



Proximity-Based Haptic Feedback for Collaborative Robotic Needle Insertion

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Abstract. Collaborative robotic needle insertions have the potential to improve placement accuracy and safety, e.g., during epidural anesthesia. Epidural anesthesia provides effective regional pain management but can lead to serious complications, such as nerve injury or cerebrospinal fluid leakage. Robotic assistance might prevent inadvertent puncture by providing haptic feedback to the physician. Haptic feedback can be realized on the basis of force measurements at the needle. However, contact should be avoided for delicate structures. We propose a proximity-based method to provide feedback prior to contact. We measure the distance to boundary layers, visualize the proximity for the operator and further feedback it as a haptic resistance. We compare our approach to haptic feedback based on needle forces and visual feedback without haptics. Participants are asked to realize needle insertions with each of the three feedback modes. We use phantoms that mimic the structures punctured during epidural anesthesia. We show that visual feedback improves needle placement, but only proximity-based haptic feedback reduces accidental puncture. The puncture rate is 62% for force-based haptic feedback, 60% for visual feedback and 6% for proximity-based haptic feedback. Final needle placement inside the epidural space is achieved in 38%, 70% and 96% for force-based haptic, visual and proximity-based haptic feedback, respectively. Our results suggest that proximity-based haptic feedback could improve needle placement safety in the context of epidural anesthesia.

Keywords: Force feedback · Collaboration · Human-robot interaction · Epidural anesthesia · Optical coherence tomography

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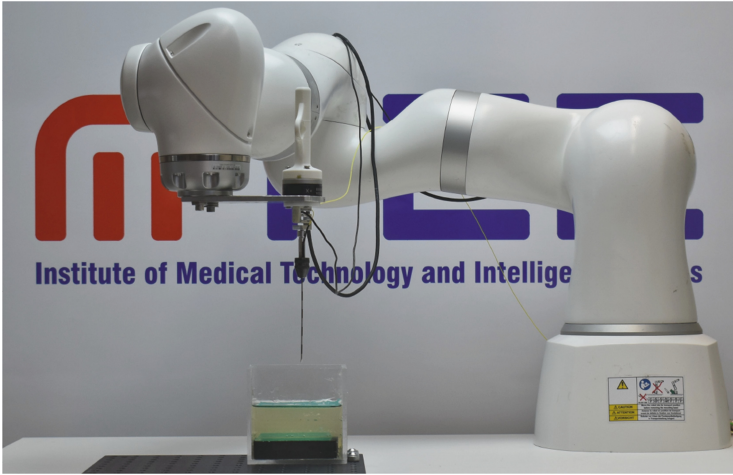


Fig. 1. Robotic system with proximity-based haptic feedback for collaborative needle insertions into tissue mimicking phantoms.

1 Introduction

Epidural anesthesia plays an important role for perioperative pain management, e.g. during orthopedic, urologic and general surgery. The procedure requires placing a needle that guides a catheter into the epidural space (ES). The ES is located directly behind the ligamentum flavum (LF) and surrounds the dura that protects the spinal cord and the cerebrospinal fluid. Major complications during epidural anesthesia are not common but potentially serious, including hematoma, post-operative neurologic deficits, infections and even death [1]. Nerve injury and long-term headache result from accidental dural perforation [2,3]. Placement within the ES without dura injury can be challenging given the small size of only 2 mm to 6 mm [4].

The most common technique for identifying the correct needle placement is loss-of-resistance (LOR). It is based on the different tissue densities in LF and ES. The entry into ES is visually or haptically perceived by the performing surgeon [5]. However, LOR requires frequent training, false-positives are possible and dura punctures still occur [5,6].

We consider robot-assisted needle insertions in the context of epidural anesthesia. CT-guided robotic needle insertions have shown promising results for soft tissue biopsy sampling [7]. In epidural anesthesia, external image guidance is challenging and tissue deformation as well as patient movement make a fully automated needle placement difficult. We consider a collaborative approach where the trajectory is guided by a robot but additional feedback is required to enable the correct axial placement by the operator. Besides LOR, experienced physicians rely on the haptic impression at the needle shaft to navigate. Consequently, haptic feedback based on force measurements has been intuitively

considered for robotic needle insertions. Multiple force sensors [8] or force modeling [9] can provide enhanced feedback on needle tip forces that are otherwise superimposed with friction forces. However, force measurements always require physical contact first, potentially damaging delicate structures.

