Experimental Study on the Effect of Point Angle on Force and Temperature in Ultrasonically Assisted Bone Drilling

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Abstract Drilling of bone is a common surgical procedure in orthopedics to produce holes for screw insertion. The force and temperature rise in bone drilling are two important factors affecting the outcome of the process. The present work attempts to investigate the effect of drill point angle on the level of force and temperature in bone in the presence of ultrasonic vibrations imposed on the drill along the drilling direction. The effect of drill speed on the drilling force and bone temperature was studied using two types of drills with different point angles. The influence of a range of ultrasonic frequencies and amplitudes of vibrations on drilling force, torque and surface temperature of bone was also investigated. The drilling force and bone temperature were found to be strongly influenced by the drill point angle in the presence of ultrasonic vibrations. The drill with larger point angle caused more force and temperature compared to the drill with smaller point angle. Ultrasonic frequency above 15 kHz was observed to produce more temperature in bone for both types of drill geometries. This study found drill with smaller point angle favorable for safe and efficient drilling in bone.

Keywords Orthopedics · Bone drilling · Drilling force · Bone temperature · Ultrasonic drilling

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1 Introduction

For centuries, bone drilling is one of the most common and oldest surgical procedure performed in orthopedics, maxillofacial, oral and trauma surgery. Mechanical and thermal damage to the bone tissue during drilling are contributing factors affecting bone integration leading to implant failure and other postoperative complications [1, 2]. Damage induced in the bone due to overheating either requires strong antibiotic medications or repetition of surgical procedure. The exact level of temperature for inducing necrosis in bone is not known and reported to be within the range between 50 and 70 °C [3, 4]. Significant ischemia in the bone is expected around the drilled holes due to thermal changes [2]. Large drilling force during the process may result in micro fractures in the bone surrounding the cutting area [5]. Drilling force and torque exceeding a certain limits may cause the breakage of the drill during surgical procedures [6]. In addition, elevated temperature in bone drilling process may cause death of the cells which may seriously affect osseointegration. Several studies have researched the effect of drilling parameters and drill geometry on force and temperature with the aim to improve the outcome of the process [7–16]. Orthopedic and dental surgeons use sterile saline to keep the drilling track clear of bone swarf and manage temperature of the bone well below the thermal threshold level. However, there is no technique currently in place to lower the force, torque and temperature during bone drilling. A comprehensive review on the bone drilling process describing parameters affecting drilling force, torque and bone temperature are briefly discussed in recent studies [17, 18].

Among other geometrical parameters of the twist drill, the effect of point angle on the level of force and temperature in conventional drilling (CD) of bone has widely been discussed in the literature [10, 14, 17, 18]. The drill point angle was found to have no significant effect on bone temperature in CD of bone [19, 20]. Karmani [9] recommended drill point angle ranging from 110° to 118° for bone drilling with no vibration assistance. Natali [10] found a drill with point angle of 118° a better option for drilling the bone. Large point angle of a drill was found to produce large drilling force compared to the drill with smaller point angle in drilling carbon fiber reinforced plastic [21]. In that study, the point angle of the drill was found to have no significant effect on the drilling torque. In another study [22], while investigating the drilling effort in woven carbon fiber reinforced plastic, the drilling thrust force was found to be strongly affected by the point angle of the drill. The drill with point angle of 140° produced much larger force compared to the drill with point angle of 90°.

Lower force, torque and temperatures are critical for safe and efficient drilling in bones. Technological advancement in bone surgical procedures is concerned with minimizing the effort to penetrate the tool into the bone tissue and temperature rise in the cutting region. Recently, ultrasonically assisted drilling (UAD) in bone has been proposed for minimal invasion to bone. In UAD, high frequency vibrations are superimposed on the drill in the drilling direction coupled with rotation of the drill. The technique has been found to reduce the drilling force, torque, bone temperature and micro-cracks in the drilling region and resulted in better surface finish compared to conventional drilling (CD) due to its enhance cutting mechanism [23–25]. Ultrasonic vibrations imposed on a plane cutting tool in the cutting direction also produced lower cutting force compared to the conventional cutting [26].

