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# FEM investigation of drilling conditions on heat generation during teeth implantation

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**Abstract**
The first step of implanting teeth is to drill a hole in the jaw bone. The excessive temperature produced during drilling is one of the destructive factors for bony tissue. If the temperature generation during surgical drilling exceeds the critical temperature, it could lead to osteonecrosis. This research intends to study drilling parameters such as drilling speed, feed rate, cooling condition, and tool geometry by FEM method in order to achieve the most appropriate drilling conditions. Three-dimensional modeling of lower jaw bone from the CT scan images is made by Mimics 10.01 software. In order to place the drill bit on the mandibular model, two teeth are removed from the final part of the model by CATIA V5R20 software. DEFORM-3D (Version 10.2) is used for mandibular cortical bone drilling simulation. For this purpose, drill bits with different geometrical parameters including point angles of 90, 70, and 118 degrees and helix angles of 20, 23, and 30 degrees are designed in the software. The simulations are carried out using different feed rates (60, 90, 120, and 200 mm/min) and rotational speeds (200, 400, 800, and 1200 revs/min). The simulation results show that the most appropriate conditions for the lowest temperature are as follows: 70 degrees for drill bit point angle, 23 degrees for helix angle, 200 mm/min for feed rate, and 200 revs/min for rotational speed. Also, by using coolant, the maximum temperature reduces by approximately 12 degrees. The results also suggest that the rotational speed of 200 revs/min and feed rate of 200 mm/min have the largest thrust force in the drilling area. The finite element results are validated by available experimental data.

## 1. Introduction

Dental implant surgery is a technique that swaps tooth roots with metal, screwlike posts and replaces broken or missing teeth with artificial teeth that look and function much like real ones. To place the dental implant, holes are needed to be drilled into the jawbone where the implant post is going to be placed. As soon as the metal implant post is placed in the jawbone, osseointegration begins [1]. During this process, the jawbone develops into and joins together with the surface of the dental implant [1]. One of the most important factors that can affect osseointegration development is heat generation while drilling [2-7].

If the temperature generation during surgical drilling exceeds the critical temperature, it could

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lead to osteonecrosis. Osteonecrosis is a disease that occurs when the blood flow to the bone reduces. An interruption to the blood flow leads to the death of the bone [8, 9]. Osteonecrosis prevents the implant from being fixed into the bone [10]. Different studies have been reported different critical temperatures at which Osteonecrosis starts to happen such as 47°C [11, 12], 50°C [13] and 55°C [14]. The reason for these different reports can be attributed to the drilling time durations [15].

Using coolants is one of the ways to reduce the temperature in most of the processes especially in bone cutting processes. Recently, nanofluids have been used as a capable coolant candidate for temperature control especially for most surgeries involving the human skeleton [16]. A nanofluid is a fluid containing nanoparticles. The presence of these nanoparticles gives a fruitful way of improving the characteristics of heat transfer [16]. Yang et al. [17] investigated experimentally and theoretically the effect of nanoparticle size on temperature field of bone micro-grinding. They showed that the temperature under using nanofluids was about 22% lower in comparison with mist cooling. Yang et al. [18, 19] also showed in other works associated with bone micro-grinding that the maximum temperature was not always proportional to mass fraction of the nanofluids. The measured temperature peak indicated both a proportional and an inversely proportional relationship with mass fraction of nanofluids. It means that within a certain mass fraction range, the relationship was inversely proportional but beyond that range, the relationship was proportional.

Another way to prevent temperature rise is to select appropriate parameters in bone cutting processes. There are several factors associated with implant drills which affect heat generation during the jawbone drilling. There have been many studies on influential parameters of drilling in heat generation. The drill bit design [11, 20, 21] and drill speed and feed rate [21-26] have been investigated by many researchers. For instance, Charcon et al. [20] investigated heat generation by 3 different implant drill bits and also after repeated process. They considered three implant drill systems in the experiments. The first system called system A were triple twist drill bit with a relief angle. Also, the second and third systems called system B and C were triple twist drill bit without a relief angle, and double twist drill bit with a relief angle respectively. According to their results, multiple uses increased the temperature. Also, the measured temperature after 25 uses for system A and C was below 47ºC. However, the temperature for system B exceeded 47 ºC from the initial use.

