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Comparison between Torsional Ultrasonic Assisted Drilling and Conventional Drilling of Bone: An *in vitro* Study

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Abstract**—**Background: Reducing torque during bone drilling is one of the effective factors in reaching to an optimal drilling process. Methods: 15 bovine femurs were drilled in vitro with a drill bit with a diameter of 4 mm using two methods of torsional ultrasonic assisted drilling (T-UAD) and convent conventional drilling (CD) and the effects of changing the feed rate and rotational speed on the torque were compared in both methods. Results: There was no significant difference in the thrust force measured in both methods due to the direction of vibrations. Results showed that using T-UAD method for bone drilling at feed rates of 0.16, 0.24 and 0.32 mm/rev led for all rotational speeds to a decrease of at least 16.3% in torque compared to the CD method. Further, using T-UAD at rotational speeds of 355~1000 rpm with various feed rates resulted in a torque reduction of 16.3~50.5% compared to CD method. Conclusions: Reducing the feed rate and increasing the rotational speed, except for the rotational speed of 500 rpm and a feed rate of 0.32 mm/rev, resulted generally in torque reduction in both methods. However, T-UAD is a more effective and desirable option for bone drilling considering its significant torque reduction.

Keywords—Torsional ultrasonic assisted drilling, torque, bone drilling, rotational speed, feed rate.

I. Introduction

BONE drilling is necessary in treatment of bone fractures as well as in manufacturing of artificial limbs and parts in which various bone-like materials such as hydroxyapatite are used. Several factors such as bone material properties, screw length, geometry and material of the drill bit, feed rate and tool rotational speed are effective in proper bone drilling [1]. Several studies on bone drilling have examined the effects of these parameters during the drilling process. However, the resultant of all these parameters appears in the form of increase in torque and thrust force and this increase leads finally to damages to bone or its surrounding tissues. In general, the failure to control the torque and the thrust force and ignoring them will lead in many cases to increased stress concentration at the drilling site, loosening or widening, reduction of drilling precision as well as inappropriate coaxial alignment [2]. Previous studies have shown that the uncontrolled torque increase during bone drilling raises the micro damages in the surrounding bone and the Histomorphometric parameters such as density of crack, number of cracks and length of crack [3]. Another reason for the importance of controlling torque is that the rise of torque in drilling can lead to the break of drill bit at the drilling site [5], [6]. The cause of increase in torque and thrust force during the drilling process is the plastic deformation of chips, the friction between drill bit and bone as well as the friction between chips and hole wall [4].

Wang et al. compared the automatic and manual drilling and found out that 30-60% of the machining time decreases in automatic drilling. Further, they found out that the torque increases with the rise of feed rate [7]. Some studies examined the effects of gas coolant on the improvement of the bone drilling efficiency during longitudinal and transverse drilling [8], [9]. However, there is currently no definitive and effective technique to reduce torque in bone drilling process. Hence, several studies have used the new drilling methods such as the ultrasonic assisted drilling (UAD) to address this concern.

Alam et al. compared in three studies the changes in torque, thrust force, rotational speed, feed rate, and frequency and amplitude of vibration in UAD and CD [10]-[12]. In similar studies, Shakouri et al. compared the changes in thrust force during drilling using UAD and CD [13]. Singh et al. compared the surface topography of bone in CD and UAD [14]. Lii et al. examined the microstructure of the bone tissue around the formed hole in the skull bone using the UAD and CD [15]. Some studies compared the parameters such as torque, thrust force, shape and roughness of chips during UAD and CD of non-bone materials [16], [17].

In UADs, a vibration, mainly in two forms, is added to the drill bit in order to improve the drilling process. A purely longitudinal vibration produces a vibration in the direction of the drill bit advancement and a purely torsional vibration produces a vibration in the direction of the drill bit twist. However, none of the previous studies used the mechanism of purely torsional ultrasonic vibrations for bone drilling. Even all the available torque transducers for drilling non-bone materials converted the longitudinal vibrations into torsional vibrations using piezoelectric elements. However, the purely torsional ultrasonic vibrations were used for bone drilling for the first time in the present study. Furthermore, the type of the transducer used in this study differed from the transducer types in the previous studies.

