Effects of Drilling Parameters in Numerical Simulation to the Bone Temperature Elevation

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Abstract. Drilling into the bone can produce significant amount of heat which can cause bone necrosis. Understanding the drilling parameters influence to the heat generation is necessary to prevent thermal necrosis to the bone. The aim of this study is to investigate the influence of drilling parameters on bone temperature elevation. Drilling simulations of various combinations of drill bit diameter, rotational speed and feed rate were performed using finite element software DEFORM-3D. Full-factorial design of experiments (DOE) and two way analysis of variance (ANOVA) were utilised to examine the effect of drilling parameters and their interaction influence on the bone temperature. The maximum bone temperature elevation of 58% was demonstrated within the range in this study. Feed rate was found to be the main parameter to influence the bone temperature elevation during the drilling process followed by drill diameter and rotational speed. The interaction between drill bit diameter and feed rate was found to be significantly influence the bone temperature. It is discovered that the use of low rotational speed, small drill bit diameter and high feed rate are able to minimize the elevation of bone temperature for safer surgical operations.

INTRODUCTION

Bone drilling is a compulsory process when installing fixators, plates and screws in the fractured bones. Frictional heat generated from interaction of drill bit and bone can cause thermal necrosis to the bone. Majority of the researchers concluded that the critical temperature for thermal necrosis is 47 °C with one minute exposure time [1]. Drilling parameters and designs are known to significantly influence the heat generation process during bone drilling.

The influences of drill bit diameter, feed rate and rotational speed on bone temperature elevation during bone drilling are still unclear. For example, increasing in the drill bit diameter was discovered to cause the increase in bone temperature rise because of the high friction energy and large contact area [2,3]. Conversely, Lee et al. [4] revealed that larger drill bit diameter effectively clear the bone debris during the drilling process and hence reduce the rise of bone temperature elevation. On the other hand, Albertini et al. [5] unveiled that the drill bit diameter had insignificant influence on the bone temperature elevation. Higher feed rate was discovered to decrease the bone temperature rise [6]. However, others revealed that bone temperatures directly increase with feed rates [7]. High rotational speeds were recommended to ensure the minimum elevation of bone temperature [8]. By contrast, [9] demonstrated that temperature rise were directly proportional to the increase in rotational speed. However, other researcher failed to discover any significant effect of rotational speed on bone temperature rise [10]. These contradictory findings had been a huge motivation to determine the relationship between rotational speed, feed rate and drill bit diameter with bone temperature elevation.

The aim of our study is to better understand how the different drill diameters, rotational speeds and feed rates influence the maximum bone temperatures generated in the drilling sites during bone drilling. The present study utilizes finite element method (FEM) to simulate the actual bone drilling process and measures the bone temperatures.

MATERIAL AND METHOD

We compared the simulations values with the experimental data of Hillery and Shuaib [11] and calculated the relative error between both studies. The drilling parameters used for the validation are listed in Table 1.

TABLE 1. Drilling conditions for validation study

Parameters	Value
Room temperature (°C)	26
Depth of cut (mm)	3 and 6
Rotational speed (rev/min)	400
Feed rate (mm/min)	50
Drill bit diameter (mm)	3.2

In this study, bone was considered as thermally isotropic. Figure 1 shows a human femur bone model (16 mm diameter and 5.5 mm thickness) and stainless steel drill bit were created with the FEM software. The drill bit point (118°) and helix (28°) angle were designed according to suggestions from previous literature. Since there was no material library for human bone in the simulation software (DEFORM-3D), the biomechanical properties of human cortical bone listed in Table 2 were fed into the software database manually.

TABLE 2. Properties of human cortical bone [11-13]

Properties	Value
Density (kg/m^3)	2100
Young's modulus (GPa)	17
Poisson's ratio	0.4
Specific heat (J/ (kg K))	1260
Thermal conductivity (W/(m K))	0.38