Despite strong dependency of drill geometry on the performance of drilling process, previous studies did not investigate the effect of drill point angle on drilling force, torque and bone temperature in UAD. The prescribed geometric parameter of the twisted drill is proved to be the most influential in affecting the outcome of the process. Drill point angle controls penetration and walking of the tip of the drill on the curved and slippery surface of the bone. Investigation about the optimum point angle of the drill is important for industries involved in designing and developing minimal invasive tools for bone surgical procedures. The present paper studies the effect of point angle on the level of force and temperature in bone in the presence of ultrasonic vibrations. The influence of ultrasonic frequency and amplitude of vibration on the drilling force, torque and temperature rise in bone using two different point angles is investigated and discussed.

2 Materials and Methods

Drilling tests were performed on a cow bone excised from the diaphysis of a fresh femur. The average age of the animal was two years. Femurs were collected from a local butcher shop immediately after the slaughter. The middle sections called cortical bone were sliced into 50–60 cm-long sections. The average thickness of cortical wall was between 7 and 8 mm. The specimens were cut in two halves with a hand hacksaw and each half was attached to a metal piece with bonding paste. A couple of holes were drilled at different locations of the specimens to see internal porosity and visible disease. Some specimens were rejected after initial drilling tests as internal damage was seen. Soft issues on the top surface of the bone were cleaned with knife. The specimens were kept refrigerated before using them in experiments.

A conventional lathe machine with variable rotational speed of the chuck was used in drilling experiments. Force and temperature data was obtained without the application of cooling (irrigation) in experiment. Drilling thrust force was measured using a two-component dynamometer (Kistler type 9271A). A Thermosensorik IR camera (InSb 320 SM/M, Germany) was used for temperature measurements in bone drilling. The camera has a central processing unit equipped with software for real-time data processing. The sensitive range of the IR detector head was between 1 and 14 μm. The camera has temperature resolution of 20 mK and spatial resolution of 20 μm per pixel. The camera was calibrated with the help of K-type thermocouples. Thermal camera was focused on the area of contact between the drill and the bone. An emissivity of 0.95, consistent with values reported in the literature [27, 28], was used in the current study. The surface temperature of the bone was recorded from the time the drill started penetration into the bone until it passed through the cortex.

An in-house experimental set up with auto-resonant control system was used in the experiments. The main feature of the experimental set up was the design of ultrasonic transducer for imposing vibrations on the drill. The design of transducer was such that it could produce vibration only in the longitudinal axis of the drill. The flexible design of the ultrasonic transducer allowed fitting to both a lath and drilling machine. The main elements of UAD system were a high frequency generator, a transducer and a drill. Experimental set up for force, torque and temperature measurement in drilling is shown in Fig. 1. Two types of standard twist drills having 4.5 mm diameter and point angles of 118° and 90° were used in drilling experiments. Drill point angle is a geometrical parameter of the twisted drill and is the angle included between the cutting lips and a line parallel to the drill axis (see Fig. 2).

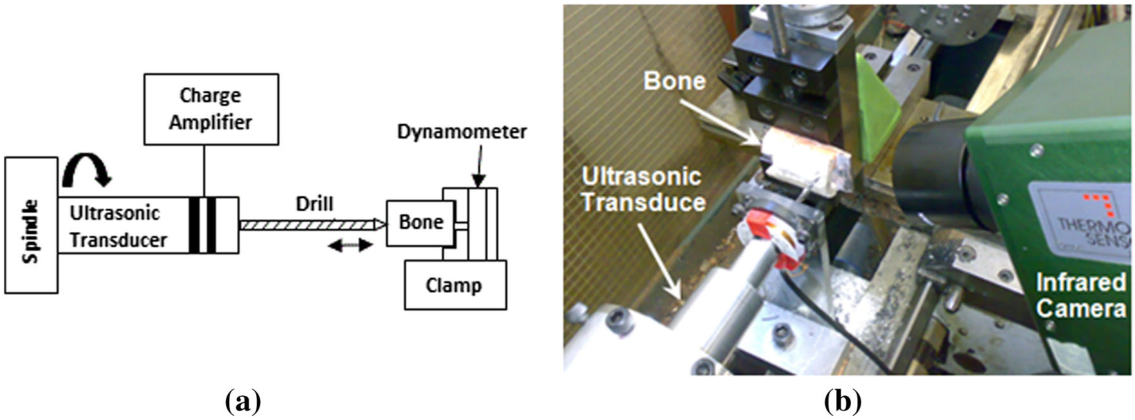

Fig. 1 Experimental set up **a** force and torque measurements, **b** temperature measurements

