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A mechanistic force model for simulating haptics of hand-held bone burring operations

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ABSTRACT

This paper presents a mechanistic model to predict the forces experienced during bone burring with application to haptic feedback for virtual reality surgical simulations. Bone burring is a hand-held operation where the force perceived by the surgeon depends on the cutting tool orientation and motion. The model of this study adapted the concept of specific cutting energy and material removal rate based on machining theory to calculate force distribution on the spherical tool surface in a three-dimensional setting. A design of experiments with three tool cutting angles and three feed motions was performed to calibrate and validate the model. Despite some variance in the results, model predictions showed similar trends to experimental force patterns. While the actual force profile also exhibits significant oscillation, the dominant frequencies of this oscillating force component were found to be independent of cutting and non-cutting instances, and hence could be imposed as a uniform background signal. Though the presented model is primarily applicable to abrasive burrs, it has far-reaching applications within other types of surgical simulations as well.

1. Introduction

Virtual reality (VR) interfaces integrated with haptic devices are increasingly being used in medical training to simulate surgeries [1–3]. Haptic devices use algorithms based on a force rendering model to calculate forces experienced during the manipulation of soft and hard tissues. However, creating realistic haptic feedback is challenging for operations involving biological material removal because of the varying position and orientation of the cutting tool and the highly dynamic and non-linear material responses, as opposed to simple elastic contact and deformation of the object.

Several haptic force models were developed during the last decade to simulate dental and temporal bone surgery using burring tools. These force models can be broadly classified into non-physics-based and physics-based models. Non-physics based models typically do not relate the cutting forces to the mechanical properties of the bone. Most of the models that fall under this category use penalty-based techniques [4–9]. These techniques compute a force output that is proportional to the overlapping volume (*i.e.*, the number of voxels) between the tool and bone material visual models. On the other hand, physics-based models typically provide a relationship between the forces and one or more mechanical properties of the bone. The most common approaches used in physics-based modeling are based on Hertz contact theory [10] and impulse-based dynamics [5]. However, these physics-based models ignore the mechanics of material removal in their formulation. More recent models have used the concepts of specific cutting force [11–13] and specific cutting energy [14] for cutting force computation, but the comparison and validation with experimental results have not been conducted.

Therefore, the objective of this research is to revisit the need for a mathematical model that can be used for realistic surgical simulation. Of particular interest is high-speed bone burring, which is commonly used in neurosurgery, otolaryngology, plastic surgery and orthopedic surgery. Burring is a process of using abrasive cutting tools to shape the bone. These tools are often spherical in shape, 2–4 mm in diameter, and operated at over 60,000 rpm. Burring is the same as grinding in their material removal mechanism, for which many theoretical and numerical models have been developed. These models take into account the abrasive rake angles, sizes, distribution, and so on to formulate the forces [15]. However, in our context, a nearly real-time computation is needed, while a 3D grinding model with all six degrees of freedom in a hand-held operation is complex, computationally expensive, and technically infeasible. The proposed model, therefore, is still based on geometrical computation but further incorporates machining mechanics and effects of tool rotation. The model concept and experimental studies are presented in the following sections. This paper will also discuss the applicability of the model and potential limitations.

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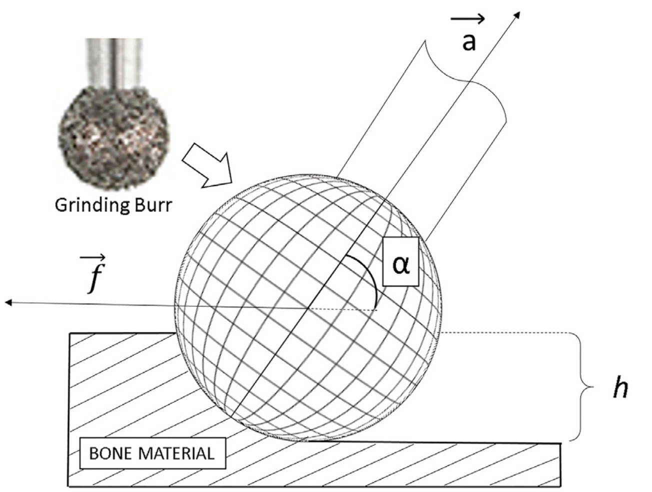

Fig. 1. Schematic of burring process with an actual image of the burr (inset). The direction of the axis of the tool ($\vec{a}$) and the feed direction ($\vec{f}$) are shown in the image. 'h' is the depth of cut. 'α' is the angle of cutting.

2. Mechanistic model formulation

In order to construct the force model for a three-dimensional burr, it is essential to understand the grinding process and the various parameters that affect it. A grinding burr is a spherical tool with diamond abrasives embedded on its surface. Other types of burrs exist as well for removing bone as reported by Danda et al. [16], whereas this study is specifically focused on the grinding burr. A schematic of the burring process is shown in Fig. 1. The angle of the cutting tool, depth of cut, feed rate, direction of cut and spindle speed (*i.e.*, RPM) of the drill are the main parameters that determine the cutting force. The tool cutting angle (denoted by α) is the angle between the axis of the tool and the cut bone surface. Depth of cut is marked as h. Feed direction ($\vec{f}$) is the direction of the tool moving forward relative to the cut bone surface.

