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Hybrid cutting of bio-tissues

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Abstract

Modern-day histology of bio-tissues requires high-precision cutting to ensure high quality thin specimens used in analysis. The cutting quality is significantly affected by a variety of soft and hard tissues in the samples. The paper deals with the next step of microtome development employing controlled ultrasonic vibration to realise a hybrid cutting process of bio-tissues. The study is based on a numerical (finite-element) analysis of multi-body dynamics of a cutting system. Conventional and ultrasonically assisted cutting processes of bio-tissues were simulated using material models representing cancellous bone and incorporating an estimation of friction conditions between a cutting blade and the material to be cut. The models allow adjustments of a section thickness, cutting speed and amplitude of ultrasonic vibration. The efficiency and quality of cutting was dependent on cutting forces, which were compared for both conventional and ultrasonically assisted cutting processes.

Keywords: Finite element method, Hybrid machining, Ultrasonic, Cutting, Force

1. Introduction

To support stratified medicine diagnoses, next-generation histology will need to process high-volume and high-quality samples with precision cutting. Due to blade wear resulting in surface damage of samples, there is a strong need for improved sample preparation.

In recent years, ultrasonically assisted machining (UAM) has shown to improve machinability of metals [1] and composites [2]. In UAM, a cutting tool is typically vibrated at a frequency of 20 kHz and above (hence ultrasonic) with low amplitudes. UAM has shown improved quality of finished products including a significant reduction in nominal cutting force.

Ultrasonically assisted cutting is also widely used in the food industry for food processing. A superposition of the blade cutting movement and the ultrasonic vibration movement produces a nearly frictionless surface between the blade and the food material thus leading to reduced smearing with less imposed pressure during processing. The technology has been shown to work effectively with sticky and/or brittle food material [3].

An ultrasonic microtome is a novel concept for histological systems with relevance to stratified medicine. The major challenges for design of such a system reside in the development of tuned devices capable of sectioning bio-tissues with controlled and repeatable thickness with minimal blade wear. This study investigates the effects of cutting parameters (including cutting speeds and section thicknesses) and characteristics of ultrasonic excitation with the aim of designing an ultrasonic cutting device for microtomy.

Numerical simulations in this study are carried out with the use of a finite-element (FE) method using general-purpose finite-element software ABAQUS. FE models of ultrasonic cutting into cancellous bone were created for evaluation of parameters involved in an ultrasonic cutting process and

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optimisation of the cutting conditions. The choice of cancellous bone is relevant as common histology often deals with presence of hard components embedded in soft tissues that lead to rapid blade wear and poor sample quality.

In this study, 2D FE models of conventional and ultrasonically assisted cutting processes of the cancellous bone tissue were developed to predict the magnitudes of cutting forces. The cutting force is one of the essential parameters in defining the efficiency of the cutting. A reduction in cutting force results in a decrease of residual stress in the section with an improvement of surface finish.

2. Finite-element analysis

An orthogonal cutting operation was modelled (Fig. 1) under different cutting conditions (Table 1) in ABAQUS/Explicit.

Reference FE models for conventional cutting (CC) and ultrasonically assisted cutting (UAC) processes were created, in which a clearance angle, section thickness, cutting speed and ultrasonic amplitude were fixed at 10º, 12.5 µm, 20 mm/s and 2 µm (vibrating in the cutting direction), respectively. The vibration direction is along the x-axis in Fig. 1. The frequency of vibration was fixed at 27 kHz.

Table 1 Cutting and ultrasonic conditions for CC and UAC

FE models parameters	
Section thickness (µm)	5; 12.5; 20
Cutting speed (mm/s)	20; 400
Ultrasonic amplitude (µm)	1; 2; 5

2.1. Model geometry, mesh and boundary conditions

In our simulations, the cutting blade was assumed as a rigid body, since its stiffness is significantly higher than that of the material being cut. The geometry of the cutting edge modelled in simulations was provided by Cellpath Ltd UK with a cutting angle of 70º in a three-bevel blade edge [4]. The dimensions of a sectioned sample in the FE models were 50 µm in length and height.

