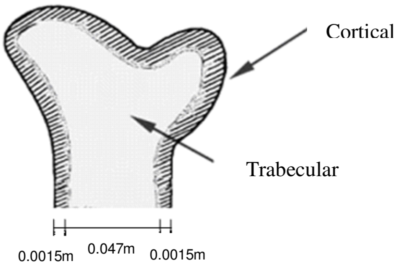

Figure 2. Bone geometry (cortical and trabecular)

According to Shimano (2001), the bone tissue is an anisotropic material, i.e. its mechanical characteristics vary, depending on the direction of the application of the load. The bone is also viscoelastic, which means it responds in different ways depending on the speed in which the load is applied and the duration of the load.

In this paper, the average values of the characteristics needed for modeling purposes are used: this a simplifying hypothesis, adopted in a primary analysis. Thus, the bone is ideally considered a homogeneous and isotropic material. This supposition was also based on recent experiments from David *et al.* (2000) that investigated some peculiarities of the bone and showed characteristic variations of no more than 10% in different directions.

The bone characteristic necessary for the formulation of the problem is the tension of the shear of the cortical bone, 45.000.000 Pa and from the trabecular bone, 1.000.000 Pa. These values were obtained by James *et al.* (2003) through experimental tests. After presenting the bone characteristics, the cutting procedure is detailed as follows.

2.1. Cutting Procedure

The cutting procedure is illustrated in Fig. 3. The tool blades move with the progress speed (v_a) and rotational or angular speed (v_r) through the working material (bone), removing a layer of the material (bone). It has been considered that the cutting procedure is executed in a single pass of the tool through the bone. This explains why the dimension of the saw is bigger than the bone's.

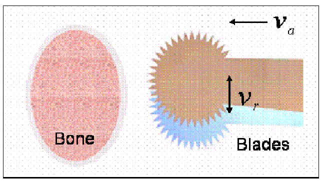

Figure 3. Cutting procedure

In order to formulate the problem, it is convenient divide the cutting procedure in four stages, as depicted in Fig. 4. At the first stage, the saw is positioned to begin the cut. At the second stage, the saw cuts through the cortical bone, only. Then, at the third stage, the saw travels through the cortical bone region, where the blades hit the trabecular part and then both, trabecular and cortical sections of the bone. Finally, at the fourth and last stage, there is only cortical bone to be cut.

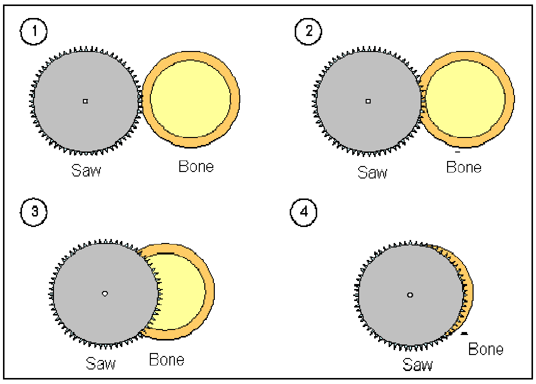

Figure 4. A four stage cutting procedure

2.2. Discretization of Bi-Dimensional Transient Heat Conduction Formulation in Finite Differences Approximation

The operational parameters of the automatic saw that directly affect the bone temperature increases during the surgical procedure are the saw forward speed and blades semi-rotational velocity. Knowing the bone temperature during the cut procedure a strategy of control these parameters can be developed to prevent the bone necrosis due to high temperature and reduce the patient time recovery.

Hence, the bone temperature must be determined using heat transfer equations. The different forms of heat transfer (conduction, convection and radiation) have common and differentiated characteristics. Basically, all heat transfer process occurs based on the matter temperature differences; and when it is happens, the heat propagate in lower temperatures directions. The differences between the heat transfer forms are the physical mechanisms of propagation and the laws by which they are governed.

In this work it was considered as preponderant, the conduction heat transfer (diffusion) that occurs when the heat is transferred between particles by microscopic transport of energy due to the temperature gradients in the continuum media, there is no macroscopic movement in the medium (convection), because no mass transport, according to Incropera (2003). The convection would be considered to study the influence of the environment in which the bone will be exposed. In the present work, the temperature of the environment (surgical room) is considered constant and without air movement.

The problem was considered, as simplifying hypothesis, bi-dimensional, with transient heat conduction, because the temperature vary at each point with the time as show on the left hand side of Eq. (1).

