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Laparoscopic surgery augmentation through vibro-acoustic sensing of instrument-tissue interactions

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Abstract: This paper presents the use of vibro-acoustic sensing to augment laparoscopic surgery procedures by analyzing the signals produced during cutting and palpation tasks on various tissue samples. Vibro-acoustic signals were acquired during an experiment on a dedicated phantom covered in dense foam, where three trocars were inserted into the phantom to place the endoscopic camera and two laparoscopic instruments. The results of the signals analysis demonstrate the potential of this approach for making laparoscopic interactions audible, differentiating between tissue types, and detecting variations in tissue properties. Vibro-acoustic sensing could be a valuable tool for integrating sound into the current clinical workflow for enhancing endoscope video images.

Keywords: Vibro-acoustic Sensing, Surgery Augmentation, Haptic Information, Laparoscopy

1 Introduction

In conventional open surgery, surgeons heavily rely on sensory modalities such as visual, tactile, and auditory senses to assess the conditions of body organs and tissue during surgery. Minimally invasive surgery (MIS), such as laparoscopic and robotic-assisted surgery, has become the preferred method of modern abdominal surgery. Complex procedures are increasingly being performed in the form of minimally invasive [1].

In MIS, these senses are significantly affected due to restricted access and limited direct contact between the surgeon's hand/finger and the target structure. Visual support using RGB cameras is provided by inserting an endoscope through a tiny incision into the abdomen. This information is presented in the form of a high-resolution real-time video and can be combined with depth information to provide a 3-dimensional representation of the operating area [2]. This partially alleviates the limitations of minimally invasive surgery but still exploits only one surgeon's sense, the vision.

Various technologies have been developed to restore haptic feedback and for surgery augmentation. Medical imaging-based technologies, when combined with instrument tracking and navigation systems, can enhance the visual perception of surgeons by providing real-time feedback on the location of instruments and targeted organs [3]. However, these technologies often come with challenges such as high costs, complexity, and cumbersome workflows.

Sensor-based solutions have also been developed to enhance surgeons' tactile sense by measuring various tactile information such as force, torque, pressure, impedance, and vibrations using often sensors embedded in instruments [4]. While these solutions can offer valuable haptic information, they may pose clinical design challenges and require the use of specific tools that may not be familiar to surgeons.

The field of Surgical Data Science, involving post-processing and analysis of recorded laparoscopic videos, has emerged as a new area of medical technology research with potential applications in surgical decision support, surgical training, and context-awareness assistance [5]. However, the limited dynamical range of video and reliance on a single observation (one endoscopic camera) may pose limitations in data analysis.

There is a growing need for complementary cost-effective and user-friendly surgical monitoring modalities that can provide an extensive dynamical range beyond human perception and offer diverse observations from the surgical process.

Surgical audio guidance (SURAG) is a new concept that exploits a completely new source of information inherent to any surgical procedure. Every medical instrument tip interact-

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ing with tissue generates a vibro-acoustic (VA) wave that naturally propagates through the instrument's shaft without the necessity of any active component embedded in its shaft or tip [6]. By connecting a sensing module at the proximal end of the instrument and by using advanced signal processing algorithms, SURAG can acquire a signal rich in haptic and navigation information. SURAG has shown potential for puncture identification in needle insertion procedures [7] and for palpation assessment in robotic procedures [8, 9].

In this work, we conduct a preliminary study to investigate the potential of acquiring, identifying, and audifying VA signals generated by interactions between laparoscopic tools and tissue. A sensing module was attached to the proximal end of a grasper and a scissor, and VA signals were recorded during cutting and palpation tasks performed on synthetic tissues with varying characteristics. Our preliminary results indicate that the instrument-tissue interactions exhibit signal-to-noise ratios that allow for direct mapping of the signals into audible ranges. Furthermore, we observed that different tissues produce distinct vibro-acoustic dynamics.

2 Materials and methods

2.1 The Surgical Audio Guidance system

The SURAG system comprises two primary components: the sensing unit and the main unit, as depicted in Figure 1. The sensing unit is an add-on system that can be easily connected to the proximal end of a laparoscopic tool through a standard connector or an attachable adaptor. It captures the subtle vibrations generated by tool-tissue interactions and wirelessly transmits in real-time the information to the main unit, which generates the audible signal and can store the data for subsequent post-processing and analysis. The SURAG system allows for the connection of up to two sensing units to a maximum of two laparoscopic instruments. For more detailed information about the SURAG technology, please refer to [9] and [6].

The main unit processes the signal for audification through a four-step algorithm. Initially, the DC component is eliminated and a gain is applied to the centered signal. Next, spectral gating is used for background noise reduction. The instrument-tissue interaction characteristics are then enhanced through a band-pass filter, which divides the signal into several scales using Discrete Wavelet Transformation. The scales where interactions appear with high energy are used for signal reconstruction.

