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Design and experimental force analysis of a novel elliptical vibration assisted orthopedic oscillating saw

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ABSTRACT

Orthopedic oscillating saws (OOSs) are widely used for plane processing in orthopedic surgery such as knee and hip replacement. However, sawing has been associated with bone breakthrough and necrosis problems. In this paper, a novel elliptical vibration assisted OOS was designed to achieve a low cutting force under the condition of deepening cut depth and reducing cutting speed, based on the analysis of brittle fractures of the bone and elliptical vibration assisted cutting kinematics. The elliptical vibration was generated using two parallel stacked piezoelectric actuators assembled with the fixture. In order to reduce the large cutting forces due to the large cutting depth, a series of experiments was also conducted to investigate the influence of processing parameters on cutting forces. It was demonstrated that cutting forces are significantly reduced by increasing the vibration frequency and vibration amplitude, and decreasing the sawing speed in the current design. The new design could minimize the cutting forces during sawing and allow surgeons to have better control over the sawing process.

1. Introduction

Orthopedic procedures such as osteotomies, and hip and knee joint replacements involve plane processing owing to the demand of implant assembly and fixation, for example, the surface to fixture interaction of the femoral component during total knee replacement. Orthopedic powered saws have been designed and widely used for plane processing since 1890s [1]. There are three main requirements for bone sawing: high efficiency, low temperature, and low cutting force. Considering the operation time of such a surgery, the high cutting efficiency is the most crucial factor for bone resection devices. One method to improve the cutting efficiency is to increase the cutting speed. OOS typically runs at 8000 to 20,000 oscillations per minute with relatively small oscillation angle (3° to 5°) [2]. However, the localized heat generation caused by the friction between the saw blade and bone increases with oscillation speed. High temperature, exceeding 47 °C, will cause cellular damage and even cell necrosis [3,4].

Increasing cutting depth with relatively low cutting speed has recently been suggested as a new method of enhancing cutting efficiency. Sugita and Mitsuishi [5,6] proposed an orthogonal bone cutting method based on crack propagation characteristics at a large cutting depth that can enhance the cutting efficiency and precision. James et al. [7] designed an OOS with orbital blade motion for improving cutting efficiency and reducing temperature. Temperature was reduced owing to the short heat transfer time and large bone chips carrying more heat from the freshly sawed surface. The basic idea of orbital blade motion is similar to Sugita and Mitsuishi's method [5]. However, a large cutting depth, employed to perform high-efficiency excision and crack propagation, will generate a large cutting force, which may induce unnecessary damage, resulting in trauma and also making it difficult to be employed in manual surgery. Elliptical vibration assisted cutting (EVC), well known in high precision machining, has a high potential for reducing cutting forces [8–11]. Furthermore, EVC could basically implement Sugita and Mitsuishi's orthogonal bone cutting method because the elliptical trajectory of the cutting tool is similar to the orthogonal method. However, EVC was often used for small cutting depths within 10 µm [12–15]. The effect of EVC in a large cutting depth for bone sawing is still unclear, and there are few studies applying EVC in bone sawing. Hence, it is necessary to explore a design that combines EVC with bone sawing and to conduct a systematical analysis on the cutting forces during elliptical vibration assisted bone sawing with a large cutting depth.

In this study, a novel elliptical vibration assisted OOS was designed to carry out sawing with a relatively large cut depth in manual surgery, based on analyzing the bone crack propagation characteristics and kinematics of elliptical vibration assisted sawing. In order to understand the influence of processing parameters on cutting forces, systematical experimental analysis of forces in elliptical assisted sawing was performed on sawbones.