Li et al. [27] also studied the effect of cooling and drilling parameters on temperature field of superhard drill. They used two medical drill bits with different geometrical shapes. The temperature fields under different conditions were simulated by utilizing a twist drill bit and a step drill bit. Their results indicated that the maximum bone drilling temperature was continuously higher than that of the brazed step twist drill bit under all conditions.

In another work, Augustin et al. [21] studied the effect of point angle of the drill bit. They showed that the drill bit point angle affects heat generation. However, they stated that its effective level depends on the other drilling parameters, i.e. the rotational speed and feed rate of the drill bit. It means that different feed rates and rotational speeds can change the results [21]. Feed rate and rotational speed are two important parameters that also affect temperature rise of the bone [21, 23, 24].

A detailed in vitro experimental study by using fresh calf cortical bones has been conducted by Karaca and Aksakal [23]. Diameter, rotational speed, force, feed rate and drill coating were their studied parameters. Similar to other research, it was shown that increasing the drilling speed led to temperature rise. Higher feed rates also decreased the temperature and drill force. It was also observed that using TiBN coated drill bits resulted in higher temperatures in the bone in comparison to the uncoated drill bits and the temperatures increased with larger drill diameters.

A study by Basiaga [26] has shown that the rotational speed is one of the influential parameters on the maximum temperature generated in the bone during drilling. However, within a certain range of speed at the early stages of the drilling it does not result in osteonecrosis. It has also been shown by Udiljak that the feed rate has a reverse effect [25]. It implies that utilizing higher feed rates causes decline in the maximum generated temperature.

Lee et al. [28] studied the effect of drilling parameters as well as drilling depth on the temperature distribution while drilling of cortical bovine femur. They also showed that increasing spindle speed causes higher temperatures. Besides, the maximum temperature is proportional to the drilling depth.

Some other factors such as the sharpness of the drill bit, the material of the drill bit and drilling depth were found to affect the bony temperature [8, 29-31]. Using sharper diamond drill bits leads to decreasing the peak temperature. However, because of contact and consequently friction between the drill bit and the bone tissue, increasing drilling depth leads to increased heat generation [32].

According to the literature, investigation of jaw bone drilling parameters based on FEM analyses has not been given enough attention and few studies have been done so far [27, 33, 34]. Moreover, there are no studies to investigate the effect of helix angle of the drill bit in peak temperature while bone drilling. So, the aim of the present study is to investigate the effect of the helix angle of the drill bit, as well as some other drilling parameters, on temperature changes generated while drilling of the jaw bone by FEM simulations.

## 2. 3D Modeling methodology and FEM model

The 3D modeling methodology is shown in Fig. 1. The initial step regarding the jawbone definition was a CT scan of the face region of a 28 years old male. The format of the medical images obtained by CT scan system is DICOM.

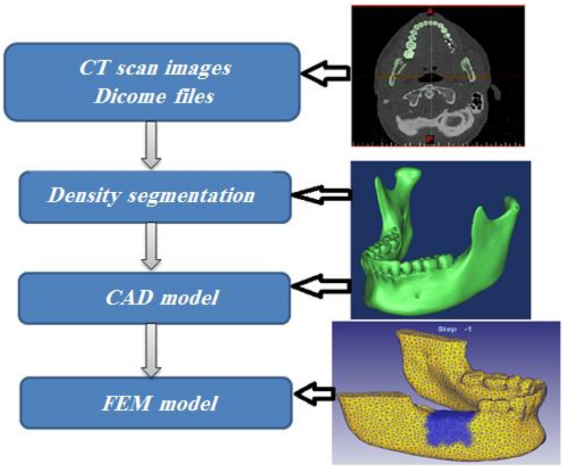


**Fig. 1.** Modeling methodology.

The DICOM images were imported into the especial software called MIMICS 10.01. This software provides a convenient environment for editing and processing DICOM files. The primary 3D model of mandible was produced in the software based on the density segmentation methods. 166 CT images with high resolution were used to produce a model of real mandible through this software. The generated primary 3D model of the mandible was exported as geometrical file for CATIA V5 R 20. In CATIA software, two teeth were removed from the end of the mandible in order to prepare a space on jawbone for drilling. Finally, the CAD model was exported to DEFORM-3D software (version 10.2) in the STL format.

