Rotary ultrasonic bone drilling: improved pullout strength and reduced damage

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Rotary ultrasonic bone drilling: Improved pullout strength and reduced damage

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A B S T R A C T

Bone drilling is one of the most common operations used to repair fractured parts of bones. During a bone drilling process, microcracks are generated on the inner surface of the drilled holes that can detrimentally affect osteosynthesis and healing. This study focuses on the investigation of microcracks and pullout strength of cortical-bone screws in drilled holes. It compares conventional surgical bone drilling (CSBD) with rotary ultrasonic bone drilling (RUBD), a novel approach employing ultrasonic vibration with a diamond-coated hollow tool. Both techniques were used to drill holes in porcine bones in an in-vitro study. Scanning electron microscopy was used to observe microcracks and surface morphology. The results obtained showed a significant decrease in the number and dimensions of microcracks generated on the inner surface of drilled holes with the RUBD process in comparison to CSBD. It was also observed that a higher rotational speed and a lower feed rate resulted in lower damage, i.e., fewer microcracks. Biomechanical axial pullout strength of a cortical bone screw inserted into a hole drilled with RUBD was found to be much higher (55–385%) than that for CSBD.

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1. Introduction

Bone fracture is common and can happen as a result of road accidents, falls, sports injuries, etc. In many cases, bone drilling is necessary to insert screws, wires and fixing plates in a surgical procedure, for immobilization and alignment of parts for proper healing.

A success rate of these surgeries depends on the recovery time of patients, as well as biomechanical pullout strength of inserted screws. The latter is one of the important parameters for screw stabilization [1], since instability of a screw in the bone tissue can occur after a surgical operation [2,3]. Such failures may be due to diminished mechanical resistance of the bond. It was reported that an implant loosening rate was 2–7% [4–6] or even higher [2]. Apparently, pullout strength of the screw depends upon its design and geometry [2,7]. Thus many studies were conducted [2,7–10] to improve this parameter. Bertollo et al. [11] performed a comparative study of pullout strength of a 4.5 mm-diameter screw, inserted into a predrilled hole made with 2- and 3-fluted drill bits with diameter of 3.2 mm. No significant difference was found between pullout strengths for holes drilled with those methods.

Holes predrilled for screws are made with a conventional drilling process. But this process itself generates compressive forces and a torque that could be a cause of microcrack generation in the drilled bone. Tensile and compression force generate different types of microcracks and damage modes in the bone [12–15]. According to previously reported in-vitro investigations [16,17], microcracks were generated on the inner surface of drilled holes after bone drilling. An increase in the level of these microcracks could be the reason for a decrease in the stiffness and elastic modulus of the bone, which may further cause damage to it [18–21]. Some of these microcracks could disappear thanks to remodeling [21–23], but an increase in the length of these microcracks can lead to fracture [16,24]. If a length of microcracks is increased significantly this may be the cause of implant failure. Since the bone-drilling process generates an excessive amount of heat it can cause thermal necrosis.

To meet this challenges, a new drilling scheme – ultrasonically assisted vibrational bone drilling was introduced with the aim to reduce cutting forces and heat generation. In this scheme ultrasonic vibrational pulses are applied to a drill bit. Alam et al. [25] performed experimental study on bovine bone using ultrasonically assisted drilling and found that force and torque
significantly reduced as compared to the conventional drilling method. They also reported [26,27] that temperature could be reduced with this technique. Wang et al. [28] performed a comparative investigation of temperature changes in bone drilling with vibrational and conventional methods. Their study showed that vibration-assisted drilling generated lower temperature as compared to conventional drilling. In another experimental study, they reported that vibrational bone drilling generated fewer and shorter microcracks [16]. It was also reported that ultrasonically assisted drilling, resulted in a better surface as compared to the normal drilling method [29]. Recently, Singh et al. [17] compared the microcracks generated by ultrasonic bone drilling with abrasive particles and by the conventional method. They reported that the former did not generate any microcracks on the inner surface of the bone. However, using loose abrasive particles in bone drilling may cause infection and the drilling took a long time.

