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Review Article

A review on recent advances in numerical modelling of bone cutting

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ABSTRACT

Common practice of surgical treatments in orthopaedics and traumatology involves cutting processes of bone. These operations introduce risk of thermo-mechanical damage, since the threshold of critical temperature producing thermal osteonecrosis is very low. Therefore, it is important to develop predictive tools capable of simulating accurately the increase of temperature during bone cutting, being the modelling of these processes still a challenge. In addition, the prediction of cutting forces and mechanical damage is also important during machining operations. As the accuracy of simulations depends greatly on the proper choice of the thermo-mechanical properties, an essential part of the numerical model is the constitutive behaviour of the bone tissue, which is considered in different ways in the literature. This paper focuses on the review of the main contributions in modelling of bone cutting with special attention to the bone mechanical behaviour. The aim is to give the reader a complete vision of the approaches commonly presented in the literature in order to help in the development of accurate models for bone cutting.

Contents

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1. Introduction

General orthopaedic and traumatologic surgery and dentistry commonly involve cutting of bone. Cutting operations entail a wide range of processes covering sawing (James et al., 2014), drilling (Fox et al., 2013) and grinding (Tai et al., 2013).

The well-known industrial concepts of productivity and surface integrity in material removal processes can be translated to medical applications. In this surgical context reduced cutting time is related to short surgery global time and bone integrity is related to the absence of cutting induced damage, mainly thermal osteonecrosis. Thermal necrosis, induced due to excessive temperature, is the main risk for the bone tissue surrounding the cutting zone. Further clinical problems such as loosening of implant interfaces could be derived from thermal necrosis during surgery. The importance of this problem has motivated the development of different research works focusing on the problem of osteonecrosis caused by bone cutting during surgery. Recent reviews dealing with bone drilling, a common operation for screw accommodation, are presented in Augustin et al., 2012; Pandey and Panda, 2013.

Despite the interest of works dealing with bone cutting, it is really difficult to extract from them concluding remarks. The main reason is the wide variety of parameters involved in heat generation during cutting, such as the tool geometry, the cutting parameters or the use of coolant, which are different in each application analysed in the literature. On the other hand in-process monitoring of temperature is still a challenge at present.

The modelling of cutting processes can help in the understanding of bone cutting and thus in the analysis and definition of cutting operations in bones. Validated models allow to obtain information about variables that are difficult to measure. Accuracy of the model predictions rely on the proper definition of the type of approach, geometry, boundary conditions, constitutive modelling of the bone tissue, thermal properties and contact characteristics. To date it is possible to find disperse information concerning the mentioned aspects. The complexity of the cutting process in general requires finite element (FE) modelling in order to reproduce the factors influencing the output variables (mainly temperature, cutting forces and surface integrity). Among these factors the most important and complex one is the constitutive model of the bone. Even in the well-known case of metal or composite cutting operations, accurate modelling of mechanical behaviour of the workpiece is crucial for machining simulation, see for instance the recent works of the authors (Miguélez et al., 2013; Santiuste et al., 2011). These applications are good examples of isotropic (metal) and anisotropic (composite) workpieces.

Concerning the structure of bone, it is composed of two main tissues: the cortical bone in the outer surface region and trabecular bone in the inner regions and epiphysis of long bones. The cortical bone is made of hard, dense tissues and takes charge of the main compressive and bending loads. The trabecular bone is made of sparse, rod-like tissue to reduce structural mass (Kim et al., 2010).

Most works in the literature deal with the cutting operations of cortical bone since damage in this tissue is critical considering its structural responsibility, especially in long bones. Although a detailed revision of literature focusing on cortical bone cutting will be included in the following sections, a brief explanation of this tissue architecture is presented below.

Cortical bone is the first layer to be cut in any surgical operation. The microstructure of cortical bone (particularly at the diaphysis of long bones) is clearly anisotropic. In a micro-level (50–500 μm) it is possible to distinguish three relevant entities at this tissue level:

Recent osteons: cylinder shaped (in a first approximation) with diameter in the range 50–200 μm and length ranging from 3 to 5 mm. The osteons are formed by the continuous process of bone remodelling (Cowin, 2001; Taylor et al., 2007).

Interstitial matrix: mainly composed of rests of old osteons, with a higher mineral content than in recent