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Finite element modeling and experimentation of bone drilling forces

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Abstract. Bone drilling is an essential part of many orthopaedic surgery procedures, including those for internal fixation and for attaching prosthetics. Estimation and control of bone drilling forces are critical to prevent drill breakthrough, excessive heat generation, and mechanical damage to the bone. This paper presents a 3D finite element (FE) model for prediction of thrust forces experienced during bone drilling. The model incorporates the dynamic characteristics involved in the process along with the accurate geometrical considerations. The average critical thrust forces and torques obtained using FE analysis, for set of machining parameters are found to be in good agreement with the experimental results.

1. Introduction

In orthopaedic surgery, drilling and tapping are extensively carried out before the insertion of screws into bone. The desired outcome of bone drilling process is accurately positioned holes without mechanical and thermal damage to surrounding tissue.

Drilling into bone is a fundamental skill that can be both very simple, such as drilling through long bones, or very difficult, such as drilling through the vertebral pedicles where incorrectly drilled holes can result in nerve damage, vascular damage or fractured pedicles [1,2]. Similarly, large uncontrolled forces experienced during bone drilling may result in drill breakthrough, imparting damage to surrounding tissue [3-5] and promote crack formation which could yield bone failure [6]. Moreover, drilling forces are main source of heat generation during bone drilling [7]. Therefore, it is important to understand the effects of bone drilling conditions and material behaviour on the bone drilling forces to select favourable drilling conditions, and assist in robotic surgery procedures [3, 8].

Various studies have been carried since late 1950 to optimise the bone drilling performance based on measurable parameters such as, drilling force, drilling torque, rotational speed, feed rate, temperature and accuracy of the drilled hole [9-16]. Although these studies resulted in various conclusions, they have not provided a functional relationship that represent the effects of drilling conditions, drill bit geometry and material behaviour on drilling forces.

Finite element (FE) models of drilling can provide insight into the underlying mechanics of material behaviour at high strain and strain-rate regimes. An accurate and reliable FE simulation of drilling

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enables good predictions of thrust forces and torque by taking into account the complex drill geometry and process parameters. In this study, a 3D finite element (FE) model of drilling in bovine cortical bone is developed. An elastic-plastic material model is used to predict the behaviour of cortical bone during drilling. The model is used to predict the thrust force and torque during the specific cutting conditions.

2. Finite element analysis of drilling in cortical bone

2.1. Methodology

A three dimensional (3D) Lagrangian FE model of drilling of cortical was developed in a commercially available FE software ABAQUS/Explicit. The model accurately characterises the dynamic characteristics of the drilling process accounting for the contact interaction between a drill bit and cortical bone surface. A dynamic failure criterion is applied to control the element removal which has undergone severe deformation. The details of this FE model are discussed in following sections.

2.1.1. Geometry and meshing.

A rectangular plate with overall dimensions of 5mm × 5mm × 5mm was modeled as cortical bone specimen. Figure 1 shows the geometrical configuration of the drill bit and the bone model. The diameter, point angle and helix angle of the drill bit used in this study are taken as 2.5 mm, 118° and 30°, respectively. The drill bit was modeled as a discrete rigid body in order to reduce the computing time and resources. In order to model the kinematics of the drill bit accurately, a lumped mass and inertia was applied at a reference point located at chisel edge of the drill bit.

