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Research Article

Experimental Investigations on Microcracks in Vibrational and Conventional Drilling of Cortical Bone

Yu Wang,[1,2] Meng Cao,[1] Yuanyuan Zhao,[1] Gang Zhou,[1,2] Wenyong Liu,[1,2] and Deyu Li[1,2]

[1] *Key Laboratory for Biomechanics and Mechanobiology of Ministry of Education, International Joint Research Center of Aerospace Biotechnology and Medical Engineering, Ministry of Science and Technology of China, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China*
[2] *Research Institute of Beihang University in Shenzhen, Shenzhen 518057, China*

Correspondence should be addressed to Deyu Li; deyuli@buaa.edu.cn

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Bone drilling is widely used in orthopedic surgery. Microcracks will be generated in bone drilling, which may cause fatigue damages and stress fractures. Fresh bovine cortical bones were drilled via vibrational and conventional ways. Drilling operations were performed by a dynamic material testing machine, which can provide the vibration while maintaining uniform feed motion. The drill site and bone debris were observed through scanning electron microscope (SEM). The experimental results showed that fewer and shorter micro-cracks were formed in vibrational drilling than those formed in conventional way. And the surface morphology of bone debris from two different drilling ways was also quite different. It is expected that vibrational drilling in orthopedic surgery operation could decrease the microdamage to the bone, which could lower the incidence of stress fracture and contribute to the postoperative recovery.

1. Introduction

Recently, minimally invasive surgery has become one of the most important trend of orthopedic surgery, and it could decrease surgical trauma and shorter the recovery time for patients. As one of the most basic and common surgical operations, bone drilling has been widely used in the orthopedic surgery [1]. Drilling operation itself could also cause damages to the bone. Recent research in this area focused on the thermal damage in bone drilling, which could lead to bone necrosis or even osteomyelitis [2, 3]. In vivo animal experiments showed that if the temperature of bone rises to 50°C for more than one minute, it will cause the cortical bone necrosis [4–6]. Lundskog and Krause showed that when the temperature of bone rises above 50°C, thermal effects will lead to the degeneration of enzymes and membrane proteins in the bone, which causes bone necrosis [7, 8].

On the other hand, high-speed drilling also makes damages to bone microstructure. Experimental studies have indicated that many microcracks were generated in bone drilling. Meanwhile, excessive microcracks will be produced when the bone strain exceeds the threshold. These microcracks may cause fatigue damages in bone, because the increase of microcracks can decrease the bone stiffness and the elastic modulus [9–12]. Only a few of these microcracks can be repaired by bone remodeling process [13–15]. Therefore, rapid accumulation of microcracks will increase the bone fragility and lead to stress fractures [16]. When microcracks accumulate at normal rate and the bone's repair mechanism is deficient, it will lead to the collapse of the bone and even fragility fractures [17, 18].

Vibrational drilling is a new drilling method, which adds axial vibration to the drill bit. Additional vibrational pulse can effectively improve the drilling effect and reduce the cutting heat in the drilling process [19]. Alam et al. reported that vibrational drilling could significantly reduce drilling force and torque in cortical bone drilling [20]. Both cutting heat and drilling force/torque represent drilling energies, which have relationship with bone microcracks. Therefore, in this work, the hypothesis is that vibrational drilling can decrease the accumulation in microcracks during bone drilling. We

Figure 1: The precision cutting machine.

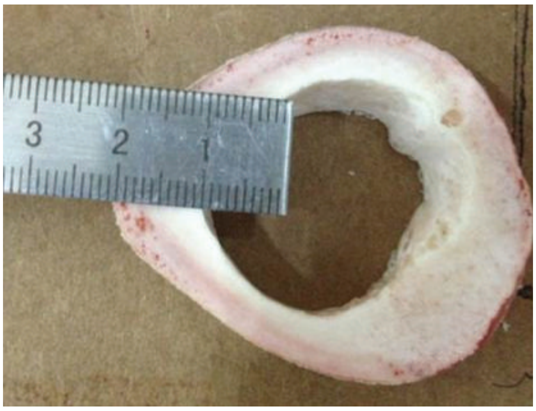


Figure 2: Specimen for drilling.

focused on the efforts to study the damages of vibrational and conventional drilling methods on bone microstructure. The differences in microcracks for different drilling methods were observed by the scanning electron microscope (SEM). This comparison research of microcracks in different drilling methods may suggest a new way to reduce the microcracks in bone drilling by changing drilling methods.