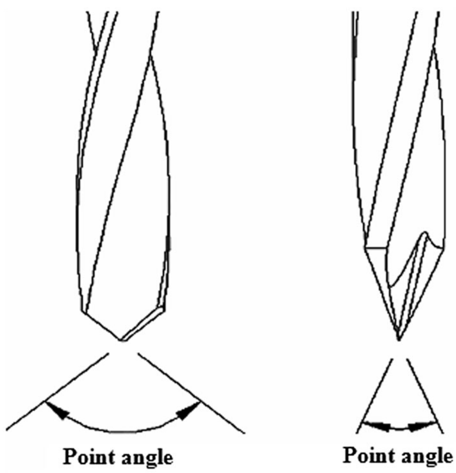

Fig. 2 Schematic diagram of drill point angle

A laser vibrometer was used to measure the frequency and amplitude of vibration in UAD. The frequency and amplitude were measured for the tip of the drill in free vibration since it was not possible to monitor them when the drill was engaged with the bone.

To obtain a reliable thermal data on bone drilling using infrared camera, temperature rise in the bone tissue was also measured using thermocouple imbedded in the bone and predicted by modeling the process using Finite Element (FE) simulation. Measurement of bone temperature using thermocouple and FE simulation is shown in Fig. 3. The thermocouple was inserted at a depth equal to approximately half of the thickness of the cortical wall of the bone and a distance of 1 mm from the drilling track. Experiment was repeated by placing the thermocouple at three different depths along the thickness of the cortical wall. The average difference in temperature was not more than 4 °C. A more significant difference was found when the thermocouple was placed at depths more than 30 mm [29]. Temperature near the drilling region was also simulated using thermomechanical FE model of bone drilling. The thermal properties of bone used in simulation are reported in a recent study on bone drilling [7]. The largest difference in temperature among the thermographic measurements, measurements using thermocouple and FE simulation was 7 °C.

3 Results

Force, torque and temperature readings were obtained from the drilling systems shown in Fig. 1. The bone was fixed in the holding device and the drill was rotated in the chuck. The force, torque and temperature data were recorded from the time when the cutting edges of the drill touched the bone surface until they were fully engaged in cutting. The values were observed to stay at maximum constant values from the beginning of the process till the cutting edges of the drill were fully engaged with the bone. Each experiment was repeated three times for a particular set of drilling and ultrasonic parameters. Evolution of force and surface temperature of bone during drilling are shown in Fig. 4. Thermographic images obtained during drill penetrating in bone are shown in Fig. 5. The effect of drilling speed and ultrasonic parameters on the level of force and temperature for two types of drills is discussed below. The feed rate was kept fixed at 50 mm/min in all experiments.

3.1 Effect of Drilling Speed on Drilling Force and Temperatures

The effect of drill speed on drilling force using two types of drills was studied. Drilling was performed for a set of drilling parameters using drill with large point angle followed by the one with small point angle. The drilling speed was changed from 1000 to 3000 rpm and the feed rate was kept constant at 50 mm/min. Ultrasonic frequency and