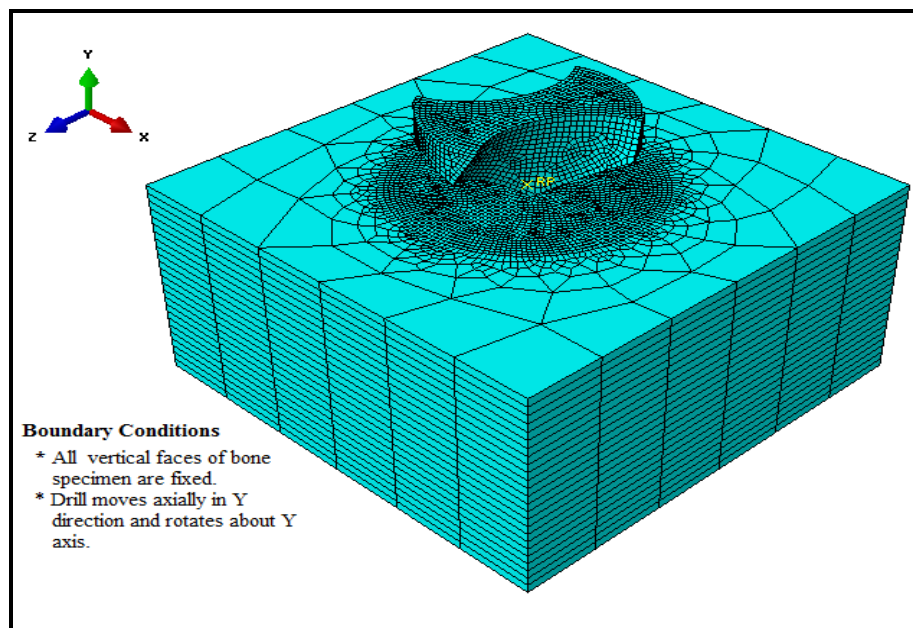


Figure1. FE model of bone drilling

An extensive mesh convergence study was carried out in this FE analysis to achieve the balance between mesh discretisation and stress distribution in cortical bone surface, for accurate prediction of drilling forces in the available computing resources. A refined mesh with a minimum size of 5 μm was used at and in the immediate vicinity of the volume to be drilled, while a coarse mesh was used to discretise the workpiece away from the path of drill bit. The cortical bone was modeled using 8-node, 3D brick elements of type C3D8R, while a twist drill was modeled with 4-node, 3D discrete rigid

elements of type C3D4. The cortical bone model consists of 101320 elements while the drill bit was meshed with 4850 elements. The drilling conditions were applied on reference point of the drill bit which has single node mass and rotary inertia.

2.1.2. Boundary conditions and contact interactions

The twist drill was fed into the workpiece in the axial direction using a velocity boundary condition, which represents the feed rate during experiments. A reference point which accounts for drill mass and inertia was constrained in X and Z directions while feed was applied in the Y direction. The combination of machining parameters used in this study to predict drilling forces are listed in table 1.

Table 1. Machining parameters used in bone drilling

Drill	HSS, \varnothing 2.5 mm, point angle 118°
Spindle speed (rpm)	800, 1200, 1500
Feed (mm/rev)	0.05, 0.1, 0.1875

Contact between the twist drill and the cortical bone was defined by the general contact algorithm available in ABAQUS/Explicit. This algorithm generated the contact forces based on the penalty-enforced contact method. The friction coefficient μ is used to account for the shear stress of the surface traction τ with the contact pressure p and can be represented as $\tau = \mu p$.

In this case, the frictional contact between a drill and cortical bone was modeled with a constant coefficient of friction of 0.7 [17]. The models require on average 54 h on 36 Intel quad-core processors with 48 GB RAM each to finish the analysis using High Performance Computing (HPC) facility available at Loughborough University.

2.1.3. Material model and failure law

The cortical bone in this study was modeled as a rate dependent transversely isotropic material. The elastic-plastic law was used for the material constitutive model of finite element simulation. The high strain rate data was obtained by using Split Hopkinson Pressure Bar (SHPB) experiments. The SHPB experiments were conducted at strain rates of 5000/s, 6400/s and 7500/s. The mechanical properties used in finite element analysis are summarized in table 2.

Table 2. Mechanical properties of bone used in finite element model

Density (Kg /m ³)	2000
Young's Modulus Longitudinal (GPa)	20
Young's Modulus transverse (GPa)	18
Strain at failure (%)	5

The dynamic failure law [18] was used to initiate and propagate the failure based on the SHPB experimental data. The failure was calculated for each element and was defined by

$$D = \sum \frac{\Delta \varepsilon^p}{\varepsilon^f} \quad (1)$$

where $\Delta \varepsilon^p$ was the increment of the equivalent plastic strain, and ε^f was equivalent strain to fracture. Failure was allowed to occur when $D = 1$, and the concerned elements were removed from the computation.

