3D Finite-Element Modelling of Drilling Cortical Bone: Temperature Analysis

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Abstract

Bone drilling is a key part of major orthopaedic surgeries for fixing fractured bones and replacing damaged joints. One of the main problems in bone drilling is thermal necrosis of tissue, which can occur due to elevated temperatures in the drilling zone. Investigation of the temperatures arising in bone drilling is necessary to analyse the extent of bone necrosis. This paper presents a three-dimensional thermo-mechanical finite-element model of a bone-drilling process to study the effect of drilling parameters (cutting speed and feed rate) and cooling conditions (air and saline solution) on the temperature in drilled bone. The drilling speed was found to have a higher effect compared to that of the feed rate in inducing thermal necrosis in bone for the tested cooling environments. The level of necrosis penetration into bone was strongly affected by the drilling speed and the application of saline cooling (irrigation) in the drilling zone. A considerable extent of necrosis was predicted even at lower drilling speeds when no cooling was used. Drilling experiments were performed on real cortical bone to measure temperatures near the immediate vicinity of the drill. Calculated temperatures were compared with experimental values and were found to be in good agreement with them.

Keywords: Orthopaedics, Bone drilling, Finite element analysis, Thermal necrosis

1. Introduction

Bone drilling is an important orthopaedic procedure widely used in fracture repair and joint implant surgeries. Several studies have been performed to investigate the effect of drilling parameters on the outcome of the process and its effect on bone [1-5]. The major concerns in bone drilling are mechanical and thermal damage (necrosis) of the bone induced by high-speed drills during surgical procedures. Necrotic tissue may cause weakening of fixative devices anchored to the bone and related post-operative complications [6]. Despite the technological advancement in orthopaedic surgical procedures, mechanical rotary drills are still widely used in clinical practice. A detailed review of the bone drilling process was presented by Pandey and Panda [7].

The magnitude and time of exposure to elevated temperatures determine the onset and extent of thermal necrosis and related abnormal changes in bone properties [3]. Necrosis of bone tissue was reported to depend on the duration of exposure [8,9]. Since elevated temperatures and subsequent bone damage have a negative impact on the outcome of the surgical procedure, it is recommended to keep bone temperature well below its threshold level. However, temperature measurement in the cutting region during bone drilling is a challenging task. Researchers have used thermocouples and thermal imaging systems to asses temperatures during bone drilling [2,3,10-13]. A comprehensive review of the parameters and data acquisition techniques used in a bone-drilling process has been published [8].

Previous studies investigated the thermal response of bone to cutting using two-dimensional finite element (FE) models [14-16]. In a recent study [11], a three-dimensional bone-drilling process was modeled using finite elements based on a bone analogue. Another study [17] analysed temperature during the drilling of cortical bone (compact bone found in the middle portion of a femur or tibia) for various parameters using the FE method without simulating chip formation. However, no research work has simulated the temperature in bone using a three-dimensional FE model of the drilling process and accounting for cooling conditions. FE simulations based on validated models of such processes could potentially reduce the experimental effort necessary for the optimisation of the cutting procedures and, hence, diminish the exposure of operators and researchers to biohazards (bone drilling produces small chips) and the costs associated with experiments. This paper presents a realistic three-dimensional thermo-mechanically coupled FE model that incorporates in-house measured properties of cortical

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bone. The FE model was used to investigate the effect of drilling parameters, namely drilling speed and feed rate, on the thermal behaviour of the cortical bone tissue. In the numerical model, the monitoring of temperatures in the drilled bone tissue and the avoidance of thermal injury by diligent cooling were the focus. Experiments on bone drilling were also conducted to validate the developed FE model.

