Tissue Discrimination via Electrical Impedance Spectroscopy for Neurosurgical Robots

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The BRIDGE project "Towards intelligent sensor-enhanced robotic neurosurgery" proposes a robotic screw placement technology and a surgical approach. It is based on local sensing and mapping techniques of the mechanical and electrical tissue properties, assessed continuously and in real-time while drilling the pedicle screw hole. The technology is developed for spine fusion surgeries, yet the fundamentals of the approach can be applied in other surgical operations involving drilling.

Pedicle screw placement is a central element in most routine spine fusion procedures. During these operations, screws are placed in adjacent vertebrae to join and support two or more of them. Free-hand placement of pedicle screws, a common but complex method for fusion procedures, remains the primary cause of potentially avoidable surgical adverse events due to misplaced screws. The rate of revision surgeries to rectify misplaced screws ranges from 1 to 8%.

Three Swiss partners (ARTORG Center of University of Bern, the Neurosurgery Department of Inselspital, and CSEM) have created a consortium to develop a robotic surgery approach with an ultimate goal of improving the accuracy of the pedicle screw placement to a level of zero misplacement. The proposed solution uses sensor guidance to analyze mechanical and electrical properties of tissues in real-time: (1) drilling force to bone density correlation for tool localization, (2) nerve distance estimation with electrical stimulation, and (3) tissue discrimination via electrical impedance spectroscopy (EIS).

This brief communication focuses on the advances in tissue discrimination via EIS. The fundamental hypothesis of this approach, that EIS allows the detection of transitions from cancellous to cortical bone and from there into the soft tissues (muscle, nerve), stems from the observation that different tissues exhibit different electrical properties such as conductivity and permittivity. However, intra- and inter-subject variabilities of these parameters pose a great challenge - which is further aggravated for the patients who need spine fusion surgeries. We hypothesize that incorporating multiple sensing modalities is key to surmount this challenge.

We have specified an EIS concept (11 frequencies from 10 to 100 kHz, measurement latency < 400 ms) to demonstrate the potential of the approach, as well as to understand its limitations, particularly originating from the measurement itself. Based on this concept, a maximum absolute percentage error <6% for the estimation of the impedance magnitude was recorded using a commercially available EIS device (customized version of ISX-3, Sciospec Inst., Germany) on technical phantoms composed of a wide range of precision loads mimicking tissue impedance. Upon system integration, in-vitro experiments were conducted with a monopolar electrode configuration on a phantom composed of silicone layers with different electrical conductivities. The probe (Figure 1) was inserted and retracted within a pre-drilled hole. Figure 1 shows the transitions between different layers of silicone and the same impedance level could be regained (5, 12, and 7 kΩ, respectively). Glitches at the transitions occurred due to delayed stabilization at the interface.

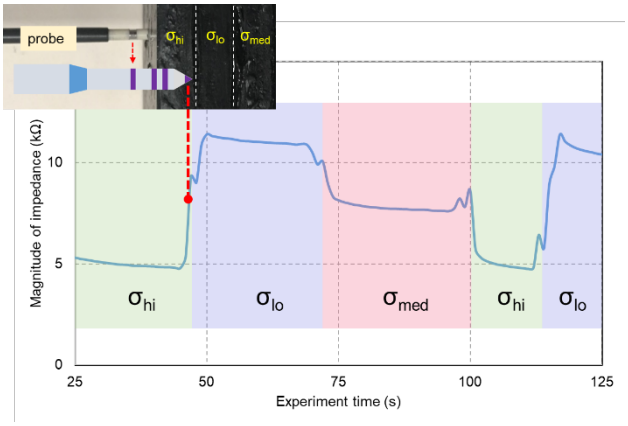

Figure 1: Impedance measurements at 50 kHz performed on a silicone phantom composed of layers with different electrical conductivities show the transition from one layer to another.

During the surgery two types of breaches can occur: frontal (as in Figure 1) and lateral (as in Figure 2). We have shown that lateral breaches are harder to detect [1] and thus concentrated our efforts on optimizing the electrode geometry and position on the probe. Finite element method simulations were performed (EIDORS) to identify the most sensitive configurations to detect lateral breaches (Figure 2). Sensitivity to detect lateral breaches is observed to increase with increasing the surface area of the tip electrode and having a ring electrode on the probe (green curve).

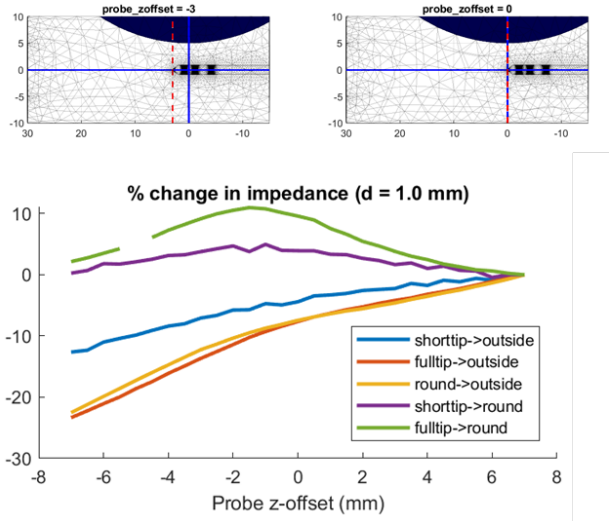

Figure 2: Electrode geometry and position optimization to improve sensitivity to lateral breach detection.

Our current activities focus on (i) designing ex-vivo experiments to validate the acquired knowledge via in-vitro experiments and simulations, and (ii) preparing for potential in-vivo experiments.

[1] Y. Jegge, *et al.*, "Tissue classification during surgical drilling using impedance spectroscopy", EIT 2019, London, UK, 2019, p. 55.