II. Material and Method

A. Specimens

15 bovine femur bones extracted from the cadaver

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immediately after slaughter were used for tests. This choice was based on the fact that the bones of cow, dog and pig have the most similarity to human bones regarding the material properties. The mid-section of the diaphysis of the femur with a length of approximately 75 mm was divided into 25 mm pieces for testing. Prior to testing, the periosteum over the drilling site was removed because the presence of this layer causes problems in chips removal and obstructs the drill bit grooves. The tests were carried out at room temperature and all specimens were drilled with a diameter of 4 mm to a depth of 9 mm.

B. Experiment Design

The torque data were recorded from the moment of the complete contact of the drill bit with the bone surface until the end of the drilling process and the highest value of each test was reported. Thereafter, the effect of the rotational speed and feed rate was evaluated and compared for the two methods of CD and T-UAD. The rotational speeds of 355, 500, 710 and 1000 rpm and the feed rates of 0.16, 0.24 and 0.32 mm/rev were examined. It should be noted that tests have also been performed for high rotational speeds (above 1000 rpm) but in high rotational speeds, vibrations were transformed linearly due to increase in oscillation and hence, no significant changes were observed in the measured torque and thrust force. The selected feed rates agreed with those in previous studies [18].

C. Test Equipment

Bone drilling using purely T-UAD is a drilling method based on adding vibrations in the direction of drill bit twist. In this process, high-frequency vibrations (about 20 kHz) with a small amplitude (4-20 micrometer) are added to CD. The velocity of the tool vibration in this method is equal to a.ω.cos(ωt) (a and ω are the amplitude and angular velocity of the tool, respectively). In the present study, a Magnetostrictive torque transducer was used to create torsional vibrations. The transducer is composed of a Magnetostrictive horn, an end plate of steel and a housing. In this transducer, a spiral magnetic field consisting of two axial and circumferential components is applied to the horn. As a result, the horn undergoes torsional deformation based on the Wiedemann effect in the Magnetostrictive materials. The vibrating instrument used in this study consists of four parts: drill bit, coupling system (collet and nuts), intermediate piece and a Magnetostrictive material (Fig. 1). To measure the drilling torque, a TML Strain Gauge (DC97A) was installed on the intermediate piece. The strain gauge converts the resistance changes to voltage using a Wheatstone bridge. The obtained voltage is amplified and filtered by a data logger and displayed on an oscilloscope (Fig. 1). The data logger sensitivity is set to 2 V per 100 ppm. It should be noted that the values obtained for each test condition were repeated for five times. The coefficient of variation between the values obtained from the tests was less than 0.36. The frequency of resonance was 7200 Hz and the amplitude of transducer without connecting to other equipment was 1.2 (mrad) or 0.77 degrees in this study. A TN50B-R lathe was used in this study to carry out experiments. The important point is that the thrust force during drilling was also compared using a Kistler 9257BA dynamometer for both T-UAD and CD method. Since the vibration generated in this study was purely torsional, and not longitudinal, no significant changes were observed in thrust force values. Hence, only the results of torsional torque for T-UAD and CD methods were reported.

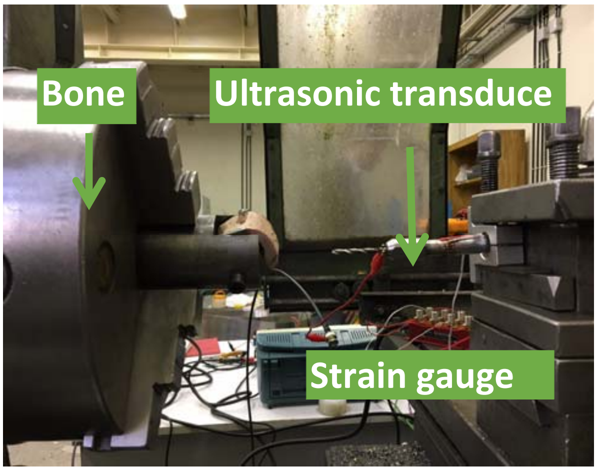

Fig. 1 (a) Overview of testing equipment

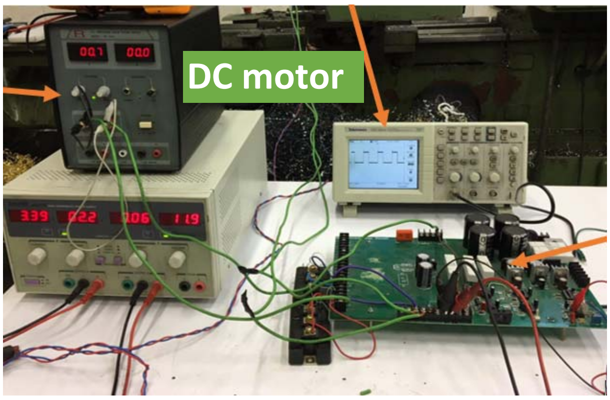

Fig. 1 (b) Auxiliary equipment for generating torsional vibration and torque measurement

D. Formulation for Torque Measurement

We have from the equation of shear stress due to shear strain and torsional torque:

$$\frac{Tr}{J} = G\gamma \tag{1}$$

where T, J, r, G and γ are torsional torque, moment of inertia, radius, shear modulus and shear strain, respectively.