2. Methods

A fully thermo-mechanically coupled FE model of the bone drilling process was developed using FE analysis software Marc (MSC Software, Los Angeles). Cortical bone was modeled as a cylindrical workpiece with a 10-mm diameter and a 6-mm height. A conical groove with dimensions similar to those of the drill tip was modeled to avoid the crushing of the material when the drill started penetrating the bone. The drill was modeled with a helix angle of 23° and a point angle of 120°, reflecting the shape of the bit used in the experiments, and was assumed to be a rigid body since its stiffness is much higher than that of bone. The developed FE model comprising the workpiece (bone) and the drill is shown in Fig. 1. The workpiece was meshed with around ten thousand tetrahedral elements. In the simulations, the workpiece was re-meshed to generate regular-shape elements from those distorted during a high-deformation process. The FE mesh of the workpiece before and after re-meshing is shown in Fig. 2.

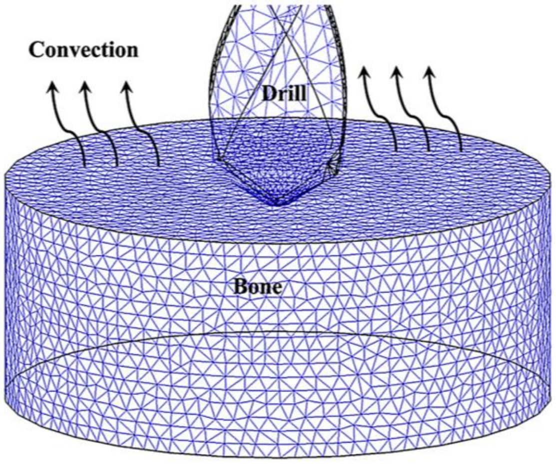
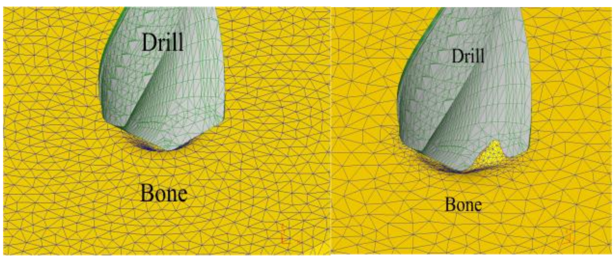


Figure 1. Finite-element model of bone drilling with cooling environment



(a) (b)

Figure 2. Finite-element model of bone drilling: (a) mesh before cutting; (b) results of re-meshing between simulation steps after cutting started.

The anisotropic and heterogeneous structure of the cortical bone tissue was approximated as an isotropic equivalent homogeneous material due to the relatively low mechanical anisotropy of the cortical tissue [18] and the relatively small dimensions (compared with those of the model) of the bone's constituents. Nanoindentation tests on bone microstructure were performed to measure the elastic moduli of osteonal and interstitial bone tissues. The required elastic moduli of the constituents were then calculated from the unloading force-displacement curves obtained from nanoindentation. The reduced modulus E_{r}, which depends on the deformation of the tested material and the type of indenter, was calculated using a traditional expression:

$$\frac{1}{E_{\mathrm{r}}}=\frac{1-\nu_{\mathrm{bone}}^{2}}{E_{\mathrm{bone}}}+\frac{1-\nu_{\mathrm{i}}^{2}}{E_{\mathrm{i}}} \tag{1}$$

where the subscripts 'bone' and 'i' represent the parameters of bone and the indenter, respectively. The elastic modulus of bone was calculated using Eq. (1) for the tests that used a standard Berkovich diamond indenter. To calculate the effective elastic modulus, a total of 40 indents were made (20 indents each in the osteonal and interstitial matrix areas). The rule of mixtures was applied to approximate the effective elastic modulus of the equivalent homogeneous material. Table 1 shows the properties of cortical bone used in the FE model; the thermal properties and density of cortical bone were taken from the literature.

Table 1. Material properties of cortical bone used in drilling simulations.

