Research Article

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Ultrasonic longitudinal torsion-assisted biotic bone drilling: An experimental study

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Abstract: State-of-the-art treatment of such orthopedic diseases as fracture and femoral head necrosis implies the installation of prosthesis or fixed equipment into patients' injured parts using bone drilling. This study proposes an ultrasonic longitudinal torsion-assisted drilling (ULTAD) technique for biotic bone drilling. A comparative experiment was carried out between conventional drilling and ULTAD drilling in biotic bone, namely porcine femur. These tests proved that under the same drilling parameters, the ultrasonic component in bone drilling could reduce the drilling temperature and forces, improve the material removal by chip breaking, shorten the length of bone debris, and facilitate their discharge. Moreover, the proposed ULTAD technique reduced the number, length, and width of microcracks in the borehole wall, thus protecting the drilled biotic bone from internal damage.

Keywords: ultrasonic longitudinal torsion, biotic bone, drilling temperature, drilling forces, effect of drilling

1 Introduction

To treat fractures and related orthopedic diseases, microholes are drilled in the patient’s injured bones to implant plates, nails, and other fixation devices by doctors. However, relatively high drilling forces and temperatures in conventional bone-drilling operations may cause serious damage to bone tissue [1,2]. Therefore, factors influencing the bone-drilling process have been thoroughly investigated [3–6].

Therefore, it is necessary to investigate the forces and temperatures during the bone-drilling process. The mechanism of bone chips’ removal during bone drilling is the continuous relative motion between the drill bit and the bone tissue surface that allows the removal of bone chips. The friction between the drill bit and the bone tissue surface and the variation of shear force during the drill feed lead to the variation of drilling temperature. Due to the poor thermal conductivity of the bone tissue, the drill bit has a high temperature in contact with the bone tissue [7]. Studies have shown that when bone tissue is continuously exposed to 47°C for 60 s or 50°C for 30 s, the cells become permanently necrotic [8].

A large number of scholars have conducted research on how to reduce drilling temperatures, drilling forces, and the number of microcracks. The study shows that the controlled machining parameters have a significant effect on the drilling force and the temperature in the drilling zone [9]. Therefore, some studies related to the processing parameters of bone drilling were carried out. Song’s team built a 3D model of a new drill bit that assembles the inner core (bit) and the drill sleeve together, conducted a drilling simulation study using a 3D cylinder instead of the skull, and found that the tip angle of the bit has a greater effect on temperature than on drilling force [10]. MacAvelia et al. found through conventional
drilling (CD) experiments that the tool speed has a direct effect on the cutting force at a constant feed rate and drill diameter [11]. Fernandes et al. [12] used thermocouples to monitor the temperature rise during bone drilling and found that bones of different densities had different drilling temperatures during the drilling process. Sugita et al. [13] designed a drilling tool for drilling cattle bones, which can reduce temperature rise and cutting force, and found that multi-groove cutting tool design can reduce the temperature during drilling. Soriano [14] found that the drilling force increases with increasing tool feed rate and decreases with increasing tool speed by studying the variation of drilling force and temperature during bovine bone drilling. Sarparast et al. [15] found that increasing the tool speed could reduce the drilling force and temperature when drilling bovine femur. Yahui et al. found that the drilling force fluctuated to some extent due to the mechanical properties of the bone, and the relationship between the drilling force and the experimental parameters was close to an exponential relationship according to the regression model established [16–18].

In addition to traditional bone drilling, a great deal of research has focused on developing new bits and new bone-drilling techniques to optimize drilling forces and temperatures and improve drilling quality [19–24]. Ultrasonic vibration-assisted machining has the advantages of reducing the drilling heat and drilling force generated during machining, improving the surface quality of the workpiece, reducing the exit burr height, and improving the drilling condition [25,26]. Wang et al. found that the temperature in the borehole area was inversely related to the frequency and amplitude of ultrasonic vibration [27]. Chen et al. [28] found that low-frequency ultrasonic vibration can effectively reduce thermal damage during drilling; compared with conventional bone drilling, the maximum drilling temperature of this drilling method can be reduced by 27% and the thermal damage coefficient can be reduced by 18.3%. To reduce the drilling force and drilling temperature and improve drilling temperature, related scholars put forward the method of rotary ultrasonic bone drill. Gupta and Pandey [29] performed rotational ultrasound and CD tests on pig bone and found that drilling force and drilling temperature decreased with increasing ultrasound amplitude and tool speed. Singh et al. [30] applied rotary ultrasonic drilling to human cadaveric bone samples and found that rotary ultrasonic drilling bone drilling temperatures could be reduced to 50–60% and drilling forces could be reduced by 30–40% compared to conventional bone drilling. However, during rotational ultrasonic bone drilling, friction between the soft tissue of the bone and the sharp edge of the drill bit can lead to increased drilling temperatures and increased drilling forces at the bone–bit interface. The increased drilling force and temperature may lead to increased microcracking and risk of bone thermal necrosis in bone repair procedures, and the drilling force may affect bone chip morphology and microcrack generation at the bone–bit interface site.

