Medical Engineering and Physics 41 (2017) 1–8

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Rotary ultrasonic bone drilling: Improved pullout strength and reduced damage

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ARTICLE INFO

Article history:
Received 27 June 2016
Revised 29 August 2016
Accepted 14 November 2016

Keywords:
Rotary ultrasonic bone drilling
Conventional surgical bone drilling
SEM
Microcracks
Pullout force

ABSTRACT

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.

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

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http://dx.doi.org/10.1016/j.medengphy.2016.11.004

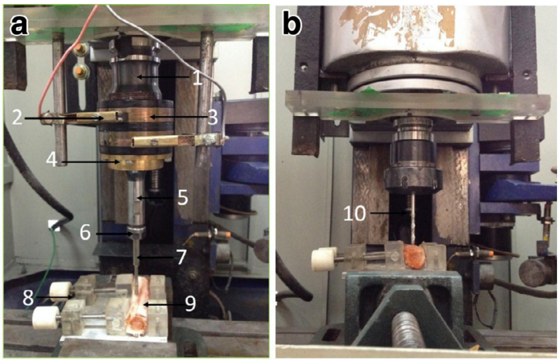

Fig. 1. Experimental setups: (a) RUBD and (b) CSBD 1) CNC collet; 2) carbon brushes; 3) slip rings; 4) collar; 5) horn; 6) nut and collet; 7) hollow tool; 8) holding fixture for bone; 9) bone sample; 10) conventional surgical drill bit.

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 bones 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 Ajex & 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

Table 1
Process parameters and their values for in-vitro experiment.

Parameters	Units	Microcracks analysis		Pullout analysis	
		RUBD	CSBD	RUBD	CSBD
Rotational speed	rpm	500–1500–2500		500–1500–2500	
Feed rate	mm/min	10–30–50		10–30–50	
Drill diameter	mm	4.5		4.0	
Vibration amplitude	µm	16	NA	16	NA
Vibration frequency	kHz	20	NA	20	NA

NA: Not applicable.

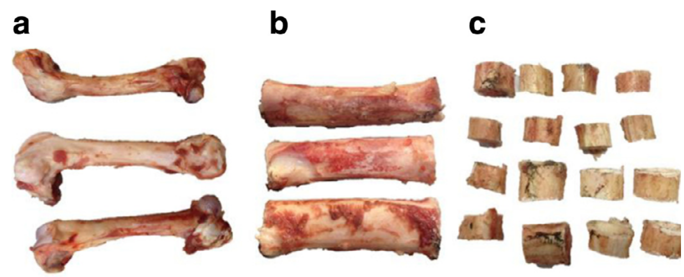

Fig. 2. Porcine bone specimens used for in-vitro study: (a) bones; (b) specimens for pullout strength and (c) specimens for microcrack analysis.

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 slaughter house 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