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Technical note

Experimental analysis of drilling process in cortical bone

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ABSTRACT

Bone drilling is an essential part in orthopaedics, traumatology and bone biopsy. Prediction and control of drilling forces and torque are critical to the success of operations involving bone drilling. This paper studied the drilling force, torque and drilling process with automatic and manual drill penetrating into bovine cortical bone. The tests were performed on a drilling system which is used to drill and measure forces and torque during drilling. The effects of drilling speed, feed rate and drill bit diameter on force and torque were discussed separately. The experimental results were proven to be in accordance with the mathematic expressions introduced in this paper.

The automatic drilling saved drilling time by 30–60% in the tested range and created less vibration, compared to manual drilling. The deviation between maximum and average force of the automatic drilling was 5 N but 25 N for manual drilling. To conclude, using the automatic method has significant advantages in control drilling force, torque and drilling process in bone drilling.

1. Introduction

Bone drilling is one of most common surgical procedures in the history of medicine and is widely performed, especially in oral surgery and orthopaedics where it is widely used for correcting bone fractures and for attaching prosthetics [1]. Prediction and control of drilling forces and torque are critical to the success of many orthopaedic operations [2]. Imprecise manipulation of the hand-piece can damage a nerve and lead to paralysis, or break a bone [3]. In orthopaedic bone cutting, also, it is desirable to control the level of cutting force to enable smooth penetration by a surgical instrument, and to avoid unnecessary damage to soft tissues surrounding the bone [4]. Therefore, there is an increasing demand to minimize the drilling force in order to avoid damage to nerves in the treated area. Another concern is that too strong a torque can cause drill breakage [5].

The previous bone drilling methods presented by Allotta et al. [6] and Bouazza-Marouf et al. [7] utilized a constant feed rate to drill a long bone. Improved drill design [8,9], comparing experiments [10], mechatronic drill [11] and bone drilling system [12] were presented to avoid unnecessary damage to soft tissue, minimize invasion or detect breakthrough. The important parameters of drill-bit on bone drilling torque and force are drill point angle [13], flutes [14], drill diameter, drill speed and drill feed rate [15]. Presently, optimization of drilling parameters for protecting against biohazards requires additional safety measures and expensive experimental equipment. Chandrasekharan et al. [16] and Gupta et al. [17] proposed the technology of modeling to calculate forces. Marsik et al. [18] presented an inevitable influence of a dynamic mechanical loading and osteoprotegerin (OPG) concentration by remodeling of living bone. The simulation results have been used to reduce drilling force [19] and predict the outcome of spine [20,21], hip [22] and maxillofacial surgeries [23].

Currently, bone drilling is mostly performed manually without detecting drilling force or torque as the drilling process mainly depends on surgeon's experience. In some situations, it could damage bone or surrounding tissue and decrease success rate. The goals of this study are, using manual and automatic methods, to (1) investigate drilling force and torque against feed rate and rotational speed; and (2) analyze drilling process with different dimensions of drill-bit.

2. Experimental methods

2.1. Expression of force and torque in twist drilling

Rubenstein [24,25] published expressions relating the force and torque to feed rate and drill diameter in drilling operations conducted with a serious of geometrically similar twist drills. The torque M and the force F are both composed of three components which arise from drill-workpiece contact at the margin, at the web and at the lips

$$M = M_0 + M' + M'' \quad (1)$$

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Table 1
Drilling parameters of bone experiments.

CNC drill	Rotational speed (rpm)	550, 900, 1200, 1500, 2000, 2500
	Feed rate (mm/min)	10, 20, 30, 40, 50
	Drill diameter (mm)	2.5, 4, 5
Manual drill	Rotational speed (rpm)	550, 900
	Drill diameter (mm)	4

$$F = F_0 + F' + F'' \tag{2}$$

where M_0 and F_0 arise at the drill lips, M' and F' arise at the chisel edge and M'', F'' originate from drill-workpiece contact at the margins. The above parameters were described by Rubenstein [26]. For hole drilling, as appropriate, results in the expressions:

$$M/d = (k_1 + K_1 f) + [(E + Gm^2) + (B + Hm^2)f]d \tag{3}$$

$$F = (k_2 + K_2 f) + [(J + Qm^2) + (U + Vm^2)f]d \tag{4}$$

where d is the drill diameter, f is the feed rate, the coefficients appearing in these equations being defined and analyzed in reference [24,26].

