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Breach detection in spine surgery based on cutting torque with ex-vivo experimental validation

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INTRODUCTION

Pedicle screws are used in different types of spine surgery, especially to correct spine deformities, such as scoliosis which is a three-dimensional deformation of the spine [1]. Pedicle preparation is a challenging procedure for scoliosis correction. The surgeon inserts screws through the pedicle from the posterior column to the vertebral body while seeing only the posterior aspect of the spine (Fig. 1). In scoliosis surgery, there is a rotation in the axial plane with a deformity of the pedicle. On the concave side of the deformity, pedicles are smaller and the dura is in contact with the medial wall of the pedicle. The risks of the procedure range from mild muscle weakness and sensory loss to complete paraplegia as breaching into the spinal canal can cause irreversible damage to the spinal cord. Breaches of less than 2 mm do not result in neurological damage [2]. Still, the conventional free-hand non-assisted pedicle screw placement can lead to a misplacement rate for idiopathic scoliosis surgery as high as 14% [3].



Fig. 1: Posterior view of the spine in scoliosis surgery. Some entry points are marked (yellow stars)

While navigation and robotics have helped to improve spinal surgery, they have many limitations, especially in terms of ease of use and precision. Precision is reduced by the patient's respiratory movements. Indeed, a slight variation in the patient's position during the preparation of the pedicle is likely to lead to registration errors [4]. In addition, these techniques rely on ionizing radiation which carries a risk for the patient, the surgeon, and the medical staff [5]. Surgeons rely on the difference in mechanical properties between trabecular and cortical bone. Bone breach detection was studied in cows' femur [6]. In the spine, Stauff et al. showed a modification of the torque after redirecting the probe during pedicle preparation [7]. The present study aims to develop a bone breach detection system, based on torque measurement, which could be integrated into surgical robotics for automated pedicle preparation.

MATERIALS AND METHODS

The experimental setup consists of a KUKA LBR Med 7 R800 robot adapted to the medical requirements. The drill is rigidly fixed to the robotic arm with a 30° angulation. It is equipped with built-in joint torque sensors allowing it to operate in a collaborative mode. It features position accuracy of ± 0.15 mm and joint redundancy (7 DoFs). The cutting torque is registered during drilling. The drilling speed is fixed at 30 rpm. We used lumbar lamb vertebrae purchased from the butcher. Vertebrae are prepared by removing the residual meat and each vertebra is rigidly fixed with a clamp. The surgeon prepares the entry point using a bone awl after removing the spinous cartilage. Then, he moves the robot and places the drill on top of the entry point. The robot performs the drilling with a 3 mm diameter threaded drilling bit. The robot is force controlled with a desired force of $f_d = 10$ N [8]. The setup is detailed in Fig. 2. A camera records the image of the spinal canal's interior to identify the breach's timestamp. We collected drilling data from 100 lamb vertebrae. Each recorded video was watched independently. The exact time of breaching (t_v) inside the spinal canal is recorded.

RESULTS

We used the Bayesian estimator of abrupt change, seasonality, and trend (BEAST) [9]. It embraces all competing models into the inference via a Bayesian model averaging scheme. It detects when changes occur and calculates how likely these changes are true. Each drilling is analyzed as a

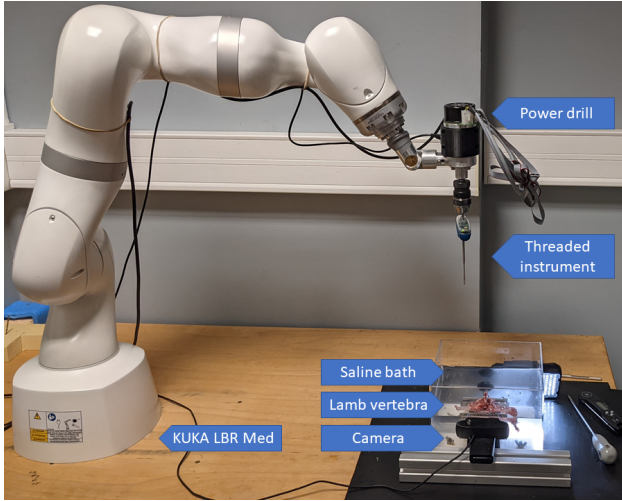


Fig. 2: Experimental setup: The vertebra is fixed with a rigid clamp. A camera records the image of the spinal canal.