According to Incropera (2003), the govern equation of bi-dimensional diffusion, under transient conditions, with constant properties and without internal energy generation, as follows:

$$\rho.c_p.\frac{\partial T}{\partial t} = k.\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{1}$$

where: ρ is the density; c_p is the specific heat; T is the temperature; t is time; k is the thermal conductivity.

According described below, the bone in this analyses was ideally considered a homogeneous and isotropic material (heat conduction constant independent of the load is applied direction).

The thermal conductive was used to determine the thermal diffusion. According to Incropera (2003), thermal diffusivity (α) measure the material capacity to conduct thermal energy in relation of its storage capacity. Materials with high thermal diffusivity change quickly the thermal conditions imposed to it, otherwise this change was slowly and needs more time to reach a new equilibrium condition. The thermal diffusivity is calculated as:

$$\alpha = \frac{k}{\rho.c_p} \tag{2}$$

From the thermal diffusivity definition, the diffusion equation - Eq. (1) - can be re-writing as:

$$\frac{1}{\alpha}.\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{g}{k} \tag{3}$$

The solution of the PDE – Eq. (3) - is obtained by numerical procedure using discretization methods to calculate the PDE in a discrete domain represented by a 2D computational grid.

In this work, an explicit method based on the finite-differences is used Incropera, (2003). This numerical method is vastly used in the heat transfer problems.

The nodal points at the grid domain are represented by indicial notation to each direction. The notation i and j are used to represent the x and y coordinates, respectively. Thus, the conduction heat transfer equations should be discretized in space and time.

According to Incropera (2003), the variable n is used to denote the time-step, in which the temperature (T) is calculated for each time. The time derivative is represented in terms of differences associated with the time $(n+1)$ and (n). The calculation is performed in successive time interval of Δt.

The explicit discretization of the Eq. (3), based on finite-difference approximation, to an internal node i, j is given by:

$$\frac{1}{\alpha}.\frac{T_{i,j}^{n+1}-T_{i,j}^{n}}{\Delta t}=\frac{T_{i+1,j}^{n}+T_{i-1,j}^{n}-2T_{i,j}^{n}}{(\Delta x)^2}+\frac{T_{i,j+1}^{n}+T_{i,j-1}^{n}-2T_{i,j}^{n}}{(\Delta y)^2}+g \tag{4}$$

Knowing the temperature at time $t=0 \quad (n=0)$ and the initial condition, the calculation start in $t=\Delta t \quad (n=1)$, in which the Eq. (4) is applied at each node to determine its temperature. After the determination of the temperature at time $t=\Delta t$, the second time integration is applied at time $t=2\Delta t \quad (n=2)$. The calculations are performed iteratively within this process successively.

According to Fortuna (2001), the time integration for transient problems can be solved by explicit form due to the accuracy, numerical stability of the PDE and the physical aspects of the heat transfer in this regime. Implicit methods as Crank-Nicholson (semi-implicit), Adams-Bashfort, and others (Fortuna, 2001) can be used too, but with small time-steps. Implicit methods are unconditionally stable and explicit methods are conditionally stable. But, to transient problems the time-step that the physical process occurs should be analyzed. Equilibrium problems present a very fast convergence rate using implicit methods.

It is very important to mention that both numerical schemes are highly dependent of the grid quality. Transient problems are very sensible with the initial values. If the initial values are incorrect, certainly the results will be not correct.

The stability of the explicit method used in this work is evaluated by the Fourier number. This parameter will be monitored to guarantee the numerical stability. The Fourier number is determined in the Cartesian coordinates, x and y by:

$$Fo_x=\frac{\alpha.\Delta t}{(\Delta x)^2} \tag{5}$$

$$Fo_y=\frac{\alpha.\Delta t}{(\Delta y)^2} \tag{6}$$

According to Fortuna (2001), the oscillations and instability causes numerical divergence. To avoid this problem the Δt value should be maintained lower than a certain limit that depends on the grid. This dependence is called stability criteria. According to Incropera (2003), in 2D problems, the stability criterion is satisfied if:

$$Fo\leq\frac{1}{4} \tag{7}$$

2.3. Boundary Condition Determination

Defined the numerical method to be used, it is necessary to determine the boundary condition to solve the PDE.