The relationship of bone model and drill bit are considered as plastic-rigid body during the drilling simulation which assumes that the stress is increased along with the strain rate until a critical strain rate which the bone deformed plastically. When ultimate stress, σ_{ult} is exceeded, the bone will be broken. The default empirical law of visco-plasticity model (Equation (1)) in the software was utilized to describe the human bone behavior. From Equation (1), σ is the stress, ε_p is the plastic strain, $\acute{\varepsilon}_p$ is the plastic strain rate, T is the temperature and T_o is the room temperature. The coefficients were depicted by *y, r, m, n* and *c*. To simulate a fast drilling and large-scale deformation process, a simple linear shear friction model was used where $f_s = m.k$ is the shear friction, *m* is the friction factor and *k* is the shear yield stress. Friction factor of 0.3 was used in this study. Meshing of the bone model and drill bit is crucial to conduct the finite element analysis of drilling simulation. The bone and drill bit model were meshed with tetrahedral elements with length of 0.05 mm to obtain high-mesh density, as shown in Figure 2.

$$\sigma(\varepsilon_p, \dot{\varepsilon}_p, T) = c.\varepsilon_p^n.\varepsilon_p^m.\left(\frac{T}{T_0}\right)^{-r} + y \quad (1)$$

The study of bone drilling is a complex process. Study of the effect of main parameters and their interactions are important. For this reason, our study applied the systematic method of design of experiments (DOE) to ensure accurate and precise estimation of the effect of selected drilling parameters. In this study, 3 drilling parameters with 3 levels with no repetition were selected. The levels of drilling process parameters were selected based on previous investigations. The drilling process parameters that were selected (drill diameter, rotational speed and feed rate) are presented in Table 3.

TABLE 3. Drilling parameters and level selected for FEM study

Drilling parameter	Symbol	Level 1	Level 2	Level 3
Drill diameter (mm)	D	2	8	13
Rotational speed	N	750	1500	3000
Feed rate (mm/rev)	F	0.038	0.076	0.203

In this study, we measured the maximum temperatures recorded during bone drilling process to examine the effect of selected drilling parameters to the temperatures elevation. Two-way analysis of variance (ANOVA) was used for statistical analysis with commercial statistical software Minitab (ver. 18, Minitab Inc., State College, PA, USA). The *p*-values equal or smaller than 0.05 was considered statistically significant.

RESULTS AND DISCUSSION

The validation analysis was conducted with the experimental data in literature [11]. Analysis of simulation results showed in Figure 3 that both studies exhibited similar trends of maximum bone temperatures. In this study, the maximum bone temperature for 3 mm depth of cut was 34.8 °C and 77.5 °C when the bone model was perforated at depths of 6 mm. Hillery and Shuaib [11] showed slightly higher maximum bone temperatures and hence, a small average error (3.2%). The possible explanation for this is due to the distinct methods of measuring the temperature between both studies. In this study, we measured the maximum bone temperature generated in the drilling hole. However, they designed a special drill bit with embedded thermocouple which was placed at 0.5–0.7 mm from the cutting edge. Nevertheless, from this result, a small difference was observed in the maximum bone temperatures between both studies. Thus, our simulation analysis for human bone is in agreement with the study of Hillery and Shuaib [11].

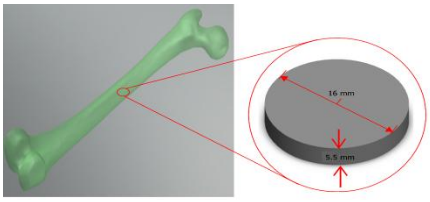


FIGURE 1. Human bone computer-aided design model

FIGURE 2. Tool and bone meshing

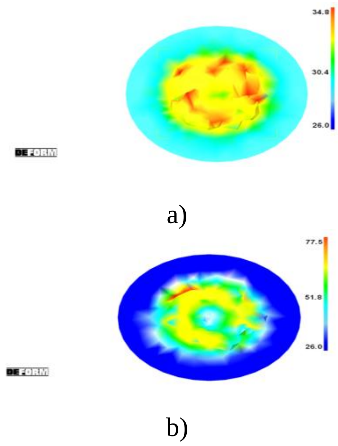


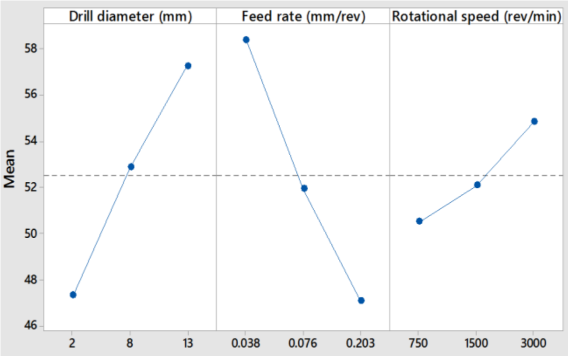
FIGURE 3. Maximum bone temperature for different depth of cut