Therefore, in this study, efforts were made to reduce microcracks and increase axial biomechanical pullout strength of the cortical bone screw in a bone drilled with RUBD. The findings were compared with results of the CSBD method used with the same process parameters. A diamond-coated hollow tool was used for RUBD while a conventional orthopaedic surgical drill bit was employed in CSBD. An in-vitro study also showed a link between microcracks generated in the drilled-hole surface and axial pullout strength of the cortical bone screw.

2. Materials and method

2.1. Experimental setup and drilling procedure

In-vitro drilling of bone was conducted using a vertical-axis CNC milling machine. To perform RUBD, a separate ultrasonic-vibration tool assembly was designed and fabricated; it was clamped on a chuck of the CNC machine. This device and a generator (acquired from Unitech Allied Automation, India) operated at a frequency of approximately 20 kHz with a power of 800 W. Electric signals were supplied to the ultrasonic device with designed slip rings and carbon brushes Fig. 1(a). The device was coupled with one end on the housing and the CNC collet attached to the other end. Hollow drill tools of constant wall thickness (0.8 mm) with diamond coating were designed in house and manufactured by the Ajax & Turner Wire Dies Company, India. These tools were attached to the ultrasonic device and the complete assembly was mounted on the CNC machine head Fig. 1(a).

To perform CSBD, the assembly was unclamped from the CNC machine, and a surgical drill bit was used Fig. 1(b). New surgical drill bits were taken from the orthopedic operation theater of Government Hospital Sector 32, Chandigarh, India, provided by Trimed Systems Pvt. Ltd. Since bones have complex shapes, for ensuring safe drilling, a special bone-holding fixture was designed and fabricated. Experiments were performed in two sets. In the first set of experiments, microcrack analysis was carried out for the RUBD and CSBD processes while mechanical pullout strength was measured in the second set.

The literature analysis showed that low magnitude of speed and feed rate is preferred in the surgical drilling [30]. The experiments were planned and performed according to the process parameters for both the drilling processes, as listed in Table 1. In this work, no statistical method was used to plan the experiments. Suitable combinations of parameters which show the effect of variable rotational speed with a constant feed rate and variable feed rate with a constant rotational speed were used to study the pullout strength and microcracks. These parameters were chosen on the basis of the literature review conducted [25–27,30,31]. Alam et al. [27] reported that variation in the vibrational amplitude from 4 to 20 μm did not show any significant effect on a process temperature. While in another study [25] it was reported that forces decreased significantly with a change in the amplitude from 5 to 15 μm, and with further increase in the amplitude, no significant change was found in the cutting forces during bone drilling. So the vibrational amplitude of 16 μm and frequency of 20 kHz were chosen for the present study.

2.2. Preparation of bone specimens

In-vitro investigations were performed on fresh middle diaphysis parts of porcine bones taken from a local animal slaughterhouse Fig. 2(a). The drilling experiments and pullout tests were performed with in two hours. Therefore the effect of dehydration was minimized. No animal was sacrificed or killed for the present in-vitro study; only samples (bone) used in the food industry were taken. Porcine bones were chosen due to their resemblance to human bones [32–35]. Bone samples were prepared separately for analysis of microcracks and assessment of biomechanical pullout strength of cortical bone screws. The latter study was carried out on the middle section of the bone Fig. 2(b), whereas for the microcrack analysis, bone samples were further sliced into small pieces Fig. 2(c).

Duration of a bone-drilling procedure is a crucial factor; for the chosen range of the feed rates, a hole in a bone with wall thickness of 5 mm can be produced within 6–30 s. Experiments were performed on the same bone and two holes drilled with two studied

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Process parameters and their values for in-vitro experiment.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
<td>Units</td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>rpm</td>
</tr>
<tr>
<td>Feed rate</td>
<td>mm/min</td>
</tr>
<tr>
<td>Drill diameter</td>
<td>mm</td>
</tr>
<tr>
<td>Vibration amplitude</td>
<td>μm</td>
</tr>
<tr>
<td>Vibration frequency</td>
<td>kHz</td>
</tr>
</tbody>
</table>

*NA: Not applicable*
drilling techniques were approximately 30–40 mm apart in order to, on the one hand, avoid interaction of holes and, on the other hand, to allow maximal comparability of the obtained results.

