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# A review of cutting mechanics and modeling techniques for biological materials

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ABSTRACT

This paper presents a comprehensive survey on the modeling of tissue cutting, including both soft tissue and bone cutting processes. In order to achieve higher accuracy in tissue cutting, as a critical process in surgical operations, the meticulous modeling of such processes is important in particular for surgical tool development and analysis. This review paper is focused on the mechanical concepts and modeling techniques utilized to simulate tissue cutting such as cutting forces and chip morphology. These models are presented in two major categories, namely soft tissue cutting and bone cutting. Fracture toughness is commonly used to describe tissue cutting while Johnson–Cook material model is often adopted for bone cutting in conjunction with finite element analysis (FEA). In each section, the most recent mathematical and computational models are summarized. The differences and similarities among these models, challenges, novel techniques, and recommendations for future work are discussed along with each section. This review is aimed to provide a broad and in-depth vision of the methods suitable for tissue and bone cutting simulations.

## 1. Introduction

Tissue cutting broadly refers to machining of biological materials inside the human body, which could be soft and elastic (e.g., skin, muscle, organs) or hard and brittle (e.g., bone, calcified plague). Tissue cutting is a common but, sometimes, a critical process in surgical operations. For example, surgeons use a scalpel to access lesions and a power drill to create burr holes and screw holes in bone. The injury caused by these cutting tools to surrounding living tissues or neurovascular system could lead to catastrophic outcomes. In particular, some specialized operations need extremely precise control over the tissue cutting process, such as deep brain stimulation, needle brachytherapy, minimally invasive spine and neurosurgery. Therefore, surgical device manufacturers continue to design the tools with better efficiency but less trauma. They also strive to develop virtual reality (VR) simulators for the increasing need for surgical training. Meanwhile, robotic-assisted surgery is being rapidly evolved for improved performance. All of these efforts link to a key enabler – tissue cutting mechanics. Tissue cutting mechanics is a subject that describes the material separation physics and the forces generated during the process. There have been many comprehensive studies on tissue mechanics and bone mechanics [1–7], while the literature regarding the “cutting” is of relatively a small amount. To enable the future development of tissue cutting mechanics, the objective of this review paper is to collect the published works on both soft tissue and bone cutting and discuss the common and special techniques used to facilitate the cutting simulation.

In the field of soft tissue cutting, deep needle insertion is of particular interest because needle bending and tissue deformation cause the trajectory deviation from the target [8–10]. Tissue cutting consists of cutting, friction, and elastic forces from the surrounding tissue. Many real-time algorithms, used for needle steering and VR simulation, are mostly focused on tissue deformation and graphic computation. The cutting force is often modeled as a constant or a threshold value [11]; this value is experimentally determined for a specific tool and tissue type. Recent development has been moved toward predictive models with more flexibility for various scenarios. Many researchers adopted fracture mechanics as the dominant mechanism to predict the cutting force [10,12–18]. These models are similar in the sense of concept but they also use different techniques.

Compared to tissue cutting, bone cutting mechanics (specifically referring to cortical bone) has been discussed much more frequently in the literature because of the broad interest in orthopedic and general surgery, where bone cutting is more traumatic and dangerous. From the modeling perspective, bone is more rigid and stiffer than soft tissues and thus can be analogized to metal cutting. For this reason, finite element analysis (FEA) based on Johnson–Cook (J–C) material model has been extensively used

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by many researchers [19–22]. However, these models all have some differences in model setup, parameter selection, and damage criteria. Some other bone cutting works used the conventional cutting mechanics with geometrical relationship to develop a mathematical model for cutting force prediction [23–25].

Heat generation as a result of bone cutting forces is another interesting topic due to the risk of thermal necrosis. Similar to metal cutting, the heat stems from the primary shear deformation within the shear zone, friction between the rake face of the tool and the chip, and also the flank face of the tool and newly created surface of the workpiece. Some studies employed a numerical FEA to study a complex drilling configuration [22,26]. Others developed a direct thermal model, also based on machining, for bone drilling processes [27,28]. A proper bone cutting model is the key to an accurate cutting temperature prediction. A thorough review on bone drilling is available elsewhere [29].

Although a number of studies have looked at the thermal issues with tissue machining, this review paper specifically focuses on the models and techniques associated with cutting forces and chip morphology. To provide clear comparisons between these models, this paper will thoroughly review them in terms of the concept, technique, implementation method, and validation. The current review paper pays special attention to soft tissues and bones and focuses on modeling of their material behaviors of cutting, including chip formation and cutting forces. Papers selected for this review were published within 10 years from the fields of manufacturing, bio-medical engineering, and robotics. Both mathematical and computational models are included.

