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RESEARCH ARTICLE

Biomechanical Evaluation of Temperature Rising and Applied Force in Controlled Cortical Bone Drilling: an Animal in Vitro Study

Mohammad Javad Ein-Afshar, PhD Candidate[1]; Mostafa Shahrezaee, MD[1]; Mohammad Hossein Shahrezaee, PhD Candidate[2]; Seyed Reza Sharifzadeh, MD[1]

Research performed at Amirkabir University of Technology, Tehran, Iran

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Abstract

Background: The present study was conducted to quantify the relationships between bone drilling process parameters (i.e., feed rate, resting time, exit rate, and drill bit diameter) and drilling outcome parameters (i.e., thrust force and maximum temperature).

Methods: This study utilized 10-cm cortical bovine samples to evaluate the effects of four independent parameters, including drill bit diameters, six different feed rates, three various resting times, and three different exit rates on thrust force and maximum temperature (MT). A total of 28 stainless steel orthopedic drill bits with a diameter of 2.5 and 3.2 mm, as well as an orthopedic handpiece were attached to the 500N load cell and an accurate linear variable differential transformer to obtain forces. Moreover, two k-type thermocouples were utilized to record the temperature-time curve near the drilling site. The data were analyzed using the two-way analysis of variance and post hoc Tukey-Kramer Honest test.

Results: Maximum thrust force (MTF) decreased by almost 230% as the drill bit diameter increased from 2.5 to 3.2 mm in the lowest feed rate. The MTF showed a 335% increase, whereas a decrease of 69% was observed as the feed rates rose from 0.5 to 3 mm/sec. Moreover, the MT decreased to 67% with an increasing exit rate from 1 to 3 mm/sec. Furthermore, a slight increase was observed in MT when the resting time increased from 0 to 2 seconds ($P>0.05$).

Conclusion: The desired drilling is drilling with lower thrust force and lower final temperature of bone. Increasing feed rate can cause an increase and decline in thrust force and final temperature, respectively. The highest rates of MT were 0.5 and 1 mm/min, and the optimum feed rate would be 1.5 mm/min due to the averaged thrust force. Moreover, the resting time had no significant effects on the final temperature. Attentions to resting time would be useful to provide a more accurate, efficient, and uniform drill hole.

Level of evidence: V

Keywords: Controlled bone drilling, Drilling thrust force, Efficiency of drilling, Heat generation

Introduction

Today, many diseases, such as traumas, tumors, fractures, and any other defects require a bone operation or bone machining (1-4). Bone machining consists of three crucial procedures, namely bone cutting, bone rimming, and bone drilling. Bone drilling is a common step in orthopedic surgery. It generates heat due to the existence of friction between the drill bit and bone. In direct contact with the drilled hole wall, the

Corresponding Author: Mostafa Shahrezaee, Department of Orthopedic Surgery, School of Medicine, AJA University of Medical Science, Tehran, Iran
Email: moshahrezayee@yahoo.com

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chips produced during drilling results in an increase in bone temperature (5). The heat from the operation may cause thermal necrosis. Since thermal necrosis generally has a negative impact on the outcome of the drilling procedure, the bone temperature must be kept at a safe level. Osteonecrosis reduces bone strength and causes loss of internal fixation (6).

Eriksson and Albrektsson indicated that osteonecrosis occurs in living rabbits when the bone is heated at 47˚C for 1 min (7). Other studies have suggested that if the temperature rises above 55 ˚C for longer than 30 seconds, irreversible damages occur to the bone (1, 8).

Excessive heat generation is not the only parameter influencing bone health during surgery, and the thrust force is another source of damage causing weakness in bone injured by heat (6, 9-13). This force is the required force to apply on the drill bit to progress the drilling process. The additional load exerted to the injured bone can also worsen the fractured parts (11, 14). Large uncontrolled forces experienced during bone drilling may result in drill breakthrough, imparting damage to surrounding tissue, and promotion of crack formation which could yield bone failure (15).