3. Drilling Experiments

To accomplish the aims of this study, bone drilling has been conducted on custom designed electromechanical test rig with single setting of specimen as per ASTM F543-02 standard. A microcontroller PIC18F6620 from the Microchip is used for interfacing test rig with the computer, and a 12-bit, eight channels data acquisition system is used for data recording. The experimental setup is shown in figure 2.

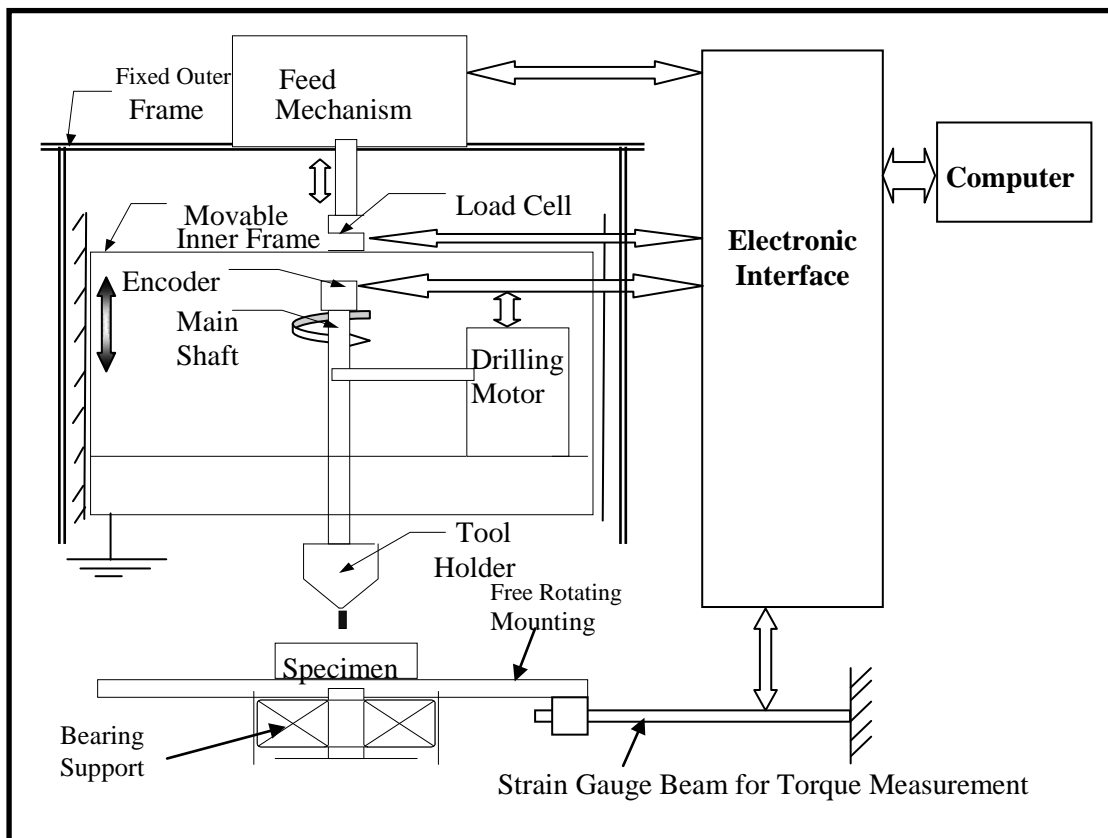


Figure 2. Schematic of Drilling Rig

Cortical bone used in this investigation was taken from mid-diaphysis of bovine femur. Bovine femur bone samples were purchased from a local butcher. Any extra tissues present around bone were cleaned using knife and scraper before testing. Bone used in saturated condition for testing. An industrial drill bit (Model A9762.2X125 Dormer UK) was used for these experiments.