2. Materials and Methods

2.1. Specimen Preparation. According to current studies, the properties of bovine bones best resemble the properties of human bone [21]. Therefore cortical bone specimens, which were cut from bovine femur, were used in this research. Considering that the thickness of the cortical bone is not completely uniform, the bovine femur was cut into 1 cm long sections by a precision cutting machine (SYJ-200, China; Figure 1). Taking into account the average thickness of the cortical bone and to ensure the same drilling depth in the experiment, the drilling depth is fixed to 8 mm. The marrow was removed, and cortical bone thickness over 8 mm was marked for drilling as shown in Figure 2. Then the specimens were kept frozen until used. One hour before each experiment, the specimens were thawed in a thermostat-controlled bath adjusted at room temperature to guarantee each of the initial specimens was at room temperature before drilling.

Figure 3: Experimental arrangement for vibrational and conventional drilling.

2.2. Experimental Setup. As shown in Figure 3, in vitro drilling operations were performed by a dynamic material testing machine (Instron E10000, USA), which can provide the vibration while maintaining uniform feed motion (v = 40 mm/min). A vise was located on the table of the machine centre to fix the specimens. A hand drill was connected with a flexible drive rod, which can transfer rotation to another drill bit. The drill bit was fixed to the testing head of the machine with stainless steel drill on it. In this research, the drill speed is fixed at 8000 rad/min, and the diameter of the drill bit is 4 mm. It is well known that cutting heat is generated from friction and internal structural damages. And the temperature was considered as an important index to reflect the drilling energy. Therefore, temperature changes of drill holes were directly measured by Pt100 platinum resistors once finishing drilling.

Before drilling, the prepared sample which has been adjusted to room temperature was fixed to the vise. Then the drill bit was aligned with the predrilled site by manual controlling. Afterward, the drilling parameters such as drilling depth and feed rate were set in the software which comes with the dynamic material testing machine. In the end, we turned on the hand drill and ran the software. When the drilling finished, we turned off the hand drill and inserted the Pt100 platinum resistors into the drill hole to measure the temperature of the drill hole.

Conventional and vibrational drillings with different parameter sets (frequency: 5~20 Hz, amplitude: 100~500 μm) were performed. The drill site of cortical bone and bone debris from conventional drilling group and the vibrational drilling group with the lowest temperature ($A = 500\,\mu$m, $f = 20$ Hz) were observed through SEM (CamScan 3400, German).

3. Results

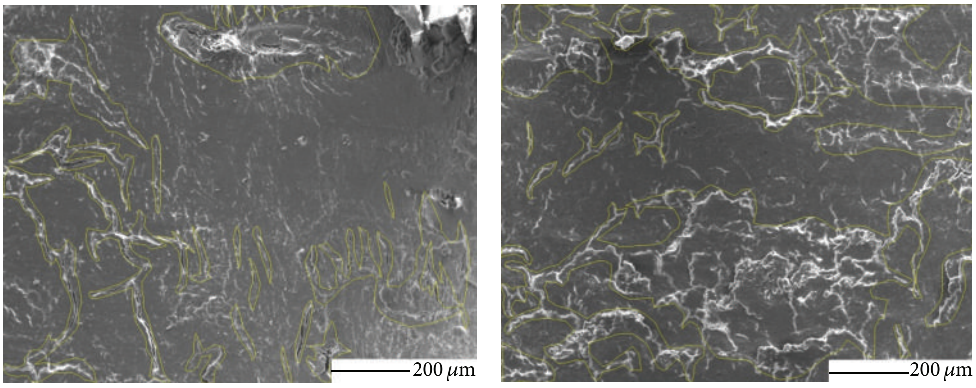
In this study, a total of 60 experiments were conducted in two drilling methods, which contained 1 conventional drilling group and 5 vibrational drilling groups. 10 drillings were carried out for each group. The mean temperatures of drill holes for every group were summarized in Table 1.

