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Mechanistic modeling of bone-drilling process with experimental validation

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ABSTRACT

In this paper, an improved mechanistic model is developed to predict the thrust force and torque for bone-drilling operation. The cutting action at the drill point is divided into three regions: the cutting lips, outer portion of the chisel edge (the secondary cutting edges), and inner portion of the chisel edge (the indentation zone). Models that account for the unique mechanics of the cutting process for each of the three regions are formulated. The models are calibrated to bovine cortical bone material using specific cutting pressure equations with modification to take advantage of the characteristics of the drill point geometry. The models are validated for the cutting lips, the chisel edge, and entire drill point for a wide range of spindle speed and feed rate. The predicted results agree well with experimental results. Only the predictions for the drilling torque on the chisel edge are lower than the experimental results under some drilling conditions. The model can assist in the selection of favorable drilling conditions and drill-bit geometries for bone-drilling operations.

1. Introduction

Bone-drilling operations are indispensable in many orthopedic surgeries such as fracture fixation and dental implantation. The drilling forces and temperature must be carefully considered to obtain satisfactory surgical results. If the torque on the drill is too large, there is a tendency for the drill to jam or even to break in the bone. Price et al. (2002) and Pichler et al. (2008) investigated the rate of instrument breakage during orthopedic procedures and its post-operative effect on patients. Moreover, if the thrust force is excessive, the drill may plunge through the distal cortex, damaging the surrounding soft tissue. Lee and Shih (2006) developed a three-axis robotic bone-drilling system to stop the drill automatically when breakthrough occurs and verified it by drilling pig bones. Louredo et al. (2012) proposed a mechatronic bone-drilling tool to effectively stop the drilling procedure when a bone layer transition or breakthrough occurs. Aziz et al. (2012a,b) proposed a force control algorithm to halt the drill and return it to a safe position when breakthrough occurs. Díaz et al. (2013) proposed a new layer detection methodology with improved performance after evaluating prior methodologies and analyzing their drawbacks. Moreover, drilling forces can directly affect the maximum cortical bone temperature and its duration, which can pose a potential danger to bone cells. Lundskog (1972) showed that cellular necrosis could be induced if the bone is exposed to 50 °C for longer than 30 s. Eriksson and Albrektsson (1983) showed that bone tissue heated to 50 °C for 1 min or 47 °C for 5 min would not remain as functioning bone. Bachus et al. (2000) evaluated the effect of the drilling force on the cortical temperature and its duration and concluded that the application of a larger force to the drill can effectively reduce both the maximum cortical temperature and its duration above 50 °C. Thermal osteonecrosis contributes to screw or implant loosening and subsequently to surgical failure. Therefore, it is significant to predict and control the drilling forces and temperature during bone-drilling operations.

Experiments have been conducted to investigate the effects of the drilling conditions and drill-bit geometry on the drilling forces and temperature. Tuijthof et al. (2013) investigated the thrust force for cortical and trabecular bone drilling using eight tools and verified that the drill geometry and bone material have effects on the thrust force. Increasing the feed rate can increase the thrust force and torque as demonstrated (Alam et al., 2011; Jacob et al., 1976; Lee et al., 2012a; Udiljak et al., 2007) and that decreasing the point angle can reduce the thrust force as verified (Basiaga et al., 2011; Udiljak et al., 2007). However, the experimental results for the effect of the spindle speed on the drilling forces from different researchers are inconsistent and even contradictory. Experimental results of Alam et al. (2011), Basiaga et al. (2011) and Jacob et al. (1976) showed that increasing the spindle speed would reduce the thrust force and torque. Yet, Lee et al. (2012a) found the contrary

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result that the thrust force and torque were increased as the spindle speed was increased. Udiljak et al. (2007) concluded that the spindle speed had little effect on the thrust force. MacAvelia et al. (2012) showed that increasing the spindle speed reduced the thrust force and torque for human femur but had little effect for artificial femur. Augustin et al. (2012) and Pandey and Panda (2013) reviewed the effect of the drill geometry and drilling conditions on the temperature rise. Cooling by irrigation has been verified by Ai-Dabag and Sultan (2009), Augustin et al. (2008), Sener et al. (2009), and Zhang et al. (2013) to be an effective way to reduce the temperature rise when drilling bone. Sener et al. (2009) concluded that external irrigation at room temperature could provide a sufficient cooling effect, whereas lower temperature saline was even more effective. Inconsistent results for the effects of drilling speed and feed rate on the temperature have been obtained by different researchers. Results of Augustin et al. (2008, 2012), Karaca et al. (2011), Lee et al. (2012b), and Udiljak et al. (2007) showed that increasing the drilling speed would increase the temperature rise, whereas increasing the feed rate would decrease the temperature rise. However, Sharawy et al. (2002) showed that the mean rise in temperature was decreased as the drilling speed was increased from 1225 to 2500 rpm. Alam (2009) showed that the temperature rise was higher at a feed rate of 50 mm/min than at a feed rate of 20 mm/min.

