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Automatic bone breach detection using electrical conductivity during pedicle drilling in spine surgery

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INTRODUCTION

Current studies conducted in the field of robotic-assisted spinal surgery are focused on using navigation as a tool for optimizing pedicle screw placement and some robotic solutions are already marketed [1], [2], [3]. However, these developments primarily concentrate on outlining and securing the trajectory. The next advancement in robotic-assisted spinal surgery involves optimizing the drilling process itself. Previous studies conducted by the medical device company SpineGuard®, in collaboration with the ISIR robotic laboratory, laid the groundwork for implementing a robotic drilling process including automatic breach detection using measurement of tissue conductivity at the tip of the drilling instrument [4], [5].

This paper aims to extend this research by improving the methodology and demonstrating its performance in a more clinically relevant setup. It presents the outcome of 50 drillings performed in pig vertebrae, using an improved breach detection algorithm applied to a trajectory going through the pedicle towards the spinal canal.

MATERIALS AND METHODS

The setup includes of a container filled with a saline solution, reproducing the electrical conductivity of the cerebrospinal fluid (CSF) and a robot LBR Med 7 of KUKA (7 DOF robot) equipped with a threaded drill bit embedded with the DSG Technology developed and marketed by SpineGuard® (Fig. 1). DSG technology is based on the measure of electrical conductivity in the tissue by means of a bipolar electrode [6].

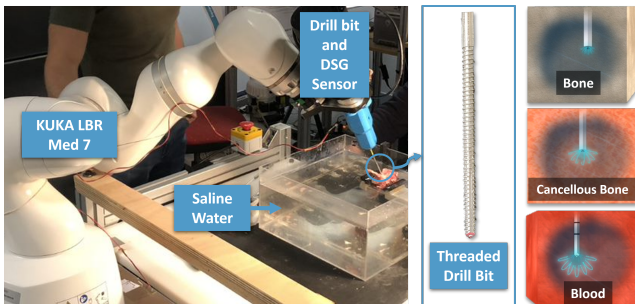


Fig. 1: From left to right: Detail of the drill placed at the entry point, detail of the threaded drill bit, behavior of electrical conductivity in different tissues

The experiments were conducted on fresh pig lumbar vertebrae, chosen for the similarity of their pedicle morphol-

ogy, closely mirroring human vertebrae [7]. The vertebrae were positioned in a clamping vice inside a transparent box and facing a camera, allowing inspection of the canal during the drilling procedure. An entry point was made manually, to which the robot was then hand-guided. The challenge of pedicle trajectories compared to spinous process drillings from previous study [5], is the potential tangentiality of the trajectory with the canal, implying less direct contact of the electrodes in the drill tip with the cerebrospinal fluid.

The robot was controlled to apply a constant 10N force along the axis of the drill while maintaining its manually defined orientation. The power drill was rotating at 30 rpm and had an allowable descent speed of 50 mm/s.

The breach detection algorithm *Algorithm 1* is derived from previous work, and was adjusted to account for the specificities of this experiment. Its parameters were adjusted with the help of a dataset provided by the ISIR laboratory, collected during prospective pedicle drillings of pig vertebrae using a similar setup. This dataset suggested that in thin pedicles, breaches could occur before the end of the previously defined measurement collection window of $z_{end_collect} = 5\text{ mm}$ [5]. The collection window was therefore changed to start at $z_{collect} = 2\text{ mm}$ and allowed to trigger an alert as early as at $z_{detect} = 3\text{ mm}$ depth.

Algorithm 1 Bone breach detection, called for each new conductivity measurement; Initially *Alert* = false, $\sigma_r = 0$ and Σ, Z are empty lists. **Blue values** are the new or modified parameters

Input: σ_k , conductivity signal in mV

Input: Z_k , depth insertion in the bone in mm

Output: *Alert*, flag used to stop the drilling

$\Sigma \leftarrow [\Sigma \ \sigma_k], Z \leftarrow [Z_k]$ ▷ Constructing lists

if $Z_k > z_{collect}$ **then**

if $Z_k < z_{end_collect}$ **then** ▷ Only at the start of the drilling

$\sigma_r \leftarrow \frac{(k-j-1)*\sigma_r + \sigma_k}{k-j}$ ▷ Update mean conductivity

end if

if $Z_k > z_{start_detect}$ **then**

$\sigma_r = \max(\min(\sigma_{max}, \alpha \cdot \sigma_r), \sigma_{min})$ ▷ Adaptive threshold

$A_1 \leftarrow \sigma_k > \sigma_r$ ▷ Compare last conductivity measurement

$m \leftarrow \underset{i \in \{1, \dots, k\}}{\operatorname{argmin}} |Z(i) - (z_k - \Delta z)|$

$n \leftarrow \underset{i \in \{m, \dots, k\}}{\operatorname{argmin}} \sum(i)$ ▷ Find lowest conductivity in last Δz mm