We can see from Table 1 that there is a downward trend in the mean temperature of drill hole with the vibration

Table 1: The mean temperature (°C) of drill hole and the P value for every group.

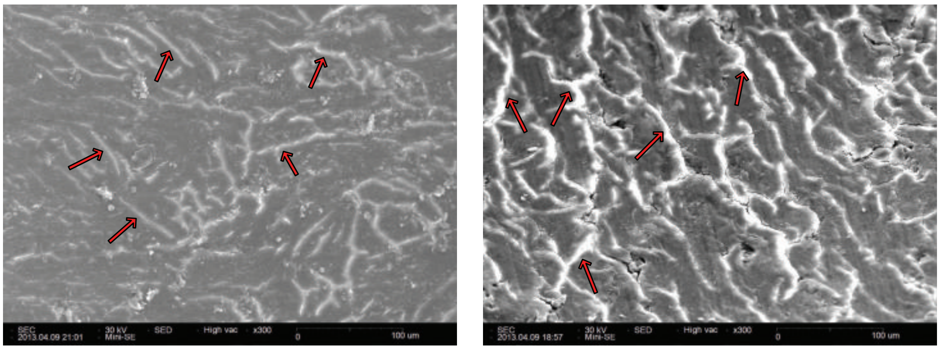
Drilling parameters	Conventional drilling	Vibrational drilling				
		$A = 100\,\mu$m $f = 10$ Hz	$A = 200\,\mu$m $f = 10$ Hz	$A = 300\,\mu$m $f = 15$ Hz	$A = 500\,\mu$m $f = 15$ Hz	$A = 500\,\mu$m $f = 20$ Hz
Mean temperature of drill hole ± SD	55.41 ± 4.60	42.87 ± 2.00	40.33 ± 2.60	39.47 ± 1.69	37.88 ± 1.67	36.38 ± 1.32
P value		0.0087	0.0001	<0.0001	<0.0001	<0.0001

SD: standard deviation.



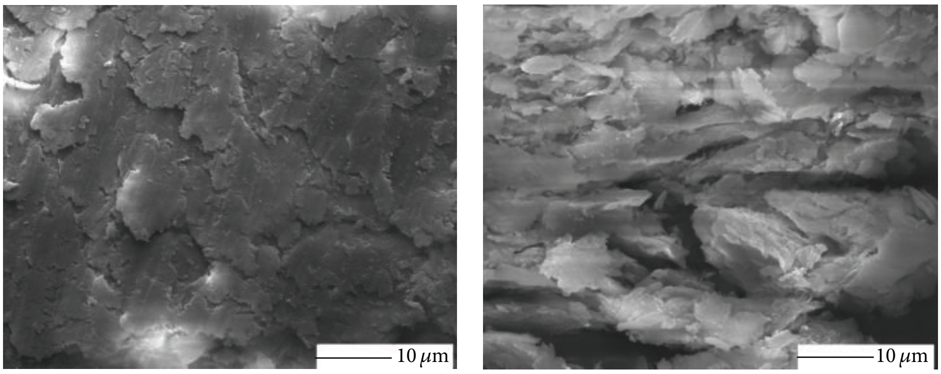
(a) (b)

Figure 4: Scanning pictures with magnification 100, left: vibrational drilling; right: conventional drilling.



(a) (b)

Figure 5: Scanning pictures with magnification 300, left: vibrational drilling; right: conventional drilling.



(a) (b)

Figure 6: SEM pictures of bone debris with magnification of 2000, left: vibrational drilling; right: conventional drilling.

Table 2: The percentages of microcracks area in the SEM picture from each group.