The FEM model of mandible and drill bit is shown in Fig. 2. The geometry of the drill bit was defined by the DEFORM-3D software. Drilling parameters and material properties for mandible and drill bit will be explained in the following sections. The meshing of the drill bit and mandible model affects the accuracy of the results. A finer mesh usually results in higher accuracy, but it takes more time to obtain the results. In this simulation, tetrahedral element type was considered for mesh structure. The automatically generated mesh structure of the mandible model and drill bit consists of 45694 elements (10197 nodes) and 23542 elements (5674 nodes) respectively. As it can be seen in Fig. 2, the mesh structure at the drilling sit is finer for increasing accuracy. Regarding the boundary conditions, a displacement constraint was applied on the lateral and bottom surface nodes so that the mandible model was fixed at those nodes.

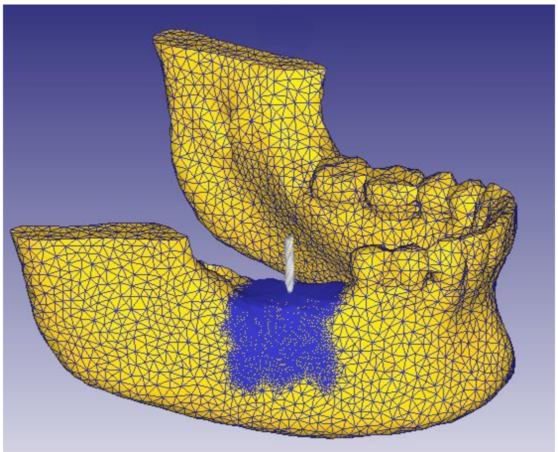

**Fig. 2.** FEM Model of mandible and drill bit.

Besides, rotational speed around the axis of the drill bit and feed rate along the axis of drilling are defined for the drill bit. The contact between the drill bit and mandible model was also defined. In this regards, drill bit and mandible surfaces were considered as master and slave in the software respectively.

## 3. Properties of the mandibular bone tissue

As it can be seen in Fig. 3, the mandibular bone tissue consists of two portions which are called cortical bone and trabecular bone tissue. The thermo mechanical properties of these two portions are different. It means that the heat transfer and also heat generation in different layers of the bone are not the same [35].
Augustin *et al*. [12] stated that since the most dense and compact portion of the bone tissue is the cortical portion, temperature rise while drilling occurs mainly in this portion and the trabecular bone contributes mostly in the thermal dissipation. So for FEM simulation the thermal properties of the cortical bone are considered.
However, the properties of the bone tissue are not the same for all people and depending on gender, age and some other parameters like diseases, change from person to person [36]. Therefore, the thermal properties can be estimated depending on certain parameters [10]. The thermal properties of the cortical bone selected from the literature are presented in Table 1.
The mechanical properties of the cortical bone at some different strain rates are shown in Fig. 4. The data were measured at room temperature. For FEM simulation, it is assumed that the cortical bone tissue is mechanically homogeneous.