By inserting γ from (2) in (1), the torsional torque is obtained according to (3).

$$\gamma = r\frac{d\phi}{dz} \tag{2}$$

$$T = \frac{GJd\phi}{dz} \tag{3}$$

dφ and dz in (2) and (3) are the radius and thickness of the element, respectively. The torsional torque has been measured according to (4) after inserting the constant values -based on the dimensions and material used in this study - in (3).

$$T=2.909444X\ SMV \quad (4)$$

It should be noted that at each stage of the test, the SMV (strain meter voltage) value in volt was read from the oscilloscope, and the torsional torque in Newton meter was recorded according to (4).

III. Results

A. The Effect of Rotational Speed

By keeping the feed rates constant, the effect of rotational speed on torsional torque due to drilling was compared for both CD and T-UAD methods in this section. Initially, the vibrational mode of the device was cut off and the bone was drilled using CD method. At each the progression rates of 0.16, 0.24, 0.32 mm/rev, the bone was drilled at the rotational speeds of 355, 500, 710, 1000 rpm. The results of the measurement of torsional torque in CD method at 3 different feed rates have been presented in Fig. 2 (a). At the feed rate of 0.24 mm/rev, raising the rotational speed from 355 to 1,000 rpm led to the decrease in torsional torque by 17.2%. The similar value for the feed rate of 0.16 mm/rev was 25.9%. However, in the feed rate of 0.32 mm/rev, the torsional torque increased by 44.8% after raising the rotational speed from 355 to 500; the further increase in the rotational speed up to 1000 rpm led to the decrease in torsional torque by 60% (Fig. 2 (a)).

Fig. 2 (b) shows the results of torsional torque measurement in T-UAD method for three different feed rates. The general trend of torque diagrams based on rotational speeds in this method is almost similar to that in the CD method. With the rise of the rotational speed from 355 to 1000 rpm at the feed rates of 0.16, 0.24 and 0.32 mm/rev, the torsional torque has decreased by 16.3%, 25.9% and 25.9%, respectively. However, with the rise of the rotational speed from 355 to 500 rpm at the feed rate of 0.32 mm/rev, the torsional torque increased first up to 2.41 times and then with the further rise of the rotational speed up to 1000 rpm, the torsional torque decreased.

B. The Effect of Feed Rate

By keeping the rotational speed constant, the effect of feed rate on torsional torque due to drilling was compared for both CD and T-UAD methods in this section. According to Fig. 3 (a), the torsional torque increased in the CD method with raising the feed rate from 0.16 to 0.36 mm/rev. The amounts of the increase for the rotational speeds of 355, 500, 710, and 1000 rpm were 74.1%, 150%, 62.8% and 34.9%, respectively (Fig. 3 (a)). It should be noted that for rotational speeds of 355 and 500 rpm, the amount of increase in torsional torque at the feed rates of 0.16 to 0.24 mm/rev was less than the torque increase at the feed rates of 0.24 to 0.32 mm/rev and this trend was reversed for rotational speeds of 710 and 1000 rpm.

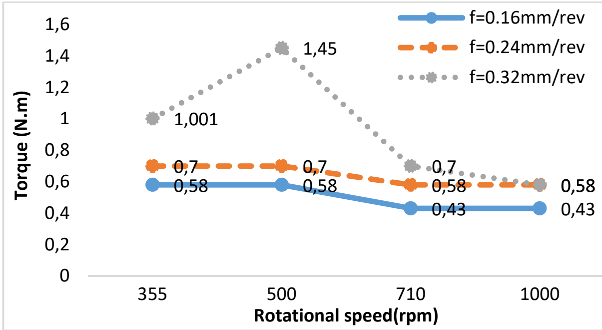

Fig. 2 (a) Torque variations based on rotational speed at constant feed rates in CD method

