Bai et al.
Chinese Journal of Mechanical Engineering (2023) 36:52
https://doi.org/10.1186/s10033-023-00879-5

Chinese Journal of Mechanical Engineering

ORIGINAL ARTICLE

Open Access

Experimental Investigation of Material Removal in Elliptical Vibration Cutting of Cortical Bone

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Abstract

To benefit tissue removal and postoperative rehabilitation, increased efficiency and accuracy and reduced operating force are strongly required in the osteotomy. A novel elliptical vibration cutting (EVC) has been introduced for bone cutting compared with conventional cutting (CC) in this paper. With the assistance of high-speed microscope imaging and the dynamometer, the material removals of cortical bone and their cutting forces from two cutting regimes were recorded and analysed comprehensively, which clearly demonstrated the chip morphology improvement and the average cutting force reduction in the EVC process. It also revealed that the elliptical vibration of the cutting tool could promote fracture propagation along the shear direction. These new findings will be of important theoretical and practical values to apply the innovative EVC process to the surgical procedures of the osteotomy.

Keywords Elliptical vibration cutting, Cortical bone, Material removal, Chip formation, Chip morphology, Fracture propagation, Cutting force, Osteotomy

1 Introduction

Bone cutting, known as osteotomy, is one of the most common surgical procedures for orthopedic surgery. It has a vital impact on the operation and postoperative rehabilitation. Various scenarios of crack propagation and deep injury of tissues have been created by the quasi-brittle and hard characters [1, 2]. The chaotic crack propagation directly affects the surface quality and subsurface damage of bone tissue. Therefore, better control of crack propagation and surface quality has become critical. In addition, the lower cutting forces in orthopaedic bone cutting are expected not only because the less mechanical forces can avoid the deep injury of tissues [3], but also because the lower forces can effectively reduce the operating load of surgeons during surgery. Furthermore, the cutting forces and friction during the tool-tissue interaction are inherently related to thermal injury [4]. To investigate the crack propagation and cutting forces, machining mechanisms of bone tissue have been introduced and developed by some scholars and various

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technological improvements have been demonstrated for cutting procedures as well as cutting tools.

The orthogonal cutting model has been employed to investigate the principle of bone machining. There are certainly no situations an orthopedic surgeon would need to operate in the directions with a specific depth, especially the orthogonal cutting is an ideal process. However, in the process of interaction between the surgical tools and the tissue, the depth and direction can be any value in the edge-bone interface. Therefore, to innovatively design and propose new cutting methods and tools, it is necessary to investigate the fracture mechanism of the bone-cutting process in depth, and find the differences of the fracture mechanism in various directions and depths. Orthogonal cutting has become an important method to study the cutting mechanism. Jacobs et al. initially investigated orthogonal bone cutting and observed the chip morphology with a microscope and SEM [5]. The fracture of secondary osteons and the crack propagation in orthogonal cutting were observed and analyzed by Sugita and Mitshushi [6], who proposed that the cut depth exceeded 20 mm, greater than the interval of concentric lamellae, and cracks were formed together with chips. Then Liao and Axinte [7] and Bai et al. [8] investigated the mechanism of chip formation with various cutting depths and directions. They demonstrated the importance of the correlation between the chip morphologies and the depth of cut and the microstructure and submicrostructure of the cortical bone. To reveal the fracture mechanisms of cortical bone under various loads, researchers have been focusing on its mechanical and fracture behaviours [9, 10]. Besides, cutting force is also an important topic in bone cutting. Variance and regression analysis were performed to investigate the effects of cutting conditions on cutting and thrust forces based on a full factorial design by Sui et al. [11]. Plaskos et al. [12] presented the cutting force components and the specific cutting energy of bovine cortical bone as a function of cutting tool geometry, depth of cut, and relative orientation between the cutting edge and bone structure. Scholars have intended to reveal the cutting mechanism of bone and establish the relationship among the tool geometry, machining parameters, surface quality and cutting force to improve the cutting performance.

Sugita et al. [13] designed a multi-grooved cutting tool to reduce the levels of cutting forces and temperature during bone cutting. Giovannini et al. [14] suggested the optimal tool-tip geometries and cutting speeds for core biopsy to reduce cutting forces. Liao et al. [15] developed a milling cutter with the main cutting edge and micro-cutting edges that allowed the limitation of surface damage. It can be seen that the optimization of tool geometry is an important way to improve bone-cutting performance, but the extent of this improvement is limited.

