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Toward automatic bone breach detection for spine surgery using tissue bio-electrical conductivity sensing

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INTRODUCTION

Scoliosis is a three-dimensional deformation of the spine [1]. The treatment consists in correcting the deformity using a rigid construct until the fusion of the spine vertebrae. The construct is formed mainly by screws inserted into the vertebrae's pedicles and two rods (see Fig. 1a).

The first step for pedicle screw placement is preparation using a pedicle probe. Pedicles are small and deformed in patients having scoliosis, while being close to vital structures such as the spinal cord. If pedicle preparation, followed by screw placement, is not optimally performed, it may cause severe complications for the patient. For instance, medial and lateral cortical perforation may cause vascular and neurological damage (see Fig. 1b). The conventional free-hand non-assisted pedicle screw placement can lead to a misplacement rate for idiopathic scoliosis surgery as high as 14% [2].

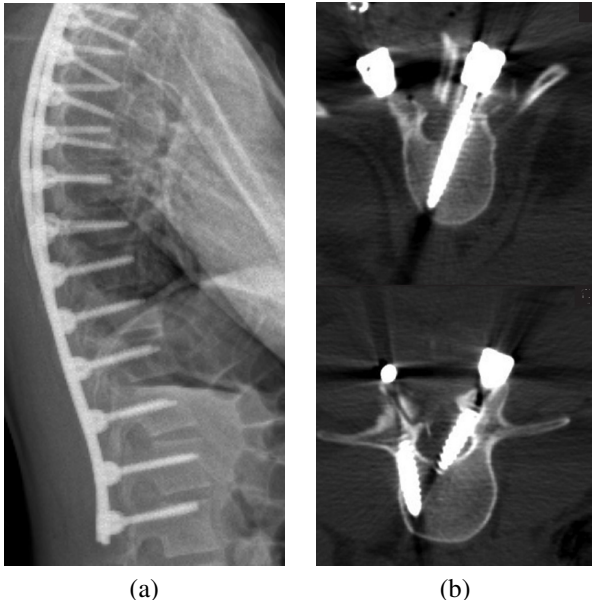


Fig. 1: (a) Sagittal X-ray of the spine after extended spinal fusion for a scoliosis patient. (b) Axial scan views of a misplaced pedicle screw [3].

Navigation systems for guiding pedicle preparation are based on irradiating imaging techniques. To reduce irra-

diation, the SpineGuard company develops surgical instruments for pedicle preparation, such as the PediGuard, which measures the tissue's electrical conductivity in contact with the instrument's tip and sends auditory and visual feedback to the surgeon [4]. Using the PediGuard instrument for spine surgery has been proven to reduce the need for fluoroscopy use by 30% while maintaining a 97.5% accuracy [5].

Several studies proved that measuring electrical conductivity and sending audio feedback to the surgeon increases accuracy for optimal pedicle screw placement [4], [6]. However, no study has directly investigated electrical conductivity values and compared them to clinical evaluation. The present study aims to develop an automatic bone breach detection system, which could be integrated into surgical robotics for automated pedicle preparation.

MATERIALS AND METHODS

Data are collected during surgeries performed on idiopathic scoliosis patients, all operated at the same university hospital. Pedicle preparation is done using the PediGuard (instrument developed by SpineGuard) that measures the electrical conductivity signal $DSG(t)$ at its tip at 5 Hz. Values are recorded through a wireless application on a laptop. The surgeries are video recorded with a 10 mm diameter endoscope with zero-degree angulation linked to an arthroscopy column (Fig. 2). All the data are recorded on the same laptop for time synchronization.

For each pedicle, the surgeon evaluates the prepared trajectory as usual, *i.e.* through palpation with a probe or a ball-tip "feeler". The palpated trajectory is defined as "optimal" if it feels like a bone tunnel without any cortical perforation; defined as "breached" if there is a bone perforation, and modification of the aiming direction is needed. Trajectories that do not meet these above definitions, such as voluntary "in-out-in" trajectories, have been classified as "undetermined" and eliminated from the statistical analysis.