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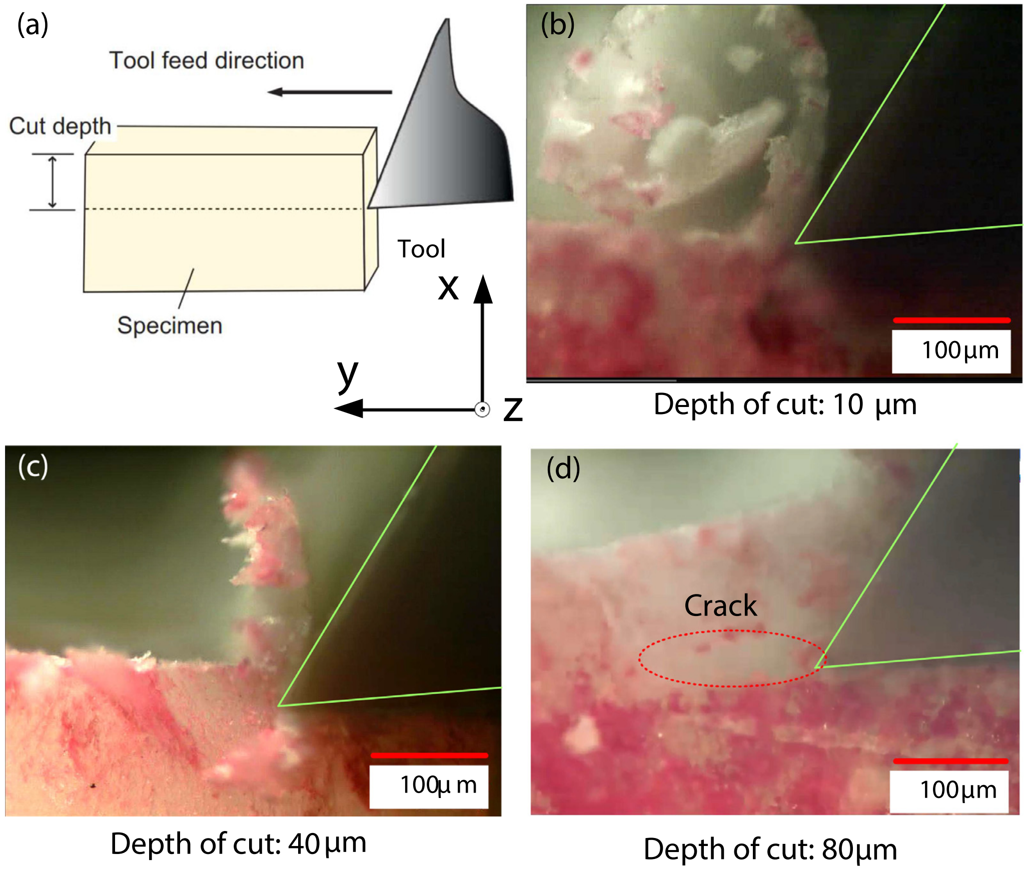

Fig. 1. Chip types at different cutting depths of orthogonal bone machining.

2. Design

2.1. Principle of the elliptical vibration assisted sawing

Osseous tissue mainly can be divided into two groups: the cancellous bone and the cortical bone, with the latter being the hardest and anisotropic kind. The cortical bone has been found to have brittle properties when using a large cutting depth during orthogonal bone cutting, as shown in Fig. 1(a). When the cutting depth is in the range of 0–30 µm, a chip is generated continuously, as shown in Fig. 1(b). In Fig. 1(c), the chip presented as a discontinuous type. The brittle property of the bones is gradually presented with the increase in cutting depth. When the cutting depth approaches 80 µm, a crack appears in the process due to brittle fractures, as shown in Fig. 1(d). Feldmann et al. [16] and Liao and Axinte [17] found the similar phenomenon and systemically analyzed the chip formation mechanism in orthogonal cutting of bone. When crack-type chips are generated by brittle fractures, the processing energy required for machining is lower, and internal heat generation on the bone also decreases compared to other processes that generate flow- and shear-type chips [18]. Sugita et al. [5] analyzed the mechanism of crack propagation and presented the propagation direction of a crack is influenced by the organizational structure of the bone and could be controlled by the feed direction of tool. As the tool rake angle is negative, the stress field around the edge becomes compressive, and shear- and crack-type chips are generated depending on the tool feed angle. What's more, it was found the strain rate during cutting has a great influence on the direction of crack propagation [19,20]. The crack penetrates the osteon when the strain rate is high enough, while the crack growth stops on the cement line or the interstitial interface when the strain rate is small.

On the basis of the analysis of bone characteristics [16,17] and the orthogonal bone cutting proposal from Sugita and Mitsuishi [5,6], a novel elliptical vibration assisted sawing method is presented, as shown in Fig. 2(a–d). The cutting tool is fed at the nominal sawing speed and vibrated elliptically at the same time and on the plane consisting of the chip flowing direction and the cutting speed direction. In other words, the tip movement is a superposition of conventional oscillation with the additional elliptical pattern. The elliptical rotating speed is set to be larger than the maximum sawing speed, which ensures the cutting tool makes contact with the bone and loses contact, in succession, along a proceeding elliptical path during sawing, as shown in Fig. 2(a). The cutting tool is initiated to contact with the bone, where a crack is generated and propagated as shown in Fig. 2(b). With tool feeding, a further crack propagation happens around the initial contact point, as shown in Fig. 2(c). Then, as the cutting tool moves along the upward elliptical path and lifts off the bone, the area surrounded by cracks is removed as a chip.

2.2. Elliptical vibration assisted OOS

The elliptical vibration was achieved by two parallel stacked piezoelectric actuators assembled with the fixture as shown in Fig. 3. The stacked piezoelectric actuator consists of multiple piezoelectric chips stacked face-to-face and bonded via epoxy and glass beads from Thorlabs Inc. (Japan). Because a large cutting depth would be expected in current bone sawing, a large maximum displacement of the piezoelectric actuators was preferred.

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