2.3. Analysis of microcracks and hole quality

Drilled samples were examined for microcracks and surface morphology using a scanning electron microscope (Zeiss EVO 50 & EVO 18 Special) with magnification of 500X. A stereo zoom microscope (Discovery V20) was employed to observe the quality of drilled holes.

2.4. Measurement of biomechanical pullout strength

Axial pullout strength of cortical screws inserted in the bone was determined with INSTRON-5582, a single-action universal testing machine with a modified setup (Fig. 3). Cortical screws were pulled out from the bone sample with a crosshead speed of 0.5 mm/min. To accommodate middle diaphyses of bone samples with different shapes, a special bone-holding fixture was designed and fabricated (Fig 3(b)).

A series of experiments were executed to assess the biomechanical pullout strength. In total 20 experiments were performed, 10 for holes drilled with each analyzed drilling process (RUBD and CSBD). Drilled holes were made in the bone samples using a drill diameter of 4.0 mm with both processes, and cortical bone stainless steel screws with diameter of 4.5 mm (length 50 mm, head diameter 8 mm and pitch 1.7 mm) were inserted into the drilled holes. New cortical bone screws were used every time to insert in the drilled bone sample for comparability of results. Thickness of bone samples was approx. 5.0 mm in the pullout study; screws were inserted in the drilled hole at a depth of approx. 6 mm (Fig. 4).

3. Results

3.1. Microcrack analysis

In the first set of experiments, effects of rotational speed of the tool and the feed rate on formation of microcracks in the drilled bone were investigated for both processes. The experiments were performed according to a run order listed in Table 2; the drill diameter (4.5 mm) was kept constant. In order to investigate microcracks generated on the inner surface of the bone, specimens drilled with different operations and techniques were observed with SEM. The effects of rotational speed and feed rate on microcrack generation are shown in typical microscopic images for the two drilling methods in Figs. 5 and 6, respectively. Microcracks generated by the two processes are marked with red. No microcracks were found in RUBD for drilling speeds of 500 rpm to 2500 rpm at feed rate of 10 mm/min (Fig. 5(a,c,e)), while in case of CSBD they were generated in all conditions. An increase in the rotational speed resulted in a decrease in the width and number of microcracks (Fig. 5(b,d,f)).

The study of the effect of feed rate on the generation of microcracks by the two bone drilling process demonstrated that for both processes the length and number of microcracks increased with the feed rate increasing from 10 mm/min to 50 mm/min. Fewer and shorter microcracks were observed for RUBD as compared to holes drilled with CSBD.

3.2. Pullout strength

In the second set of experiments, effects of tool rotational speed and feed rate on the axial pullout strength were studied for cortical bone screws. The experiments were performed by varying the rotational speed and the feed rate while other process parameters were kept constant (Table 3). For each process, two experiments were performed for each rotational speed, and feed rate and the maximum pullout force was measured. For the final results, the average of the two trials was taken into account.

Typical force – displacement diagrams obtained in these tests are given in Fig. 7; they show a change in bone resistance to pullout with respect to time. The data demonstrates that axial pullout strength of cortical bone drilled with RUBD is higher than that of CSBD. Comparison of the two drilling techniques demonstrates that the axial pullout strength of a cortical bone screw grew with the increased rotational speed (Fig. 8(a) and decreased with the increased feed rate (Fig. 8(b) for both methods. Moreover, pullout strengths of cortical bone screws inserted in the RUBD drilled holes are consistently higher – from 5% to 38% – than for CSBD.