Instead, we propose a method that can detect structures before physical contact occurs. We have recently shown that an optical coherence tomography (OCT) fiber embedded into an epidural needle can enable the detection of rupture events during needle insertions [10]. We now employ high resolution OCT needles to measure the distance to structures. During collaborative needle insertions, the distance is converted to a resistive force and employed as haptic feedback. We perform experiments on tissue mimicking phantoms simulating the epidural cavity. We compare haptic feedback based on force measurements as well as the visual representation of the proximity with and without additional haptic feedback. We evaluate our methods in a user study with ten participants that each conduct needle insertions with the three different feedback modes.

2 Methods

Our system setup contains an optical needle probe, a 7-degree-of-freedom (DOF) medical robot with a custom handle for collaborative robot manipulation and a tissue mimicking phantom (see Fig. 1).

2.1 Sensor and Phantom Setup

The proximity sensor is based on OCT imaging. An optical fiber is fitted into a standard Tuohy needle with a diameter of 1.4 mm for forward-facing, common-path OCT imaging. Axial depth scans (A-scans) are acquired with a spectral domain OCT system (Telesto I, Thorlabs) with a axial resolution of 6.5 μm in air. The maximum imaging depth in tissue is approximately 1.77 mm, assuming a constant refractive index of 1.45 for tissue. Our proximity sensor output is the distance d to structures, which are positioned along the insertion trajectory in front of the needle tip. It is obtained from detecting the closest intensity peak within the processed A-scan (see Fig. 2, top right).

To evaluate our system, we employ phantoms from tissue mimicking gelatin gels. We replicate the ES within the gelatin gels with two successive layers of cellulose (see Fig. 2, bottom right). The layers are spaced 3 mm apart and represent the LF and the dura respectively. The synthetic dura is supported by polyethylene foam that represents the area of the subdural space.

2.2 Robotic System

The robotic system consists of a 7-DOF light-weight robot (LBRMed 14, KUKA) and a specially manufactured handle for the collaborative control by the surgeon. The handle (see Fig. 2, left) includes a 6-DOF force-torque sensor (M3703, Sunrise Instruments) that measures the forces and torques applied to the handle

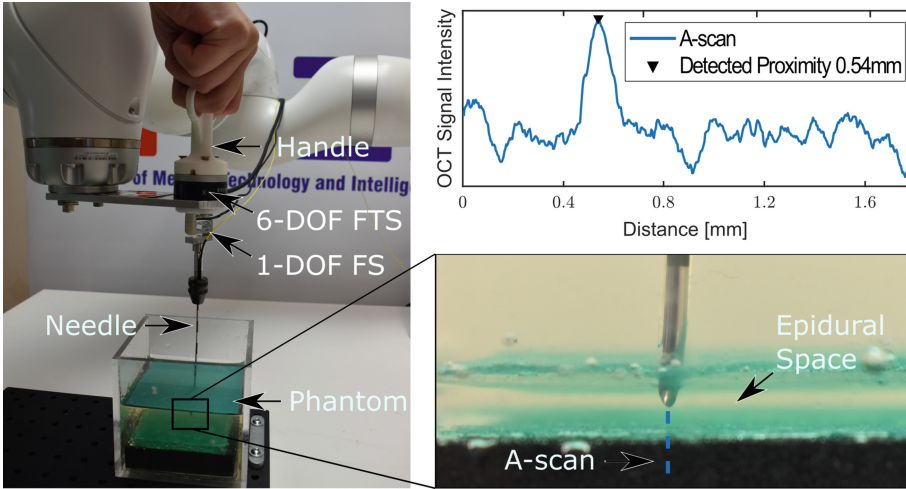
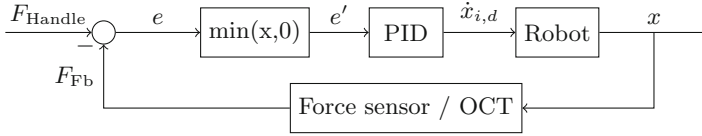


Fig. 2. The custom handle for collaborative needle insertions is shown on the left. A 6-DOF force-torque sensor (FTS) detects the users input and the 1-DOF force sensor (FS) registers forces acting on the needle. A close-up of the needle tip within the ES mimicking phantom and the visualization of approaching structures via the A-scan are shown on the right.

by the surgeon. Additionally, a 1-DOF force sensor (KD24s, ME-measurement systems GmbH) measures the forces acting on the needle shaft.