The problem formulation is state as follows:

- ✓ Which is the heat flux generated by the saw blade for a determined set of cutting parameters?
- ✓ Which percentage of this heat is transferred to the bone?
- ✓ For the heat flux generated, how the temperature changes with the time and saw displacement in the bone?

The boundary conditions are obtained from the answers of the first and second questions and the bone temperature is obtained by the answer of the third question.

All details of boundary conditions implementations are described in work of Hyppolito (2007).

2.3.1. Determination of the Heat Flux Generated by the Cutting Process

To answer the first questions it is necessary to first investigate the structure and proprieties of the bone tissue and after that the heat flux generated by the cut process was determined.

Part of the necessary energy for bone shearing is converted into heat generated by the attrition between the saw blades and the bone. There could be identified two forms of attrition in this process: frontal and lateral.

The frontal attrition is generated by the friction of the frontal part of the saw tooth of the blades with the bone. The lateral attrition is generated by the contact of the lateral (superior and inferior surfaces) between the blade and the bone.

According to Slade *et al.* (2003), the manipulation of the saw by a robot guarantees the cut is done in a superficial and plain way, thus the lateral attrition was not taken into account for the heat generation model.

According to Merehant (1945), almost all the energy used in the removal of the material is converted into heat. The heat generated during the cut may, then, be determined by the magnitude of the mechanical work, calculated, according to James et *al.* (2003), as:

$$\frac{\partial Q}{\partial t} = F_C . v_C \tag{8}$$

where: Q is the heat generated by the cutting action; t is the cutting time; F_C is the shear force; v_C is the shear speed.

2.3.1.1. Shear Speed

To determine the shear speed (v_C) it is necessary to analyze the progress speed (v_a) and the rotation speed (v_r) of the saw. Figure 5 show the vectors that indicate the trajectory of the speeds present in the bone cutting procedure.

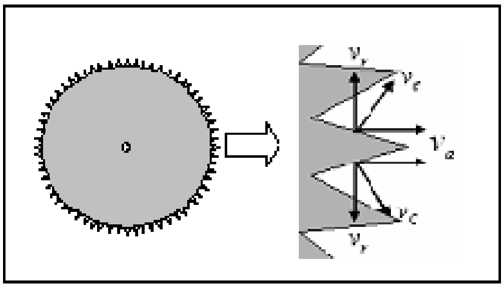

Figure 5. Trajectories procedure stages

The progress and rotation speeds are taken as steady during the cutting process; thus the shear speed is calculated as:

$$v_C = \sqrt{v_a^2 + v_r^2} \tag{9}$$

2.3.1.2. Shear Force

Due to the presence of both regions (cortical and trabecular) constituted of materials with different characteristics, the assessment of the total shear force on the material that is being removed by the cutting tool, has been modeled separately, as follows:

Shear force of the cortical region (F_{Cc}):

$$F_{Cc} = \tau_{Cc} . A_{Cc} \tag{10}$$

where: τ_{Cc} is the shear tension and A_{Cc} is the area of the cortical bone that is being sheared.

Shear force of the trabecular region (F_{Ct}):

$$F_{Ct} = \tau_{Ct}.A_{Ct} \tag{11}$$

where: τ_{Ct} is the shear tension and A_{Ct} is the area of the trabecular bone that is being sheared.

After the determination of the shear forces of the cortical and trabecular regions, the total shear force (F_{CT}) can then be calculated as:

$$F_{CT} = F_{Cc} + F_{Ct} \tag{12}$$

2.3.1.3. Shear Area

Just as the shear force, the assessment of the shear area has been obtained separately for the cortical and trabecular portions. Initially, the total area of the circular sector of the saw that is in contact with the bone has been calculated, as shown in Fig. 6a. Then, this figure is multiplied by the (f) factor, that corresponds to a percentage of the area of all the circular section of the saw. This is a necessary correction, because only the saw teeth of the blade actually shears, see Fig. 6b.