For computing the cutting force, the model uses the concept of specific cutting energy (U_s), which is the energy expended in removing (*via* machining) a unit volume of workpiece material. The total energy for material removal should be equal to the work done by the external forces. The specific cutting energy is not only a material constant but also highly related to chip thickness and cutting edge angles [17,18]. A constant U_s is used here to represent a combined effect for given burr and work-material. Assuming abrasive burrs have many small cutting edges uniformly distributed on the surface, the model divides the surface into finite elements and to find the forces on each elemental surface (Fig. 2(a)). These distributed forces do not necessarily mean the forces acting on each cutting edge; instead, they represent a force distribution on the burr surface. Therefore, the total force experienced by the burr is the vector summation of the forces of all elements.

In implementation, the first step is to calculate the amount of volume removed within a time increment (Δt) by each elemental surface. This will be identical to the volume swept by each elemental surface along the feed direction in burring (Fig. 2(a)). The curved elements can be approximated as planar quadrilaterals since the number of elements is sufficiently high (over 2500 elements on a 4 mm diameter spherical surface in our case). Therefore, the volume (V) swept by each element per unit time will be equal to the dot product of the elemental area vector ($\vec{A}$) which is normal to the respective element and feed rate ($\vec{v_f}$) as given in Eq. (1). The amount of energy consumed (or W, work done) to remove this volume will be computed from the specific cutting energy (U_s).

$$V = \left(\vec{A} \cdot \vec{v_f}\right)\Delta t \quad (1)$$

The force components experienced by each element during burring include a tangential force ($\vec{F_t}$) and a normal force ($\vec{F_n}$), as illustrated in Fig. 2(b). Since the tangential speed (associated with the tool rotational speed) is much higher than the normal speed (tool feed rate), the majority of the work done can be attributed to the tangential force, as described by Eq. (2). This energy equilibrium relationship can be simplified as in (3), where $\vec{v_t}$ is the tangential velocity of the element. Therefore, if the specific cutting energy is known, the tangential force distribution on the burr surface can be determined.

$$W = U_s V = \left(\vec{F_t} \cdot \vec{v_t}\right)\Delta t = |F_t||v_t|\Delta t \quad (2)$$

$$|F_t| = \frac{(U_s V)}{|v_t|\Delta t} = \frac{U_s(\vec{A} \cdot \vec{v_f})}{|v_t|} \quad (3)$$

The normal force is generally proportional to the tangential force with a constant of proportionality K based on the theory of grinding [19], as expressed by Eq. (4). It is known from the literature that this coefficient is about 1.3 [19], but could vary depending upon the grinding conditions. For simplicity and computational efficiency, the proposed model takes a constant $K = 1.3$ as an initial trial value. Finally, normal and tangential forces are calculated on each element and integrated across the surface to find the total force on the burr. A vector addition of all the normal and tangential forces is conducted to obtain the resultant force, and transformed to the three orthogonal directions, namely feed ($\vec{f}$), normal ($\vec{n}$), and lateral ($\vec{l}$) directions, as shown in Fig. 3. The resultant force calculations are given in Eq. (5).

$$|F_n| = K|F_t| \quad (4)$$

$$\begin{aligned}
\vec{F}_{\text{feed}} &= \vec{f} \cdot \sum \vec{F_n} + \vec{f} \cdot \sum \vec{F_t} \\
\vec{F}_{\text{lateral}} &= \vec{l} \cdot \sum \vec{F_n} + \vec{l} \cdot \sum \vec{F_t} \\
\vec{F}_{\text{normal}} &= \vec{n} \cdot \sum \vec{F_n} + \vec{n} \cdot \sum \vec{F_t} \\
\vec{F}_r &= \vec{F}_{\text{feed}} + \vec{F}_{\text{lateral}} + \vec{F}_{\text{normal}}
\end{aligned} \quad (5)$$

3. Experimental study for model calibration and validation

Experiments were designed to determine the U_s value for the model, and to further validate the force model across the test design space. The relevant setup and testing variables are detailed in this section.

3.1. Experimental setup

The experimental setup is designed to explore the effects of tool feed motion and tool cutting angle (α in Fig. 1) on the forces experienced during bone burring. This can be achieved by recording the force in all three orthogonal directions when burring a synthetic cortical bone using a surgical tool in different configurations. The synthetic cortical bone was made using a ProJet® 160 3D printer and hardened with epoxy, following a composition-recipe to mimic the properties of real human bone. This synthetic bone has been shown to respond in a very similar manner during burring processes as compared to real cortical bone [20,21]. The synthetic model can also eliminate the inconsistency and uncertainty of using animal or cadaveric bone samples. The experimental setup is shown in Fig. 4. The workpiece (synthetic bone) was attached to a powered linear slider which provided the constant feed rates for

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