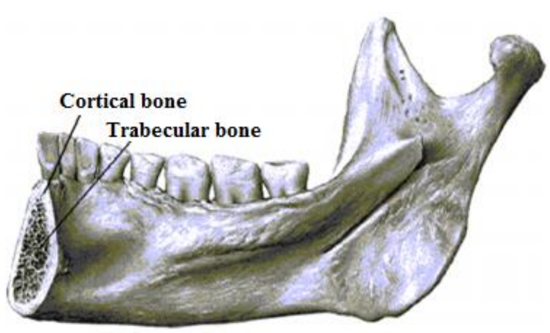


**Fig. 3.** The mandibular bone [35].

**Table 1.** Thermal properties of cortical bone.

| Properties | Value |
|---|---|
| The specific heat capacity [36] | 1256 $\frac{J}{kg.°K}$ |
| Thermal conductivity [36] | 0.53 $\frac{W}{m.°K}$ |
| Coefficient of thermal expansion of bone [37] | $8.8\times10^{-5}K^{-1}$ |

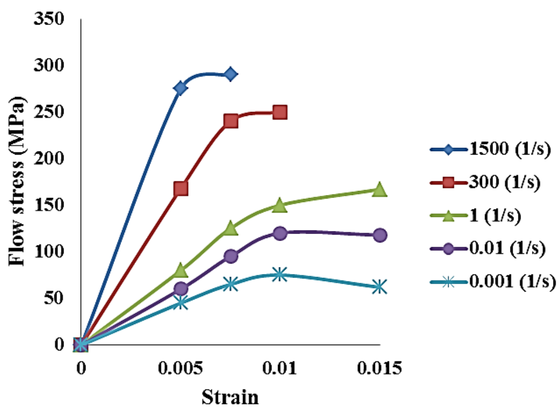


**Fig. 4.** True stress-strain curve of cortical bone at varying strain rates [40].

According to the results reported by Schwartz-Dabney and Dechow [36], the density of the cortical bone is between 1850 and 2000 kg/m$^3$. So, the average of the obtained values, i.e., 1925 kg/m$^3$, is considered for the simulation. Also the values used for Poisson ratio of the cortical bone is 0.3 [38, 39].

## 4. Drilling parameters

Having defined the geometry and the cortical bone properties of the mandible, it is needed to define the drill bit geometry and some working conditions. Fig. 5 shows the geometry details of a drill bit. The most important geometrical parameters of the drill bit affecting heat generation during drilling are diameter, helix angle and point angle.
To evaluate the effect of the drill bit parameters on heat generation while drilling, three point angles and three helix angles are considered for FEM simulations. The values mentioned in Table 2 were chosen based on the most common dental and orthopedic bone drill bits [42]. The material considered for the drill bit is stainless steel AISI 440. However, it is considered to be rigid in FEM simulations. The thermal properties of the drill bit (Table 3) are assigned through the available library in the Deform 3D software.

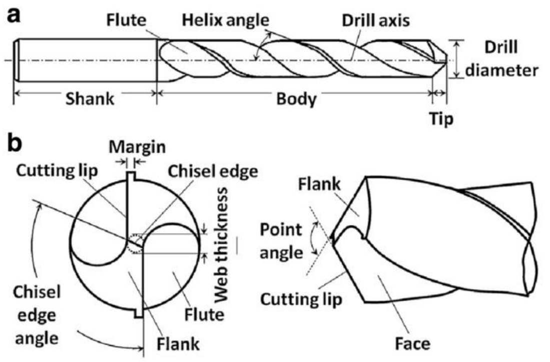


**Fig. 5.** Terminology of a drill bit: (a) Whole drill bit, (b) Tip of a drill bit [41].

**Table 2.** The geometrical parameters of drill bit.

| | |
|---|---|
| Point angle | 70 º- 90 º- 118 º |
| Helix angle | 20 º- 23 º- 30 º |
| Diameter | 2mm |

**Table 3.** Thermal properties of drill bit.

| Properties | Value |
|---|---|
| The specific heat capacity | 480 $\frac{J}{kg.°K}$ |
| Thermal conductivity | 22 $\frac{W}{m.°K}$ |
| Coefficient of thermal expansion of bone | $1{\times}10^{-5}\ K^{-1}$ |

Hole depth of drilling is 2 mm for all the simulations. Depending on the parameter being assessed, the amount of other drilling parameters, i.e. rotational speed and feed rate, are chosen.

## 5. Results and discussion

### *5.1. The effect of feed rate*

To evaluate the effect of the feed rate on heat generation while drilling, four feed rates are chosen. Other constant parameters are according to Table 4.