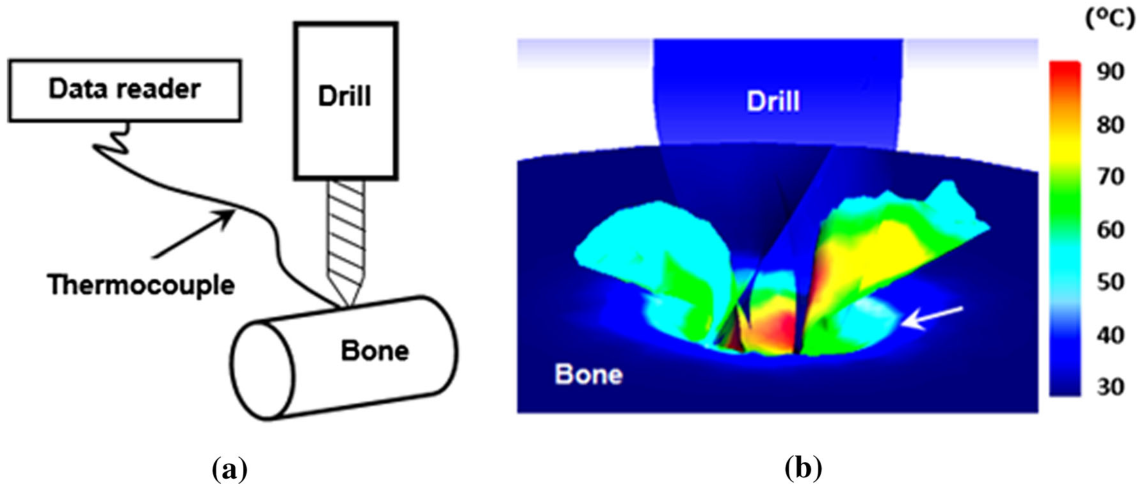

Fig. 3 Temperature measurement in bone drilling **a** measurement with thermocouple, **b** prediction using FE simulation

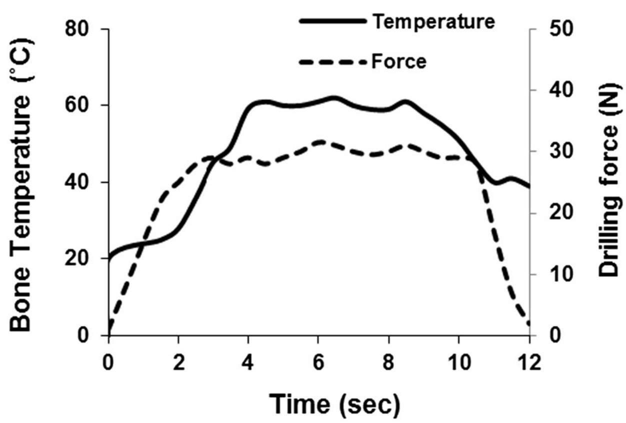

Fig. 4 Evolution of drilling force and temperature in experiments (drill point angle—118°, frequency 15 kHz, amplitude 10 µm, drill speed—2000 rpm)

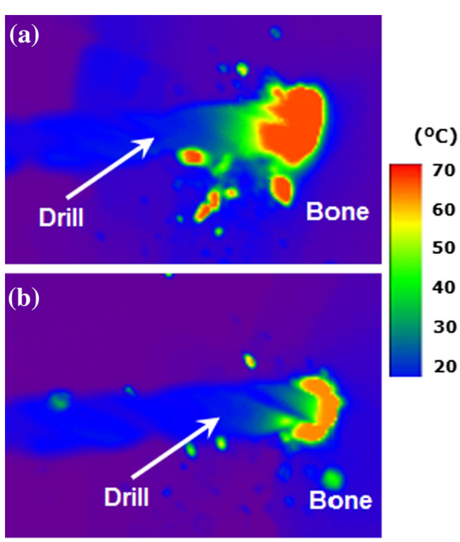

Fig. 5 Images from infrared thermography of bone drilling **a** drill point angle—118°, **b** drill point angle—90°

amplitude were kept at 15 kHz and 10 µm. Variation of drilling force with drill speed for both types of drills is shown in Fig. 6. The drilling force was observed to decrease linearly with drill speed. The force was decreased by 56% (from average maximum force of 41 to 18 N) when the drilling speed varied from 1000 to 3000 rpm using large point angled drill. A decrease of 62% (from average maximum force of 35 to 13 N) was noted for similar change in drilling speed when smaller point angled drill was used. The drill with larger point angle produced, on average, 4–6 N more force than with smaller point angle for the range of drill speeds used in the experiments. The drop in the force with increase in the drill speed was also observed for other values of feed rates used in this study.