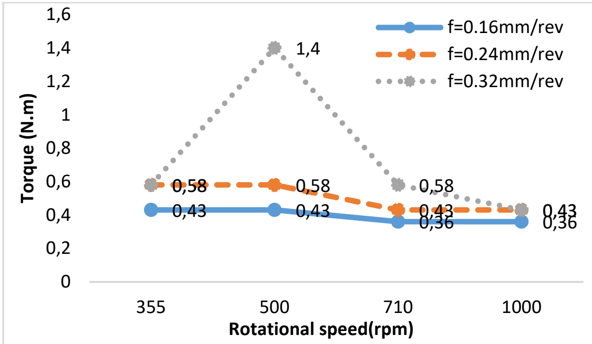

Fig. 2 (b) Torque changes based on rotational speed at constant feed rates in the T-UAD method

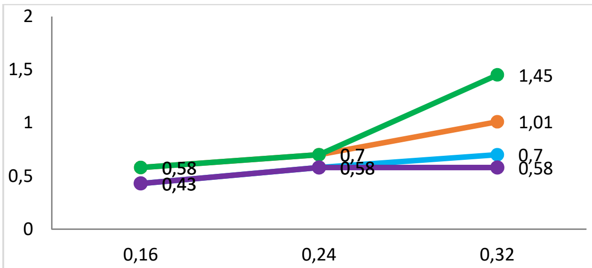

Fig 3 (a) Torque changes based on feed rate at constant rotational speeds in CD method

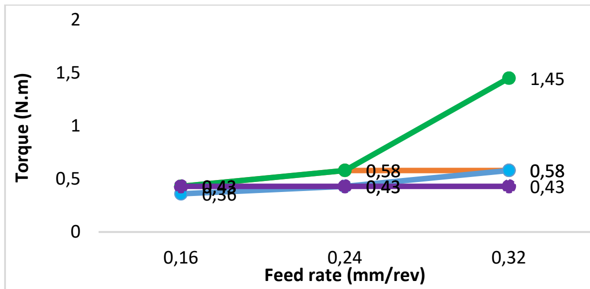

Fig. 3 (b) Torque changes based on feed rate at constant rotational speeds in T-UAD method

According to Fig. 3 (b), the trend of torque diagrams based on feed rates at the same rotational speeds in the T-UAD method was similar to that in the CD method. The torque rise due to the increase in feed rate from 0.16 to 0.32 mm/rev at rotational speeds of 355, 500, 710, and 1000 rpm was 34.9%, 225.6%, 34.9% and 19.4%, respectively (Fig. 3 (b)).

IV. Discussion

The drilling force measurement showed that applying torsional vibrations to the instrument did not have any significant effect on the thrust force and this could be attributed to the direction of applying the vibration. Since the vibrations were applied in the direction of the drill bit twist, the reduction of friction and flue stress at the longitudinal direction were also very small and unnoticeable.

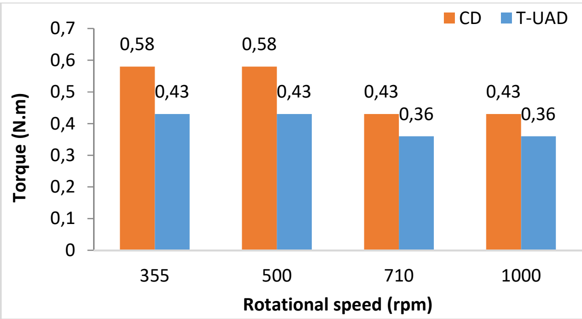

Fig. 4 (a) Comparison of torque values based on rotational speed at feed rate of 0.16 mm/rev between CD and T-UAD methods

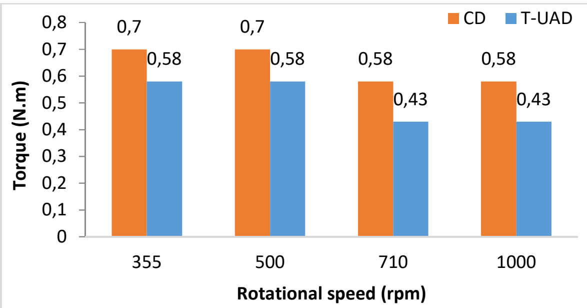

Fig. 4 (b) Comparison of torque values based on rotational speed at feed rate of 0.24 mm/rev between CD and T-UAD methods