Fig. 6 shows the relation between the feed rate and the maximum temperature occurred while drilling. As seen in Fig. 6, higher feed rates cause less temperature rise. This result explaines that higher feed rates take shorter time of drilling.

**Table 4.** Drilling parameters.

| Feed rate (mm/min) | Rotational speed (rev/min) | The point angle of drill bit | The helix angle of drill bit |
|---|---|---|---|
| 60, 90, 120, 200 | 200 | 70º | 23º |

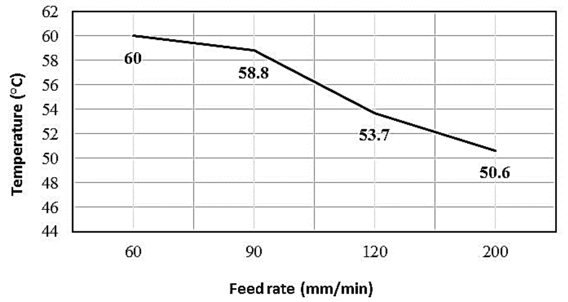


**Fig. 6.** Maximum temperature vs. feed rate graph at rotational speed=200 revs/min.

### *5.2. The effect of rotational speed*

To investigate the influence of the drill rotational speed on the maximum generated temperature, four rotational speeds are chosen in accordance with Table 5. The relation between drilling speed and maximum temperature while drilling is shown in Fig. 7. It shows that the maximum generated temperature and rotational speed are directly related to each other.

### *5.3. The effect of point angle of the drill bit*

Similar to other simulations, to evaluate the effect of point angle on maximum generated temperature, three point angles are considered in accordance with table. Some other constant parameters are mentioned in Table 6. Fig. 8 indicates that if other parameters are kept constant, increasing the point angle of the drill bit causes more heat generation.

**Table 5.** Drilling parameters.

| Rotational speed (rev/min) | Feed rate (mm/min) | The point angle of drill bit | The helix angle of drill bit |
|---|---|---|---|
| 200, 400, 800, 1200 | 200 | 70º | 23º |

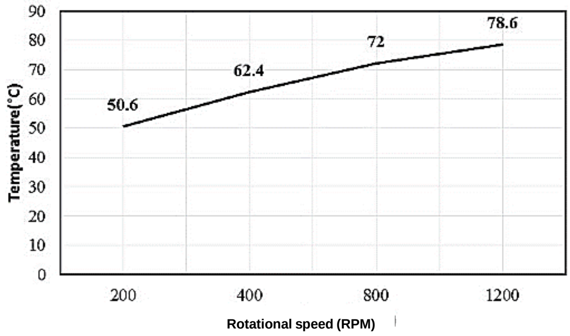


**Fig. 7.** Maximum temperature vs. rotational speed graph at feed rate=200 mm/min.

**Table 6.** Drilling parameters.

| Points angle of drill bit | Feed rate (mm/min) | Rotational speed (rev/min) | Helix angle of drill bit |
|---|---|---|---|
| 70°, 90°, 118° | 120 | 200 | 23° |

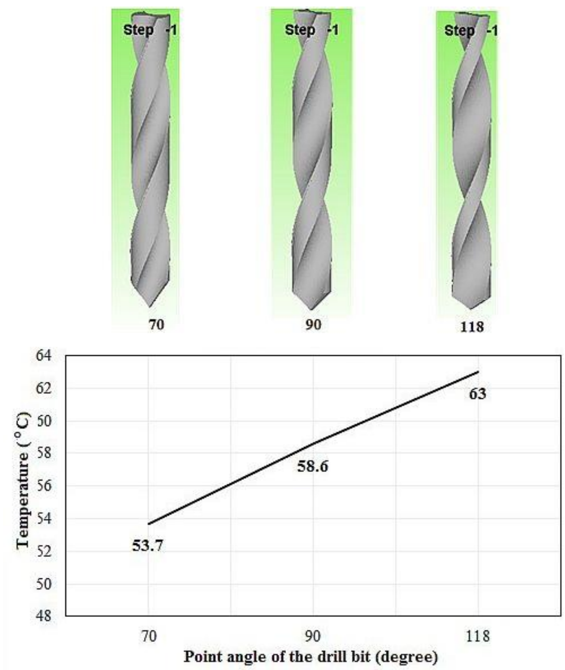


**Fig. 8.** Maximum temperature vs. point angle of the drill bit.

The relation between the point angle of the drill bit and maximum temperature during drilling is shown in Fig. 8.