2.2. Preparation of specimens

Experiments were performed on fresh bovine bone (age 3–4 years) as it replicated the properties of human bone according to [27,28]. Femur bones were obtained from a local butcher a short time after the animals were butchered. Because of the difference in density, the epiphysis was cut off thus leaving the bone's diaphysis to be tested. Prior to conducting experiments, the specimens were fully immersed in saline solution for 24 h at room temperature. In order to firmly attach the specimen and to avoid vibration, the bone was cut into two parts along its longitudinal axis. One part of the bone (specimen) was mounted to the surface of a metal plate, with the bone's exterior surface facing the drill. A total of 12 samples were prepared on which to perform experiments, each sample accommodating approximately 25 drilled holes. 10 samples were used for CNC drilling and 2 samples were drilled by manual drill. The bone pieces were approximately 90 mm in length with an average thickness of the cortical wall of 8–10 mm.

2.3. Experimental setup

Each bone specimen was attached to an ATI mini40 sensor (ATI Industrial Automation, USA) which could measure force/torque during drilling as a function of time. The experiments were carried out on a CNC milling machine (GSDMC510A, GoldSun Group, Guangdong, China). The maximum spindle speed of the machine is 12,000 rpm and the maximum feed rate is 8 m/min. The drilling was performed perpendicular to the long axis of the bone to minimize variations due to the orientational dependence of bone properties. Manual drilling experiments based on power-tool cordless manual drill (CD8023, maximum no-load speed is 900 rpm) were performed with the same drill bit (diameter is 4 mm) to compare the manual drilling to the milling machine.

The force and torque signals generated by ATI mini40 were transmitted to a data acquisition card (National Instruments DAQ). The experimental setup is shown in Fig. 1. Two plates were manufactured and mounted on the surfaces of the ATI mini40 sensor. One was used to hold bone samples; the other one was used to mount the sensor onto the drilling machine. Rotational speed, feed rate and diameter of twist drill have important influence on the quality of bone drilling and temperature [14,15]. Thus, the parameters shown in Table 1 were chosen to minimize bone damage and avoid high temperature.

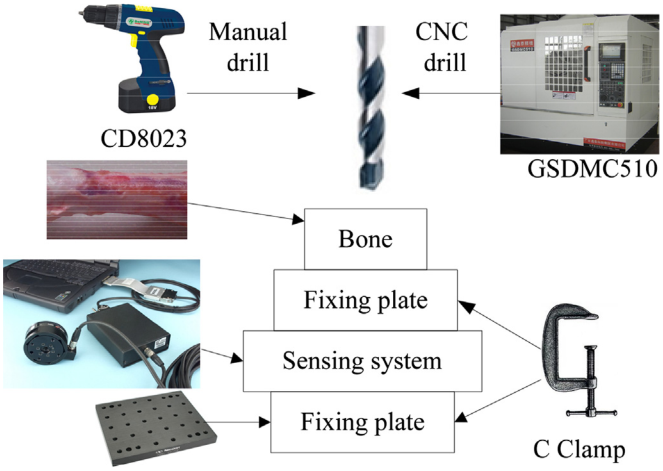

Fig. 1. Schematic illustration of experimental system.

3. Results

3.1. Effect of rotational speed and feed rate on force

Using a CNC milling machine, the effect of rotational speed and feed rate on the force was measured and the obtained results are presented in Fig. 2. The force decreased with the increase of rotational speed under the same feed rate; the force varied with diameter; in addition, the force is proportional to feed rate. Each graph shows three different drill bit diameters, measured in mm.

3.2. Effect of rotational speed and feed rate on torque

The effect of rotational speed and feed rate on torque was also discussed. In Fig. 3(a), the torque decreased 30% as the rotational speed changed from 550 rpm to 2500 rpm. In Fig. 3(b), the torque data was presented as Torque (M) against feed rate (f), it shows that the drilling induced torque rose with the increasing feed rate; each different case shows that the maximum induced torque occurred when the drilling was performed at the maximum feed rate in the tested range.

3.3. Effect of diameter on force and torque

In Eqs. (3) and (4), diameter has effect on drilling force and torque. Drill bits of diameter 2.5 mm, 4 mm and 5 mm were used to test the effect on drilling force and toque. The results, see Fig. 4, show that drilling force and torque rose with the increasing diameter of drill bit. It was observed that when the diameter of drill bit increased from 2.5 mm to 5 mm, drilling force increased between 20% and 30% and torque increased between 20% and 50%.

3.4. Comparison of manual drill and CNC milling machine

The same points were drilled at 900 rpm/min with 4 mm drill bit by manual drill and CNC milling machine; the corresponding drilling curves were shown in Fig. 5. In Fig. 5(a), the drilling curve was not stable as the force varied from 0 N to 85 N during the drilling process. In Fig. 5(b), the vibration of the force obtained from the CNC milling machine was insignificant compared to Fig. 5(a).

The average and maximum forces obtained by both the manual drill and the CNC milling machine against rotational speed were recorded under the feed rate of 30 mm/min.

By recording the drilling time, the manual drill needed a longer time to drill through the bone than the CNC milling machine did.