The sample was partitioned into four even blocks with the size of 25 µm×25 µm. The mesh density was higher in the cutting zone, which was directly affected by the cutting process. In this analysis, C3D8R elements were used for the cutting sample. A Lagrangian model with element deletion was used to represent a complex process of cutting progression with an appropriate failure criterion.

A relative movement of the sample and the blade was defined by imposing translation of the sample with a constant velocity. In UAC, harmonic oscillation with frequency 27 kHz with varying vibration amplitudes was applied to the blade edge in the cutting direction.

The maximum vibration velocity known as *critical velocity* for harmonic oscillation is described by the following equation [5]:

$$V_{\text{crit}} = 2\pi f A, \tag{1}$$

where f is the vibration frequency, A the amplitude and V_{crit} the critical velocity, beyond which the cutting tool does not separate from the chip in each cycle of vibration, reducing UAC to a conventional cutting process. For the UAC reference model, the critical velocity is computed to be 339.3 mm/s.

At cutting speeds lower than the critical speed, vibro-impact micro-cutting process is expected to improve the overall cutting of the sample with a microtome.

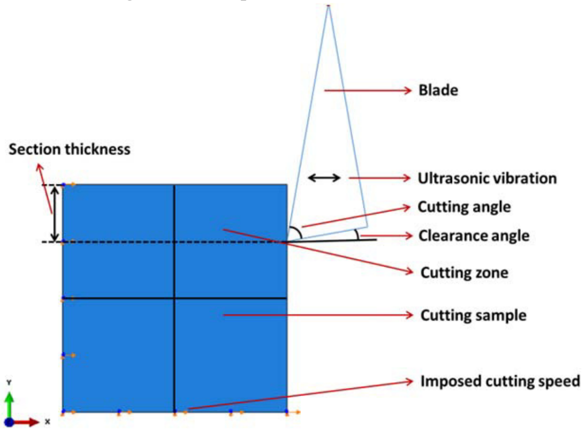

Fig. 1 Schematic diagram of 2D cutting model

2.2. Material model

The cancellous-bone material was modelled as isotropic with shear damage. Its mechanical behavior was described in terms of an elastic-plastic material model. The fracture properties of bone were determined using the shear damage model in ABAQUS.

Material properties for the simulation are listed in Table 2 [6]. The material model for the cancellous bone using the parameters below was verified via a simplified compression test by FE analysis. The mechanical behavior of the material model in the test is presented in the Fig. 2 with stress strain curve, which matched well with the experimental results from [6].

Table 2 Material properties of cancellous bone [6]

General parameters	Cancellous bone
Density (kg/m^3)	530
Elastic modulus (MPa)	831
Poisson’s ratio	0.35
Yield stress (MPa)	51.1
Fracture strain	0.142

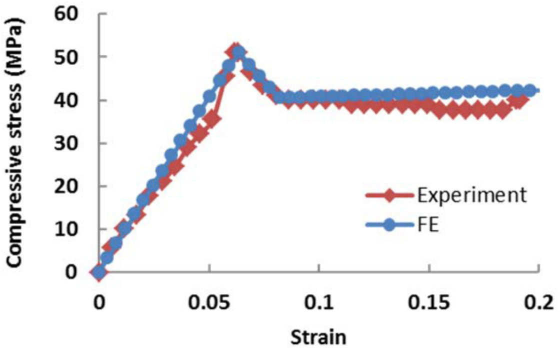

Fig. 2 Stress-strain behaviour of the cancellous bone from the experiment [6] and the FE model