In cortical bone drilling, a wide variety of parameters affects the final temperature and thrust force. According to the literature (1-3), these parameters are divided into three groups of 1) drill bit parameters, 2) bone characterization, and 3) drilling process parameters. Drill bit diameter, point angle, helix angle, and initial drill bit temperature are categorized in the first group (15-19). Furthermore, bone-sex, bone density, and age are included in the second group (2-4). In addition, the third group included spindle speed, feed rate, and applied force (1, 5, 8, 20).

The helix angle, point angle, relief angle, and clearance are essential parameters in drill point design. It seems that drill bit point angle and drill bit diameter are the most essential parameters for drill bit design (17, 18). Regarding the kinematic of the bone drilling, the rotational speed and feed rate are the most important parameters (9, 21, 22). Furthermore, the initial temperature of the drill bit is also another important parameter in drill bit design illustrated by Lee et al. (8).

Although some researchers have focused on the new methods of bone drilling, such as vibrational and ultrasound bone drilling (10, 23), others are interested in finite element validation of thrust force and temperature (9, 19, 21, 22). Unfortunately, there are yet some problems regarding the optimization of bone drilling parameters, especially the feed rate and exit rate. Moreover, other bone drilling parameters, such as resting time between inserting and pulling-out the drill bit, could also be considered.

This study aimed to set a controlled drilling procedure in order to minimize the damage induced by bone drilling. Therefore, different parameters of the bone drilling process, including feed rate, exit rate, resting time, and drill bit diameter, were taken into account. In addition, two essential dependent variables, including temperature-time and force-displacement curves, were measured during testing.

Materials and Methods

Sample preparation

This study used two mid-diaphysis sections of bovine femora (age 2-3 years) with an approximate length of 100 mm. Every shaft was divided into a shorter part for placing in the clamp [Figure 1]. The mean thickness of the cortical wall was about 10 mm. Bone samples were obtained from a local slaughterhouse shortly after animal death, and no animals were sacrificed, especially for this study. The muscles and soft tissues were removed to prevent soft tissue drilling. A total of 10 samples were prepared for testing, and each sample had an approximate 50 drilling possible part. The samples were then maintained in saline solution and kept at -20˚C according to guidelines by An and Draughn (1999) (24). Before the beginning of the experiment, the samples were rasped to flatten the surface and avoid sliding the tip of the drill bit.

Drilling devices

An orthopedic drilling handpiece (Iranian TajhizSina OR2013-02, Iran) was used in this study. This handpiece has a dimmer for adjusting spindle speed from zero to 900 rpm. It is worth mentioning that this study utilized the spindle speed of 900 rpm (2, 5). The drilling handpiece was connected to the dynamic testing machine with an adjustor [Figure 1]. The perpendicularity of the drill bit was regulated by adjusting four screws and bolts. In total, 28 stainless steel orthopedic two-flute drill bits with a diameter of 3.2 and 2.5 mm were used in this study. The point and helix angles were 80 and 35 degrees as well as 70 and 25 degrees, respectively. Principally, drill bits were used no more than 20 times.