Experimentation results unveiled that the maximum bone temperature during the drilling process peaked at 68.6 °C and exceeded the threshold temperature for bone necrosis. The minimum bone temperature rise was 43.4 °C with the 750 rev/min rotational speed, 0.203 mm/rev feed rate and drill bit diameter of 2 mm. The highest bone temperature elevation of 58 % can be seen within the studied drilling parameters when the rotational speed was 3000 rev/min, feed rate of 0.038 mm/rev and drill bit diameter of 13 mm.

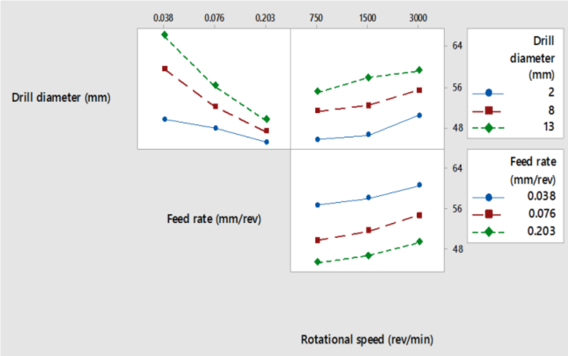
TABLE 4. ANOVA results

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
D	2	447.18	223.58	116.72	0.000	Significant
F	2	575.93	287.96	150.33	0.000	Significant
N	2	86.61	43.304	22.61	0.001	Significant
D*F	4	123.05	30.762	16.06	0.001	Significant
D*N	4	6.01	1.502	0.78	0.566	Insignificant
F*N	4	1.25	0.314	0.16	0.951	Insignificant
Error	8	15.32	1.916			
Total	2	1255.3				

The ANOVA was executed to study the significant drilling parameters to the temperatures elevation during drilling process and the results are shown in Table 4. The significant effects of rotational speed, feed rate, drill diameter and the interaction of drill diameter and feed rate on the elevation of bone temperatures are clearly depicted with all the p-values smaller than 0.05. It is evident that within the investigated range of drilling parameters, feed rate has the largest influence on bone temperature elevation. Feed rates are inversely linear with the temperature rise (Figure 4). The decrease in the maximum bone temperature with increasing feed rate during bone drilling can be expounded by the significant increase in the drilling force with higher feed rate. Large drilling force could shorten the drilling period and hence, reduce the friction energy because of the shorter contact period between the drill bit and bone. Consequently, less contact time contributes to the lower heat accumulation in the drilling holes and a lower maximum bone temperature. The results obtained are in line with the results in [6]. The drill bit diameter was the second largest effects on bone temperature elevation, followed by the interaction of drill bit diameter and feed rates. The rotational speed contributed to the smallest effect on bone temperature rise. A similar trend for rotational speed [9] and drill diameter [3] were discovered by previous studies. The interaction effects of the drilling parameters are shown in Figure 4. The biggest interaction effect on the elevation of bone temperatures is the combination of drill diameter and feed rate. The change of feed rate has the greatest effect at the biggest drill diameter. The interaction effect of drill diameter and rotational speed showed similar trend with the interaction effect of feed rate and rotational speed. It was demonstrated that when drilling with constant feed rate, the highest maximum bone temperature was caused by bigger drill bit diameter. However, when the drill diameter was fixed, the highest maximum bone temperature was contributed by lowest feed rate.



(a) Main effects



(b) Interaction effects

FIGURE 4. Effects of the drilling parameters on the bone temperature elevation

CONCLUSIONS

The objective of this study was to understand the effects of drilling parameters on bone temperature elevation. The investigation has concluded that, feed rate has the biggest effect on bone temperatures elevation during bone drilling process. Bone temperatures increased significantly with the increased of the feed rate, drill diameter and rotational speed. In addition, statistically significant effect of interaction between drill bit diameter and feed rate on bone temperatures elevation was discovered in this investigation. The evidences from this study suggests that using the combination of lower rotational speed, high feed rate and small drill bit diameter can reduce the temperature rise during bone drilling for safe surgical procedures and avoid thermal necrosis in bone.

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