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Vibrational cutting of soft tissue with micro-serrated surgical scalpels

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Abstract

This paper reports on a preliminary study of vibrational cutting of soft tissue with micro-serrated surgical scalpels with curved blades. Although surgical scalpels are being widely used, the influence of edge geometry and blade motions during cutting remain largely unexplored. This paper is aimed at exploring the possibility of improving the cutting performance of these medical devices through laser micro-machining of serrations on their curved cutting edges, of vibratory cutting motions and their combination. Experimental studies on biological and phantom tissue will be presented to demonstrate the impact of micro-texturing and vibrational motion on the cutting efficiency of surgical scalpels. This preliminary study is intended as a basis for the future investigation of the observed responses to enhance cutting efficiency in surgical procedures.

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Keywords: micro-serrations, surgical scalpels, vibrational motion

1. Introduction

Surgical scalpels are fundamental devices, utilized in numerous clinical procedures to guarantee access to different organs and muscles of the human body. Since the dawn of modern medicine, almost all the disposable surgical tools were characterized by plain cutting edges. This paper is aimed to explore the benefits coming from the application of serration patterns and vibrational motions to the cutting edge of curved surgical scalpels. The results can be potentially extended to multiple medical tools and improve the outcome of ordinary medical procedures and surgical operations.

Several studies have already been conducted to show that cutting edges featuring micro-serrations can achieve better cutting performance. The concept of applying specific shapes and geometries to the cutting edges and surfaces through micro-texturing is inspired by nature [1]. In fact, across millions of years of evolution, several species of animals and plants have developed refined mechanisms to ensure their survival and optimization of living processes. For instance, the cutting edge of a mosquito`s maxilla features several micro-serrations which are ultimately aimed to support penetration and reduce nerve stimulation during the bite [2]. Izumi et al. [3] studied the importance of micro-serrations on mosquito's proboscis by performing several cutting experiments into artificial skin by adopting micro needles made of silicon. Also, Oka et al. [4] conducted similar studies with solid and hollow micro-needles obtained by application of MEMS techniques. In these experiments, needles featuring a jagged shape similar to the mosquito's maxilla were capable of penetrating the surface of hard silicon rubber through standard insertion. However, few studies have been performed on the application of micro-texturing to the cutting edge of surgical tools such as blades or scalpels in order to improve their cutting performance.

Surgical scalpels are often adopted in many clinical procedures to perform incisions through several layers of skin. The outcome of these operations in terms of efficiency and targeting accuracy depends on the ability of the blades to effectively cut biological tissues. This research is aimed to provide a preliminary study on the impact of micro-serrations on the cutting performances of curved surgical scalpels.

Commercial and micro-serrated surgical scalpels were tested by applying linear and vibrational motions to the blade during the cutting of pig skin and phantom tissue. One of the key aspects of the cutting process of soft tissue is represented by the relative motion of the cutting edge with respect to the reference target tissue. Several researchers have focused their attention on this subject to provide a deeper understanding of

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the parameters and conditions that could lead to an optimal cutting motion. Atkins et al. [5] investigated the effectiveness of slicing motions on the cutting forces of a blade by using an energy-based fracture mechanics approach. As an outcome, it was found that an increase in the slice/push ratio leads to reduced cutting forces. Also Begg et al. [6] studied the impact of vibration amplitude and frequency on tissue cutting by means of medical needles. However, no studies were performed on the application of vibrational motions to surgical scalpels.

The author already performed some studies on tissue cutting by means of micro-serrated surgical blades [7], however, the medical devices involved were characterized by linear cutting edges and the tests were performed exclusively on phantom tissue without the implementation of any vibrational motions. In this work, we describe the design and micro-manufacturing of serrations on curved surgical blades. These devices were subsequently investigated in steady and vibrational cutting of pig skin and phantom tissue. The experimental results demonstrate the differences in performance between plain edge and serrated edge blades and the potential benefits of the vibrational motions.

2. Experimental Methods

2.1. Laser micro-texturing

A pumped Nd:YVO4 picosecond laser with a 532 nm wavelength was used in order to micro-serrate the cutting edge of surgical scalpels. This laser features a pulse duration of 8 ps and is characterized by an average power ranging from 0.19 W at 10 kHz to 1.31 W at 500 kHz. The system is also equipped with a 5-axis programmable motion system (Fig. 1), which is responsible for the rotation and translation of the workpiece during the laser ablation process [8].