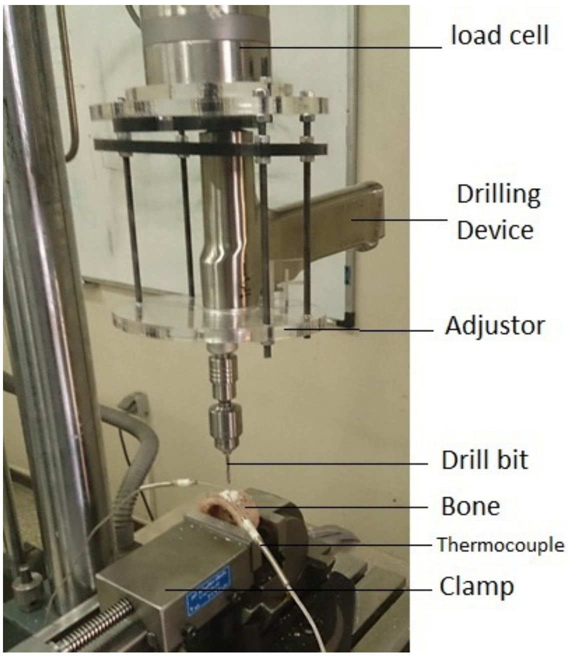

Figure 1. Set up for the drilling process and recording thrust force and temperature versus time for each bone sample.

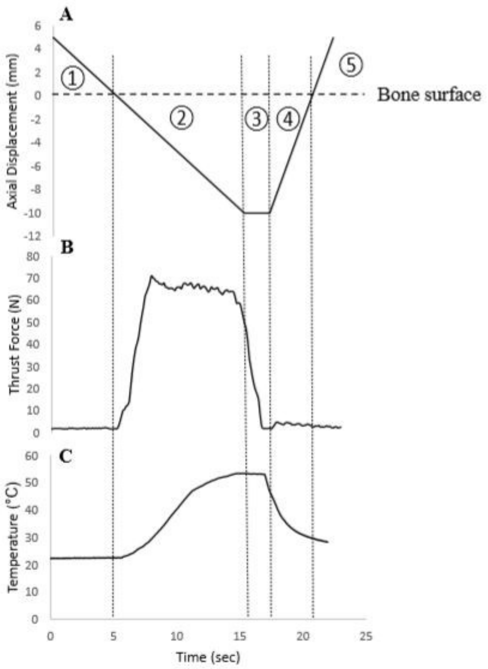

Figure 2. A) Displacement versus time of drill bit for a typical test which has a 1 mm/sec feed rate, 2 second resting time, and 3 mm/sec exit rate, B) Thrust force versus time for same feed rate, resting time, and exit rate, and C) Temperature versus time for same drilling process specifications.
For every drilling process, there are five different regions: ① descending drill bit but no contact with bone happened yet, ② drilling stage, ③ resting stage, ④ exit stage with contact to the bone, ⑤ exit stage without contact to the bone. All figures specified for 3.2 mm drill bit diameter.

Force and temperature recording device

The dynamic testing machine (Zwick/Roell, DTM, Germany) consists of an accurate linear variable differential transformer (LVDT) with an accuracy of 100 µm and a resolution of 10 µm. All forces were detected by a 500N load cell attached to the LVDT, which was calibrated at an accuracy of 1% of its full capacity [Figure 1]. The drilling process requires a load to push the drill bit into the bone. This load varies during the time. Figure 2.B illustrates a typical force-time graph.

The temperature changes during bone drilling were measured with two k-type thermocouples connected to a two-channel thermometer (TM-946, Lutron, Taiwan). A layer of silicon paste was covered to the tip of every thermocouple as a heat sink for maximum heat transfer to the sensors. The diameter of the thermocouples was 1 mm. Regarding the placement of thermocouples, two 1-mm diameter holes were drilled 1 mm near the drilling wall. Tip of each thermocouple planted into the depth of 3 mm (25). A typical temperature-time graph is shown in Figure 2.C.

Drilling procedure

The tip of the drill bit was initially kept 5 mm over the surface of the bone samples [Figure 2. A first stage]. Drilling depth was defined as 10 mm; therefore, the controller descended drill bits 15 mm down while the drilling device was working. These numbers were deduced from the thickness of the bovine samples. The feed rate was adjusted to be 0.5, 1, 1.5, 2, 2.5, and 3 mm/sec. The exit rate of the drill bit was set at 1, 2, and 3 mm/sec. The resting time, which is defined as the time between the entrance and exit of the drill bit, was considered at 0, 1, and 2 seconds [Figure 2. A third stage]. A typical drilling procedure is depicted for 1 mm/sec feed rate, 1-sec resting time, and 3 mm/sec exit rate [Figure 2]. The drilling process consists of five different chronological steps, including drill bit descending without contact, drilling bone stage, resting stage, exiting stage with contact, and exiting stage without contact.