In addition, external energy-assisted cutting has become a new method for bone removal, e.g. vibration [16], laser [17], and water jet [18]. Among them, vibration-assisted cutting is favored by scholars and doctors due to its compact structure and less soft tissue damage [19]. Many investigations compared the performance of conventional and vibration-assisted drilling on cutting force [20, 21], temperature [16, 22], and surface quality [23, 24]. Wang et al. also investigated the chips (sections) quality in the vibration-assisted sectioning for the creation of extremely thin biological tissue sections [25]. However, the understanding of the vibration-assisted cutting mechanism of bone, especially in the orthogonal cutting process, is limited. Sugita et al. [26] proposed a cutting method utilizing impacts by vibration and results indicated with the principal cutting force decreased by more than 80% in each cutting direction. Bai et al. [27] investigated a high-frequency impact cutting method, and its effects on fracture propagation, chip formation, and cutting forces were studied for orthogonal cutting. Experimental results showed that the cutting-induced fractures expanded along the main shear direction, generating small pieces of triangular segmented chips in impact cutting. Shu et al. [28] developed a 2D vibration-assisted machining method to reduce the cutting force and temperature which is mainly applied to saw-tooth bone-cutting tools during bone sawing. It can be drawn that a novel tool or assisted vibration has the potential to enhance the machinability of bone. However, few studies have investigated the orthogonal cutting process of cortical bone in EVC, and it is necessary to investigate the interaction mechanism and material removal of cortical bone by this cutting regime.

This study presented an elliptical vibration cutting (EVC) method and investigated the material removal in EVC of cortical bone. The principle of EVC and experimental details were shown in Section 2. Chip formation and cutting forces of the EVC and conventional cutting (CC) with the cortical bone were investigated in Section 3. Finally, conclusions were made in Section 4.

2 Materials and Methods

2.1 Characteristics of Cortical Bone

Cortical bone, which is a dense and rigid outer layer of the bones with a multiscale structure, is investigated in the study. It mainly consists of osteons, interstitial matrix and cement lines. Osteons are the basic unit of cortical bone whose diameter and length are approximatively 100–200 μm and 3–5 mm, respectively [29, 30]. Osteons are formed by lamellae with 3–7 μm thickness, and contain a Haversian canal [31]. It is known that the elastic modulus and fracture strength of cement lines are considered to be lower than those of osteons and interstitial matrix [8, 26, 32], which results in differences in crack propagation during various cutting processes.

2.2 Principle of EVC with Cortical Bone

An EVC process was proposed for cortical bone cutting, which was inspired by a new cutting method with back-and-forth tool movement by Sugita et al. [33]. Their cutting method was proposed based on the determined crack propagation characteristics. In this study, the schematic diagram of the EVC process with cortical bone was presented in Figure 1. The tooltip was actuated elliptically at a high-frequency f with semi-major axis amplitude of a in the cutting direction (x) and semi-minor axis amplitude of b in the feed direction (y). The relative motion trajectory of the tool to bone was spiral. The bone was set in a continuous cutting speed V in the cutting direction. The relative tool motion path to bone (tool trajectory) in the orthogonal EVC process was as follows:

$$\begin{cases} x(t) = -a\cos\left(2\pi ft\right) + Vt, \\ y(t) = -b\sin\left(2\pi ft\right), \end{cases} \tag{1}$$

where t was the time. The relative tool velocity to the bone could be expressed in two directions:

$$\begin{cases} v_x(t) = -2\pi fa\sin\left(2\pi ft\right) + V, \\ v_y(t) = -2\pi fb\cos\left(2\pi ft\right). \end{cases} \tag{2}$$

Figure 1 showed the different statuses of the EVC process. First, the cutting tool was fed forward along the tool trajectory when the tool was approaching the chip (Figure 1a). Then the tool movement deflects in the y-direction resulting in fracture propagation in the shear direction (Figure 1b). As the tool moved, the chip started removing from the shear zone (Figure 1c). When the relative tool velocity to the bone in the x-direction was zero, the tool separates from the tool-chip interface and retreated to the highest (Figure 1d) and furthest (Figure 1e) points successively. Then the tool entered the next cycle (Figure 1f).

2.3 Sample Preparation and Cutting Directions

To investigate the mechanism of material removal of cortical bone in EVC, the bone samples were prepared and cut in three different directions.

The cortical-bone samples were taken from a fresh bovine femur of the age of 2–3 years owing to their comparable material properties with human cortical bone [34, 35] along its circumference, axial and radial directions, to obtain samples of transverse, parallel, and across