	×100	×300	×500
Conventional drilling	43.09%	32.34%	16.85%
Vibrational drilling ($A = 500\,\mu$m, $f = 20$ Hz)	22.69%	14.66%	6.67%

increase. Moreover, compared to conventional drilling, vibrational drilling can significantly reduce the cutting heat in drilling of cortical bone ($P < 0.01$).

In order to show the microcracks in bone via different drilling operations, the drilled specimens in conventional drilling group and the fifth vibrational drilling group ($A = 500\,\mu$m, $f = 20$ Hz), which hold the highest and the lowest drill hole temperature, respectively, were observed by SEM.

The specimens were cut along the axis of the drilling hole, and then the drilling site and bone debris, which were collected during drilling, were sprayed with gold and observed with SEM. The microcracks in the SEM pictures were sketched manually using medical image analysis software Digimizer. Table 2 shows the percentages of microcracks area in the SEM pictures from each group with three different magnifications. The SEM results show that the microcracks in vibrational drilling are significantly less than those in conventional drilling. Figure 4 shows two typical scanning pictures from the two groups. The left one is from vibrational drilling group and the right one is from the conventional drilling group.

For a clearer observation of the microcracks in two drilling methods, the magnification was raised to 300 in Figure 5. Similarly, the microcracks were measured manually by Digimizer. In general, it is observed that the length of most microcracks from vibrational drillings is shorter than that from conventional drillings.

Meanwhile, the bone debris generated in drilling process was also observed by SEM. It is found that the surface morphology of the bone debris differed in the two groups. Figure 6 is the SEM pictures of bone debris from two groups with magnification of 2000. In conventional drilling group, the gullies on the bone debris surface are very obvious and clear. However, the bone debris surface in vibrational drilling group is relatively flat.

4. Discussion

Extensive practice in machining areas has proved that vibrational drilling compared to conventional drilling has obvious advantages [22–26]. Studies have shown that the pulse of high-frequency vibration has a significant effect in reducing bone cutting heat [27, 28]. Therefore, the hypothesis is that vibrational drilling may also bring less damage to the bone microstructures and reduce the microcracks generated in bone drillings.

According to Table 1, vibrational drilling can significantly reduce the cutting heat in drilling of cortical bone. We speculate the reason is that vibrational drilling can reduce the contact time of drill bit and drill hole and promote air flow in drill hole, which can carry away part of the cutting heat. On the other hand, the result of SEM showed fewer that micro cracks were formed in vibrational drilling than those formed in conventional way. Therefore, vibrational drilling may also decrease the cutting heat generated by internal structural damage of bone.

Figure 4 shows the scanning pictures with magnification 100 via two drilling operations. From these results it can be observed that drilling method is a critical factor in the generation of microcracks in bone drilling. Compared to the conventional drilling, vibrational drilling has significantly reduced the accumulation in microcracks. As mentioned before, increases in micro-cracking may cause the fatigue damage even to stress fracture. Furthermore, on the terms of the mean length of microcracks, O'Brien et al. reported that microcracks of less than $100\,\mu$m in length stopped growing when they encountered a cement line [9]. However, microcracks in the range 150–300 μm continued to grow after encountering a cement line surrounding an osteon. Only microcracks greater than $300\,\mu$m were obverted to cause failure [7]. As shown in Figure 5, the mean length of microcracks for vibrational drilling is $100\,\mu$m, approximately. But most of the microcracks generated by conventional drilling are about 300 μm in length, which are subject to cause fracture. Therefore, we speculate that vibrational drilling could decrease the incidence of stress fracture.

Figure 6 shows the difference in surface morphology of bone debris. Because the generation of bone debris is related to the energy of drilling, the flat surface in vibrational drilling group may suggest that less energy was transformed to the bone. And we infer that there may be a certain relationship between the surface morphology of the bone debris and the generation of microcracks.