Statistical Analysis

The parameters involved in this study were divided into three types of classification, namely independent variables, dependent variables, and constant parameters. The independent variables were drill bit diameter, feed rate, exit rate, and resting time. The dependent variables were maximum thrust force and maximum temperature. Room temperature, initial temperature of the drill bit and bone samples, spindle speed, and quality of bones were assumed to be constant in this study. All data for each test condition (i.e., dependent variables) were statistically analyzed using two-way ANOVA (Microsoft Excel 2003, Microsoft Corp., Remond, WA, USA). A *P-value* of less than 0.05 was considered statistically significant. Furthermore, a Tukey-Kramer Honest Significant Difference post hoc test was used to determine significant differences among the results in each test group.

Results

Thrust force was defined as the maximum force that occurred during the drilling stage [Figure 2.A stage 2] (10). The maximum and minimum thrust forces occurred at the feed rate of 3 mm/sec and 0.5 mm/sec, respectively, for the drill bit diameter of 2.5 mm. Similarly, for the drill bit diameter of 3.2 mm, the maximum and minimum thrust forces were observed in the same feed rates [Figure 3].

There was a significant difference among the groups in terms of both drill bit diameter (*P<0.05*), except for the feed rates of 0.5 and 1 mm/sec (*P=0.44* and *P=0.49*, respectively, for 2.5 and 3.2 mm drill bit diameter) or 2 and 2.5 mm/sec (*P=0.32* and *P=0.31*, respectively for 2.5 and 3.2 mm drill bit diameter).

The maximum drilling time amongst 54 test groups was obtained at 32 seconds, which occurred at 0.5 mm/sec feed rate, 2 seconds resting time, and 1 mm/sec exit rate, which is denoted as 0.5-2-1 in Table 1. The minimum drilling time was 6.6 seconds, which found in the 3-0-3 group. The times mentioned above were the contact time that was defined as a duration of stage two, three, and four of the drill bit and bone sample, whereas the hole drilling process took 47 and 10 seconds, respectively.

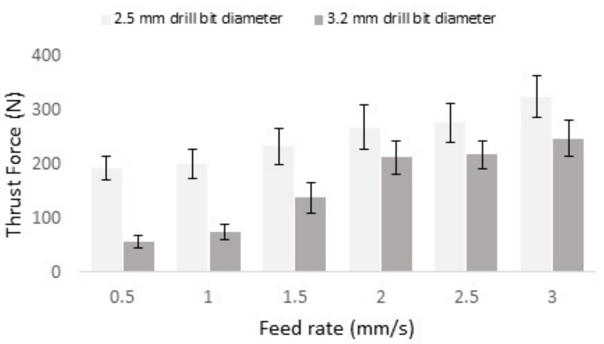

Figure 3. Thrust force versus six different feed rates for 2.5 and 3.2 mm drill bit diameters.

The temperature-time curve was recorded for every five tests of each group and peak temperature reported [Figure 2.C; Figures 4-6]. The maximum peak temperature was observed in the 0.5-2-1 group, which significantly was different from that of the other groups (*P<0.001*). In the same vein, the minimum peak temperature occurred in the 3-0-3 group [Figures 4; 6]. All temperature bar charts depicted in Figures 4, 5, and 6 illustrate a decrease in temperature with an increase in the feed rate.