*5.4. The effect of the helix angle of the drill bit*

As already mentioned, the effect of helix angle, as one of the influential geometrical parameters of a drill bit, has not been investigated so far. Therefore, to evaluate the effect of this parameter on the temperature rise, three helix angles are considered in accordance with Table 7. The effect of helix angle on maximum temperature occurred while drilling is shown in Fig. 9. According to Fig. 9, the helix angle of 23° generates the least temperature in comparison to the helix angles of 20° and 30°.

**Table 7.** Drilling parameters.

| Helix angle of drill bit | Feed rate (mm/min) | Drill speed (rev/min) | Point angle of drill bit |
|---|---|---|---|
| 20°, 23°, 30° | 120 | 200 | 70° |

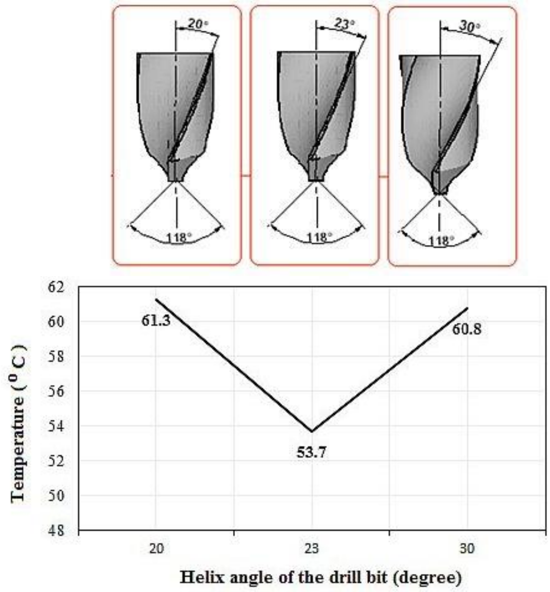


**Fig. 9**. Maximum temperature vs. helix angle of the drill bit.

*5.5. The effect of coolant*

There are numerous advantages to utilizing coolant while drilling. Guiding the coolant to the cutting edge not only improves lubricity but also lessens the temperature at the contact area. To evaluate the effect of coolant on the increase in temperature, two simulations (with and without applying coolant) are implemented. Other constant parameters are mentioned in Table 8.

The most common coolant is water. The temperature of water as a coolant and its thermal conductivity applied in the simulation are 4° and 0.6096 w/(m.°C) [43] respectively

Fig. 10 shows the temperature distribution during drilling with and without using coolant. As can be seen in Fig. 10, the maximum temperature has reached 41.6° and 53.7° with and without using coolant respectively. It means that using the coolant decreases the maximum temperature by approximately 12°.

*5.6. The effect of drilling parameters on the applied force*

Applying high thrust force during drilling can increase heat generation, because it causes the deformation to increase.

**Table 8.** Drilling parameters.

| Drill speed (rev/min) | Feed rate (mm/min) | Helix angle of drill bit | Point angle of drill bit |
|---|---|---|---|
| 200 | 120 | 23° | 70° |