5. Conclusion

According to the experimental results of the microcracks accumulation via vibrational and conventional drilling, it is concluded that vibrational drilling can reduce the generation of microcracks which may contribute to the postoperative recovery.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

Acknowledgments

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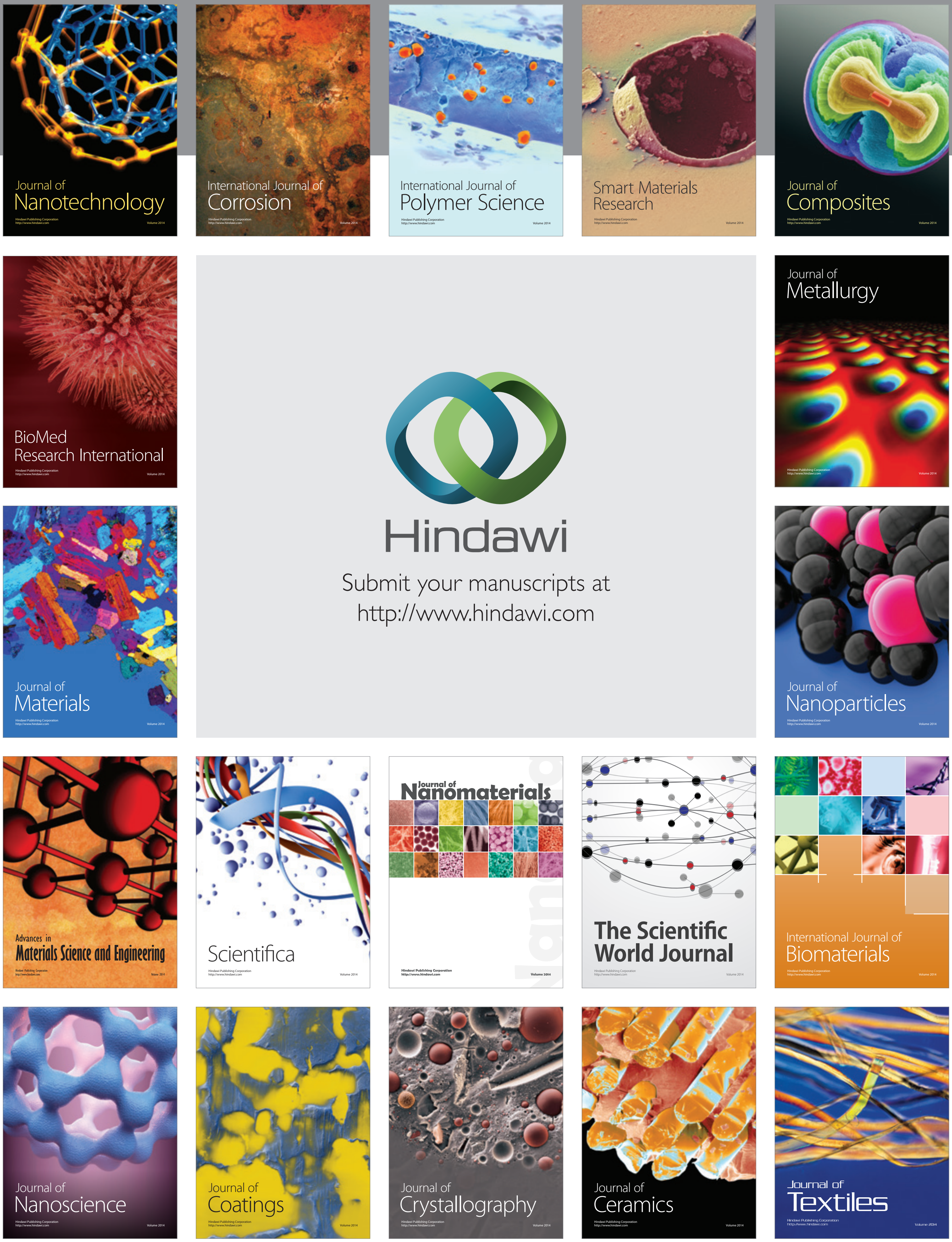
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