Significant differences were observed among the 0.5, 1.5, and 2.5 mm/sec feed rate groups (*P<0.001*). Similarly, the 0.5, 1, 2, and 3 mm/sec feed rate groups showed statistically significant differences (*P<0.05*). Despite an increase in the maximum temperature in different groups with increasing resting time, no significant differences

Table 1. All different groups named base on feed rate- resting time- exit rate for six different feed rates, three different resting time and three different exit rates

Groups	0.5-0-1	1-0-1	1.5-0-1	2-0-1	2.5-0-1	3-0-1
Contact time	30	20	16.7	15	14	13.3
Groups	0.5-1-1	1-1-1	1.5-1-1	2-1-1	2.5-1-1	3-1-1
Contact time	31	21	17.7	16	15	14.3
Groups	0.5-2-1	1-2-1	1.5-2-1	2-2-1	2.5-2-1	3-2-1
Contact time	32	22	18.7	17	16	15.3
Groups	0.5-0-2	1-0-2	1.5-0-2	2-0-2	2.5-0-2	3-0-2
Contact time	25	15	11.7	10	9	8.3
Groups	0.5-1-2	1-1-2	1.5-1-2	2-1-2	.5-1-22	3-1-2
Contact time	26	16	12.7	11	10	9.3
Groups	0.5-2-2	1-2-2	1.5-2-2	2-2-2	2.5-2-2	3-2-2
Contact time	27	17	13.7	12	11	10.3
Groups	0.5-0-3	1-0-3	1.5-0-3	2-0-3	2.5-0-3	3-0-3
Contact time	23.3	13.3	10	8.3	7.3	6.6
Groups	0.5-1-3	1-1-3	1.5-1-3	2-1-3	2.5-1-3	3-1-3
Contact time	24.3	14.3	11	9.3	8.3	7.6
Groups	0.5-2-3	1-2-3	1.5-2-3	2-2-3	2.5-2-3	3-2-3
Contact time	25.3	15.3	12	10.3	9.3	8.6

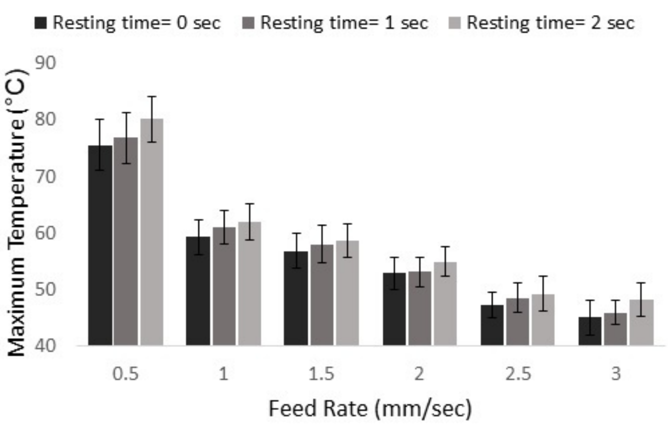

Figure 4. Bar chart of maximum temperature versus different feed rates for three different resting time and exit rate of 1 mm/sec.

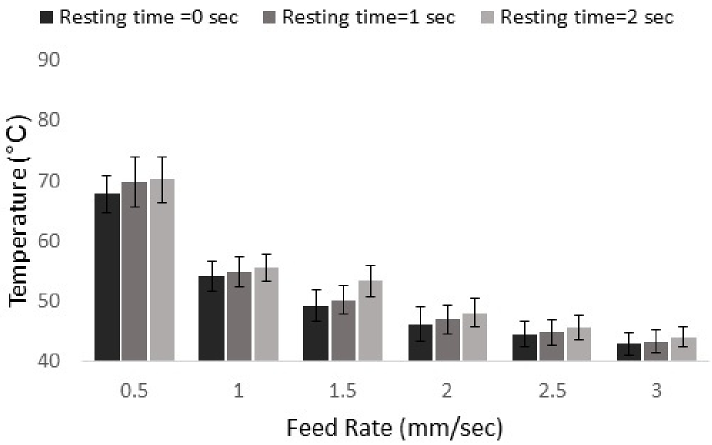

Figure 5. Bar chart of maximum temperature versus different feed rates for three different resting time and exit rate of 2 mm/sec.