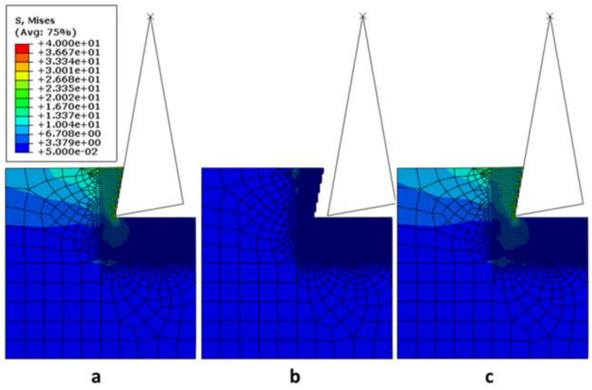

Fig. 3 Meshed FEA results in the process of UAC (a and b) and CC (c)

2.3. Contact conditions

Interaction between the specimen of bio-tissue and the cutting blade in dynamic simulations of the cutting process is required to model the cutting process accurately. In this study, contact was defined in ABAQUS using a surface-to-surface contact, in which the cutting zone was selected as the node region contacting an analytical rigid surface. A Coulomb friction condition with a friction coefficient of 0.61 was specified for an interface between the cutting edge and the cut material [7].

3. Results

The von Mises stress distribution on the FE mesh is shown in Fig. 3 for CC and UAC. Fig. 3(a) and Fig. 3(b), shows the stress distribution in UAC at maximum penetration and maximum retraction of the cutting tool, respectively. The stress is observed to vary due to the nature of the vibratory cutting. In CC the von Mises stress is observed in Fig. 3(c), which is similar to the stress at maximum penetration in UAC.

All the FE simulations were performed for CC and UAC. To obtain the average force, the force data were averaged every 7.5×10^{-5} s, which corresponds to approximately two vibration cycles.

A significant difference in the level of average force acting on the cutting-blade edge was found for UAC and CC from the reference FE models (Fig. 4). In the modelled CC process, the cutting force grew steadily from the moment of first contact between the cutting edge and the cutting sample until it reached a stable cutting force level, when the tool was sufficiently engaged with the cutting material. The average force magnitude in UAC was about 25% of that in CC. This is primarily due to kinematic separation between the tool and the material because of vibration.

For the cutting speed of 400 mm/s (i.e. higher than V_{crit}) there was no perceived force reduction (Fig. 5) confirming the fact that tool separation is essential for benefits observed in UAC. In the microtome, the typical cutting speed is less than 30 mm/s. Therefore, the average force reduction in the ultrasonic microtome cutting process is expected.

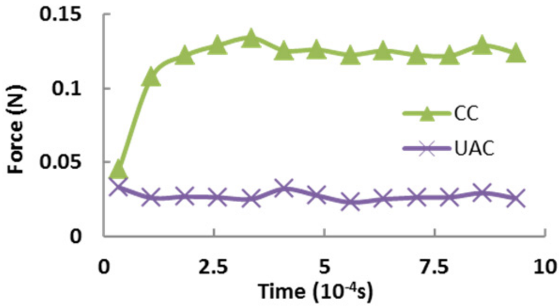

Fig. 4 Comparison of average force on cutting-blade edge in cutting direction for CC and UAC in reference models where the parameters used are clearance angle: 10º, section thickness: 12.5 µm, cutting speed: 20 mm/s, and ultrasonic amplitude 2 µm

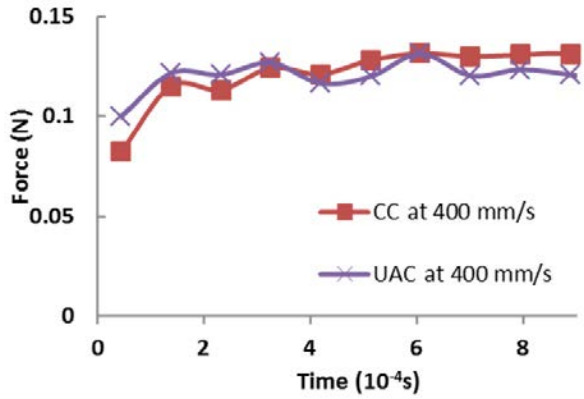

Fig. 5 Comparison of average force on cutting-blade edge in cutting direction for the CC and UAC at cutting speed of 400 mm/s; other parameters used are clearance angle: 10º, section thickness: 12.5 µm, and ultrasonic amplitude 2 µm

FE simulations were also conducted to study the effect of vibration amplitude on the cutting force; the respective results are shown in Fig. 6 for UAC. It was found that the average cutting force decreased with an increase in vibration amplitude.

