Computed Tomography-based Mechanical Impedance Identification for Breach Detection in Pedicle Screw Placement

Ayoob Davoodi*, Maikel Timmermans*, Ruixuan Li, Gianni Borghesan, Kathleen Denis and Emmanuel Vander Poorten

KU Leuven, Department of Mechanical Engineering, Robot-Assisted Surgery Group, Belgium

INTRODUCTION

Nowadays, spinal disease has gradually increased due to population aging, improper lifestyle, or accidents; for example, intervertebral disc herniation, spinal degeneration, and scoliosis are well-known spine disorders. They all require Pedicle Screw Placement (PSP) as a crucial step during surgical interventions. Robotic-assisted spine surgery combined with imaging modalities such as fluoroscopy and Computed Tomography (CT) have improved surgical outcomes for PSP. Taking advantage of these modalities, the surgeon pre-operatively estimates the ideal trajectory for PSP, and fluoroscopy can help visualize the drilled trajectory intraoperatively. The pre-operative CT image is a rich data set that can enhance surgical accuracy. For instance, Qi *et al.* proposed a path-planning method based on pre-operative CT scans where the spine of the patient is segmented, and then each individual vertebra is classified by using a trained deep-learning network model [1]. Cheng *et al.* also used pre-operative CT images to do automatic vertebra landmark detection and trajectory planning for PSP with the help of a Convolutional Neural Network (CNN) [2]. Ma *et al.* improved the pre-operative drilling trajectory causing the highest pull-out force and hence better fixation after surgery [3]. Pre-operative CT imaging is also used to model drilling thrust force in bones as a function of different drilling speed, feed rate, and drill bit geometry [4].

To the author's knowledge, using the pre-operative CT image to predict the drilling breach is still at the early stage. This work aims to use the Hounsfield unit of pre-operative CT images over the drilling trajectory, which helps to predict the bone drilling mechanical stiffness and force profile. Using this metric as pre-knowledge during drilling helps to identify the instantaneous moment when a breach happens and stop the robotic system. Therefore, in this work, the correlation between the Hounsfield unit and the force and stiffness was investigated to show the usability of the CT data to provide extra pre-operative information and aid intraoperative drilling state identification.

* These authors contributed equally to this work.

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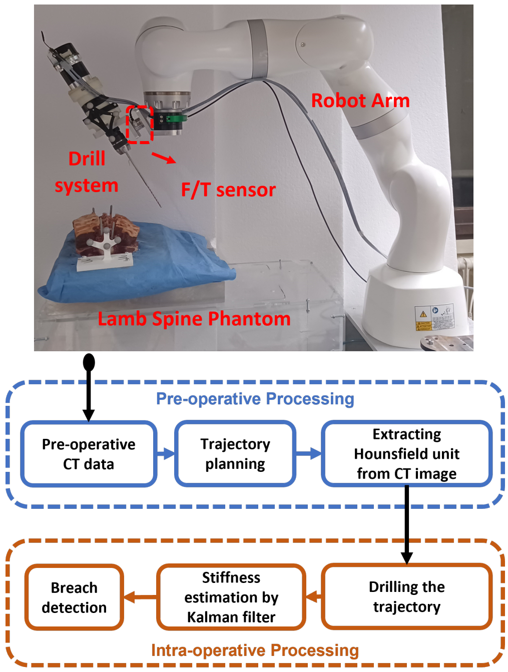

Fig. 1: (Up) Illustration of the Robotic drilling system, lamb spine is used for the experiment. (Down) Workflow of the current study on using the pre-operative CT image.

MATERIALS AND METHODS

The drilling experiment is done by a robotic drill system which consists of a robot arm (KUKA Robot Med7, Augsburg, Germany) and a custom-designed drilling system. During testing, the interaction force/torque was measured by a 6 DOF F/T sensor (Nano 25, ATI Industrial Automation, USA) mounted exactly to the robot end effector by an attachment piece. A lamb spine phantom that was rigidly fixed to a wooden board was utilized for experimental validation. A custom-made optical marker was also rigidly attached to the wooden board next to the spine. Fig1 illustrates the current study workflow and the experimental setup. A pre-operative CT of the lamb phantom was acquired before drilling executions. These CT images are used to generate the 3D segmented spine model by Materialise Mimics Software. The pre-operative trajectory is planned on the 3D model of the spine, such that 8 trajectories are non-breach and 8 trajectories are breach trajectories. The average Hounsfield unit within the dimensions of the drill is calculated for each CT slice along the path for each planned trajectory. A robotic drilling system is employed to execute the drilling, in which an Optical Camera-Guided Navigation System(OCGNS) transforms the planned trajectory from the pre-operative CT to the robot frame. Two calibration routines were done beforehand. First, the optical camera frame is calibrated to the robot base frame; thus, the optical marker on the phantom can be used to convert the drilled trajectory to the robot base frame. Second, to avoid custom-designed drilling errors, a pivoting point calibration is conducted to find the drill tip w.r.t to the robot end effector. The position-based control approach is used to move the drill tip to the vicinity of the planned trajectory; then, a force-based control is used to execute drilling along the trajectory. The desired drilling force is set at 20N along the Z-axis(drilling trajectory), and the drilling rotation speed is set to 500 rpm. The interaction force/torque and drill tip pose are recorded during the experiment. The interaction between the drill tip and the vertebrae can be modeled as a spring-damper system as follows:

$$F = k(x(t)) - x_0) + b\frac{dx(t)}{dt} \quad (1)$$

where k and b are the stiffness and damping over the drilling path. $x(t)$, $\frac{dx(t)}{dt}$ are the drilling depth and its derivative. x_0 is the rest length of the spring. The modeled stiffness k is not exactly the mechanical bone stiffness, and it also has a correlation with drilling speed, feed rate, and drill bit geometry. Since the bone properties change over the drilling path, an extended kalman filter is used to estimate the stiffness and damping during the drilling. After drilling execution, the drilling data are post-processed and registered with the pre-operative CT images to identify the correlation between the Hounsfield unit, the interaction force, and the estimated stiffness.

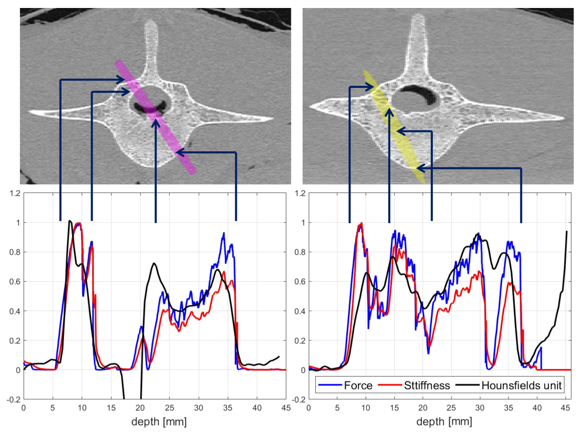

Fig. 2: (UP) Illustration of the breach and non-breach drilled trajectories. (Down) Hounsfield unit, force, and stiffness over the drilling path.

RESULTS

Experimental data over the trajectory are demonstrated for a breach (left) and a non-breach (right) trajectory in Fig2. The corresponding Hounsfield unit (black line), measured force (blue line), and estimated stiffness (red line) are shown over the drilling depth. Each signal is normalized to its maximum. When the drill passes the cortical bone, one can see an increase in the three signals. When the drill goes to the cancellous bone, the force and stiffness drop the same as in the Hounsfield unit. Since the inside of the spinal canal is empty in this region, the three parameters converge to zero. The correlation between the Hounsfield unit and the force is 71.39 ± 8.8% and 81.63 ± 9.89% for breach and non-breach trajectories, respectively, while this correlation between the Hounsfield unit and stiffness is 66.14 ± 9.63% and 78.94 ± 8.21% for breach and non-breach trajectories. Results are summarized in TABLE I.

Feature	Breach	Correlation mean (%)	std (%)
Force	Yes	71.39	8.8
	No	81.63	9.89
Stiffness	Yes	66.14	9.63
	No	78.94	8.21

TABLE I: The correlation results between the Hounsfield unit, force, and stiffness for the breach and non-breach trajectory.

CONCLUSIONS AND DISCUSSION

This study demonstrates how using the pre-operative CT image as pre-knowledge can help predict the drilling force and mechanical stiffness patterns over the drilling trajectory. The proposed framework uses the CT image to calculate the Hounsfield unit on the pre-planned PSP drilling trajectory. Then a robotic drilling system is used to execute drilling. Meanwhile, an Extended Kalman filter is used to estimate the mechanical stiffness using interaction drilling force. Experimental evaluation on 8 breach and 8 non-breach drilled trajectories is conducted, showing 81.63% and 78.98% correlation between the Hounsfield unit and the force and stiffness for non-breach trajectories, respectively.

The result shows that pre-operative CT and the corresponding Hounsfield unit over the drilling trajectory provide a pre-knowledge of the physical environment. By using this information, if there is a deviation between the measured force profile or estimated stiffness with the pre-knowledge profile, the robotic system would be able to halt the drilling procedure. This approach embeds intelligence in the robotic system, makes it aware of the environment, and it also helps to reduce harm to the patient.

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