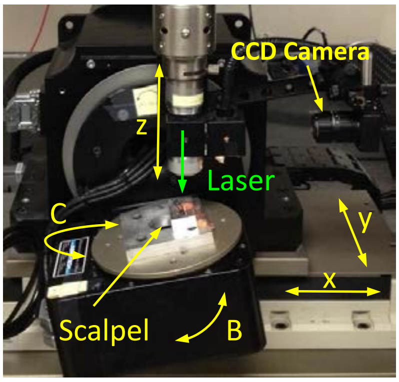

Figure 1. Laser micromachining system, the 5 axes of the precise positioning system (x, y, z, B, C) are highlighted.

A customized testing fixture has been built in order to correctly place the blade on the 5-axis programmable motion system. The setup is composed of three main sub-assemblies: (1) a scalpel fixture, (2) a focusing and (3) vision subsystem.

The aluminum blade fixture is mainly devoted to rigidly supporting the surgical scalpels during laser ablation. The focusing and vision subsystems are composed of a polarizing beam splitter, polarization-insensitive beam splitter, laser focusing lens, fiber optical illuminator, CCD camera, camera lens, and a notch filter. The CCD camera, namely Point Grey's Chameleon with a 50 mm focal length lens (Edmund Optics), was adopted in order to attain a magnified image of the surgical blade. In addition, the focal position of the CCD camera was precisely aligned (accuracy range of ±10 µm) with the laser focus along the Z-direction. Focusing of the laser on the blade was obtained through focusing the camera on the cutting edge of the scalpel. Moreover, since the geometry of the commercial blade contains a sharpened angle of 20° along the cutting edge (Fig. 2), the rotation axis has been inclined by 10° in order to achieve precise orthogonality between the laser beam and the cutting edge.

After laser ablation, the micro-serrated scalpels were subjected to ultrasound cleaning in order to remove debris from the ablation process. This operation was routinely performed before any surface measurements were taken to guarantee a better visualization of the micro-features.

2.2. Micro-serration design

Micro-serrations were generated on a commercial scalpel No. 10. The surgical scalpel (overall length (l) equal to 42 mm) features a curved shape with a 1 mm width (w), a thickness of 0.35 mm (t) and an included angle (α) of 20°. In this paper, starting from the original shape (Fig. 2), a specific serration pattern was designed and implemented (Fig. 3).

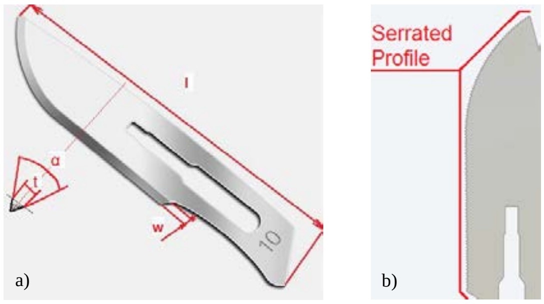

Figure 2. 3D view of commercial surgical scalpel No.10 (a) and 2D view of the cutting edge of the micro-serrated surgical blade.

Micro-serrations were generated by laser machining the cutting edge of the original scalpel in order to generate the desired serrated pattern. The laser power was set at 0.15 W with a pulse repetition rate equal to 25 kHz (Fig. 3).

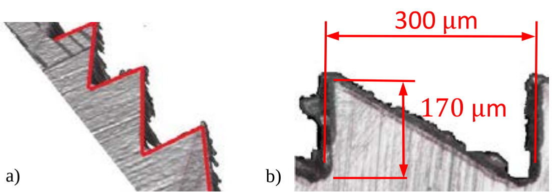

Figure 3. Micro-serrated geometry as it appears in 3D (a) and in 2D (b) from the Alicona 3D optical profilometer. The red line highlights the serrated profile.

An aggressive serration pattern characterized by an overall size of 300 µm by 170 µm (Fig. 3) per tooth has been selected in order to better observe the differences in terms of cutting performances between serrated and continuous cutting edges.