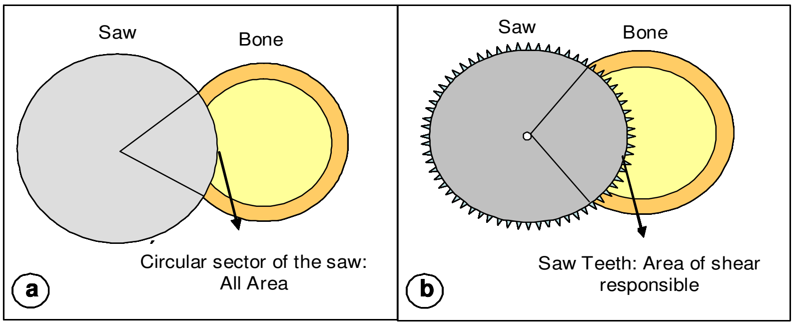

Figure 6. Bone shear area

The shear area of the cortical region (A_{Cc}) is calculated as:

$$A_{Cc} = r_s.\theta_c.e_l.f \tag{13}$$

where: r_s is the radius of the saw; θ_c is the angle of the circular section in relation to the diameter of the cortical bone; e_l is the thickness of the blade; f is the factor that represents the contact area between the blade and the bone.

Similarly, the shear area of the cortical region shear (A_{Ct}) can be obtained as:

$$A_{Ct} = r_s.\theta_t.e_l.f \tag{14}$$

where: θ_t is the angle of the circular section in relation to the diameter of the trabecular bone.

2.3.1.4. Heat Flux Generated in the Bone

The heat generated by the cutting process is conducted through the tool (saw blades); material removed (bone); atmosphere and the working material/piece (bone).

It is extremely difficult to determine the fraction of heat, η, that goes to the bone from the mechanics bases and heat conduction. Alternatively, the empiric approximation was proposed by James *et al.* (2003), and the fraction was determined by comparing the temperatures previewed by the analyses of James *et al.* (2003), with the temperatures measured in five different tests in vivo of the bone perforation, done by Abouzgia (1995). The perforations parameters of these in vivo tests were used as input data for thermal simulations and the values of the maximum temperature were compared. The value of η, found by James et *al.* (2003), that better related the experimental values with the theoretical values was 0.5, the value also used in this paper.

Combining the previous equations, the final equation for the heat flux, Q_w, that goes to the bone during the cutting procedure is:

$$\frac{\partial Q_w}{\partial t} = \eta.\frac{\partial Q}{\partial t} = \eta.A_C.\tau_C.v_C \qquad (15)$$

The heat flux, Q_w, can be calculated as:

$$q = \frac{\partial Q_w}{\partial t}.\frac{\Delta t}{A_{CT}} \qquad (16)$$

where: Δt is the time step (different between cortical and trabecular bones).

2.3.2. Temperature Distribution

To answer the second and third questions the Eq. (3) was used. This equation model the bi-dimensional transient heat conduction using finite differences approximation.

The heat flux through the bone during the cutting procedure, determined in the first question of the problem formulation, was used with source term, responsible for external heat generation.

Hence, it is possible calculate the heat flux generated at each node point, where the temperature vary with time and saw displacement on the bone.

3. RESULTS AND DISCUSSION

In this analysis, the data used for the simulations were: v_a = 0.002 m/s and v_r = 5 rad/s. Afterwards, for others analyses, these speeds can be modified in order to evaluate how they influence the temperature alteration of the bone during the cutting procedure.

Figure 7 show the shear force applied on the trabecular bone due to the displacement of the saw in relation to the bone. It can be observed that from 0 to 0.0015 m and from 0.0485 to 0.05 m there is no force being applied on the trabecular bone as this region is the cortical bone.

The force applied in the 0.0015 to 0.0485 m range has shown the expected behavior: the bigger the area sheared, the bigger the necessary force to shear it.

The highest shearing force on the trabecular bone during the whole cutting procedure was applied on the centre of the bone (0.025m).

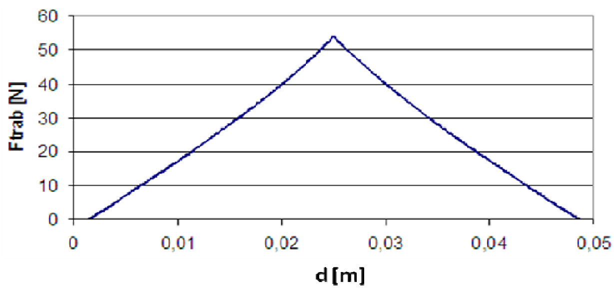

Figure 7. Shear strength on the trabecular bone (F_{trab}) x Displacement on the bone (d)

Figure 8 show the shearing force applied on the cortical bone. Differently from the trabecular, the cortical bone is always in contact with the saw blades, that is why there is force being applied during the whole cutting procedure.

