Two-Step Trajectory Visualization for Robot-Assisted Spine Radiofrequency Ablations

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Abstract

Radiofrequency Ablations (RFAs) can be employed for the treatment of spine metastases. Instruments are therefor inserted through the vertebra's pedicle into cancerous tissue within the vertebral body. This requires high precision during interventions. We present a two-step method to increase risk awareness during intervention planning and execution of manual and robot-assisted spine RFAs. Three medical experts evaluated our method and stated that it yields two advantages: First, improved visualizations for manual interventions and second, increased safety in hand-guided, robot-assisted setups.

1 Introduction

The health of bones depends on the well-balanced communication between *osteoclastic* and *osteoblastic* bone cells, which break down and synthesize bone tissue, respectively [Ortiz, A and Lin, S, 2012]. Infiltrating cancer cells can disturb this balance [Abrams, H. L. and Spiro, R. and Goldstein, N., 1950].

Many patients with vertebral metastases are in palliative care and suffer from symptoms such as pain and motor deficits. In very severe cases they may also suffer from paraplegia or spinal cord transections. Chemo- and radiation therapy, and surgery are mainly used for treatment. Radiofrequency Ablations (RFAs) can be used as an image-guided and minimally invasive alternative or additional therapy [Gazis, A N and Beuing, O and Franke, J et al., 2014]. A transpedicular RFA is the most common approach, where a pathway is created by hammering a cannula and trocar through a vertebra's pedicle. Pedicles are the bony connections between the vertebra and the vertebral arch that encompass the spinal canal laterally. After pathways were created, RFA needles are inserted to perform an ablation and cancer cells within the vertebral body are coagulated. RFAs are effective [Callstrom, M R and Charboneau, J W and Goetz, M P et al., 2006], but must be performed with high precision: Lumbar pedicles are between 5 to 8 mm thick while upper thoracic pedicles are only 3 to 4 mm thick. This results in physical stress for surgeons. Figure 1 shows a Dyna-Computed Tomography (Dyna-CT) scan of a conserved vertebra and it illustrates the spatial relation between a pedicle and an inserted drill. The scan was recorded after drill insertion and the pathway's contour is highlighted in yellow for better visibility.

In this work, we focus on manually implemented and hand-guided, robot-assisted RFAs for spine metastases. A hand-guided robot augments the surgeon´s abilities with tremor-free [Becker, B C and Maclachlan, R A and Lobes, L A et al., 2013], scaled [Guthart, G S and Salisbury, J K, 2000] and constrained motions [Davies, B L and Harris, S J and Lin, W J et al., 1997]. Therefore, we propose to combine robot

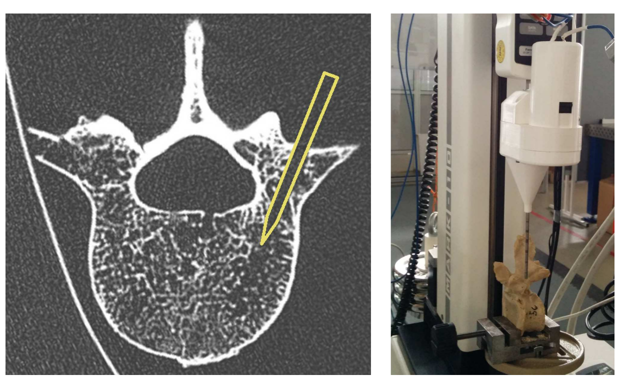

Figure 1: *Left*: 10 s Dyna-CT scan with highlighted insertion path for a conserved lumbar vertebrae. *Right*: Experimental setup where forces are measured during automatic drill insertion with constant velocity of 2 mm per second.

assistance with image-guided interventions, where highly accurate motions are derived from diagnostic image scans. The main benefits are increased intervention and patient safety.

Our clinical partners use CT and Magnetic Resonance Imaging (MRI) scans for diagnosis. This combination enables them to conclude about the metastasis' origin and the bone density. This knowledge is important, because the RFA needles have to be inserted deep enough into the vertebra and metastasis to be effective. Depending on the primary tumor's location, the metastasis will be very hard or soft [Halvorson, K G and Sevcik, M A and Ghilardi, J R et al., 2006]. Therefore, the physician has to be aware of the required forces beforehand: Instruments have to be inserted deep enough while avoiding pedicle fractures and injuries of the lung, the aorta, or the spinal canal.

2 Materials and Methods

We propose a two-step method using diagnostic image scans to increase safety during instrument insertion. Figure 2 shows these steps (orange boxes) with respect to the clinical workflow (blue boxes). The first step, a *Map Visualization of Trajectory Risk*, uses the CT scans to present the risk of multiple trajectories with respect to the instrument's size and the absolute, minimum distance to risk structures. When a trajectory is chosen, a *Force Prediction* is conducted to assess a single trajectory in more detail.