Studies have shown that ultrasonic longitudinal torsion-assisted drilling (ULTAD) can improve the drilling forces and excessive drilling temperatures during machining. However, ULTAD technology has not been applied to bone-drilling tests [31].

Herein, we propose a novel technique for biotic bone drilling: ULTAD. The proposed technique is compared with CD of biotic bone to clarify trends of drilling force and temperature during drilling and compare the surface quality of biotic bones after drilling.
2 Kinematics analysis in ULTAD

2.1 Basic principles of the ULTAD

Figure 1 describes the ULTAD motion model of drill bone. The axial displacement equation of the blade in ULTAD is:

\[ Z(\theta) = -f_r \theta/2 \pi + A \sin(f\theta/n) \]  

where \(A\) is the ultrasonic amplitude (unit: \(\mu\)m); \(\theta\) is the angle between any point on the cutting edge and the \(X\)-axis; \(f_r\) is the feed rate of tool or workpiece (unit: \(mm/r\)) and \(n\) is the rotation speed of tool (unit: \(rpm\)).

The tool path at a specific moment during the ULTAD can be expressed as:

\[
\begin{align*}
X(\theta) &= \rho \cos \theta \\
Y(\theta) &= \rho \sin \theta \\
Z(\theta) &= -f_r \theta/2 \pi + A \sin(f\theta/n).
\end{align*}
\]  

At zero amplitude \(A = 0\), the cutting edge path during the CD can be determined as follows:

\[
\begin{align*}
X(\theta) &= \rho \cos \theta \\
Y(\theta) &= \rho \sin \theta \\
Z(\theta) &= -f_r \theta/2\pi.
\end{align*}
\]  

According to equations (2) and (3), the cutting tool paths during ULTAD and CD bone-drilling processes at \(f = 35\) kHz, \(A = 4\) \(\mu\)m, \(\rho = 2\)mm can be constructed, as shown in Figures 2 and 3, respectively.

As can be seen in Figures 2 and 3, there is a clear difference between the two cutting edge paths: in CD, the cutting edge path is a regular spiral curve; in ULTAD, the cutting edge path is wavy and can be approximated by a sine curve. This can be attributed to the change in tool motion (regular feed) due to the presence of ultrasonic longitudinal torsional vibrations. This also indicates that ULTAD has a larger repetitive cutting area for the same drilling conditions, which facilitates the change of chip thickness, achieving bone chip breakage and improving the surface finish of the drilling.

2.2 Chip thickness analysis

During the drilling process, the crushing and discharge of bone chips have a direct impact on the drilling temperature. The longer the chip is, the more difficult it is to remove and the higher the drilling temperature. Therefore, it is necessary to analyze the bone chip fracture effect.

According to the twist drill design, at the same time, two main cutting edges (a cutting edge, b cutting edge) on the point of symmetry about the central axis, their angle difference is \(\pi\). Therefore, the axial displacement equations of \(a\) and \(b\) are:

\[ Z_{fa} = -f_r \theta/2\pi + A \sin(f\theta/n), \]  

\[ Z_{fb} = -f_r (\theta + \pi)/2\pi + A \sin\left(f(\theta + \pi)/n\right). \]

Therefore, the variable cutting thickness under ULTAD can be obtained:

\[ Z = Z_{fb} - Z_{fb} = -f_r/2 - A \sin(f\theta/n) + A \sin(f(\theta + \pi)/n). \]
The motion track diagram and chip thickness curve diagram of ultrasonic vibration drill bone cutting edge are drawn in MATLAB, as shown in Figure 4.