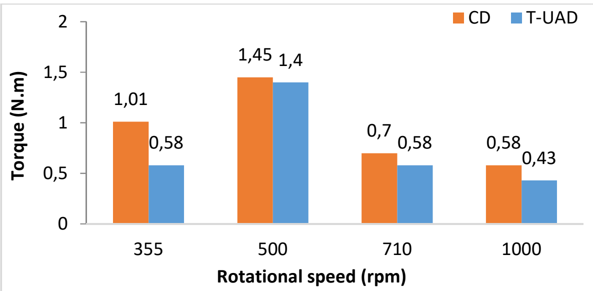

Fig. 4 (c) Comparison of torque values based on rotational speed at feed rate of 0.32 mm/rev between CD and T-UAD methods

According to the results in Figs. 4 (a) and (b), raising the rotational speed from 355 to 500 rpm and from 710 to 1000 rpm at the feed rates of 0.16 and 0.24 mm/rev caused no changes in the torque amount in both CD and T-UAD methods. However, raising the rotational speed from 500 to 710 rpm in the CD method resulted in a decrease of 25.9% and 17.1% in the torsional torque amounts at feed rates of 0.16 and 0.24 mm/rev, respectively. The amount of the torque reduction in the T-UAD method was 16.3% and 25.9%, respectively. In general and under similar conditions, using the T-UAD method for bone drilling at feed rates of 0.16 and 0.24 mm/rev leads in a decrease of at least 16.3% and 17.2% in torque compared to the CD method (Figs. 4 (a) and (b)).

According to Fig. 4 (c), raising the rotational speed at the feed rate of 0.32 mm/rev - except for the rotational speed of 500 rpm – has led to the torque increase. At other rotational speeds, using the T-UAD method reduces the torque by 17.2-42.6% compared to the CD method.

The torsional torque decreased in both CD and T-UAD methods by increasing the rotational speed (Fig. 4) and this provided more desirable conditions for drilling. However, this trend did not exist for the rotational speed of 500 rpm at the feed rate of 0.32 mm/rev. This can be due to the reduction of the unreformed chip thickness. Generally, the cause of torsional torque reduction with the rise of rotational speed can be the increase in the exiting speed of bone chips as this will reduce the chips accumulation in the drill bit grooves and consequently the torque. The trend of torque reduction in the T-UAD method is almost similar to the CD. However, the T-UAD method results in a greater torque reduction (16.3-42.6%) by reducing the size of chips through generating torsional vibrations at the tool tip and creating microcracks in bone. Observations also showed that friction between the chips and tool as well as between the chips and the hole walls decreased due to the continuous vibration of the tool in the T-UAD method and the chips exited the grooves without accumulation.

The results of Fig. 5 showed that the unreformed chip thickness and consequently the torsional torque increased with the rise of the feed rate and these made the drilling conditions undesirable. The torque reduction with raising the feed rate from 0.16 to 0.24 mm/rev at the rotational speed of 355 rpm was in the T-UAD 14.1% higher than that in the CD method. However, increasing the feed rate from 0.24 to 0.32 mm/rev caused no changes in torque in the T-UAD method (Fig. 5 (a)). In general, using the T-UAD method with the rotational speed of 355 rpm at feed rates of 0.16, 0.24 and 0.32 mm/rev resulted in a torsional torque reduction of 25.9%, 17.1%, and 50.5%, respectively, compared to the CD method (Fig. 5 (a)).

The results of Fig. 5 (b) showed that at the constant rotational speed of 500 rpm and the feed rates of 0.16, 0.24 and 0.32 mm/rev, using the T-UAD method led to a torsional torque reduction of 25.9%, 17.1% and 3.1% compared to the CD method. The torque reduction with raising the feed rate at the constant rotational speed of 500 rpm was in the T-UAD method 14.2% to 34.5% higher than that in the CD method. This demonstrates the effectiveness of the T-UAD method (Fig. 5 (b)).