$A_2 \leftarrow ((\max_{i \in \{n, \dots, k\}} \sum(i)) - \sum(n)) > \Delta max$

$Alert \leftarrow Alert \ || \ A_1 \ || \ A_2$

end if

else $j \leftarrow k$ **end if**

The inputs of the algorithm are conductivity measurements σ and drilling depth z . An adaptive threshold σ_r is automatically computed using conductivity measurements gathered during the first millimeters of drilling. In addition

to the maximum threshold $\sigma_{max} = 500 \text{ mV}$ that prevents false negatives if the first collected values are too high, a minimum threshold $\sigma_{min} = 150 \text{ mV}$ was added to avoid false positives. The above-mentioned dataset indeed suggested that the high density of pig pedicles yielded very low conductivity values, leading to a low σ_r threshold making the algorithm too sensitive to signal variations. Coefficient $\alpha = 2.4$ was empirically defined in [5] and reused here. The alert, and subsequent robot stop, are triggered either by an electrical conductivity measurement exceeding threshold σ_r (triggering alert A_1), or by a variation of conductivity $\Delta\sigma$ over the last few millimetres ($\Delta z = 2 \text{ mm}$) exceeding threshold $\Delta max = 230 \text{ mV}$ (triggering alert A_2). These parameters were tuned offline using the previously mentioned dataset, until all false positives and false negatives were eliminated. No further modifications were added during the experiment.

RESULTS

A 100% rate of automatic stops before the breach was obtained during the experiment, using the acceptance criteria of $\pm 2 \text{ mm}$ between the bone and the spinal canal, according to grade "A" and "B" of Gertzbein-Robbins classification [8].

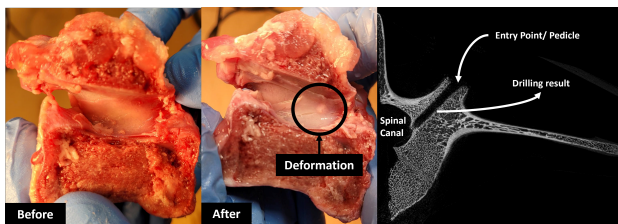


Fig. 2: Vertebra showing the deformation caused by the drill tip (left, middle) and μ CT-Scan (right)

Multiple methods were used to verify the results. Firstly, to discard the existence of a breach, a ball-tip feeler palpation was used. Subsequently, a visual inspection of the spinal canal was performed to observe deformations caused by the drill bit tip. Finally, using CT-Scan and the video recorded during the drilling, the absence of false positives was confirmed (Fig. 2).

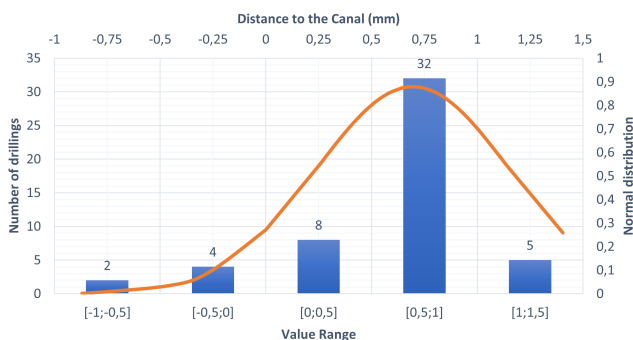


Fig. 3: Data distribution of deformation due to the drill tip

The mean deformation σ measured was 0.7 mm, with a standard deviation of 0.45 mm. All measured deformations were in a range of -0.9 mm to $+1.4 \text{ mm}$ (Fig. 3).

Figure 4 shows high conductivity values during the first millimeters, when the tip is not yet fully docked into the bone, purposely not triggering the stop of the drilling process ($z_k < z_{detect}$). The conductivity then decreases when entering in contact with the cancellous bone and then further decreases while going through cortical bone. Finally, a sudden peak is observed, caused by a micro breach bringing saline solution in contact with the tip.

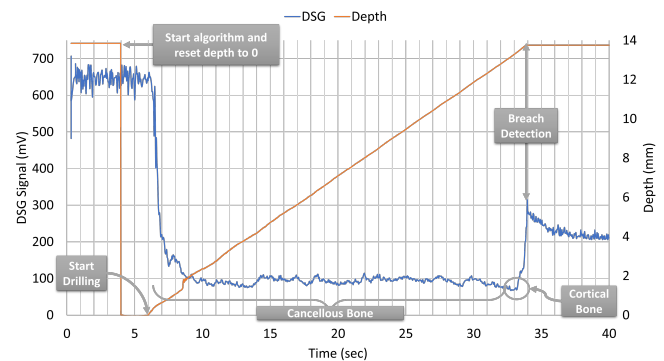


Fig. 4: Evolution of the electrical conductivity and the penetration depth of the instrument

CONCLUSION AND DISCUSSIONS

The automatic bone breach detection algorithm for a pedicular trajectory has been successfully tested with a relevant clinical setup, opening the way for further research. Pig vertebra has proven to be a good alternative to test pedicular trajectories given their similarities with human morphology.

Future experiments might use a regular drill bit to compare the results obtained in this study using a threaded drill bit. A regular drill tip is indeed more commonly found in operating rooms, while also being sharper and compatible with higher-speed drilling.

Finally, the effect of breathing was not considered in this study. The breathing cycle could induce a significant displacement of the specimen during the drilling process, and would need to be taken into account to replicate clinical conditions.

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