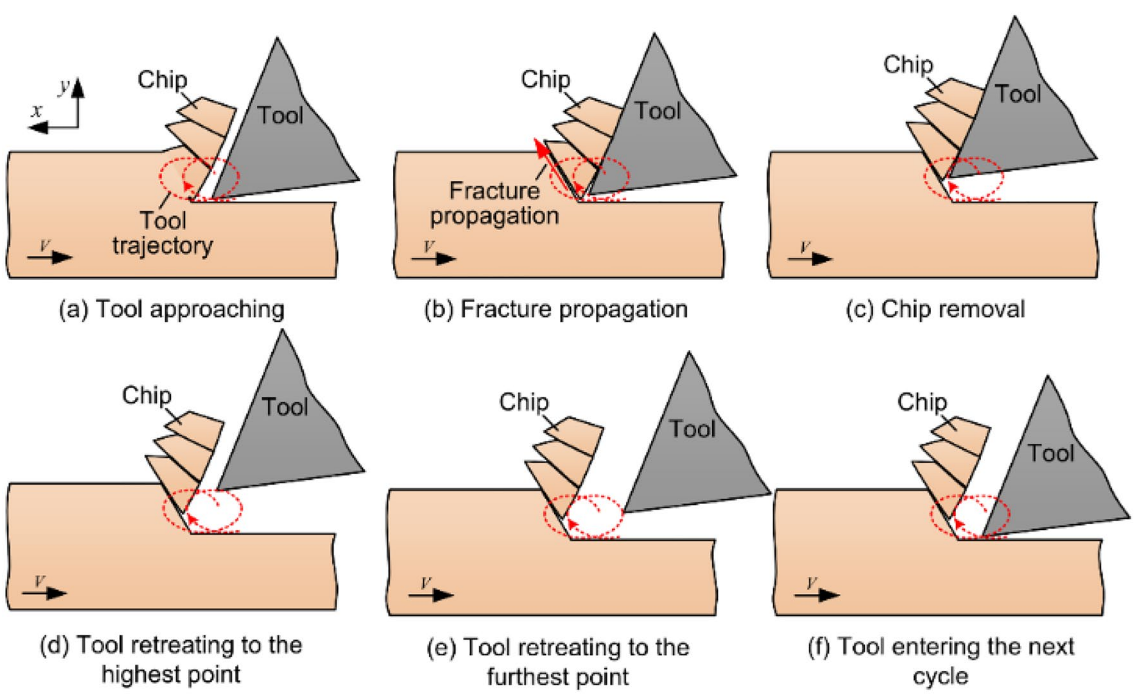

Figure 1 Schematic diagram of the EVC process with the cortical bone

directions based on the osteon orientation. The size of the prepared samples was 20 mm × 3 mm × 20 mm, in which the width was 3 mm. Samples were polished with 400-grit to 1200-grit sandpaper, immersed in a normal saline solution, and stored in a refrigerator at a temperature of −70℃ after air drying. Then they thawed before the experiments by immersion in physiological saline. Previous studies presented that the freezing and thawing processes had no significant effect on the mechanical properties of bone tissue [36–38]. In addition, previous studies [6, 11] about sample preparation for bone machining adopted the same treatment as in this study. Since the osteon orientation resulted in anisotropy of cortical bone, comparison tests were conducted in three cutting directions in this study. The cutting diagrams for the three directions of cutting were shown in Figure 2.

2.4 EVC Device

A two-dimensional low-frequency vibration-assisted cutting system was proposed in this study. The system uses piezoelectric transducers to convert electrical energy into mechanical vibrations, thereby removing cortical bone material with assisted two-dimensional elliptical vibrations.

A simplified schematic diagram of the two-dimensional low-frequency vibration cutting device was shown in Figure 3. There were two piezoelectric transducers (Thorlabs Inc., United States) inside the device, which were driven by two independent voltage signals. A hemisphere end plate connection between the top of the piezoelectric transducer and the amplitude transformer ensured the free extension and contraction of the piezoelectric transducer. The two piezoelectric transducers vibrated in the axial direction under two signals with a phase difference of 90°, and transmitted the vibration to the tool through the amplitude transformer, forming an elliptical trajectory. In the experiment, the vibration trajectory of the tooltip was measured under a high-speed camera. The major axis and minor axis of the obtained elliptical trajectory were $2a$ and $2b$, respectively.

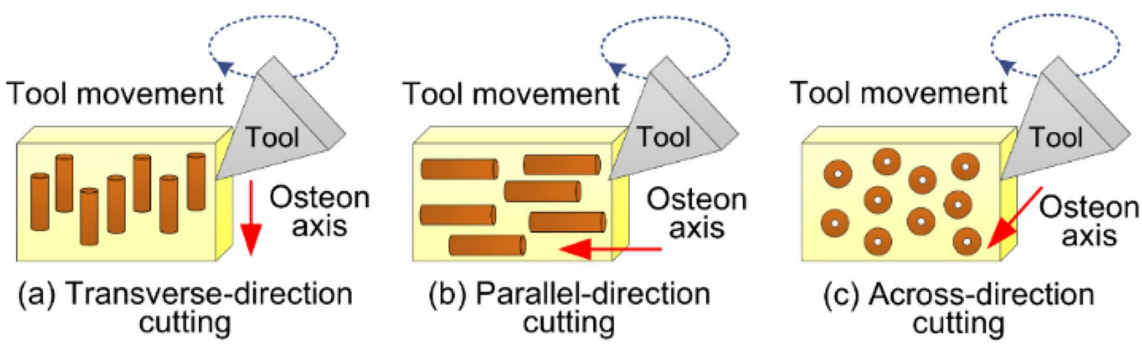

Figure 2 Schematic diagram of the cortical bone cutting in three directions: **a** Transverse-direction cutting, **b** Parallel-direction cutting, **c** Across-direction cutting