It was observed that the axial pullout of the cortical bone screw from the drilled hole caused delamination near the hole in the RUBD method (Fig. 9(a)); however, no such delamination was observed for the CSBD method (Fig. 9(b)). This also confirms that significantly higher forces were required to pullout the screw from the hole drilled with RUBD.

4. Discussion

In this work, two drilling methods - an existing (CSBD) method used in the orthopaedic operation theaters and a newly proposed (RUBD) were compared in terms of microcracks generated on the inner surface of drilled holes and a biomechanical pullout force for the cortical bone screw. According to the best knowledge of the authors, no study has been reported on analysis of the effects of rotational speed and feed rate on these two features. Measurement of the axial biomechanical pullout strength is an adequate way to evaluate the stability of screws inserted in the bone [17,36].
Table 2
Run order and process parameters in experiments for microcracks analysis.

<table>
<thead>
<tr>
<th>Drilling method</th>
<th>Run order</th>
<th>Rotational speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>Drill diameter (mm)</th>
<th>Vibration amplitude (μm)</th>
<th>Vibration frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUBD</td>
<td>1</td>
<td>500</td>
<td>10</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1500</td>
<td>10</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2500</td>
<td>10</td>
<td>4.5</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>500</td>
<td>30</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>500</td>
<td>50</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>500</td>
<td>10</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1500</td>
<td>10</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2500</td>
<td>10</td>
<td>4.5</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>500</td>
<td>30</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>500</td>
<td>50</td>
<td>4.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Effect of rotational speed on microcracks generation: (a), (c), (e) RUBD; (b), (d), (f) CSBD group. (a), (b) 500 rpm; (c), (d) 1500 rpm; (e), (f) 2500 rpm (feed rate 10 mm/min; drill diameter 4.5 mm; for RUBD: vibration amplitude 16 μm; frequency 20 kHz).
Most of the pullout-strength studies for the bone screws were performed with the perpendicular pullout method [2,7-10,37-42], which was also used in this study.

The obtained experimental in-vitro results showed that the length and width of the generated microcracks decreased with the increase in the rotational speed (Fig. 5) and feed rate (Fig. 6). Previously reported investigations of the conventional bone-drilling technique demonstrated that the magnitude of cutting force and torque dropped significantly with an increase in the rotational speed [25,31,43,44] and increased with an increase in the feed rate [25,31,44]. The ultrasonically assisted bone drilling also showed similar trends [25,45]. The hypothesis was that with the increase in the cutting force and torque, more microcracks were caused. O’Brien et al. [18] investigated the effect of microcracks generated on the compact bone of bovine tibiae. They reported that microcracks with length up to 100 μm could be repaired and controlled by using a cement line, while cracks with the lengths between 100 and 150 μm continued to grow even with a cement line close to an osteons. Furthermore, it was concluded that if the length of the microcracks was equal to, or greater than, 300 μm, they could cause bone failure.

The maximum length of microcracks generated by the two drilling processes with respect to each rotational speed [Fig. 5] and feed rate [Fig. 6] was measured with the medical image analysis software Digimizer. Table 4 shows that the maximum length of microcracks generated by CSBD process exceeded 300 μm (except in one case shown in Fig. 5(d)), whereas no microcracks were observed in the bone drilled with RUBD refer Fig. 5(a), (c) and (e). Only Fig. 6(c) and (e) show some microcracks with lengths of 87.6 and 122.2 μm, which were present at higher feed rates of 30 and 50 mm/min, respectively.

For the biomechanical pullout test, two trials were performed for the same combination of processing conditions. Since the drilling experiments were conducted on the CNC machine and the
Table 3
Run order and process parameters in experiments for biomechanical pullout.