As can be seen in Figure 4, the distance between two adjacent main cutting edges in the ULTAD drill bone varies regularly and periodically. With the twist drill rotating at high speed and constantly feeding, there will be a regular intersection between the two insert trajectories, i.e. the chip thickness between the two cutting edges changes periodically during the ULTAD bone-drilling process, and when the chip thickness of the two cutting edge trajectories intersecting is zero, thus achieving bone chip crushing. According to this property, the desired chip effect (thickness and length) can be obtained theoretically by changing the ULTAD parameters and machining parameters.

3 Materials and methods

3.1 Materials

It was found that the bone density and fracture stress of pigs and dogs were closest to those of human bones [32]. Therefore, fresh pig bones were selected as the test material to ensure the accuracy of the test results. First, the two large ends of the femur of pigs slaughtered and purchased on the same day were sawed off, leaving the spine. Then, to facilitate clamping and to facilitate the observation of drilling quality and repeated cleaning of the inner wall of the hole after the experiment, the pig femur before and after treatment is shown in Figure 5.

3.2 Equipment

The test tool is a 4 mm diameter stainless steel twist drill with a tip angle and spiral angle of 118 and 28°, respectively, as shown in Figure 6.

Fresh pork bone-drilling tests were conducted on a VMC850E machine on a vertical machining center. The test platform is shown in Figure 7. A crystal piezoelectric triaxial dynamometer model 9257B was used to collect drilling forces during drilling, in conjunction with a 5070A multi-channel charge amplifier. A FLIR T640 infrared thermometer was used to capture the temperature changes during drilling. SEM was used to observe microcracks on the surface of the biologic bone.

3.3 Tool ultrasonic amplitude test

Measurement of drill end amplitude output is performed using a KEYENCE-LK laser displacement sensor. The device has a sampling period of 128–2048 μs and a repeatability accuracy of 0.01 μm. When measuring the tool tip amplitude, the beam needs to be focused at the tool to be tested, and by adjusting the distance between the laser displacement transducer and the tool, the vibration data can be collected stably, and the value of the measured amplitude is known by the auxiliary software. Since the tip of the drill is not a flat surface, it is very difficult to gather the beam at the tip. On the premise of ensuring the accuracy of the measurement data, a small part of the tip of the drill to be measured is ground off with a grinding wheel to form a microplane. The maximum axial amplitude measured was 8 μm, as shown in Figure 8.
Since this experiment uses a longitudinal twist type composite variable amplitude rod, in addition to calibrating the axial vibration of the drill, this experiment also deflects the laser displacement sensor by a certain angle to calibrate the cutting edge amplitude and to improve the accuracy, multiple points of amplitude calibration were performed on both the left and right sides of the drill.

### 3.4 Approach

The selection of machining parameters is determined according to the previous research, as shown in Table 1 [33]. The cutting edge path at any time was derived via Eq. (2). Each drilling test was conducted three times with the same parameter, and the mean value was adopted as the test result. Under the same processing parameters, the ULTAD and CD were conducted on the same pig femur by alternating processing. First, zero ultrasonic component was used for CD. Then, a non-zero one was added to provide the ULTAD to ensure the test reliability.

![Figure 5: Test materials. (a) Untreated pig bone and (b) treated pig bone.](image1)

![Figure 6: Experimental tool.](image2)

![Figure 7: The test platform.](image3)
Table 1: Selected test parameters and their values

<table>
<thead>
<tr>
<th>Processing parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bit diameter (mm)</td>
<td>4.0</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>35,000</td>
</tr>
<tr>
<td>Amplitude (μm)</td>
<td>0, 2, 4, 6, and 8</td>
</tr>
<tr>
<td>Spindle speed (rpm)</td>
<td>800, 1,400, 2,000, 2,600, and 3,200</td>
</tr>
<tr>
<td>Feed rate (m·min⁻¹)</td>
<td>10, 20, 30, 40, and 50</td>
</tr>
</tbody>
</table>

4 Results

The following discussion is related to the results of the test group with a spindle speed of 2,000 rpm, a feed rate of 20 mm·min⁻¹, an ultrasonic-assisted frequency of 35 kHz, and an ultrasonic amplitude of 4 μm.

4.1 Drilling temperature during ULTAD

Drilling zone temperatures measured via the FLIR T640 infrared thermometer during the ULTAD and CD as shown in Figure 9. Herein, the blue part was the processed pig femur. As observed, ULTAD bone drilling could effectively reduce the maximal temperature in the drilling zone by 4°C. The discharge of hot chips released part of the heat.

