Using Changes in Bioimpedance Values to Infer Applied Force for Tissue-Specific Force-Sensing During Minimally Invasive Robotic Surgery

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Robotic-assisted minimally invasive surgery (RAMIS) was used in millions of procedures in 2024. Despite its widespread use, it overwhelmingly lacks force sensing. Few systems offer this feature, and none can differentiate between tissue types, which contributes to injury in 7% of delicate operations. This gap underscores the need for a device capable of real-time tissue differentiation and precise force feedback. To address this, a bioimpedance (BI)-based measurement system was developed, integrating an AC signal generator, op-amp amplification stage, and a voltage-divider circuit. Tissue samples—muscle, fat, and bone—were subjected to controlled forces from 0N to 10N using a linear actuator. Impedance was recorded across five frequencies (10 Hz–100 kHz) under forward, reverse, and super-hydrated conditions. Creating predictive models revealed linear impedance-force relationships at low frequencies and tissue-specific nonlinear behavior at higher frequencies, attributed to the capacitive effects of the lipid bilayer. Bone showed negligible changes due to its low fluid content, while super-hydrated conditions caused impedance patterns to be indistinguishable between muscle and fat due to homogenized ionic concentrations. These findings support the first model-based link between mechanical force and bioimpedance. The system's code enables real-time display of tissue type at 86.5% accuracy and inferred force on an LCD. This low-cost device leverages bioimpedance in a novel way to bridge a critical gap in RAMIS, offering a new input for existing ML-based haptic feedback systems. Additionally, the impedance data can help train anomaly detection algorithms to identify tumors and calcifications intraoperatively, enhancing safety and precision in surgical interventions.

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