Figure 7 shows the numerical results for the effect of section thickness on the cutting force. An increase in the average force is observed with the increase in section thickness, both in CC and UAC processes.

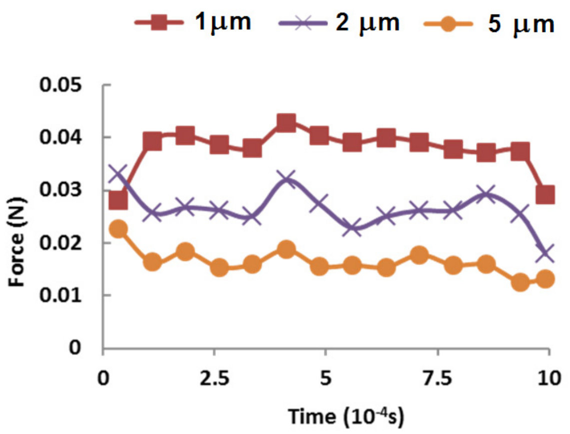

Fig. 6 Comparison of average force on the cutting-blade edge in the cutting direction for the UAC at various vibration amplitudes; other parameters used are clearance angle: 10º, section thickness: 12.5 µm, and cutting speed: 20 mm/s

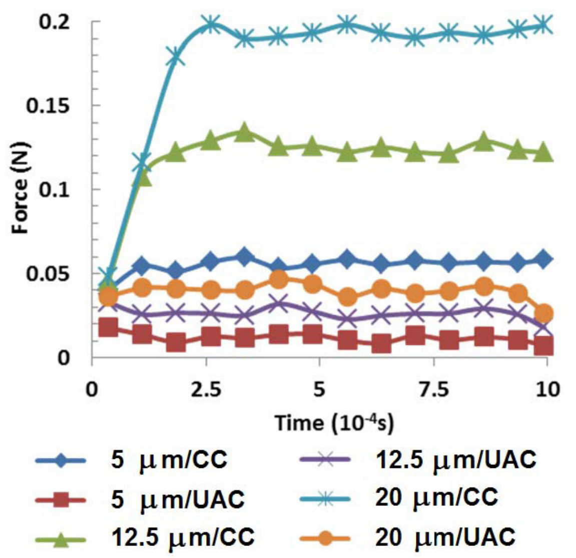

Fig. 7 Comparison of average force on cutting-blade edge in cutting direction for CC and UAC at various section thicknesses; other parameters used are clearance angle: 10º, cutting speed: 20 mm/s, and ultrasonic amplitude 2 µm

4. Conclusions and discussions

The elastic-plastic model with shear damage was found to be a good representation of mechanical behavior of cancellous bone in the FE analysis. FE models were developed for simulation of conventional and ultrasonically assisted cutting and used to investigate the effects of section thickness, cutting speed and ultrasonic amplitude on the cutting process (in terms of the average cutting force in the cutting direction) for both cutting techniques. The results show that UAC is capable of significant cutting-force reduction at low cutting speeds, which are common in microtomy. The average force acting on the cutting blade is related to section thickness. An increase in the average cutting force with an increase of section thickness was observed both in CC and UAC. The vibration amplitude plays an important role in the force reduction in the UAC process. An increase in the vibration amplitude led to increase in the extent of average force reduction. Additionally, the reduced cutting force would yield tangible improvements in the blade life (thanks to a reduced blade wear) and diminish residual stresses in the cut sample that cause wrinkling in conventional cutting.

Experimental tests will be performed in the near future to validate these findings from numerical studies. We are developing full blown 3D FE models to better address the effect of tool geometry and the effect of engagement on cutting outcomes.

Acknowledgements

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