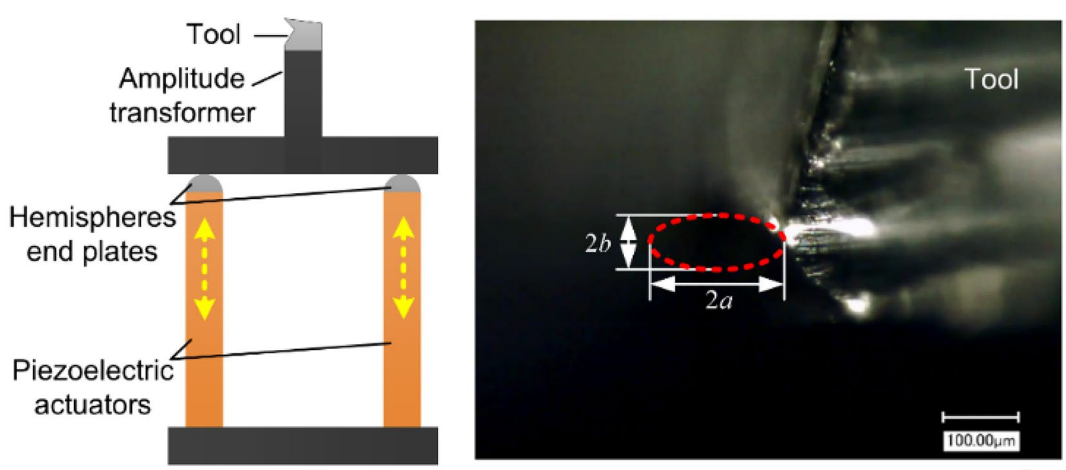

Figure 3 Schematic diagram of the EVC device and measurement of the vibration trajectory

2.5 Experimental Setup

To study the orthogonal EVC process of cortical bone, a three-axis high-precision electric translation table was used, and the movement of each axis was accurately controlled by the upper computer software. The three-dimensional translation table was fixed on the precision optical vibration isolation platform to reduce the influence of environmental vibration in the experiment. The experimental orthogonal cutting process was captured by Keyence VW-9000 high-speed camera (Keyence, Japan) with a Keyence VW-600c lens (Keyence, Japan). The maximum resolution of this high-speed camera was 640 × 480, and the highest frame rate was 230000 fps. To ensure sufficient light in the process of high-speed acquisition, an Olympus LGPS 150W light source (Olympus, Japan) was used in the experiment. Cortical bone samples were fixed on Kistler 9256A1 (Kistler, Switzerland). The three-channel data collected by Kistler 9256A1 (Kistler, Switzerland) were transmitted to Keyence GR-7000 (Keyence, Japan) to display the cutting forces of three directions. The experimental setup was shown in Figure 4.

To study the mechanism of the chip formation and cutting force in two-dimensional low-frequency vibration-assisted cutting of cortical bone, orthogonal cutting experiments were carried out in three cutting directions: transverse direction, parallel direction and cross direction. In the experiment, the driving frequency was set as 200 Hz and the horizontal vibration amplitude $2a$ was 38 μm. The cutting speed was 3 mm/s and the depth of cut was 10 μm. The tool rake and relief angles were 30° and 10° respectively. The lens magnification was 400 times, the shutter speed 1/6000 s, the frame rate 2000 fps, and the image resolution 640 Í 480.

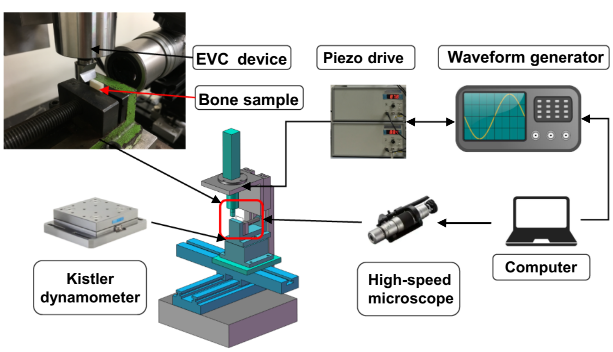

Figure 4 Experimental setup of the EVC with the cortical bone

3 Results and Discussions

3.1 Chip Formation of the EVC with Cortical Bone

Bone samples considered the anisotropy were prepared. This section carried out orthogonal CC and EVC of cortical bone in transverse, parallel, and across directions.