Variation of surface temperature with drill speed using both types of drills was also studied. Ultrasonic frequency and amplitude were kept at 15 kHz and 10 µm respectively. The bone surface temperature was found to rise

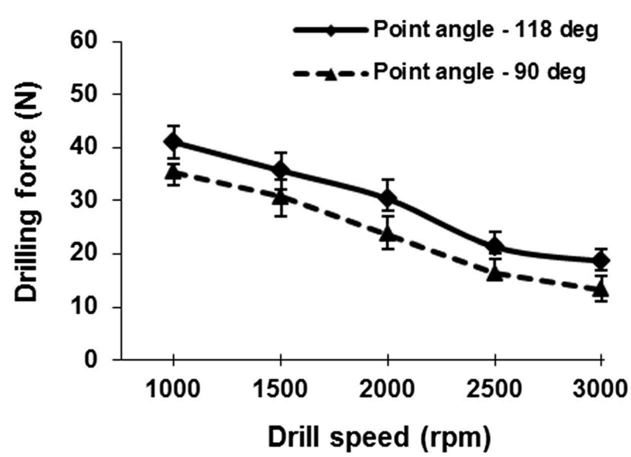

Fig. 6 Effect of drill speed on drilling force (frequency—15 kHz, amplitude 10 µm)

linearly with increase in the drill speed. The variation of temperature with drill speed for both types of drills is shown in Fig. 7. It was observed that the surface temperature of the bone increased from an average value of 44–70 °C when the larger point angled drill's speed was increased from 1000 to 3000 rpm. A similar rise in temperature was also recorded while using drill with smaller point angle.

3.2 Effect of Frequency and Amplitude on Drilling Force and Torque

The effect of ultrasonic frequency and amplitude on the level of drilling force and torque was investigated. To study the effect of frequency on drilling force and torque, the amplitude of vibration, drill speed and feed rate were kept constant. Similarly, to find the effect of amplitude of vibration on the drilling force, torque, frequency, drill speed and feed rate were kept at constant values. The drilling force was found to decrease linearly with increase in frequency imposed on the drill for both types of drills. The effect of frequency on drilling force for both types of drills is shown in Fig. 8. The drill with large point angle produced more force compared to the one with small point angle. The force was observed to decrease from an average value of 47 to 21 N when the frequency was increased from 5 to 25 kHz using drill with larger point angle. Similarly, the force was dropped from 37 to 14 N, for similar increase in frequency using drill with smaller point angle. The effect of amplitude of vibration on drilling force was rather insignificant for the range of amplitudes used in the experiments (see Fig. 9).

The effect of ultrasonic frequency and amplitude on drilling torque for both types of drills is shown in Figs. 10 and 11, respectively. The effect of frequency and amplitude

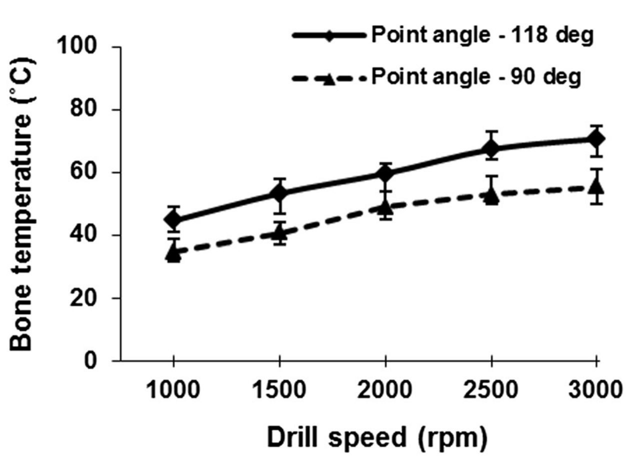

Fig. 7 Effect of drill speed on surface temperature of bone (frequency—15 kHz, amplitude 10 μm)

