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# The influence of anisotropy in numerical modeling of orthogonal cutting of cortical bone

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ABSTRACT

Cutting operations in bone are involved in surgical treatments in orthopaedics and traumatology. The importance of guaranteeing the absence of damage in the living workpiece is equivalent in this case to ensuring surface quality. The knowledge in this field is really far from the expertise in industrial cutting of mechanical components. Modeling of bone cutting is a challenge strongly dependent on the accurate modeling of mechanical behaviour of the bone. This paper focuses on modeling of orthogonal cutting of cortical bone. The intrinsic anisotropic nature of the cortical bone that makes it comparable to a composite material is taken into account. The influence of anisotropy is analysed comparing this behaviour with an isotropic approach. It is shown that both chip morphology and temperature are affected by the anisotropy of the cortical bone that acts as a workpiece.



## 1. Introduction

Cutting of bone is a common operation in orthopaedic/traumatologic surgery and dentistry. Cutting operations in bones involve a wide range of operations including grinding, sawing or drilling, see for instance [1–3]. It is well known in the field of manufacturing the importance of proper definition of machining operations for process efficiency (including both time and cost) and surface integrity. This concept is translatable to bone cutting since it is required to conjugate low cutting time (in order to diminish the total time of the surgery) and surface quality (mainly related with thermal bone damage) because the thermal affected layer at the machined bone could involve osteonecrosis [4].

The importance of the cutting processes for further evolution of the patient has motivated the study of bone machining. Thermal necrosis of the surrounding bone is the most important consequence of aggressive cutting of the bone. Osteonecrosis due to excessive temperature could cause further clinical problems such as loosening of bone-implant interface. Also grinding operations have received attention since they are commonly applied in intracranial surgery. The heated zone involves not only the bone, but also the blood vessel and nerves located close to the grinding zone [1]. Recent papers focus on the problem of osteonecrosis caused by cutting bone during surgery. For instance, drilling is one of the most important operations and a summary of the state of the art is presented in [4,5].

It is difficult to extract general conclusions from the works reviewed since the parameters involved in heat generation, such as the tool geometry, the cutting parameters or the use of coolant, are different in each application. The complexity of the problem makes the analysis of bone cutting very difficult with a purely experimental approach.

The use of validated modeling tools, such as the finite element method (FE) could help in the analysis and definition of machining operations in bones. However one of the most important factors in the achievement of accurate simulations is the statement of proper constitutive equations representative of bone behaviour.

Concerning the structure of the workpiece in surgery, it is worth that bones are composed of two main tissues: the cortical bone in the outer surface region and trabecular bone in the inner regions. The cortical bone is made of hard, dense tissues and takes charge of the main compressive and bending loads. The trabecular bones are made of sparse, rod-like tissue to reduce structural mass [6,7].

This paper focuses on cutting of cortical bone. In fact it is the first bone layer to be cut in any surgical operation. More specifically we concentrate on the case of diaphysis of long bones; it is important to note that significant differences in the structure can be found in other types of bone (for instance cranial).

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The damage in this part of the bone is critical considering its structural responsibility. In a micro-level (50–500 microns) the cortical bone is an anisotropic material suitable to be considered as a composite. It is possible to distinguish three relevant entities at this tissue level:

- **Recent osteons** they are cylinders (in a first approximation) with diameter ranging between 50–200 microns and length in the range 3–5 mm. The osteons are formed in the continuous process of bone remodelling [7,8].
- **Interstitial matrix** it is composed mainly of rests of old osteons with higher mineral content than recent osteons. The matrix presents lower toughness than recent osteons [7].
- **Cement line** it is a thin layer (about 1–5 microns [9]) surrounding the young osteons that appears during the formation of osteons. This zone exhibits low toughness, thus being a weak zone promoting crack propagation around the osteon [9,10,26].

A simplified scheme of the cortical bone is shown in Fig. 1. A common assumption is to consider the cortical bone transversely isotropic, thus the mechanical properties in directions 2 and 3 would be identical but different of those in direction 1 (see Fig. 1).

Concerning the values of elastic properties it is possible to find contributions of different authors in the literature, mainly dealing with strength analysis of bone, since cutting has been poorly studied up to date. This fact will be further discussed in the following section.