3.1.1 Transverse-direction Cutting

The chip formation process of the CC and EVC with cortical bone in transverse-direction cutting was shown in Figure 5. It could be seen that the chips were continuous in CC (Figure 5a), while they were semi-continuous in EVC (Figure 5b). It was because the cortical bone was cut in the transverse direction and the depth-of-cut was 10 μm, shear cracks appeared in CC, and there were continuous chips composed of alternately mixed osteons and bone matrix. In the EVC process, because the instantaneous depth-of-cut changed in each cycle, and the tool had a pulling process relative to the bone [39], the curvature of the chip was smaller and it was easier to break into a discontinuous chip.

3.1.2 Parallel-direction Cutting

When cutting in the parallel direction, the chip formation of the two cutting methods was shown in Figure 6. In CC, the chip was still continuous (Figure 6a), while in EVC, the curvature radius of the chip decreased and the chip was curly (Figure 6b). The reason was that the thickness of the removed lamellae in the parallel direction was uneven due to the fluctuation of the transient depth-of-cut in

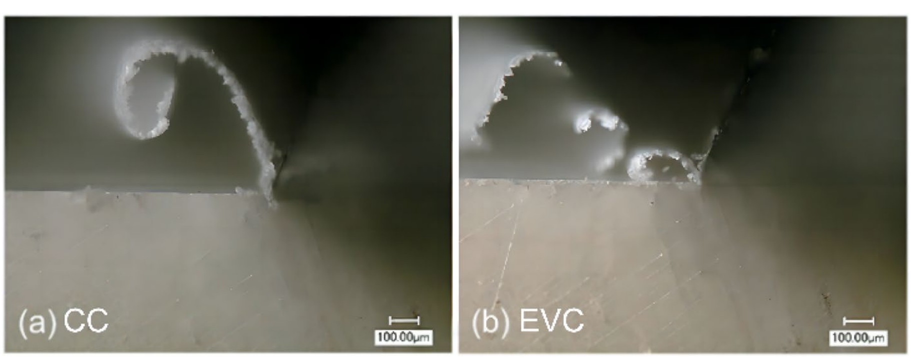

Figure 5 Chip formation under the high-speed camera in transverse-direction cutting by **a** CC and **b** EVC

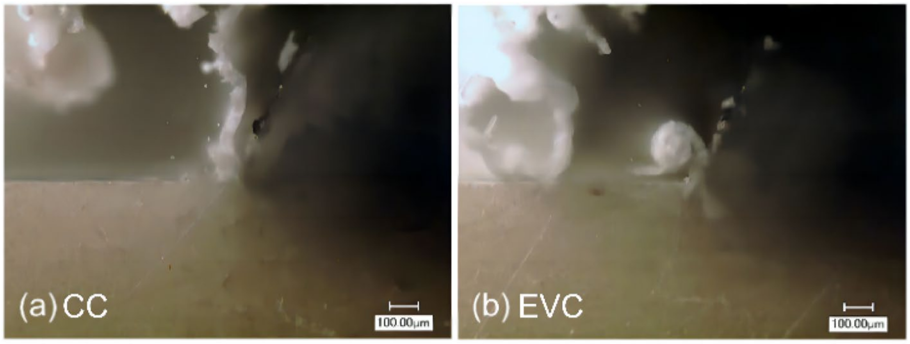

Figure 6 Chip formation under the high-speed camera in parallel-direction cutting by **a** CC and **b** EVC

a vibration cycle of the tool, and the chip was more likely to curl under the reciprocating impact of the tool.

3.1.3 Across-direction Cutting

As for cutting in the cross direction, the chip formation of the two cutting methods was shown in Figure 7. In CC, the chip morphology was continuous (Figure 7a), and so was it in EVC (Figure 7b). This was because the chips are composed of part lamellae of the osteon and interstitial matrix under the two regimes. However, the curvature of the chip in EVC was slightly smaller, and an irregular sawtooth appeared in the chip, which was all caused by the non-uniform transient chip thickness and higher strain rate in the EVC process.

In general, compared with the CC, the curvature of the chip was smaller and the chip was easier to break in EVC. Similarly, Alam et al. [40] compared conventional and ultrasonically-assisted bone drilling and concluded that ultrasonically-assisted drilling generated small and broken chips compared with conventional drilling. Although the drilling process was different from the orthogonal cutting, it could still be seen that the high-frequency vibration would promote the break of bone chips.

3.1.4 Mechanism of the Material Removal in EVC of Cortical Bone

To further reveal the reason for different chip morphologies generated in two regimes, this study retreated the bone samples by applying red dye to the section of samples; thus, the part of the tissue textures and microstructures could be observed under the microscope. The lens magnification increased to 500 times. To observe the chip removal clearer, the depth-of-cut was set as 80 μm. Other microscope and vibration parameters were kept the same. In this section, a case of parallel-direction cutting was carried out.