<table>
<thead>
<tr>
<th>Drilling method</th>
<th>Run order</th>
<th>Rotational speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>Drill diameter (mm)</th>
<th>Vibration amplitude (μm)</th>
<th>Vibration frequency (kHz)</th>
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</thead>
<tbody>
<tr>
<td>RUBD</td>
<td>1,2</td>
<td>500</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3,4</td>
<td>1500</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5,6</td>
<td>2500</td>
<td>10</td>
<td>4.0</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>7,8</td>
<td>500</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>9,10</td>
<td>500</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSBD</td>
<td>11,12</td>
<td>500</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>13,14</td>
<td>1500</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15,16</td>
<td>2500</td>
<td>10</td>
<td>4.0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>17,18</td>
<td>500</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>19,20</td>
<td>500</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7. Force–displacement diagram for axial pullout of cortical bone screw (rotational speed 1500 rpm; feed rate 10 mm/min, drill diameter = 4.0 mm; for RUBD: vibration amplitude 16 μm; frequency 20 kHz).

The designed RUBD tool could drill without cracks providing high surface quality with very good circular profile, the measured force data demonstrate low variability. The axial biomechanical pullout strength for the cortical-bone screw increased with an increase in the rotational speed and decreased with an increase in the feed rate (Fig. 8). The error bars in Fig. 8 represent the maximum and minimum values of the measured pullout force. This shows that the grip of the inserted cortical bone screw is higher when there are fewer microcracks on the inner surface of drilled holes. As discussed, the proposed RUBD process demonstrated fewer and shorter microcracks on the inner surface of the drilled holes. As a result, the axial pullout strength in this case is much higher as compared to that of the existing bone-drilling method (CSBD). The reason for this is a lower cutting force and torque generated in RUBD similar to the previous studies reporting lower cutting forces and torques generated by ultrasonically assisted bone drilling [25]. In RUBD, the cutting mechanism is different, resulting in a cylindrical machined rod and powdered chips obtained in the drilling due to the hollow profile of the tool Fig. 10(a), whereas fragmented chips were formed in CSBD Fig. 10(b).

Fig. 8. Effects of rotational speed (a) and feed rate (b) on axial pullout force for two bone-drilling methods.
Table 4

<table>
<thead>
<tr>
<th>Rotational speed (rpm)</th>
<th>Feed rate (mm/min)</th>
<th>RUBD</th>
<th>CSBD</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>10</td>
<td>No cracks</td>
<td>350.0 μm</td>
</tr>
<tr>
<td>1500</td>
<td>10</td>
<td>No cracks</td>
<td>241.9 μm</td>
</tr>
<tr>
<td>2500</td>
<td>10</td>
<td>No cracks</td>
<td>328.6 μm</td>
</tr>
<tr>
<td>500</td>
<td>30</td>
<td>85.6 μm</td>
<td>375.8 μm</td>
</tr>
<tr>
<td>500</td>
<td>50</td>
<td>122.2 μm</td>
<td>422.3 μm</td>
</tr>
</tbody>
</table>

![Image](https://example.com/image.png)

Fig. 10. (a) Drilling of bone with RUBD produced powdered chips and cylindrical machined rod. (b) CSBD produced fragmented chips. Edge quality of holes drilled with RUBD (c) and CSBD (d) (black arrows show delamination near drilled hole edge) (rotational speed 500 rpm; feed rate 10 mm/min; drill diameter 4.5 mm; for RUBD: vibration amplitude 16 μm; frequency 20 kHz).

The hollow tool in the RUBD process generates lower cutting forces and torque ensuring better edge quality produced as compared to that in CSBD. As a result no delamination was observed in the area surrounding the holes drilled with RUBD Fig. 10(c). However, the use of the CSBD method led to poor hole-edge quality resulting in visible signs of delamination around it Fig. 10(d).

5. Conclusion

The findings obtained in the in-vitro test confirmed that RUBD could be a better alternative to conventional bone-drilling techniques. RUBD generated less damage, i.e. fewer and shorter microcracks and, as a result, significantly higher forces are needed to pull the screw out from the drilled hole, providing higher stability for implants and screws inserted in the bone. The obtained results also showed that the increase in the length of microcracks led to decrease in the strength of the bone screw bond: hence, there is a strong correlation between the microcracks and the pullout strength of the bone screw.

Conflicts of interest

None.

Funding

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Ethical approval

Not required.

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