2.2 Experimental setup

The experimental setup shown in Figure 2 aimed to evaluate the quality and characteristics of the instrument-tissue VA signals generated by laparoscopic tasks performed on different tissue samples. A dedicated phantom was created using a plastic box where the inner surface of the box as well as the inner and outer surfaces of the lid were covered in dense foam. Three holes were created on the lid to place trocars for inserting an endoscopic camera, a grasper (HICURA Atraumatic Grasper, Olympus, Japan), and scissors (HICURA Metzenbaum Scissors, Olympus, Japan). Tissue samples of different materials were placed inside the box according to the two main palpation and cutting tasks. For palpation, wood, felt, foam, and ultrasound gel pad were used, while for cutting, paper, carton, and a 1.5mm diameter packaging string were used. The user performed a total of 20 palpation events and 20 cutting events for each tissue sample, with an additional 20 cutting events performed in the air. VA signals were displayed as acoustic feedback and recorded simultaneously with the endoscopic video for post-analysis.

2.3 Signal processing analysis

A post-analysis was conducted on the recorded VA signals to investigate the distinctive signal dynamics resulting from laparoscopic tasks performed on different materials. The videos were used to annotate each VA signal event, including its type (cutting or palpating), the corresponding time occurrence, and the specific material involved. These annotations facilitated the creation of a dataset comprising labeled signal segments corresponding to the type of tissue being interacted with.

Matlab R2022a was employed for the VA signal analysis. For qualitative analysis, the time domain and time-spectral energy dynamics of cutting events were investigated. This involved computing the Continuous Wavelet Transformation (CWT) for each cutting signal segment and performing frequency averaging. In the case of palpation events, the emphasis was on studying the variations in frequency components present in the signal. The CWT was computed and subsequently normalized to highlight frequency analysis. Averaging was performed over time to estimate a CWT-based stationary spectrum with normalized values ranging from 0 to 1.

Furthermore, a quantitative analysis was conducted for both palpation and cutting events. The average of the instantaneous dominant frequency of each signal event segment was computed from the CWT time-frequency spectrum by determining the frequency value with the highest energy at each time instant.

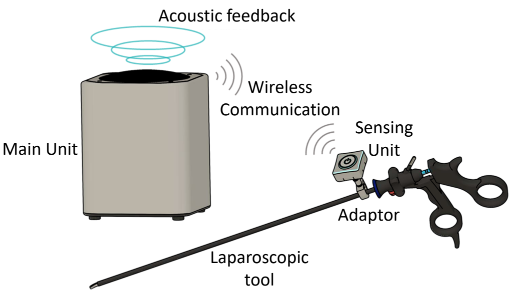

Fig. 1: Mock-up of the audification system showing the sensing unit attached to a laparoscopic tool and main unit providing acoustic feedback.

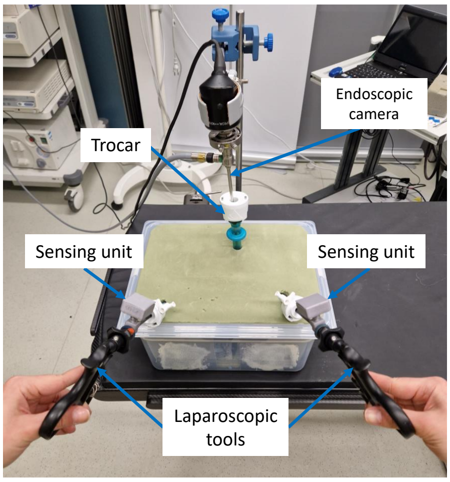

Fig. 2: Experimental setup for palpation and cutting experiments.

3 Results and discussion

Figure 3a provides a comprehensive overview of the VA excitation characteristics during the cutting of various tissue samples. The time-domain representation incorporates the spectral energies obtained from the Continuous Wavelet Transformation (CWT) spectrum, and each energy segment corresponding to a cutting event for a specific tissue sample is concatenated with segments from other tissue samples. The figure presents the concatenated signals, allowing for visual comparison of the time-domain spectral energy signals for different events: scissors opening movement, scissors closing movement cutting in the air, scissors cutting paper, scissors cutting carton, and scissors cutting the packaging string.

An important observation is that the tool-tissue interaction excitations are clearly identifiable from the signal background for all the cutting events, resulting in clearly audible cutting sounds displayed by the acoustic feedback.

The dynamics of the spectral energies represent a sort of envelope of the original signal and exhibit distinct modulation characteristics among different tissues. The stability of these characteristics is observed when the scissors cut the same tissue, with consistent signal signatures across cutting events and different tissue samples. Moreover, the modulation levels are higher for carton, which involves less homogeneity compared to paper and string. The complexity of the signal time-domain signature is also greater when cutting through tissue compared to air cutting or scissors opening movement, aligning with VA behavior. This arises from the modulated acoustic excitations resulting from the interaction between the scissors blade and the tissue. The less homogeneous nature of the carton leads to a less smooth cut, resulting in noticeable variations in the time-domain spectral energy changes, characterized by a bumping behavior.