It may be observed that from 0 to 0.0015 m and from 0.0485 to 0.05 m there are two regions where the highest shear force is applied. It happens because this two are the regions where there is only cortical bone, so the area is bigger.

While the cut is getting bigger, until the centre of the bone, the shear strength is reducing, and from the centre of the bone to the end of the cutting procedure it gets higher again. This behavior is due to the reduction of the shear area, followed by a reverse behavior.

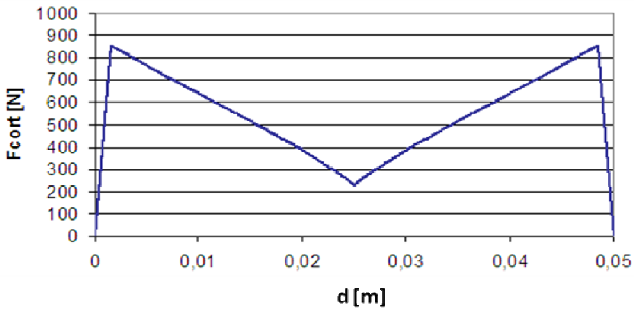

Figure 8. Shear force on the cortical bone (F_{cort}) x Displacement on the bone (d)

Figure 9 show the total shear force due to the displacement of the saw in relation to the bone. This total shear strength is the result of the sum between the shear force on the trabecular bone – Fig. 7 – and the shear force on the cortical bone – Fig. 8.

As it has been pointed out before, one of the principal differences between the two types of bone tissue is that the cortical one is dense and hard whilst the trabecular is tender. These characteristics can be easily visualized on Fig. 9, because the highest force applied during the whole cutting procedure is at the regions where there is only cortical bone. Just as the shear area of the bone gets smaller, the force necessary to shear also gets smaller, getting to its lower value in the middle of the cutting procedure.

The shear area of the trabecular bone has a low influence in the determination of the total cutting strength.

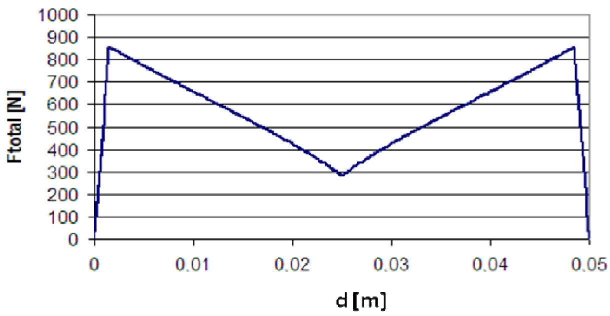

Figure 9. Total shear force (F_{total}) x Displacement on the bone (d)

Figure 10 show the heat flux due to the displacement of the saw in relation to the bone. This heat flux is a result of the frontal attrition of the saw blades with the bone during the cutting procedure.

It may be observed that the highest heat flux was generated in the region where the area of the cortical bone is bigger, as already expected.

The analysis of the heat flux generated in the region where both cortical and trabecular bone are present, it is possible to notice that the bigger the shear area of the trabecular bone and, consequently, the smaller the area of the cortical bone is and, consequently, the heat quantity gets smaller. It occurs due to the fact that the trabecular bone is tender, making the cutting procedure easier and generating lower quantity of heat.

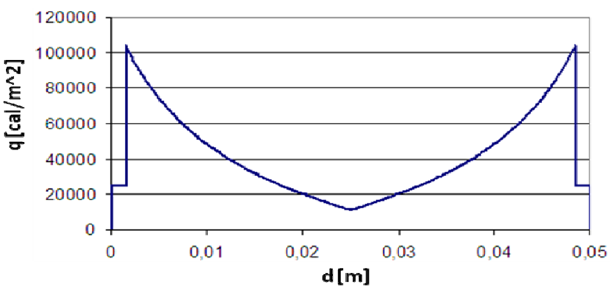

Figure 10. Heat flux (q) x Displacement on the bone (d)

Figure 11 show the results of instantaneous temperature values in the bone during the cutting procedure. Figures 12, 13 and 14 show the temperature gradient in j direction. Note that after saw passage the temperature decrease with the time due to the heat dissipation. To detect the temperature variation with the time experimentally, is necessary to install a lot of temperature sensors along cut region.