4. Results and Discussion

In order to allow a better comparison of the experimental and simulated thrust force and torque in drilling cortical bone, a feed of 150 mm/min was chosen from the experimental feed data with a spindle speed 800 rpm. The FE simulations were carried out using these process parameters and later used to predict the thrust force and torque for other feed rates. Figure 3a and b shows the experimental and simulated data for the thrust force and torque in drilling of cortical bone. The average maximum thrust force (obtained for the period of complete drill engagement) in the experimental trial was 70 N whereas FE model estimated 72. The experimentally measured torque was 1.62 N-cm compared to the torque value predicted as 1.7 N-cm by FE simulation. This shows that the FE model estimated the thrust force and torque accurately, with 2.9% and 8% deviation from the respective test results.

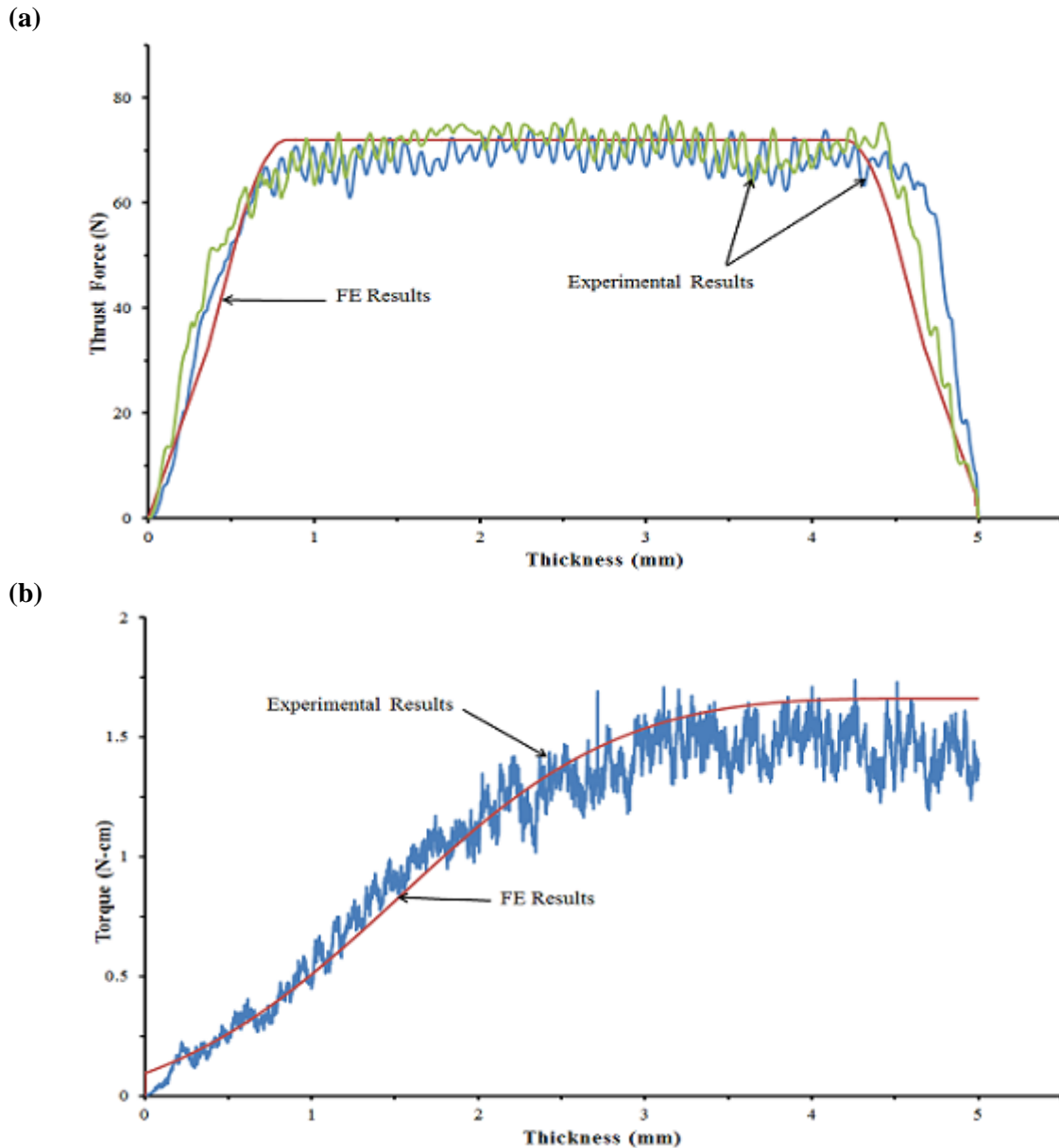


Figure 3. a) Comparison of thrust force and b) torque obtained from FE and experiments at spindle speed of 800 rpm and a feed rate of 0.1875 mm/rev.

Figure 4a shows the effect of drilling conditions on the average maximum thrust force. The FE model estimated the thrust force between 28 N and 70 N for the range of feed rates modeled. The obtained results indicate that thrust force in drilling increases with the increasing feed rate. It can be observed from Figure 4a