Property	Value	Source
Effective elastic modulus (GPa)	20.0	Calculated
Thermal conductivity (W/m·K)	0.54	[4]
Specific heat (J/kg·K)	1260	[4]
Density (kg/m^3)	2.26×10^3	[19]

The Johnson-Cook (JC) material model, which is primarily used for the machining of metals and incorporates strain-rate-dependent material properties, was utilised in the FE model. The JC model has already been successfully applied in two-dimensional FE bone cutting models [14,15]; it has the following form:

$$\sigma_{Y}=\left(A+B\varepsilon_{\mathrm{p}}^{n}\right)\left(1+C\ln\left(\frac{\dot{\varepsilon}_{\mathrm{p}}}{\dot{\varepsilon}_{\mathrm{o}}}\right)\right) \tag{2}$$

where *A*, *B*, *C*, and *n* are constants and ε_{p}, $\dot{\varepsilon}$, and $\dot{\varepsilon}_{\mathrm{o}}$ are the plastic strain, effective plastic strain rate, and reference strain rate, respectively. The term of the JC model involving temperature was neglected in Eq. (2) as no data was available on temperature-dependent plasticity for cortical bone tissue; the allowed temperature excursions, limited by the onset of thermal necrosis, are relatively small. Tension tests were performed to quantify the post-yield behaviour and strain rate sensitivity of cortical bone using dog-bone-shaped specimens, as advised by the standard. The specimens used in tension tests were excised from the middle diaphysis (cortical bone) of a bovine femur. The constants of the JC model used in simulations were obtained from previous tests [14]. A total of thirty specimens were tested at three strain rates (0.00001/s, 0.001/s, and 1/s),

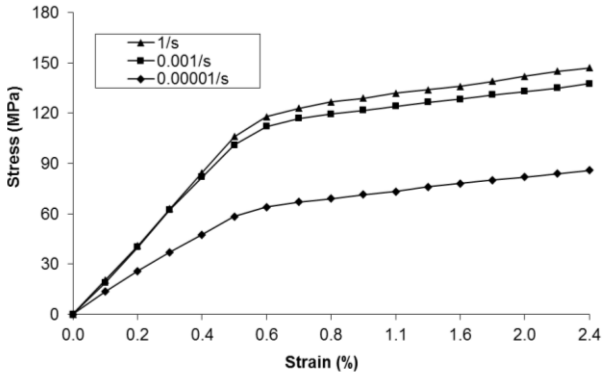


Figure 3. Elastic-plastic material behaviour of cortical bone with strain-rate dependency.

with 10 samples for each strain rate. Figure 3 shows the obtained test results indicating the strain rate dependency of the bone material. The JC constants were fitted to the stress-strain graphs obtained from the tensile tests of bone specimens. The maximum stress obtained for cortical bone in the tension test (140 MPa) was assigned as a criterion for material separation ahead of the drill's cutting edges.

Table 2 presents the drilling parameters used in our numerical simulations of the bone drilling process. The magnitudes for drilling speed and feed rate were varied over ranges widely reported in the literature for the drilling of bone [2,3]. The initial temperature of the bone was set as 37 ℃ to reflect the *in vivo* thermal conditions of bone. In surgical bone drilling procedures, bone is cooled by applying saline solution to the cutting region to avoid overheating of bone and carrying bone chips away from that region. Three cooling conditions were considered in the FE model: (i) no cooling (denoted as h_0); (ii) free convective cooling by air (h_air), and (iii) cooling by saline solution (h_saline). Convection heat transfer was applied to the mesh domain of the workpiece to simulate the cooling effect of air and saline solution (see Fig. 1). Dynamic analysis was used with the simulation interval subdivided into 1,000 time increments of 1.25×10^{-6} s. Each simulation took about four hours to execute on a workstation with an Intel Core i5 3.5-GHz CPU and 4 GB of RAM.

Table 2. Parameters used in bone-drilling simulations.