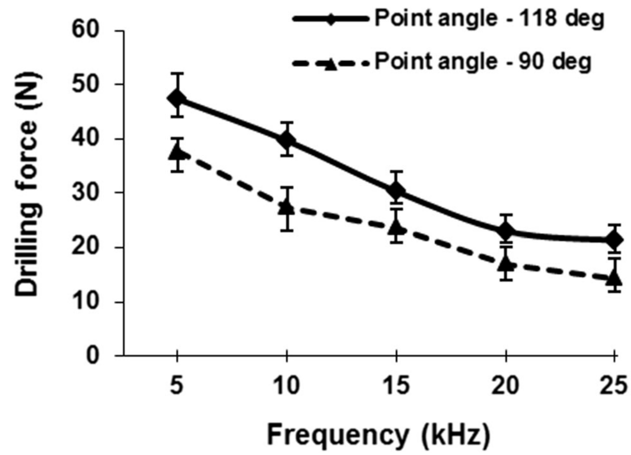

Fig. 8 Effect of ultrasonic frequency on drilling force (amplitude 10 μm, drill speed—2000 rpm)

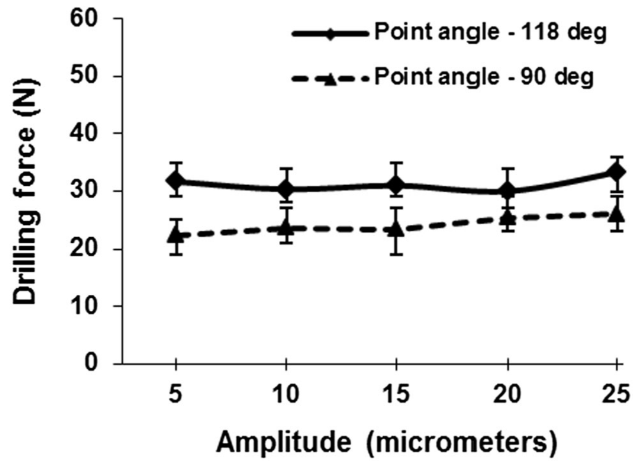

Fig. 9 Effect of amplitude of vibration on drilling force (frequency—15 kHz, drill speed—2000 rpm)

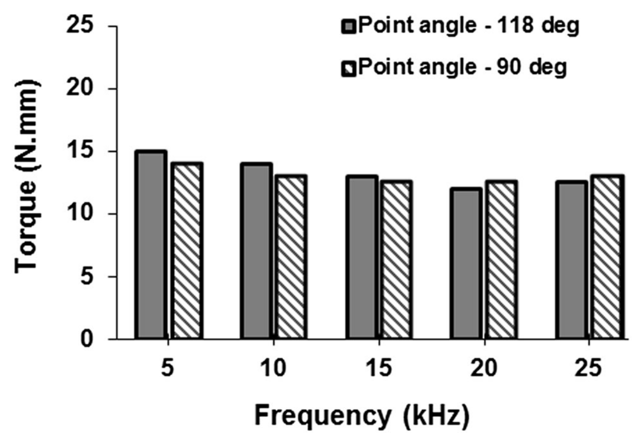

Fig. 10 Effect of ultrasonic frequency on drilling torque (amplitude 10 μm, drill speed—2000 rpm)

of vibration on drilling torque was insignificant for both types of drills used in the experiments.

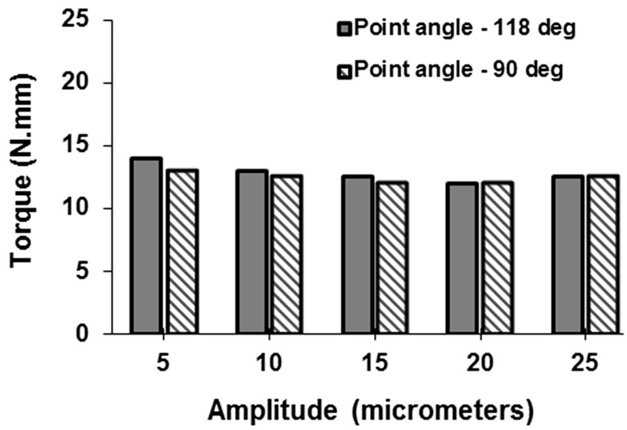

Fig. 11 Effect of amplitude of vibration on drilling torque (frequency—15 kHz, drill speed—2000 rpm)