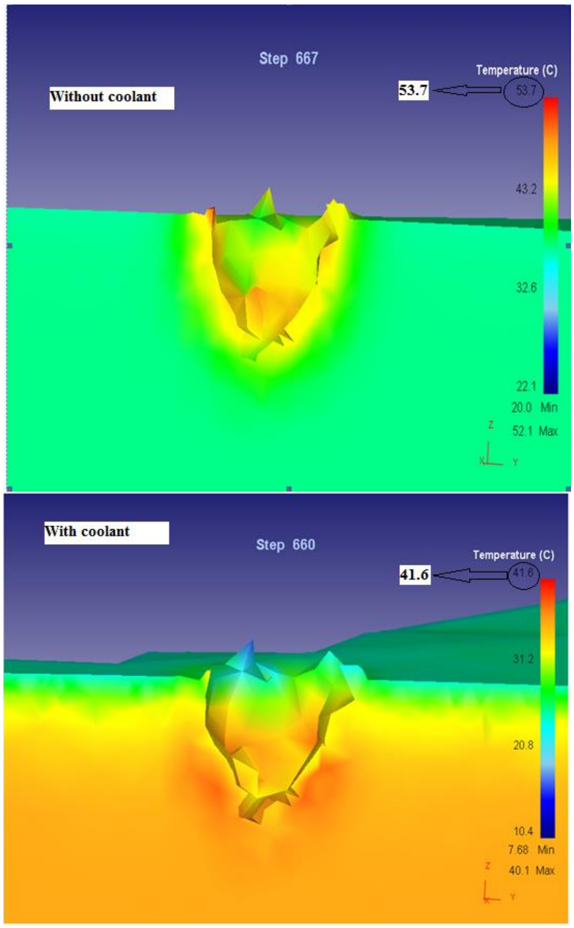


**Fig. 10.** Temperature distribution on the hole surface while drilling, with and without coolant.

Besides, high trust force can damage the jaw bone. That is why it is necessary to have an investigation into the amount of the applied force while drilling under different drilling conditions.

*5.6.1. Thrust force in varying feed rates*

The drilling parameters mentioned in Table 9 are chosen for simulation to evaluate the relation between the amount of the thrust force and feed rate. Fig. 11 shows that increasing feed rate results in an increase in the amount of the applied force. In other words, higher feed rates can damage the jaw bone.

**Table 9.** Drilling parameters.

| Feed rate (mm/min) | Rotational speed (rev/min) | Helix angle of drill bit | Point angle of drill bit |
|---|---|---|---|
| 90, 120, 200 | 400 | 23° | 70° |

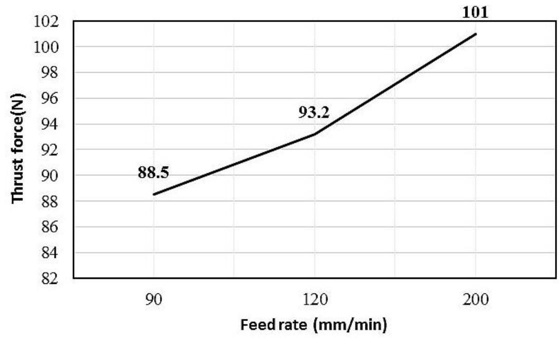


**Fig. 11.** Thrust force vs. feed rate at rotational speed=400 revs/min.

*5.6.2. Thrust force in varying rotational speeds*

To study the effect of the drilling speed or rotational speed on the applied thrust force to the jaw bone, four rotational speeds are considered in accordance with Table 10. Fig. 12 indicates that increasing the rotational speed causes decrease in the thrust force. It has already been shown in Fig. 6 that using higher rotational speeds increases the maximum temperature during drilling. Therefore, it is essential to choose an optimum rotational speed to control both temperature rise and thrust force.

## 6. Validation of the simulation

In order to validate the FEM simulation, the obtained results from simulations are compared with the existing experimental data reported by Abayazid [15].