2.1 Step 1: Map Visualization of Trajectory Risk

Figure 3 depicts our conceptual map visualization to present risk categories for multiple trajectories. Physicians have some spatial freedom to define a trajectory. All possible paths to a target point (TP) lie inside the red triangle and the parameters that define this zone are the pedicle's width and height, and the instrument's diameter. The clinically feasible paths lie in the yellow and green triangle. The color-coding is related to Rieder et al. [Rieder, C and Weihusen, A and Schumann, C et al., 2010], but in contrast to their work, we convey risk awareness and do not visualize coagulation zones. Yellow color-coded trajectories are only somewhat safe. Trajectories are assigned to this category if their absolute distance to risk structures, such as the spinal canal, lies in an user-defined interval, e. g. between 2 and 5 mm.

2.2 Step 2: Force Prediction from Diagnostic Scans

Anatomical densities, thus Hounsfield Units (HUs) in Dyna-CT scans, vary for cortical, cancellous, and metastatic bone tissues. Our medical partners reported that the required drill force depends on the type of bone tissue. Therefore, we evaluated how feed rate changes correlate with HU changes in image scans. Here, feed rate describes the velocity at which the drill is advanced into the vertebra.

Experimental Setup: We built a construction to insert a hollow drill with an outer diameter of 3 mm and an inner diameter of 2 mm with a constant velocity of 2 mm per second into five series of two lumbar and one thoracic vertebrae each (Fig. 1). During drilling the timestamps, covered distance, and feed rate forces were logged. First results show that forces up to 10 N are required to insert the drill into conserved

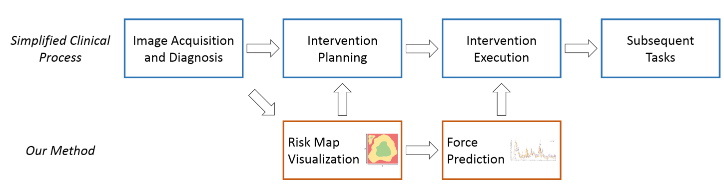

Figure 2: Our proposed two step method to assist manual and robot-assisted RFAs. Our two-step method (orange boxes) is presented in relation to the clinical stage (blue boxes), where it should be used.

lumbar vertebrae.

Image Acquisition and Processing: Dyna-CT scans were recorded before and after drilling. For all scans, all acquisition parameters were kept the same. In consultation with our medical partners, we set the acquisition time to be 10 s to get scans whose image quality is comparable to those in clinical routine.

The main difference between both scans are the low intensity values from the drill hole in the second scan, which are close to air. Therefore, to segment and assess only the intensity values from the drill hole, we use a two-step image processing chain: First, the scan with the drill hole is subtracted from the reference scan without drill hole. After subtraction an intensity threshold is applied to segment the cylindric drill path. Due to image noise and minor rigid registration inaccuracies, the result images contain many segmentation artifacts (Fig. 4(A)).

We address this problem by applying a Principal Component Analysis (PCA) on the result images, where the eigenvector with the largest eigenvalue represents the drilling direction. Knowing the drill's outer diameter, we can assume a virtual cylinder, which we use to mask the drill hole in the reference images (Fig. 4(B)). Then, the trajectory is divided into equidistant sample points and the step size equals the smallest voxel dimension. Finally, the intensity values are perpendicularly projected on the drill path. The averaged intensity values can be seen in Figure 5, where they are plotted in orange.

3 Results

To compare the measured force and averaged HU values, both value sets are normalized before plotting (Fig. 5). Steep graph curve changes indicate transitions between bone tissues with different anatomical densities. Because of restrictions in our experimental setup, the drill's feed rate had to be lowered at the corticalis. Therefore, the force graph curve (blue) has an offset of 2mm to the right. First results show that force changes imply changing image intensity values, but changing intensities can, but do not have to, result in force changes.

3.1 Evaluation

We evaluated our method by interviewing three clinical experts and we asked them to assess our method's feasibility. The experts stated that our method can increase intervention safety for manual, but especially for hand-guided, robot-assisted spine RFAs. The reason is the combination of map and graph visualizations to convey risk awareness. One expert also advised us not to use conserved vertebrae in the future, because