3.3 Effect of Frequency and Amplitude on Surface Temperature of Bone

To study the effect of ultrasonic frequency and amplitude on surface temperature of bone, the drilling speed and fed rate were kept at 2000 rpm and 50 mm/min, respectively. The effect of ultrasonic frequency on surface temperatures is shown in Fig. 12. The average surface temperature of bone was observed to drop when frequency was increased from 5 to 15 kHz. However, an increase in surface temperature was noted when frequency above 15 kHz was used. Bone temperature was found to drop from a mean value of 80 to 60 °C when frequency was changed from 5 to 15 kHz using drill with larger point angle. Bone temperature was increased from 60 to 75 °C when frequency was increased from 15 to 25 kHz. Similar behavior was also observed using drill with smaller point angle. Variation of surface temperature with increase in amplitude of vibration is shown in Fig. 13. The effect of ultrasonic

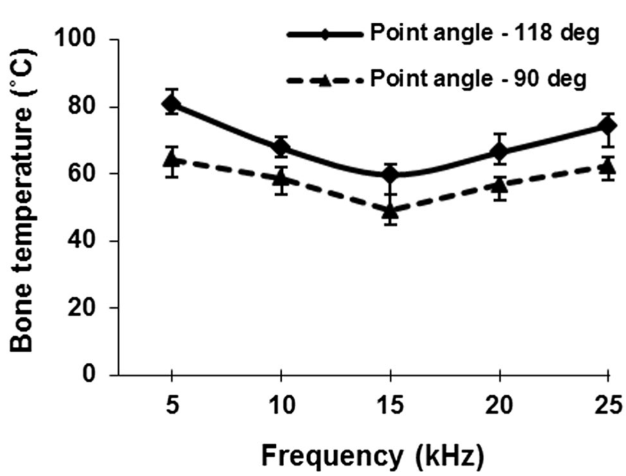

Fig. 12 Variation of surface temperature of bone with ultrasonic frequency (amplitude 10 μm, drill speed—2000 rpm)

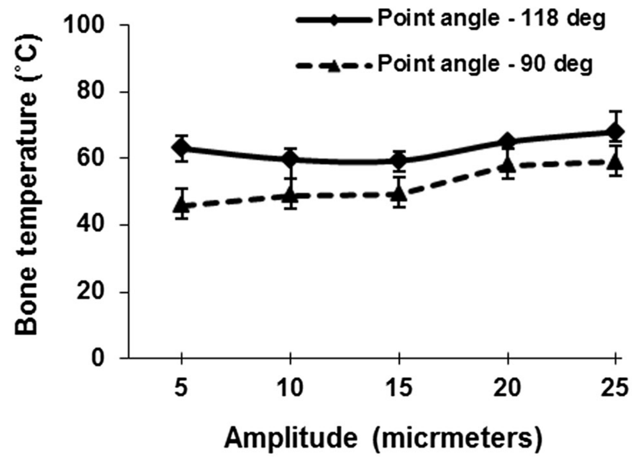

Fig. 13 Variation of surface temperature of bone with amplitude of vibration (frequency—15 kHz, drill speed—2000 rpm)

amplitude on surface temperature of bone was found insignificant up to 15 μm. A small increase in bone temperature was recorded when amplitude was varied from 15 to 25 μm.

4 Discussion

Higher drilling speed caused lower friction between the drill and the bone which reduced the drilling force. The drop in the force could be the result of the chip formation mechanism at higher drilling speeds due to the vibration which may affect the drilling force. Smaller chips were observed to produce at higher drilling speeds which could be a possible reason for lower drilling force. Higher frequency imposed on the drill produced more tiny chips compared to those produced using lower frequency. This phenomenon significantly reduced the drilling force. Large point angle provided full contact of the cutting lip with the bone as soon as the drilling started. Smaller point angles allowed the drill to penetrate with more ease preventing walking of the drill. However, small point angle may cause less portion of the cutting lip involved in the cutting action.