**Table 10.** Drilling parameters.

| Rotational speed (rev/min) | Feed rate (mm/min) | Helix angle of drill bit | Point angle of drill bit |
|---|---|---|---|
| 200, 400, 800, 1200 | 200 | 23° | 70° |

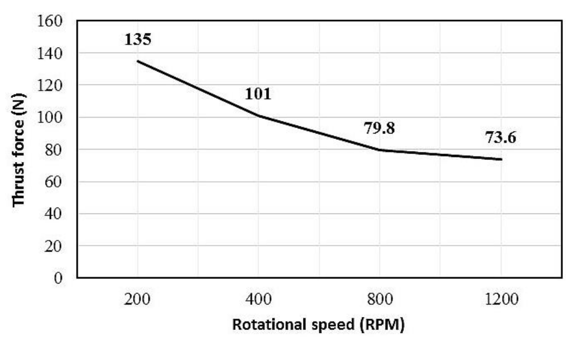


**Fig. 12.** Thrust force vs. rotational speed at feed rate=200 mm/min.

The material used by him in the experiments was Polymethylmethacrylate (PMMA). One of the reasons that he employed this material in the experiments is that the properties of PMMA including mechanical and thermal properties are very similar to the properties of bone tissue as shown in Table 11.

Abayazid [15] also utilized thermocouples and infrared sensors to monitor and measure the maximum temperature in the bone tissue while drilling. All the input parameters of the simulation are according to the experimental setup. Fig. 13 shows the comparison between the experimental and FEM results of the maximum temperature at feed rates of 120 and 200 mm/min and at rotational speeds of 800 revs/min. Both experiments and FEM simulation show that increasing feed rate leads to decreasing the maximum temperature while drilling. The obtained results from simulation are in good agreement with the experimental data. Although the thermo mechanical properties of PMMA are very close to the properties of the bone tissue, PMMA is a little more ductile. On the other hand, PMMA is able to store energy more than the bone tissue and consequently heat generation during drilling of PMMA is higher. Therefore, as it could be expected, the maximum temperature obtained by experimental tests is higher in Fig. 13.

**Table 11.** Comparison between the properties of PMMA and cortical bone [15].

| | Cortical bone | PMMA |
|---|---|---|
| Specific heat (J/kg. ºK) | 1256 | 1400 |
| Thermal conductivity (W/m.ºK) | 0.16-0.34 | 0.4 |
| Ultimate shear strength (MPa) | 48-80 | 21-48 |
| Density (kg/m$^3$) | 1800-2000 | 1200 |

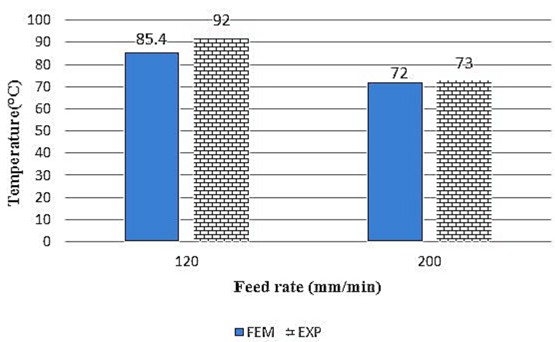


**Fig. 13.** Comparison of experimental and FEM results of maximum temperature at rotational speed=800 revs/min.

**7. Conclusions**

Many studies have shown that excessive heat generation during jaw bone drilling when implanting could lead to osteonecrosis. In the present work, the influence of drilling parameters including the rotational speed of drill bit, feed rate, and tool geometry on the increase in temperature was investigated by FEM simulation. For that purpose, a three-dimensional model of lower jaw bone was produced in the MIMICS software from CT scan images and based on the density segmentation methods. From this study, the following conclusions were made:

- Regarding the effect of drilling parameters, higher feed rates cause less temperature rise. However**,** increasing the feed rate results in an increase in the amount of applied force. The temperature rise is proportional to the rotational speed. Conversely, increasing the rotational speeds causes decreasing the thrust force. It was also shown that the use of coolant decreases the maximum temperature by almost 12 degrees.
- Regarding the effect of drill bit geometry, increasing the point angle causes more heat generation and the helix angle of 23º generates the least temperature in comparison to the helix angles of 20º and 30º.
- The most appropriate conditions for the lowest temperature are as follows: 70 degrees for drill bit point angle, 23 degrees for helix angle, 200 mm/min for feed rate, and 200 revs/min for rotational speed.
- The results of the FEM simulation are in good agreement with the available experimental data.

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