## 2. Cutting of soft tissues

Soft tissue cutting involves three types of force: cutting force, frictional force, and the elastic force of tissue deformation. For needle insertion analysis, the frictional and elastic forces are considered the dominant factors particularly for a long and small needle insertion, while the cutting force is often modeled as a constant acting at the needle tip [11]. There is a large number of works in the elastic or visco-elastic modeling of tissue mechanics in deformation, as reviewed elsewhere [9,10], but only a few of the cutting mechanics. The cutting force, in fact, plays an important role as it is directly related to tissue damage. This section summarizes the recently developed mathematical and computational models that describe tissue cutting phenomena.

### 2.1. Mathematical models

### 2.1.1. Elemental cutting tool (ECT) models

A mechanics-based tissue cutting model was presented by Moore et al. [8,30] and the continuous works [31,32]. These models were all based on the concept of the elemental cutting tool (ECT). ECT method is commonly used in machining tool modeling (e.g., drill or end mill cutters), which divides a complex cutting edge geometry into multiple small elemental cutters. Each of these ECTs performs an orthogonal cutting or an oblique cutting with its own characteristic angles such as rake angle ($\alpha$) and inclination angle ($\lambda$), as shown in Fig. 1. The summation of all the ECT forces is the total cutting force.

According to metal cutting theory [34], the cutting force (in the feed direction) is highly dependent on $\alpha$ and $\lambda$. Therefore, Moore et al. [30] first measured the cutting force using a set of cutting blades with various $\alpha$ and $\lambda$. They established an empirical model (i.e., the response surface) of the specific cutting force, denoted by $f(\lambda, \alpha)$ (unit in force per length) by interpolation across the data points, as shown in Fig. 2(a). The cutting force $F_c$ can be calculated by integrating $f(\lambda, \alpha)$ along a defined cutting edge geometry. For example, Fig. 2(b) shows an example of single-bevel, hollow needle and the identified cutting edges. The cutting force is

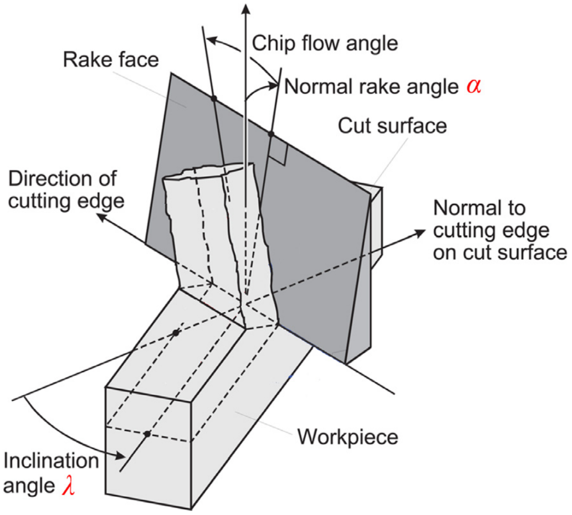

**Fig. 1.** Elemental cutting tool (ECT) and the definitions of rake angle and inclination angle [33].

$$F_c = \int f(\lambda, \alpha) ds = \int_0^{\theta} f(\lambda, \alpha) r(\theta) d\gamma \tag{1}$$

where $r(\theta)$ is the radial distance from the axial center line at the rotation angle $\theta$. It was also found that the inclination angle $\lambda$ had a more significant force reduction effect than that of the rake angle $\alpha$. Wang et al. [31,32] further proved this statement by comparing the cutting force of various needle tips inserted into porcine liver tissues. The ECT-based model is capable to predict the performance of a cutting tool design; however, the use of this model requires extensive pre-tests to determine the specific cutting force, and this force function is specific to the tissue selected.

Han and Ehmann [35] adopted Atkins and Xu's cutting theory based on slice/push ratio [36] to simulate the needle cutting, in particular a dynamic (rotational) cutting condition. All types of cutting were assumed dependent on the slice/push ratio ($k =$ speed parallel to the cutting edge/speed perpendicular to the cutting edge). The cutting forces perpendicular to ($f_v$) and along ($f_h$) of a unit length of the cutting edge are given by

$$f_v(k) = \frac{R(1 + M\sqrt{1 + k^2})}{1 + k^2} \tag{2a}$$

$$f_v(k) = \frac{R(1 + M\sqrt{1 + k^2})}{1 + k^2} \tag{2b}$$

where $R$ is the fracture toughness and $M$ is the friction factor. The slice/push ratio $k$ depends on the cutting edge geometry and the motion of insertion. For a simple cannula needle tip (no bevel), the total axial force would be $2\pi r f_v(k)$ with $r$ being the needle radius. The model was able to capture the force change on a PVC-based phantom tissue when the rotational speed or feed changes.

### 2.1.2. Fracture mechanics models

Tissue cutting is considered to be a continuous crack propagation from the tool cutting edge. Therefore, energy-based approaches have been used to describe the tissue crack phenomenon as reviewed by Azar and Hayward [37]. Based on the existing studies, they further developed a more comprehensive model for needle insertion considering the cutting force, frictional force, and deformation of the tissue. The work done by the total insertion force is equal to the summation of the material fracture energy, strain energy of tissue deformation, and the work done by the friction,