time series by taking the cutting torque as a variable with respect to time. We applied a LOESS (locally estimated scatterplot smoothing) filter to smooth the data. LOESS is a non-parametric filter to reduce the variability of the data [10]. The package Rbeast in R[®] is used to apply the BEAST (Bayesian evolutionary analysis by sampling trees) algorithm. We have multiple change point detections for each drilling, with the probability of each change point and the signal's slope (Fig. 3). Then we choose the change point where there is a change in the slope's sign from positive to negative. In case of multiple change points with this criteria, we selected the one with the highest probability provided by the output of the Rbeast package.

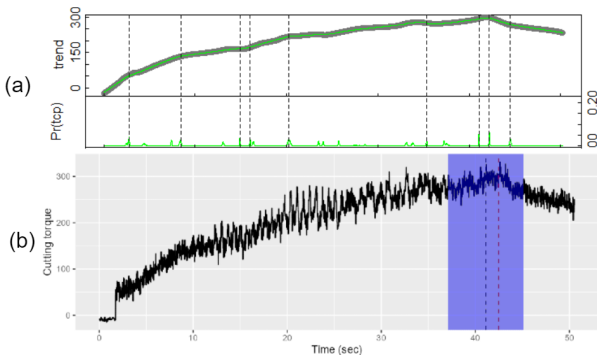


Fig. 3: (a) example of Rbeast output. (b) Example of a detected breach (red line), video timestamp (black line). A ± 2 mm blue zone centred on the perforation instant is plotted for visualization. Detection must occur before the lower and upper limits of the blue zone to be considered satisfactory (i.e. grade "A" or "B" perforations).

We recorded the detected change points by the Beast algorithm t_b for the 100 lamb vertebrae. For each vertebra, we calculated the error between the corresponding depth for t_v and t_b (Δ_{depth}). We obtained $\Delta_{depth} \in [-1.11, 1.06]$ mm and $Mean(\Delta_{depth}) = 0.075 \pm 0.42$ mm. The results are

summarized in Fig. 4

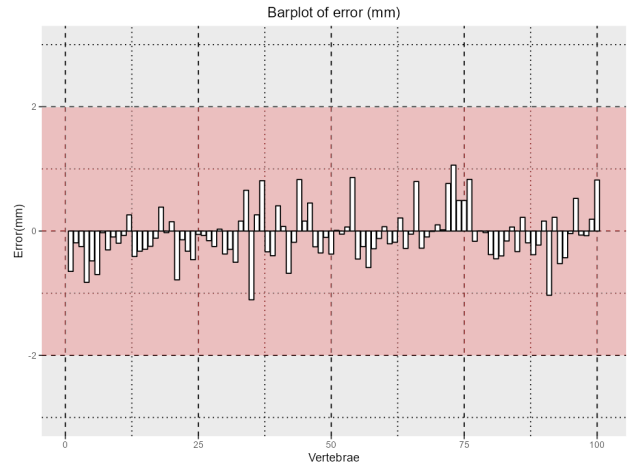


Fig. 4: Δ_{depth} of the 100 lamb spinous processes drilling

DISCUSSION

In this study, we showed that the cutting torque can be used to detect a breach in the cortical bone. We used an offline breach-detecting model. The use of an online method will be more appropriate in the future to detect breaches in real-time. Testing this method in pedicle preparation is also needed because it is more relevant clinically.

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