The microscopic material removal of cortical bone in CC with two states was shown in Figure 8. The red textures verified that the osteons and bone lamellae were distributed along the horizontal direction, that was parallel-direction cutting. As the tool cut forward, the bone tissue started to tear and the crack initiated in the cutting direction with large width (Figure 8a). The possible reason was the osteon with an approximate diameter of 100–200 μm, which was larger than the depth-of-cut. The crack propagated in the interstitial of lamellae when the cutting direction was along the axial direction of the osteons. Then as the tool cut,

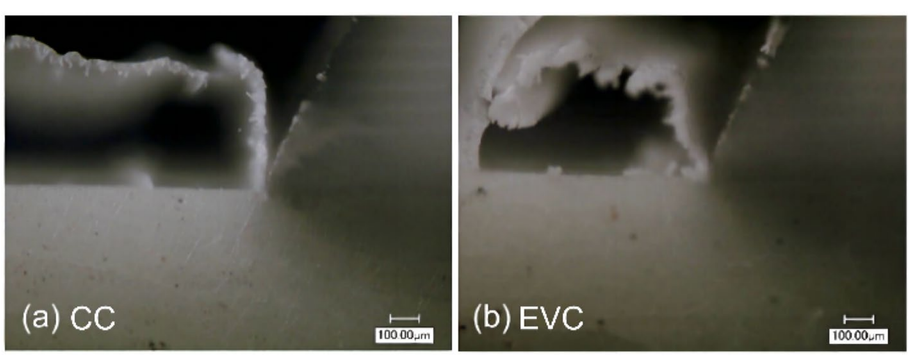

Figure 7 Chip formation under the high-speed camera in across-direction cutting by **a** CC and **b** EVC

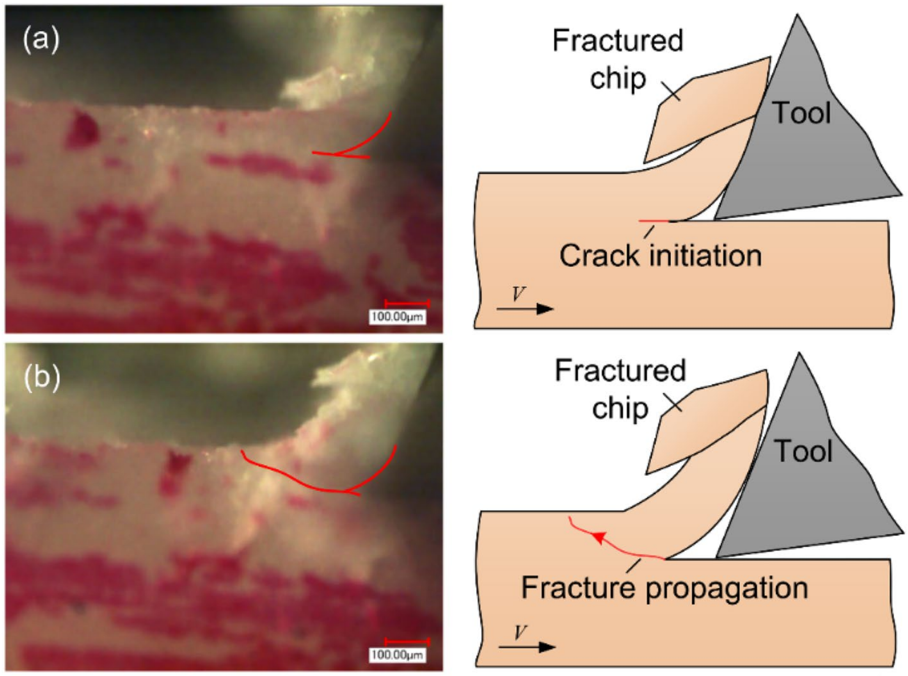

Figure 8 Microscopic material removal of cortical bone in CC with two states: **a** Crack initiation, **b** Fracture propagation

a block fractured chip was generated due to the large bending force resulting from the tool rake face. This irregular fracture led to chaotic fracture propagation (Figure 8b). Therefore, the microscopic fractured chips connected each other into an irregular chip.

The same experiments were carried out in EVC. The microscopic material removal of cortical bone in EVC with two states was shown in Figure 9. As the tool cut forward, the cracks initiated not only in the cutting direction but also in the shear direction (Figure 9a). Besides, the width of the cracks was not visible. Then the tool continued to move with an elliptical vibration, the fracture propagated in the shear direction. The trapezoidal chip was generated in this direction; thus, the regular sawtooth chip was formed (Figure 9b). It could be explained that a pulling process relative to the bone emerged in the tool-chip interface due to the tool moving from the lowest point to the highest point. Shu and Sugita [41] also found that the vibration promotes upward crack propagation. In addition, the vibration of the tool might change the fracture toughness of cortical bone during vibration-assisted cutting [27], which resulted in the crack penetrating the osteons directly instead of deflection. These reasons might lead to fracture propagation in the shear direction and change the chip morphology.