Parameter	Value
Drilling speed (rpm)	1000-4000
Drill diameter (mm)	4
Drill cutting edge angle (degrees)	65
Feed rate (mm/min)	10-50
Coefficient of friction, μ [20]	0.3
Initial temperature of bone (℃)	37
Convection heat transfer, h_air (W/m^{2}K)	20
Irrigation, h_saline (W/m^{2}K) [21]	8000

3. Validation of FE model

Before the implementation of the main program for numerical simulations, the developed FE model was validated using experimental data obtained for a drill speed of 2500 rpm. The drilling experiments were performed on a fresh bovine femur using a vertical drilling machine with multiple speeds. The average wall thickness of the cortical bone was 9 mm. The

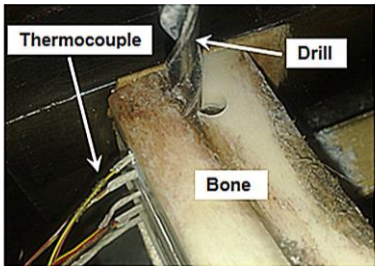


Figure 4. Experimental setup for temperature measurements in bone drilling.

experimental setup for bone drilling with a thermocouple embedded in the bone specimen is shown in Fig. 4. The experiments were conducted without applying cooling (irrigation) at the drilling zone. The initial temperature of the bone specimen was measured to be 25 ℃. Hence, additional simulations were run with this initial temperature of bone for comparison. Before the experiments, 10-mm-deep holes were drilled in the bone specimens with a 1.5-mm high-speed steel drill for the placement of thermocouples. Standard K-type thermocouples were embedded in the bone sample so that their end was at a distance of approximately 0.5 mm from the drilling track. Temperature values were recorded at a drilling depth of 7 mm from the top surface of the specimen using a digital data logger system (FMSDL48 Glasgow, UK). The drill whose specifications are shown in Table 2 was used in the drilling experiments. The results of simulations demonstrated a good agreement with the test results. The calculated temperature was 56 ℃ and the average measured value was 51 ℃ (see Fig. 5).

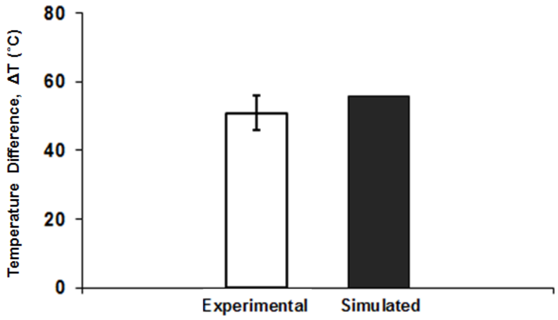


Figure 5. Comparison of experimental and simulated temperatures (drill speed: 2500 rpm, feed rate: 50 mm/min).

4. Results and discussion

The FE model assumed the formation of a continuous chip similar to those observed in high-speed filming experiments of bone drilling [22] and reported elsewhere [23,24]. After the initial engagement of the drill with the bone, the temperature increased with time and attained almost a constant value when the drill lips were in full contact with the workpiece. Temperature distributions at the start of chip formation and when the drill lips were fully engaged with the bone are shown in Fig. 6. Depending on the exposure time, the average temperature reported in the literature for necrosis threshold is 47-70 ℃ [8]. This study considered 70 ℃ as the thermal necrosis threshold for the studied bone tissue. In simulations, the temperature values were measured in the bone adjacent to

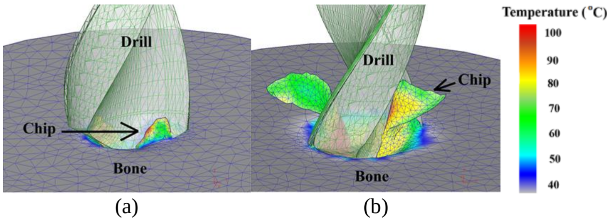


Figure 6. Close-up view of the temperature distribution in the drilling zone: (a) initial engagement stage; (b) full engagement of drill (drill speed - 2500 rpm, feed rate - 50 mm/min).

the cutting edges (lips) of the drill. The temperature increased linearly when the drill started penetrating the bone specimen and stabilized when the chip had fully developed and the drill-chip contact length had attained a constant value. Each data point in the subsequent plots represents the maximum temperature calculated after the chip had fully separated from the workpiece.