Interestingly, UAD produced lower temperature with frequency up to 15 kHz and below compared to CD for the same drilling speed and feed rate. A slight drop in the bone temperature up to 15 kHz was due to the intermittent contact between the drill and the bone. The vibrational motion of the drill up to frequency of 15 kHz caused quick engagement and disengagement of the drill with the bone that decreased the average friction at the contact of the drill and the bone over the time. Decrease in the average friction between the drill and the bone interface produced lower temperature. The drop in the average friction between the drill and the bone was dominant over the heat dissipation into the bone by the vibrational motion of the drill with lower values of frequency. However, using frequency above 15 kHz, the amount of heat dissipation, due to high frequency of vibration of the drill, was dominant over the decrease in the friction between the drill and the bone.

In UAD of carbon fiber reinforced plastics, the feed rate above 20 mm/min, the drill did not separate from the workpiece and a condition similar to CD was observed [30]. It is reasonable to expect increase in bone temperatures with frequency above 15 kHz due to the increase in the rate of material deformation of bone during the cutting process. The increase in temperature at higher drilling speed caused the thrust force to drop and it may be attributed to the local softening of the bone material adjacent to the cutting lips of the drill as well the change in the frictional condition between the drill and the bone. Ultrasonic bone aspiration yielded lower thermal rise in precision bone removal than rotary mechanical drills [31].

A small increase in surface temperature at amplitude above 15 μm was due to the increase in the contact time between the drill and the bone. That condition allowed the cutting edges of the drill to remain in contact with the bone for more time which caused more heat generation in the drilling zone in one cycle of ultrasonic vibration. We expect similar trend of drilling force and temperature if ultrasonic drilling is used to drill holes in spongy (trabecular) bone. It is important to mention here that the largest change in the drilling force, bone temperature and torque was for the drilling speed of 3000 rpm used in this study. Different optimum values for the range of vibration frequency and amplitude can exist for drilling speeds higher than 3000 rpm. One of the advantages of using UAD in bone is the lower level of torque produced at all times which will help in preventing the drill from breakage and stalling during surgical incisions.

5 Limitations of the Study

Contrary to the real orthopedic surgeries, where saline solution at lower temperature is used to cool the drilling region, cooling (irrigation) was not performed in the current study. It is expected that the acquired data of force, torque and temperature will vary if a coolant medium is used in the drilling experiments. The use of saline solution will certainly keep the temperature at the interface of the drill and bone lower than those observed in this study. The cooling medium will also alter the frictional condition at the drill-bone interface which will obviously change the drilling force and torque.

The frequency and amplitude of vibrations were measured when the drill was freely rotated (without drilling into bone). We expect that the frequency and amplitude values will remain the same while drilling the bone since the bone is relatively soft material. However, real time measurement of the frequency and amplitude values are to be measured during drill penetration in future studies. Imposing ultrasonic vibrations on the drill in the presence of coolant will alter the mechanics of the process in the drilling zone. One of the possible consequences of ultrasonic vibration would be the vaporization of the coolant in the drilling zone which should get attention in future studies. The current study relied on the results observed in [7], where yield stress of the cortical bone was found insensitive to strain rates above 1/s. Further research is required to investigate cell response of the bone to higher strain rate experienced in UAD.

6 Conclusion

This study investigated the effect of an important geometrical parameter (point angle) on the drilling force, torque and temperature in ultrasonic drilling of bone. Higher drilling speeds should be used in bone drilling to avoid overstressing of the bone. Drill with smaller point angle was found more appropriate for ultrasonic drilling since it requires lower effort for penetration. Ultrasonic frequency up to 15 kHz may be used to produce lower temperature in bone. A combination of lower frequency ranging from 5 to 15 kHz with amplitude of vibration up to 25 μm may be used for safe and efficient drilling in the bone. Right selection of ultrasonic parameters together with optimum drill geometry may be used for minimal invasive drilling in harder portion of the bone. This study suggests the use of efficient cooling system when frequency is higher than 15 kHz in bone drilling.

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