3.2 Cutting Forces of the EVC with Cortical Bone

The cutting forces of CC and EVC under three cutting directions were recorded by the Kistler dynamometer. The time history of cutting force and average cutting force was collected. The comparison of cutting forces in CC and EVC of cortical bone was shown in Figure 10. The cutting force in the transverse-direction cutting showed that the main cutting force (MCF) and the thrust force (TF) fluctuated periodically in the EVC, and the fluctuation trend was similar to that predicted in Ref. [39]. For the main cutting force, it could be seen that the CC force was relatively stable, with an average value of 45.9 N, while the average value of the main cutting force in the EVC was 16.6 N, and the reduction percentage of the cutting force was 63.8% (Figure 10a). However, the thrust force obtained by the two machining methods was greater than the main cutting force, which was mainly caused by the low stiffness of the experimental device, and the tool concession phenomenon occurred when the tool cut into the bone material. The thrust force included not only the real thrust force, but also the supporting force of the bone material to the tool caused by the tool concession. But the results of thrust force still showed that the average thrust force of the EVC was less than that of the CC. The cutting force in the parallel direction showed that the main cutting force of the EVC was 14.9%

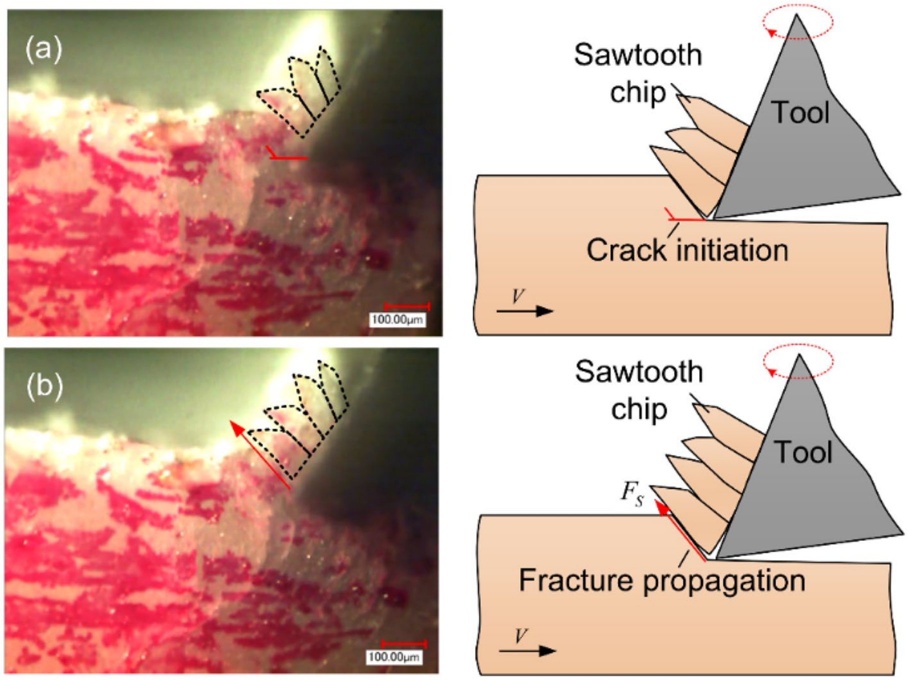

Figure 9 Microscopic material removal of cortical bone in EVC with two states: **a** Crack initiation, **b** Fracture propagation