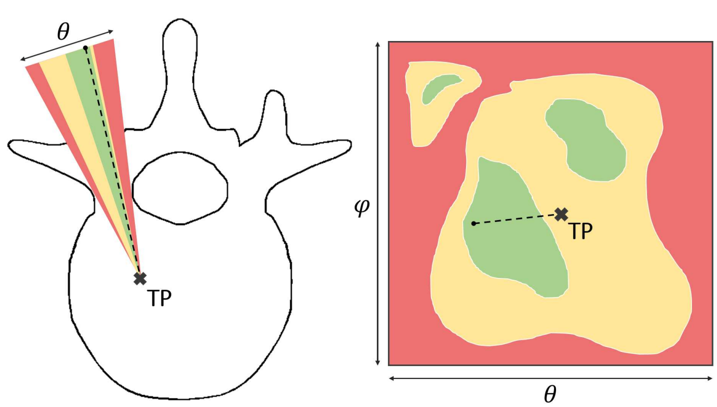

Figure 3: Given a Target Point (TP) and the pedicle's size, trajectories get categorized and color-coded. The dashed line is the user-defined trajectory to TP. Each path can be described as a triple (TP, θ, ϕ), where θ is the horizontal and ϕ the vertical angle.

fresh or dried bones have different mechanical properties than conserved bones.

Our method does not influence the current clinical workflow, as it can be used on image scans that are already recorded for diagnosis and intervention planning. The force prediction requires no additional effort from the physician. The risk map requires the physician to detect anatomical structures such as the pedicle and the spinal canal, and to define a safety interval to apply the categorization.

4 Discussion

We presented a two-step method to convey risk awareness that increases safety for manual and hand-guided, robot-assisted spine RFA. Both steps do not require much additional effort from physicians.

We think that the risk map visualization is underused and we plan to evaluate how it can be used during intervention execution, e. g. if the drill's distance to risk structures comes close or falls below a user-defined minimum threshold, the drill's feed rate is decreased or all movement is stopped, respectively.

The force prediction is highly relevant for robot-assisted setups. We argue that force changes imply changing image intensity values. Therefore, if measured force changes cannot be confirmed by changing image intensity values, the system should warn the physician during intervention. Our method predicts these changes from diagnostic image scans using an effortless image processing chain consisting of image subtraction, thresholding, and a PCA analysis.

Drilling is a complex task. The required force to move the drill depends on the drill's feed rate and rotation speed. Both can be measured during intervention execution. Because of the discussions with our medical partners, we are aware that mechanical properties of conserved and non-conserved vertebrae are different. Therefore, we plan to extend the experiments to non-conserved vertebrae, if current observations are confirmed by additional experiments.

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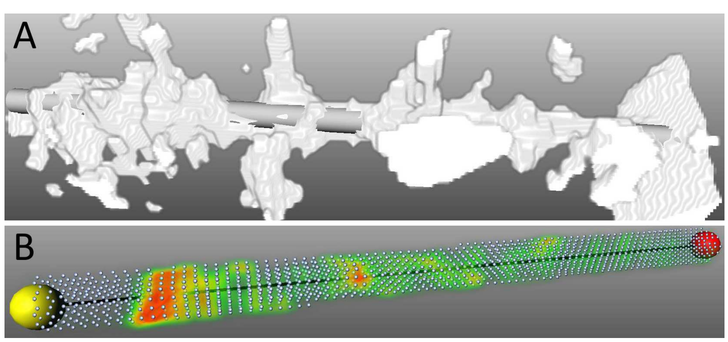

Figure 4: (A) Remaining intensity values after image subtraction and thresholding with a high number of segmentation artifacts. (B) The drill was inserted from the yellow to the red sphere. The red area on the left is the result of high intensity values: It depicts the position of the vertebral corticalis, which is harder than the vertebral body.

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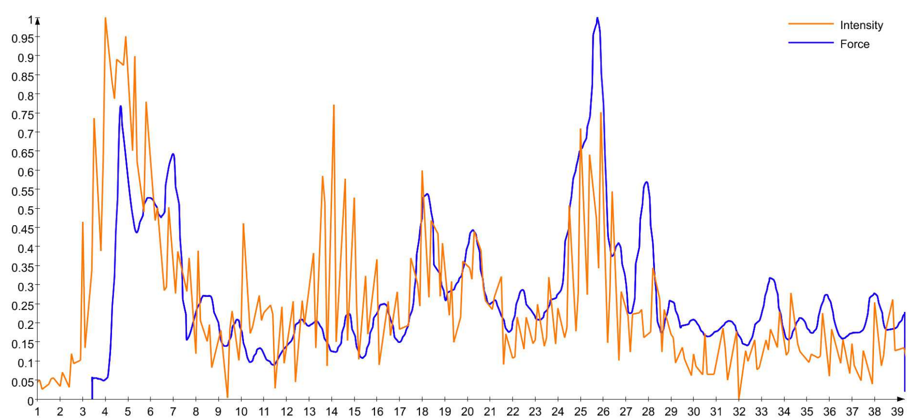

Figure 5: Normalized forces (blue) and normalized, averaged intensities (orange) during insertion with constant velocity through a lumbar pedicle (Fig. 1).