The outer control loop is designed with an admittance controller. Prior to insertion, the 6-DOF force-torque sensor allows the operator to freely position the needle axis along a desired trajectory. During collaborative insertion, the task space is restricted to the needle axis. The operator controls the 1-D movements by the forces exerted on the handle. Haptic feedback is implemented by an opposing resistive force. We employ a feedback control loop as illustrated in Fig. 3. The input value of the control loop is the control error e . It is defined as the difference between the feedback force F_{Fb} and the handle force applied in the insertion axis F_{Handle} . Negative values of e are not considered in order to prevent stability problems caused by oscillations. The control error is converted to the desired movement $\dot{x}_{i,d}$ by the PID controller. Execution by the robot results in the new insertion depth x of the needle tip. For $F_{Handle} < 0$ the handle force is directly mapped to the corresponding motion without any feedback to allow retraction.

The handle enables three different feedback modes. Switching between the three modes changes the source of the applied feedback force F_{Fb} . In mode 1, haptic feedback consists of the measured needle force. In mode 2, the user is provided no haptic feedback, but a visual representation of the OCT signal (see Fig. 2, top right). In mode 3, this visual feedback is supplemented by the haptic feedback of the computed distance. During mode 1, we measure the force acting on the needle, which is then used as direct feedback $F_{Fb} = F_{Needle}$. As mode 2 contains only visual feedback, the feedback loop is not closed with $F_{Fb} = 0$ at



Mode 1: $F_{Fb} = F_{Needle}$, Mode 2: $F_{Fb} = 0$, Mode 3: $F_{Fb} = F_{Prox}$

Fig. 3. Control Scheme during Insertion. Three modes are considered for the feedback loop. In mode 1, the needle shaft force is used as feedback. In mode 2, no feedback is used and in mode 3, a force is generated based on the proximity according to Eq. 1.

all times. For the proximity-based haptic feedback (mode 3), the sensor output d computed from the OCT signal is mapped to a corresponding resistive force $F_{Fb} = F_{Prox}$, for which

$$F_{Prox}(d) = \tanh\left(2 * \left(1 - \frac{d}{d_{Max}}\right)\right), d_{Max} = 1.77 \text{ mm} \quad (1)$$

is used. Robot communication and control is realized with the Robot Operating System (ROS). The controller runs with a frequency of 1 kHz, both force sensors update with 200 Hz and the computed distance is updated with a frequency of 100 Hz. The latency of the system is 30 ms.

2.3 Experiments

Ten participants with limited experience in needle insertions are asked to position the needle tip within the ES. We conduct five insertions per participant per feedback mode. Pullback is permitted and the insertion is stopped once the participant releases the handle. The participants are granted one test run in each mode to familiarize with the system behaviour. The order in which the three modes are employed is randomized for each participant.

For evaluation, we determine the position of our mimicked dura relative to our robot coordinate system. Based on the end-effector robot poses, we consider the distance to the target height in mm. We report mean and standard deviation at maximum extension d_{Max} and for the final position d_{End} . Insertions with correct needle placement refer to all insertions where $0 \text{ mm} < d_{End} < 3 \text{ mm}$. Insertions with $d_{Max} < 0 \text{ mm}$ correspond to dura puncture. The insertion is aborted if the operator inserts the needle more than 15 mm beyond the dura.

3 Results

In total, we conduct 150 insertions. A single insertion is aborted as the participant fails to identify the ES in mode 2. Figure 4 shows the dura puncture rate and the successful needle placement separated by the three feedback modes. For force-based haptic feedback (mode 1), placement within the ES is successful in 38% of cases. 62% of insertions result in dura puncture and no insertions are stopped before the LF. For purely visual feedback (mode 2), one insertion is

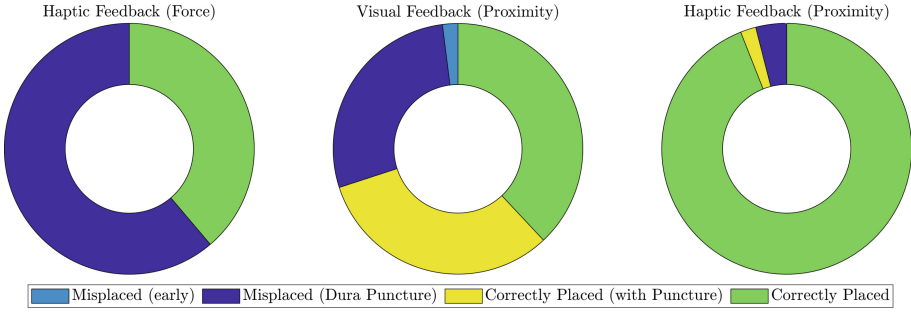


Fig. 4. Combined results for the dura puncture rate (including overshoot) and the placement success rate based on the maximum and final insertion position respectively.