Figure 3b and c present the VA excitations generated by the palpation of the laparoscopic grasper on different tissues. Figure 4b displays an example of a signal segment containing the palpation events for four palpated tissues: wood, ultrasound gel pad, foam, and felt. The figure demonstrates that, in all palpated tissues, signal changes can be identified during the palpation task compared to the signal background. While it was expected to see changes in a hard tissue such as wood, it is noteworthy that even during the palpation of foam and US gel pads, important signal behavior changes could be observed as a result of the tool-instrument interaction event.

Figure 3c shows the frequency analysis of the 20 palpation events performed on all the palpated tissues. The primary objective was to determine whether the VA signal would produce different frequency signatures. The figure represents a color-coded matrix divided into four zones, each representing a palpated tissue in the same order than in Figure 4a. Each row of the matrix represents the normalized stationary CWT spectrum (see Section 2.3) of a single palpation event, and the colors depict the energy of the CWT spectrum at a given frequency. The matrix demonstrates that there is a frequency component in all the palpation events at approximately 1850 Hz that may correspond to the natural vibration frequency of the grasper structure. The primary differences between the tissues are apparent in the frequency band ranging from 220 Hz to 920 Hz, where features can be extracted to enable automatic differentiation between the tissues. Importantly, the frequency bands are relatively stable row to row for a given tissue, indicating a stable VA excitation for a specific tissue.

Figure 4 presents box plots that illustrate the variation in dominant frequency behavior during cutting (Figure 4a) and palpating (Figure 4b) tissues. The average dominant frequency feature differs among tissues for both cutting and palpation tasks. Specifically, when cutting the string, significantly higher frequencies are generated compared to other tissues. In the case of palpation, harder tissues such as wood exhibit higher frequency characteristics. The box plot for gel palpa-

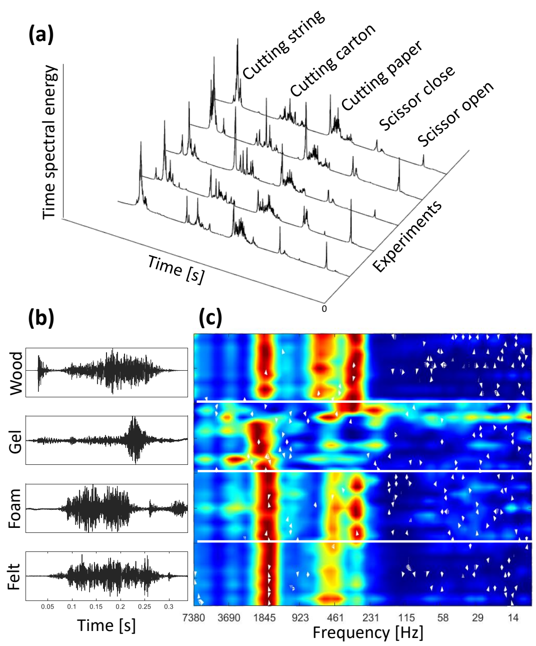

Fig. 3: a) Time-domain spectral energies for the concatenated signal segments, b) Time-domain signal example per palpated tissue, c) Matrix representation of the stationary CWT spectrum for the VA signals resulting from the whole set of palpation events.

tion demonstrates a larger dispersion, which can be attributed to the inherent instability of the interaction with the elastic Ultrasound pad. This instability can result in varied bumping behaviors that significantly influence the dominant frequency with each excitation.

4 Conclusions

This paper proposed the use of vibro-acoustic sensing to augment laparoscopic surgery procedures. The analysis of vibro-acoustic signals obtained during cutting and palpation tasks on various tissue samples revealed that the signals resulting from tool-tissue interactions can be used to create audible feedback. Additionally, the results showed that the approach has the potential to differentiate between tissue types and detect variations in tissue properties. These findings suggest that vibro-acoustic sensing could be integrated into the current clinical workflow to provide surgeons with an additional sensory modality complementary to the real-time video endoscope.

Author Statement

Research funding: This research received no external funding. **Conflict of interest:** The authors N.E., T.S., A.B., and A.I. are shareholders of SURAG Medical GmbH, which provided the sensing device that was used in this study.

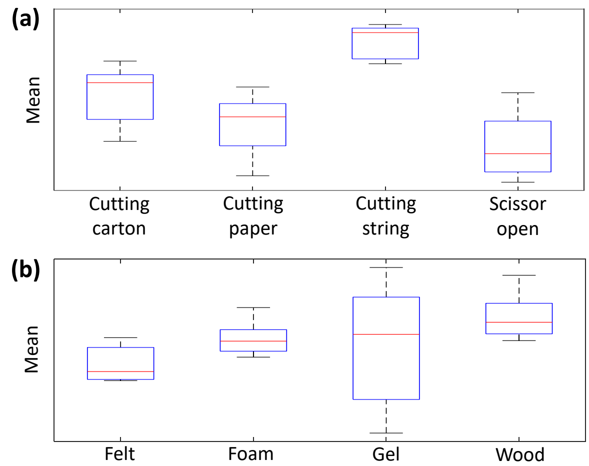

Fig. 4: Box plots for cutting (a) and palpation (b) events to assess the average of the dominant frequency.

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