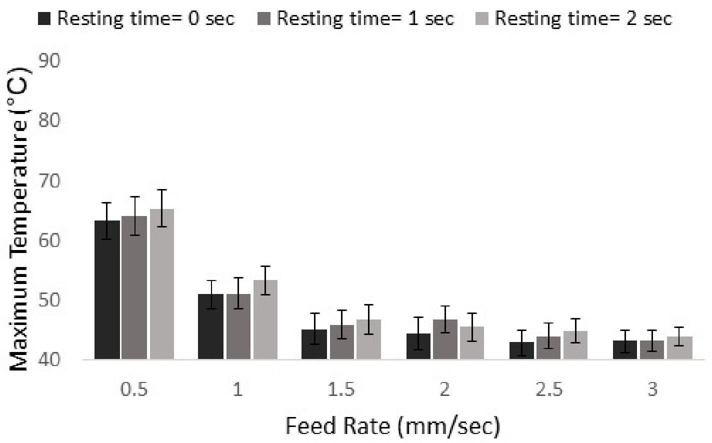

Figure 6. Bar chart of maximum temperature versus different feed rates for three different resting time and exit rate of 3 mm/sec.

were observed in this regard. Moreover, the maximum change in the peak temperature was about 3.2˚C at the feed rate of 0.5 mm/sec and exit rate of 1 mm/sec which is about 4% of the temperature, whereas the standard deviation was more than 4.5˚C in these groups. Observations about the exit rate indicate a significant difference between the exit rate of 1 and 3 mm/sec in all three resting times and all feed rates (*P<0.01*). Additionally, a significant difference was observed among the exit rates in terms of the feed rate of 1 mm/sec (*P<0.05*).

Discussion

Bone drilling is a commons step not only in human orthopedic operations but also in different animal studies using scaffolds (1, 26). According to the literature, there are two methods of drilling in-vitro independent of using animal bone samples or human cadaver. The first one is the use of kinematics of drilling for input parameters and recording of temperature as well as the kinetics of drilling, including applied force and torque (9-11, 27). The next one is the utilization of the kinetics of drilling procedure and recording of bone temperature (in this procedure the kinematics of drilling will change) (6). The main question is that which method should be used for controlled bone drilling? According to different studies, real surgical bone drilling involves both methods (1-3). In this study, the effects of the input parameters, including feed rates, resting time, exit rate, and drill bit diameters, on thrust force and maximum temperature were discussed for drilling bovine samples. Other parameters of the kinematics of bone drilling, including spindle speed, are considered constant.

The method of internal fixation for faster recovery is advantageous when the thermal necrosis of bone (8, 28) and excessive applied force (11, 13) be avoided. These undesirable temperatures and forces develop in different stages of the drilling process. The first stage is the descending of the drill bit with no contact [Figure 2]. Bone drilling starts when the surgeon positions the drill bit near the drilling site (stage one). In this stage, there is no production of temperature and forces; however, in real patient surgery, it would be important based on the citation and orientation of the drilling (29, 30).

The second stage itself consists of two different phases, including drilling engagement and drilling phases (10, 11). The third stage includes the resting time to permit the generated heat to conduct. The fourth stage is about the exit stage in which the drill bit and bone are still in contact, and the temperature can transfer to the bone. Similar to the first stage, the fifth stage does not involve direct contact of the bone with a drill bit; however, it should be implemented exactly in the direction of bone drilling. The maximum thrust force occurs in the second phase of the second stage (10, 12) as was measured for different drill bit diameters. Moreover, the maximum thrust force was observed for the 2.5 mm drill bit diameter and a feed rate of 3 mm/sec. The maximum thrust force increased by 70% and 335% for drill bit diameter of 2.5 and 3.2 mm, respectively, as the feed rate increased from 0.5 to 3 mm/sec (31).