Then, for data post-processing, at each time sample, the insertion depth of the PediGuard's tip inside the vertebra is calculated using image processing techniques thanks to the recorded videos using the endoscope. The electrical conductivity values are only taken into account when measured after 10 mm of depth. Before 10 mm, the data might not be relevant because of the blood in

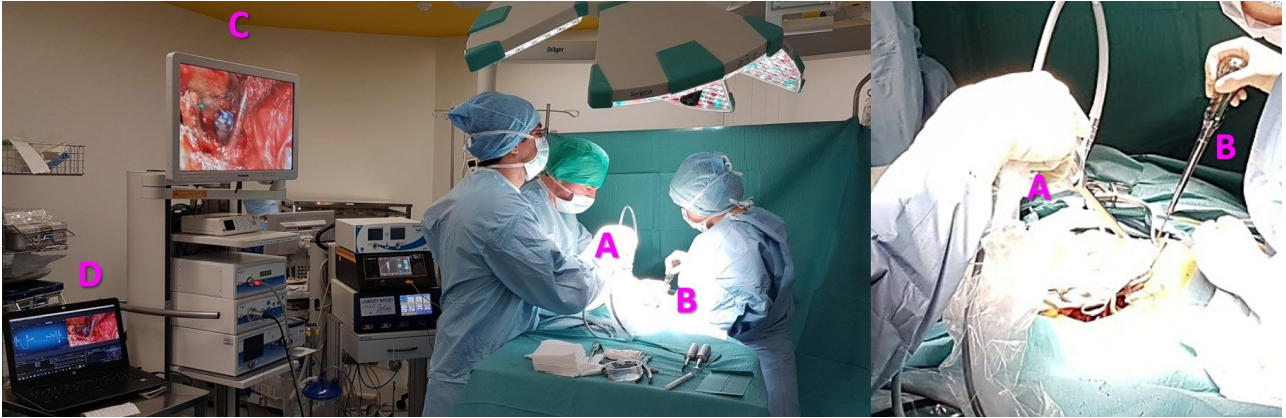


Fig. 2: Setup used in the operating room: A: endoscope, B: Pediguard, C: Arthroscopy column, D: Laptop recording synchronously video and electrical conductivity data.

the pre-drilled entrypoint. Finally, the electrical conductivity difference ΔDSG_{1sec} is computed between values separated by 1-second time interval, *i.e.*, $\Delta DSG_{1sec}(t) = DSG_t - DSG_{t-1}$.

RESULTS & DISCUSSION

A total of 457 pedicle preparations are recorded on 21 patients. 266 are classified as "optimal", 40 as "breached", and 151 as "undetermined". The maximum value ΔDSG_{max} of the signal $\Delta DSG_{1sec}(t)$ is computed for each pedicle. The median of ΔDSG_{max} across all the data are 159 mV for the "optimal" group, and 579.5 mV for the "breached" group ($p < 0.05$) (see Fig. 3).

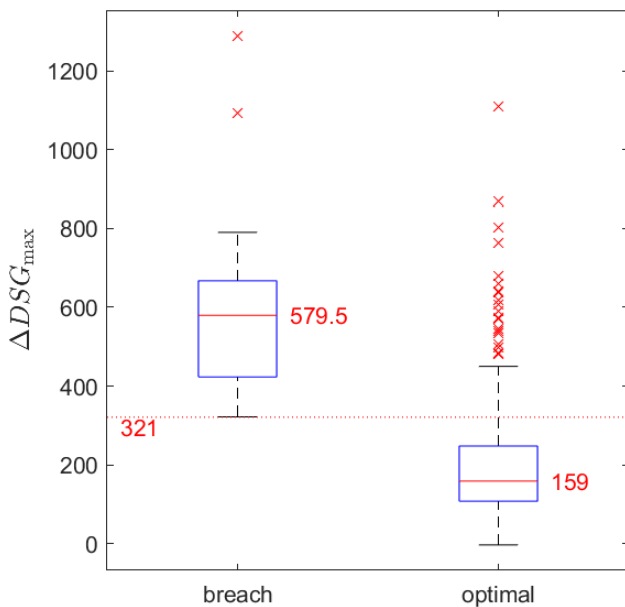


Fig. 3: Distribution of ΔDSG_{max} according to the quality of the pedicle aiming.

No pedicle preparation in the "breached" group has a maximum value less than 321 mV ($\Delta DSG_{max} < 321$ mV), and only 7.9% in the "optimal" group have $\Delta DSG_{max} > 321$ mV. Therefore, this shows that ΔDSG_{max} can be used to detect if a pedicle preparation is optimal in

92.1% of cases. The presence of intraspinal hemangioma, a benign vascular tumor, or remnants of growth plates in the vertebral body might explain the lack of detection in 7.9% of cases; the incidence of intraspinal hemangioma is between 10-27% [7].

This study demonstrated that an increase in the electrical conductivity measurement of more than 321 mV in a 1-second time interval evokes the possibility of a breach with a 92.1% chance. The 321 mV corresponds to the minimum value of ΔDSG_{max} of the "breached" group. Therefore, this information could be valuable to inform surgeons that a change in the direction of the trajectory is necessary before inserting the screw. Also, the obtained results show that a breach detection model could be used to increase the safety of robot-assisted pedicle screw placement preparation [8].

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