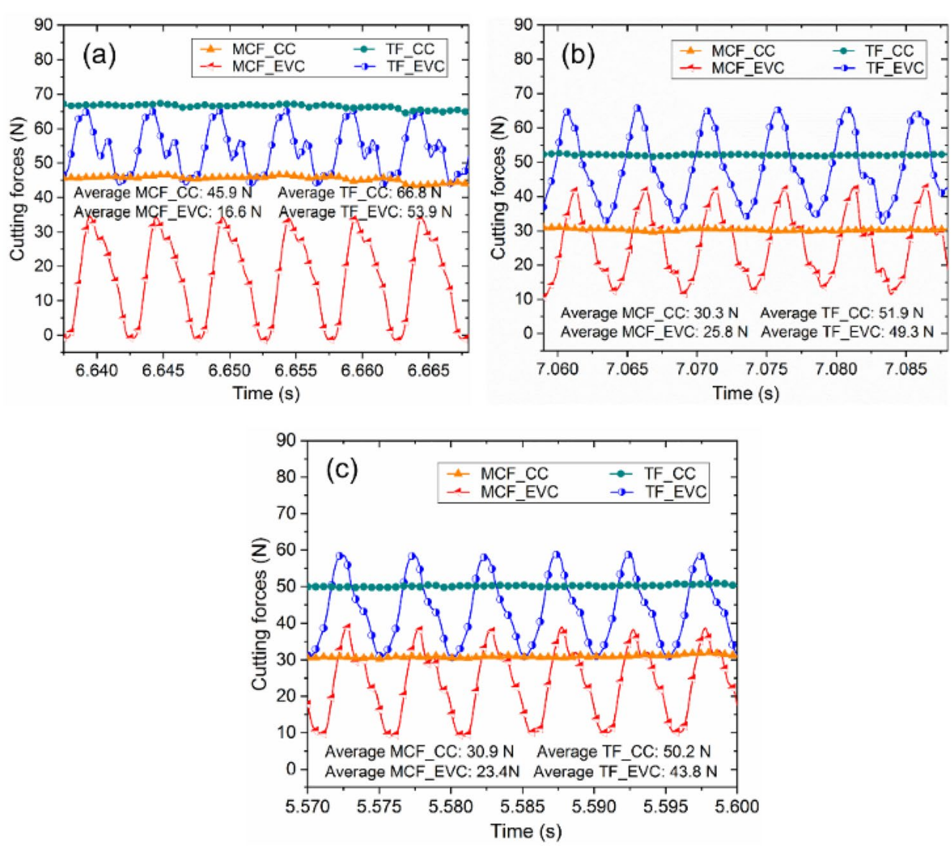

Figure 10 Comparison of cutting forces in CC and EVC of cortical bone in three cutting directions: **a** Transverse-direction cutting, **b** Parallel-direction cutting, **c** Across-direction cutting

lower than that of the CC, and the average thrust force was also slightly reduced (Figure 10b). The results of cross-direction cutting were similar to those of parallel-direction cutting. The main cutting force of the EVC was 24.3% lower than that of the CC, while the average thrust force was reduced by 12.7% (Figure 10c).

Although the thrust force obtained was largely due to the stiffness of the experimental device, the experimental results still showed that the main cutting force and thrust force could be reduced in three cutting directions. The reduction of cutting forces was also observed by experiments with an elliptical vibration-assisted orthopedic oscillating saw [28] and elliptical vibration V-grooving [42]. These results indicated that the assisted elliptical vibration could change the tool-material interaction and decrease the average contact forces.

As a new cutting method, the reliability of the EVC device could be improved. However, the experimental results presented in this paper still reflected that the elliptical vibration changed the chip formation in the CC of cortical bone, resulting in smaller chip curvature and less random crack propagation. At the same time, the EVC also reduced the cutting force in different cutting directions.

4 Conclusions

This study compared the chip formation and cutting forces in orthogonal CC and EVC of cortical bones. The chip morphology and material removal process were observed and analysed by the high-speed camera. Transient and average cutting forces were measured by the Kistler dynamometer. The significant differences in the machinability were obtained between the two regimes. The following conclusions can be drawn from the experimental results and their analyses:

(1) The chip formation process in EVC was changed significantly compared to the CC, where the chips were semi-continuous with smaller chip curvature;

(2) Microscopic material removal of cortical bone in CC and EVC revealed that the elliptical vibration led to fracture propagation in the shear direction, which made chips easier to remove with fewer forces required;

(3) The EVC reduced the cutting forces in various cutting directions compared with the CC. For the main cutting force, the reduction percentages of the cutting force in the transverse, parallel and cross directions were 63.8%, 14.9% and 24.3% respectively.

Based on the fracture characteristics of bone tissue, this study innovatively proposed a two-dimensional elliptical vibration cutting method and verified the effectiveness of this process from the perspective of tissue fracture and cutting force. Although our previous study found that the main cutting force could be reduced by 70% using 1D vibration cutting, which was based on experimental results under high frequency vibration conditions [27]. However, it should be also mentioned that the frequency of the proposed EVC device was only 200 Hz, which limited the cutting speed and efficiency when bone cutting was performed. It is necessary to further design EVC devices with ultrasonic frequency to improve the cutting performance. This is the first time introduce EVC in the orthogonal cutting of cortical bone, which will inspire more experimental studies on the mechanism and application of EVC with the cortical bone. Furthermore, the histology and thermal damage of the machined surface are also very important for evaluating the performance of surgical instruments, which will be investigated in future studies.

Acknowledgements

Not applicable.

Author contributions

Conceptualization: WB, LS and DW; Methodology: GH and LS; Investigation: YZ and JZ.; Writing—original draft preparation: WB, LY and YZ; Writing—review and editing: WB and XZ. All authors have read and agreed to the published version of the manuscript.

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Funding

Supported by National Natural Science Foundation of China (Grant Nos. 52005199 and 42241149), Shenzhen Fundamental Research Program (Grant Nos. JCYJ20200109150425085 and JCYJ20220818102601004), Shenzhen Science and Technology Program (Grant Nos. JSGG20201103100001004 and JSGG20220831105800001), Research Development Program of China (Grant No. 2022YFB4602502) and Knowledge Innovation Program of Wuhan-Basic Research (Grant No. 2022010801010203).

Data availability

The datasets supporting the conclusions of this article are included within the article.

Competing Interests

The authors declare no competing financial interests.

Received: 12 July 2022 Revised: 20 March 2023 Accepted: 23 March 2023
Published online: 11 April 2023

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