The reason that thrust force has a lower value for higher drill bit diameter is the availability of larger cutting faces, compared to smaller drill bits [Figure 3] (1). It should be noted that the resting time and exit rate had not any effects on the thrust forces, and this is reasonable due to the chronological stages defined in Figure 2. The thrust force rose during the beginning of the second stage and stabilized at the end of this stage, whereas the resting time and exit rate affect the maximum temperature of the third and fourth stages indicating the independent effects of resting time and exit rate on the thrust force.

The main cause of heat generation is friction between drill bit faces and bone (2, 3); nonetheless, the main sources of heat conduction are bone chips produced in the drilling process, which are inevitable (3). However, a decrease in the maximum temperature by reducing the duration of drilling would be helpful (1, 6). A reduction in the duration of the drilling process can be obtained by increasing the feed rate and exit rate, as well as decreasing the resting time [Table 1].

The drilling duration (summation of all stage durations, except for stage number one and five) decreased to 16.7 seconds for maximum and minimum feed rates in all cases; however, the maximum temperature did not obey this fixed-value principle and varied between 20.8 and 31°C as confirmed in a study conducted by Karaca et al. (32). The main reason is that the ratio of exit duration (10, 5, and 3.3 seconds for different exit rates) to the duration of the total difference for different feed rates (16.7 seconds) decreased from 0.6 to 0.2. Therefore, the heat has more opportunity for transferring to the bone and rising the final bone temperature. Overall, for an exit rate of 1 mm/sec maximum temperature increased by almost 67% as the feed rate elevated from 0.5 to 3 mm/sec. Likewise, regarding the lowest exit rate, the temperature increased by 59% and 48% for exit rates of 2 and 3 mm/sec, respectively.

Considering the resting time, a slight increase in maximum temperature was observed; nevertheless, this was not significantly different in different resting times (*P=0.27*). Resting time adds a maximum of 2 seconds to the total drilling duration, whereas feed and exit rates could add 16.7 and 6.7 seconds, respectively. The advantage of resting time during the drilling process would be the prevention of several feeding and exiting of drill bit requirements. Resting time had no significant effect on maximum temperature, and therefore, the thrust force (*P=0.27* and 0.34, respectively).

The current study was conducted based on varying kinematic of the drilling process; however, the spindle speed was not included in the independent variables. The main reason was to decrease the involved parameters. In addition, many studies have demonstrated the effect of spindle speed (2, 3, 5, 20). Another limitation of this study is that the final temperature of bovine samples may be increased more than human bone due to the more density of bovine samples (2, 3), and it will be more reasonable to carry out the test on human cadaver for more accurate conclusions.

The effects of various parameters during drilling were investigated in detail in this study. It was found that larger drill bit diameter resulted in lower maximum thrust force due to the availability of larger cutting faces. Moreover, to avoid thermal necrosis, high feed rates and thrust forces could reduce the final bone temperature. In this regard, the main sources of increasing temperature in bone are drilled chips, and the opportunities to transfer heat to the bone by these chips should be decreased either using an increase in the feed rate or exit rate. Furthermore, it was observed that resting time had no significant effects on final bone temperature; therefore, it could be helpful to uniform the drill hole. Finally, feed rates, exit rates, and resting time should be optimum in order to have desired bone drilling. The optimum values for feed rate, exit rate, and resting time were 1.5 mm/sec, 3 mm/sec, and zero seconds, respectively, based on the results of the study.

Declaration of interest and Level of evidence: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this article. The level of evidence is level one.

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Mohammad Javad Ein-Afshar PhD Candidate[1]
Mostafa Shahrezaee MD[1]
Mohammad Hossein Shahrezaee PhD Candidate[2]
Seyed Reza Sharifzadeh MD[1]
1 Department of Orthopedic Surgery, School of Medicine, AJA University of Medical Science, Tehran, Iran
2 School of Dentistry, Tehran University of Medical Science, Tehran, Iran

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