4.2 Axial force in ULTAD

A piezoelectric crystal three-way dynamometer was used to collect the axial force data under the two bone-drilling conditions, as shown in Figure 10.

The axial force started to rise slowly when the drill bit touched the porcine femur and started drilling; when the
Drill bit was completely in the porcine femur, the axial drilling force showed a steady state with slight fluctuations at this stage; and when it was in the drilling-out stage, the axial force started to decrease slowly. The maximum axial force was 41.98 and 32.05 N for CD and ULTAD, respectively, with a difference of 23.65%. This strongly indicates that ULTAD effectively reduces the axial drilling force.

This improvement was mainly due to the change in contact modes between the tool and bone from continuous contact to intermittent contact, which reduced the effective contact area, thus reducing the friction between tool and bone and then reducing the maximum axial force. As observed, the ULTAD had a slightly larger fluctuation range than CD because there was acceleration between the bit and biotic bone under the ULTAD bone-drilling conditions. The acceleration changed periodically, which induced the larger fluctuation range under ultrasonic-assisted conditions.

### 4.3 Chip-breaking effect of ULTAD

Bone debris obtained via these two processing methods (see Figure 11) was selected for the comparative analysis.

As shown in Figure 11, the bone debris under the CD conditions included chips with a relatively long length. This increased the possibility of bone debris wrapping around the tool, inhibiting their removal, and scratching the inner wall of the hole in their removal process. The bone debris lengths under the ULTAD conditions were much shorter than under CD conditions. This was mainly because the paths between the two cutting edges in CD were parallel. The chip thickness was stable, and there was only a mechanical chip-breaking mode. In the ULTAD bone drilling, due to ultrasonic vibration, the two paths of cutting edges changed periodically, thus changing the thickness of bone debris and forming the geometrical chip-breaking effect to a certain extent.

### 4.4 Borehole cracking under ULTAD bone-drilling conditions

Drilling can easily cause tissue damage or even cracking of the biotic bone. It was necessary to study the microcracks of the inner wall of boreholes obtained via the CD and ULTAD bone drilling under the same processing parameters.

![Figure 11: Bone debris obtained by the two processing methods.](a) ULTAD and (b) CD.)
For bone drilling and microcrack on the inner wall of the hole, the images were selected for comparative analysis. The comparison of the microcracks on the inner wall of the boreholes drilled via the ULTAD and CD under the same processing parameters is presented in Figure 12 with magnifications of 45×, 100×, and 300×.

Figure 12: The comparison of the microcracks on the inner wall of the boreholes drilled. Left: CD; right: ULTAD. (a) 45×; (b) 100× and (c) 300×.
In Figure 12, at 45× and 100×, magnifications, the number, length, and width of cracks induced by CD were larger than that of ULTAD. Besides, in the former case, the inner wall of the borehole was rougher, and the knife mark was more obvious. At a 300× magnification, flake bone debris on the inner wall surface of the workpiece could be observed under both different processing methods, but the bone debris of the ULTAD was more compact. According to Agarwal et al., the strength of microcracks increases with increasing cutting force [34]. Compared to CD, ultrasonic torsional drilling has lower drilling forces and therefore better surface quality. In addition, the ultrasonic impact reduced the fracture stress of the workpiece, making the material removal easier and reducing the number, length, and width of microcracks.

5 Discussion

1) Due to the experimental conditions, this article does not study the effect of ultrasonic frequency on the maximum axial force and maximum temperature law. The tool used in this article is relatively single, and the next twist drill with different parameters can be selected for more detailed study.

2) Since the workpiece in this article is a fresh pig femur, there will be some differences between each individual workpiece. To eliminate the influence of experimental materials, fresh pig femurs of the same batch and the same growth cycle can be used in the next study.

6 Conclusions

In this article, we demonstrate that ULTAD is a method to improve the quality of bone drilling and reduce the risk of the procedure through the development of ULTAD model and drilling characteristics.

Compared with CD, ULTAD can effectively reduce the axial force in the borehole. The stress distribution in the ULTAD bone borehole is more uniform, and the maximum stress distribution area is smaller. Under the same processing parameters, the area temperature is lower in ULTAD compared to CD. The CD chip is in a continuous state, while the shape of the UVAD chip becomes intermittent, indicating that ULTAD bone drilling facilitates chip fracture. Also, ULTAD bone drilling can reduce the number, length, and width of microcracks on the hole wall.

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References