The three cooling conditions described earlier were used to study the effect of drilling speed on the temperature values in the drilled bone. The feed rate was fixed at 50 mm/min for this comparison. In the subsequent plots, ΔT represents a rise in bone temperature above its initial temperature of 37 ℃. The maximum bone temperature was found to increase with increasing drilling speed, as shown in Fig. 7. The reason for the temperature rise with drilling speed is an increase in the rate of the irreversible deformation of the cut material (bone). A maximum temperature rise of 86 ℃ was obtained for a drilling speed of 4000 rpm without saline cooling (irrigation). An increase of 49 ℃ was obtained with cooling by saline solution for this drilling speed.

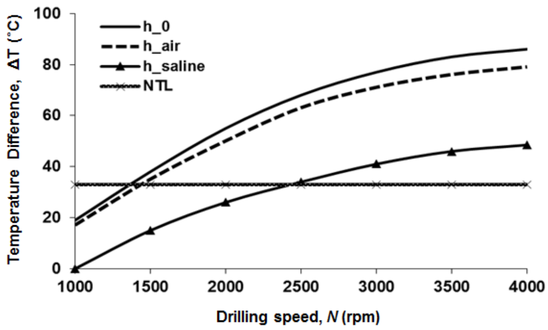


Figure 7. Effect of drilling speed on maximum temperature in bone for three cooling environments (feed rate: 50 mm/min).

Cooling with air did not reduce the maximum temperature for the range of drilling speeds used in this study. Without cooling, the thermal necrosis threshold (ΔT = 33 ℃) was reached at a drilling speed of around 1500 rpm, whereas with cooling with saline solution, the calculated temperatures were well below the necrosis threshold for drilling speeds below 2500 rpm. This response was expected since most of the heat generated in the drilling zone was taken away by the coolant. At drilling speeds above 2500 rpm, the threshold was reached for all cooling conditions studied with the FE model.

The effect of feed rate on the temperature was also analyzed. To study this effect, the drilling speed was fixed at 2500 rpm. The temperature was found to vary linearly with the feed rate, as shown in Fig. 8. In the absence of a cooling environment, the calculated temperature increased from 60 ℃ to 68 ℃ when the feed rate was changed from 10 to 50 mm/min. Similarly, for the same increase in the feed rate, an increase from 23 ℃ to 36 ℃ was obtained when the saline solution was used as a coolant (see Fig. 8). The reason behind the insignificant rise in bone temperature with feed rate as compared to that for drilling speed is due to the feed rate's minimal contribution to the rate of material deformation during drilling, which is a major factor for inducing higher temperatures. With the application of saline cooling, the temperature increase was diminished almost by 50% for the highest feed rate used in the simulations. The necrosis threshold was reached in simulations for all values of feed rate when either no cooling or convection by the surrounding air was considered.

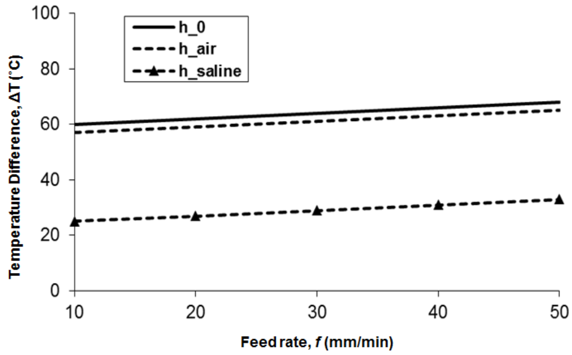


Figure 8. Effect of feed rate on temperature for three cooling environments (drill speed: 2500 rpm).