Despite the anisotropic structure of bone, an isotropic approach in cutting bone modeling was presented in Alam et al. [11]. The authors carried out an experimental and numerical study focused on orthogonal cutting of bone. A two dimensional model of the process assuming elastic-viscoplastic behaviour of the bone for cutting forces and temperature prediction was presented. The mechanical response is represented by the Johnson–Cook law (without thermal softening). The Johnson–Cook model has been widely used for the simulation of metal cutting (see for instance recent works of the authors [12,13]). The same approach to the mechanical behaviour of bone was used in [14]. In this work a two dimensional model was applied to predict temperatures reached during bone drilling. Although the process is simplified considering orthogonal cutting and assuming an equivalency to cutting with the external side of the drill edge, reasonable accuracy is observed in temperature prediction.

Tu et al. [15] developed a model for drilling in the FE code ABAQUS explicit assuming an isotropic elastic–plastic behaviour of the bone, however no details concerning failure model were included in the paper. The influence of thrust force and cutting speed in temperature was obtained, finding decreasing temperature when both variables increased. Three dimensional approach required for drilling modeling involves rigorous simulation of rotation and feed movement of the tool (including penetration of the drill in the workpiece and element erosion) and usually leads to elevated computational cost. Lughmani et al. [16] developed a FE model in ABAQUS explicit for prediction of force and torque. In this work the bone was considered to be anisotropic and only elastic properties are presented in the paper. Even in the case of carbon fibre composites, there are few works dealing with a complete approach to drilling and they have been recently developed [17,18].

The detailed analysis of bone cutting is difficult using a 3D approach of the current operation, especially when the chip morphology is to be analysed. Orthogonal cutting has the advantage of allowing detailed simulation of the contact tool/chip and the use of small elements. Even in the case of metal cutting it is widely used to analyse the mechanisms involved in the cutting process.

The simulation of bone cutting has been poorly described in the scientific literature. This paper focuses on orthogonal cutting of cortical bone comparing an isotropic approach with an anisotropic behaviour of the bone which is assimilated to a composite material. In this work the simple case of orthogonal cutting is modelled with the aim of obtaining basic information concerning cutting forces, chip morphology and temperature, depending on material behaviour and cutting conditions. Two different models were developed: 2D for isotropic behaviour and 3D allowing the simulation of different orientations of the osteons. In the second model recent results obtained by the authors in composite cutting were considered, such as the influence of fibre orientation on chip morphology [19] and the prediction of temperature distribution [20]. Interesting conclusions were obtained, finding a strong influence of the anisotropy in chip morphology and temperature.

## 2. Modeling behaviour of cortical bone

Different models have been developed [11,21–28] with the aim of reproducing the behaviour of cortical bone. In this work, cortical bone of bovine femur is used as a reference and the numerical results are compared with the experimental data in the literature. The interest of this type of bone is related to its mechanical, fracture and thermal properties, very similar to those exhibited by human bone [11,26]. Two different models of cortical bone have been used: a rate dependent isotropic material and an anisotropic model dependent on the osteon orientation. Moreover, two different numerical models have been developed: 2D (for isotropic model of the bone) and 3D model allowing the simulation of the influence of osteon orientation.

The bone models are described in detail in the following subsections.

### 2.1. Rate dependent isotropic material

This model assumes von Mises J2 plasticity criteria based on a Johnson–Cook hardening law. Von Mises yield surface is defined by tension/compression symmetry. The Johnson–Cook hardening law is frequently applied to analyse the dynamic behaviour of

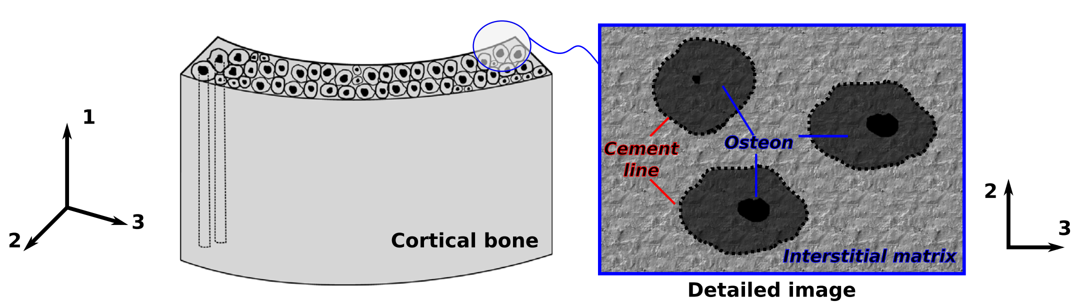


**Fig. 1.** Scheme of the cortical bone structure: Young osteons surrounded by cement line in an interstitial matrix composed by old osteons.