Only a few studies have attempted to develop force and thermal models for bone-drilling operations to capture the effects of the drilling conditions and drill-bit geometry on the drilling forces and temperature. Powers (2006) evaluated the applicability of three empirical models (Cook, 1966; Karalis and Galanos, 1982; Langella et al., 2005) to the bone-drilling process and attempted to correlate the specific energy or drilling strength with the bone material density. XU et al. (2011) developed a force model by dividing the cutting lips and chisel edge into a number of elemental sections and applying empirical formula for each element. However, they unrealistically assumed that the thrust force was uniformly distributed along the chisel edge and cutting lips and that the chisel edge contributed 50% of the thrust force. These empirical models mainly include the effects of the feed rate and drill-bit diameter on the drilling forces. The effects of the spindle speed and drill-bit geometry are neglected. Moreover, numerous calibration experiments are required to obtain the coefficients for these empirical equations. Theoretical models, which take advantage of the bone material properties and drill-bit geometry and require no calibration experiments, are not available because the machining mechanics of the bone material is not fully understood and bone material properties like the plasticity and the damage initiation and propagation are unavailable or vary widely range as a result of the age, sex, and illness of the individual whose bone is being tested. Therefore, mechanistic models are introduced to avoid the requirements of a large number of experiments for empirical models and accurate material properties for theoretical models. Mechanistic models can effectively predict the thrust force and torque using only a few calibration experiments and material properties. Mechanistic models have been used successfully for the metal drilling process as demonstrated (Chandrasekharan, 1996) and have been extended to drilling operations for anisotropic materials like fiber-reinforced composite materials (Chandrasekharan et al., 1995). Lee et al. (2012a) first introduced a mechanistic model for the bone-drilling process and showed that the trends and average values of the thrust force and torque could be predicted successfully. However, an analysis of the force transformation on the cutting lips using this model contains some errors and the indentation zone adopted from Mauch and Lauderbaugh (1990) is inaccurate. This was verified and improved by Bono and Ni (2001). Davidson and James (2003) first introduced an overly simplified heat-generation model and heat-conduction model for the bone-drilling process. Only the heat generated from the primary shear zone for the cutting lips was included in this model, whereas the heat generated from friction and the chisel edge was completely neglected. Heat conduction with a ring heat source was assumed to calculate a steady temperature with the depth of the drilled hole. Lee et al. (2011) included the heat generated from the friction between the chip and the tool, but still neglected the heat generated from the chisel edge. Heat balance equations for bone and drill bit were developed and the temperature distribution was obtained using a finite difference method. A three-dimensional finite element model in Abaqus has been developed by Yuan-Kun et al. (2013, 2011) to study the effect of drilling conditions on temperature. The above three thermal models lack experimental validation. Therefore, their results are not convincing. Sezek et al. (2012) also developed a finite element model in MSC to evaluate the effects of the speed, feed rate, applied drill force, drill diameter, bone density, and bone sex on the temperature. However, the temperature curve increased twice with respect to time, which is not true for the temperature change when drilling bone.

In this study, an improved mechanistic model based on early work done by Bono and Ni (2001), Chandrasekharan (1996), and Lee et al. (2012a) was developed to predict the thrust force and torque when drilling the bovine bone material. First, the improved mechanistic model, including an analytical description of the drilling forces with respect to the drill-bit geometry and drilling conditions at each section of a twist drill, was developed. Then, a set of calibration experiments was conducted to derive the coefficients of the specific cutting pressure equations, which can be used to calculate the drilling forces under different drilling conditions for the cutting lips and the secondary cutting edges. Finally, a series of experiments under a wide range of drilling conditions were conducted to evaluate the mechanistic model.

2. Mechanistic force model formulation

The most commonly used drill is the conventional conical point drill, and surgical drills mainly originate from this type of drill with minor revisions. Therefore, in this paper, drilling force models are developed for this type of drill. The significant parameters that describe the geometry of a conical point drill (Fig. 1) include the drill diameter ($D = 2R$), point angle ($2k$), helix angle (δ_0), web thickness ($2w$), and chisel edge angle (φ). The drilling forces from the friction between the drill margins and the hole surface are assumed to be small enough compared to those from the cutting lips and chisel edge and can rationally be neglected. In addition, the temperature rise during drilling is assumed to have little effect on the drilling force change, and its effect is neglected. Therefore, the cutting action at the drill point can be divided into three distinct regions: the cutting lips, secondary cutting edges, and indentation zone (Fig. 1). Models that account for the unique mechanics of the cutting process for each of these three regions are formulated.

2.1. Force model formulation for the cutting lips

The cutting action along the cutting lips is a three-dimensional oblique cutting process (Fig. 2). The cutting velocity, as well as the inclination angle and normal rake angle, varies with the radial distance (r) along the cutting lips of the drill. The radial distance is the distance of the considered point on the cutting lips from the drill axis measured in a plane that is normal to the axis. Fig. 3 shows the variation in the cutting angles with the radial distance along the cutting lips of a typical conical point drill. As seen in Fig. 3, the normal rake angle varies considerably along the cutting lips, from negative values toward the chisel edge and to large positive values near the outer radius of the drill. The tangential cutting velocity is a