The temperature values were different during the cutting procedure due to the cortical and trabecular bones had different physical properties. In this analysis, bone thermal necrosis not occurs because the bone temperature did not exceed 47°C.

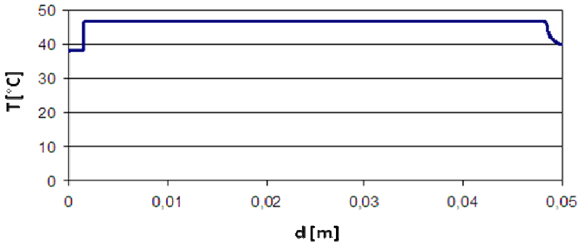

Figure 11. Bone temperature (T) x Displacement on the bone (d)

Figures 12, 13 and 14 show the bone temperature distribution, and the diffusion modeled by equation $\frac{1}{\alpha}.\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{g}{k}$, during surgical procedure.

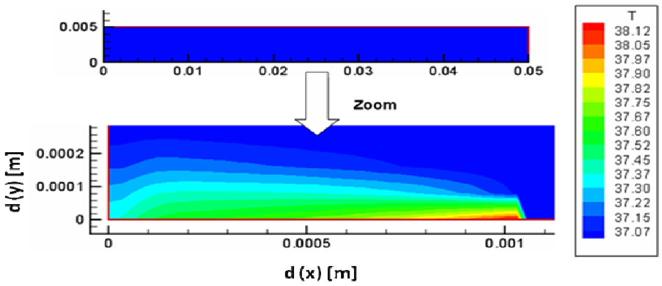

Figure 12. Bone temperature during cortical bone cutting procedure (software Tecplot 8.0)

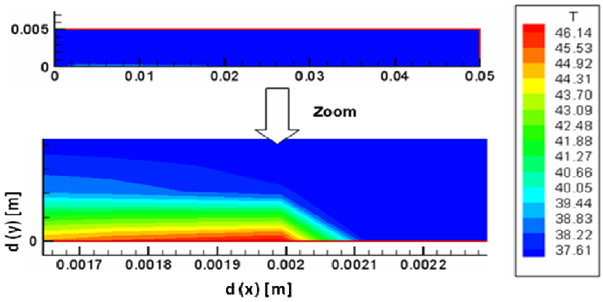

Figure 13. Bone temperature during cortical + trabecular bone cutting procedure (software Tecplot 8.0)

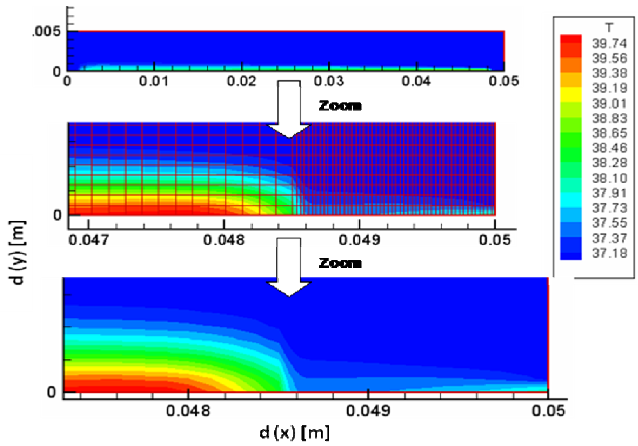

Figure 14. Bone temperature during cortical bone cutting procedure (software Tecplot 8.0)

4. CONCLUSIONS

During the surgery process, the bone temperature should be controlled to avoid thermal necrosis due to the high temperature, mainly if the surgery is performed with automation resources. To determine the model of temperature distribution during the cut phase, it is necessary to know the heat flux generated due to the friction during the cut time interval. To do so, some operational parameters of the robotic equipment the saw is part of should be known. They are: saw forward speed, blades semi-rotational velocity, total cut time; furthermore, some physical properties as the bone thermal conductivity, density, thermal diffusivity and the shear stress should also be known.

Based upon the values of these parameters, this work presented a heat flux saw/bone model during the bone cut process. Later, the calculated heat flux was used as boundary condition to solve the 2-D and the heat conduction transient partial differential equation, in a qualitative way, to determine the temperature distribution.

Finally, by knowing the temperature value along the bone during the cut process, it is possible to predict if the monitored parameter values do not exceed the acceptable limits, avoiding the bone thermal necrosis.

5. ACKNOWLEDGEMENTS

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