that the average maximum thrust force was the highest at the feed rate of 0.1875 mm/rev and lowest at the feed rate of 0.05 mm/min. Figure 4b shows the drilling torque corresponding to different spindle speeds. The overall results show that the torque increased with the increase in spindle speed.

5. Conclusion

In this paper the effect of different machining parameters on thrust force and torque in drilling of a cortical bone was investigated both experimentally and numerically. A 3D FE model of drilling in

cortical bone was developed. The dynamic failure criterion for damage initiation was used for hole making process in drilling. The following observations were made in this study:

- The FE model predicted the drilling thrust force and torque with reasonable accuracy when compared to experimental results.
- The validated drilling model was used to determine the thrust force, and torque for different drilling conditions. It was observed that the thrust force and torque increased with an increase in the feed rate and spindle speed. Thrust force and torque may be reduced by using the low feed which can be achieved by a combination of low feed rate and high spindle speed, while drilling in cortical bone.

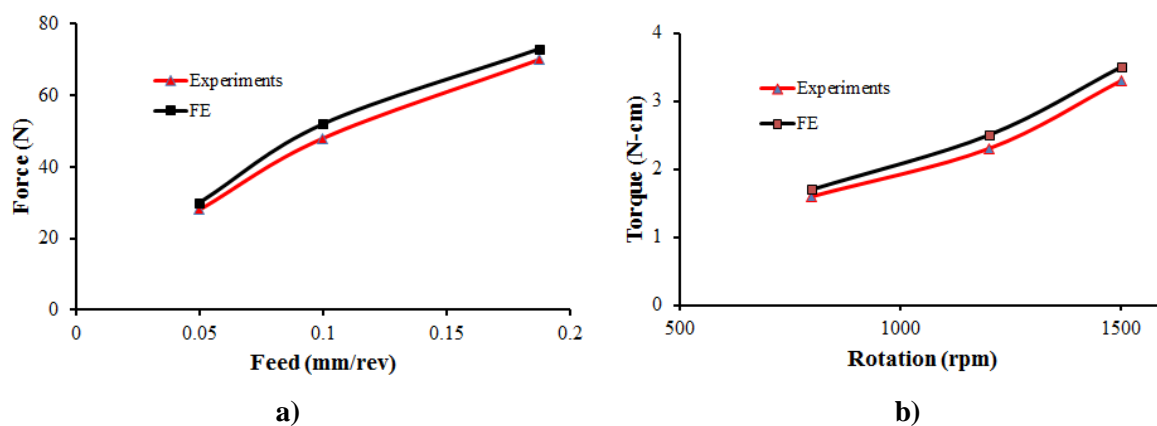


Figure 4. a) Comparison of thrust force b) torque obtained from FE and experiments at different cutting conditions

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