The effect of drilling speed and cooling conditions on necrosis penetration into bone material was also studied. Necrosis penetration refers to the size (in micrometers) of the area in bone around the drill where the necrosis threshold is reached. The depth at which the thermal necrosis threshold (ΔT = 33°C) was reached around the cut surface is shown in Fig. 9 for various conditions. The necrosis values for the various drilling conditions were calculated when the chip had been fully generated and the temperature values had stabilized. The depth of thermal necrosis was observed to be strongly affected by the drilling speed and cooling conditions. Necrosis penetration was found to increase with increasing drilling speed and to decrease significantly when the bone was cooled by saline solution. Interestingly, necrosis penetration was observed for drilling speeds above 2500 rpm even in the presence of saline cooling.

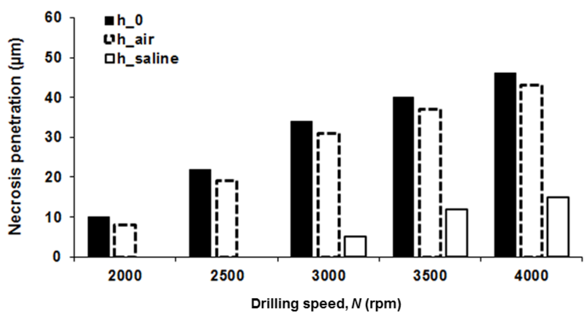


Figure 9. Effect of drilling speed on depth of thermal necrosis for three cooling environments (feed rate: 50 mm/min).

A comparison of experimental and simulation temperatures in bone during the drilling operation is presented in Table 3. Here, the values represent the rise in bone temperature above the initial set temperature of 25 ℃ both in the experiments and FE simulations. For the experimental temperature measurements, five tests were performed for each level of drilling speed. The standard deviation in the measured values obtained from experiments is also presented in Table 3. The bone temperature increased with drilling speed, as predicted by the FE model. In addition, the temperature predicted in the simulations has the same trend as that obtained in the drilling experiments. The FE model predicted thermal necrosis for a drilling speed of approximately 1700 rpm, which was within a standard deviation of the experimental results. The difference between the experimental and numerical results may be attributed to the assumptions employed in the FE model as well as limitations in the experimental measurements.

Table 3. Comparison of measured and simulated temperatures during bone drilling with no cooling (SD: standard deviation; FEA: finite element analysis).

Drilling speed (rpm)	**Rise in Temperature (℃)**		
	Experimental		**FEA**
	Mean (SD)	**[Range]**	
1000	8.2 (5.81)	[3-18]	7
1500	23.4 (4.72)	[17-28]	26
2000	35.4 (4.4)	[31-42]	43
2500	51.6 (4.39)	[46-56]	56
3000	60.2 (3.42)	[58-65]	65
3500	62.6 (5.46)	[58-72]	71
4000	69.8 (5.63)	[63-78]	74

5. Conclusion

Measurements of bone drilling temperature are crucial for the prevention of thermal necrosis, which detrimentally affects bone regeneration. A three-dimensional thermo-mechanically coupled FE model of bone drilling was developed to predict temperature evolution in bone for various drilling parameters and cooling conditions. Higher levels of drilling speed and feed rate were found to increase thermal necrosis in the bone tissue. By employing saline solution as a coolant in the drilling zone, higher drilling speeds and feed rates may be used without inducing thermal necrosis in bone. With cooling with saline solution, drilling speeds of up to 2500 rpm were found to be safe, causing no thermal necrosis in bone. Necrosis penetration into bone was found to be strongly affected by the drilling speed and cooling conditions. The temperatures calculated using the developed FE model agree well with the experimental results.

The use of optimal drilling parameters will help to avoid thermal injury to bone, improving bone regeneration near the implantation site. Based on the numerical results, appropriate magnitudes of the drilling parameters and an efficient cooling system should be used to prevent necrosis of bone tissue. Advanced cooling systems, which incorporate thermocouples and cooling channels within the drill bit, may be used to prevent overheating in the drilling region of bone.

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