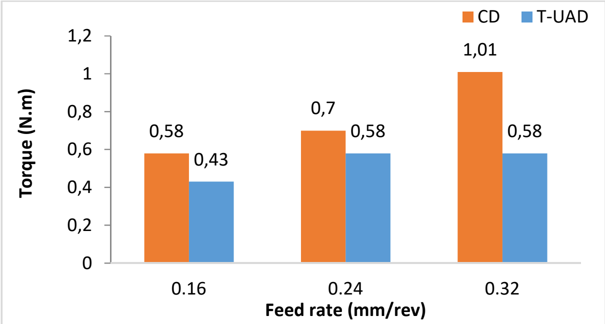

Fig. 5 (a) Comparison of torque values based on feed rate at the rotational speed of 355 rpm between CD and T-UAD methods

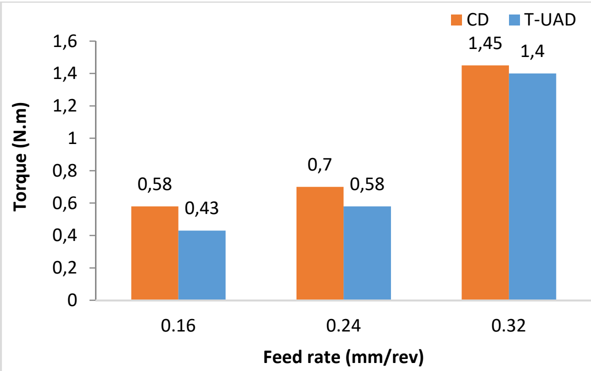

Fig. 5 (b) Comparison of torque values based on feed rate at the rotational speed of 500 rpm between CD and T-UAD methods

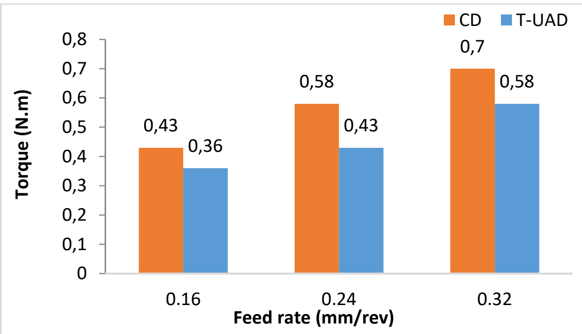

Fig. 5 (c) Comparison of torque values based on feed rate at the rotational speed of 710 rpm between CD and T-UAD methods

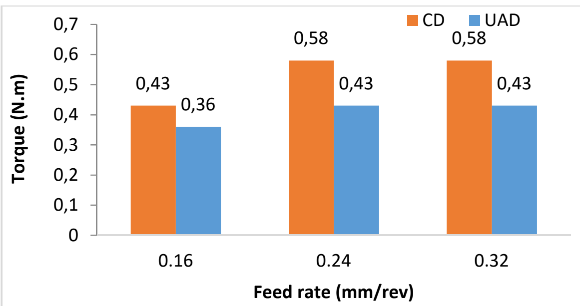

Fig. 5 (d) Comparison of torque values based on feed rate at the rotational speed of 1000 rpm between CD and T-UAD methods

The trend of torque variation at the constant rotational speeds of 710 and 1000 rpm was similar to that of the rotational speed of 500 rpm (Figs. 5 (c) and (d)). For both rotational speeds of 710 and 1000 rpm, using the T-UAD method at the feed rates of 0.16, 0.24 and 0.32 mm/rev led to a torsional torque reduction of 16.3%, 25.9% and 17.1% compared to the CD method.

V. Conclusion

In the present study, bovine femur was drilled at different feed rates and rotational speeds by adding torsional vibrations to UAD, and the results were compared with the results of the CD method. Since vibration was applied in the direction of the drill bit twist, no significant changes were observed in the amount of thrust force measured in both T-UAD and CD methods. Further, the general trend of torque changes based on rotational speed and feed rate was similar in both T-UAD and CD method. The results showed that using T-UAD for bone drilling at feed rates of 0.16 and 0.24 mm/rev resulted at all rotational speeds in a torque reduction of at least 16.3% and 17.2% compared to the CD method. Raising the rotational speed at the feed rate of 0.32 mm/rev - except for the rotational speed of 500 rpm – led to torque rise. At other rotational speeds, using the T-UAD method reduced the torque by 17.2~42.6% compared to the CD method. The results also showed that using T-UAD at the rotational speed of 355~1000 rpm with different feed rates led to a reduction of 16.3~50.5% in torsional torque compared to the CD method. Despite the fact that reducing the feed rate and increasing the rotational speed, except for the rotational speed of 500 rpm and feed rate of 0.32 mm/rev, resulted in torque reduction in both methods, the significantly smaller value of torque in the T-UAD method compared to the CD method showed that T-UAD method is an effective and proper alternative to the CD method for bone drilling.

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