Table 1. Needle placement accuracy for each feedback mode in comparison of the first and last insertion.

Feedback mode		1	2	3
d_{Max} [mm]	First	-0.35 ± 1.86	-1.96 ± 4.37	0.62 ± 0.38
	Last	-0.75 ± 2.07	-0.15 ± 1.25	0.67 ± 0.53
d_{End} [mm]	First	-0.08 ± 1.66	-1.37 ± 4.63	0.76 ± 0.408
	Last	-0.67 ± 2.06	0.39 ± 1.38	0.80 ± 0.66

stopped prematurely and 38% of insertions are correctly stopped in front of the dura. Dura puncture occurs in 60% of cases, but is detected and corrected by a subsequent pullback in 32% of all insertions. The proximity-based haptic feedback (mode 3) increases the correctly placed insertions without dura puncture to 94%. The dura is punctured during three insertions (6%), one position is successfully corrected.

We further report the distance to the dura for the three feedback modes (see Fig. 5). Considering d_{Max} (red boxes), needle insertions with both mode 1 and 2 are extended below the dura, with a mean of (-0.33 ± 2.01) mm and (-0.65 ± 2.37) mm, respectively. On average, insertions with proximity-based haptic feedback (mode 3) are stopped (0.58 ± 0.68) mm before the dura. Mean distances to the dura at the final needle position d_{End} are (-0.19 ± 1.98) mm, (-0.19 ± 1.98) mm and (0.21 ± 0.62) mm for mode 1 to 3, respectively.

In order to evaluate the learning effect of the participants, the positions from the first and the last attempt of each mode are displayed in Fig. 5. The mean accuracy and standard deviation (SD) is also given in Table 1.

4 Discussion and Outlook

The results from our phantom study show that the needle shaft forces (mode 1) provide insufficient haptic feedback for the operator to accurately place an epidural needle within the ES. The large variation in final needle placements

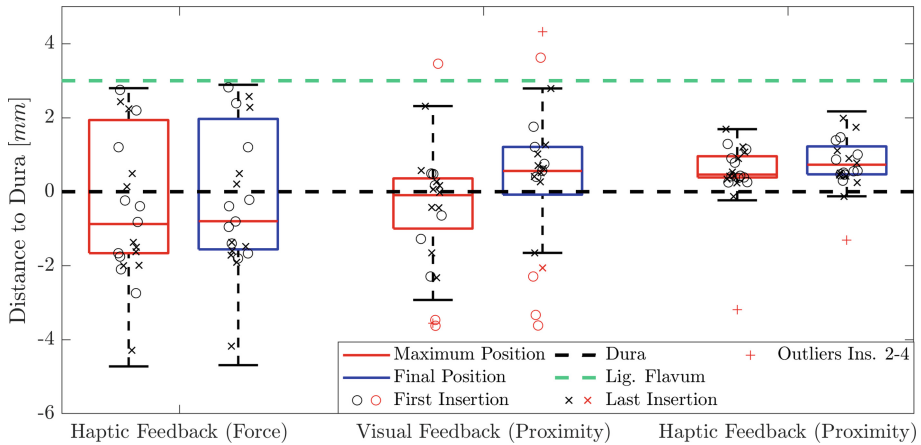


Fig. 5. Distance to the dura for the maximum and final extension for each of the three feedback modes. Additionally, the first and the last attempt from each participant is displayed. Outliers are marked in red, the aborted insertion is not shown.

implies that the participants have difficulty distinguishing the two boundary layers. Multiple insertions are stopped after only partially rupturing the mimicked LF signified by points directly under the 3 mm line in Fig. 5. With visual feedback (mode 2), the puncture rate is nearly identical to mode 1. The higher transparency compared to mode 1 and 3 also results in the only aborted attempt posing a significant safety issue. However, the participants are able to detect and correct the overshoot in half of the cases. This implies that they are able to detect the dura but fail to react in time. Higher damping for finer movements and a more intuitive visual representation could help mitigate the overshoot. In mode 3, the number of needle placements where no puncture occurs and the needle is stopped inside the ES increases to 94% from 38% in mode 1 and 2. This indicates that users have less difficulty distinguishing the two boundary layers and can more intuitively insert the needle within the ES.

Regarding the learning effect, the comparison between the first and last attempt for each mode results in relatively small differences compared to their standard deviations. This makes definitive conclusions difficult, considering the small sample size. Nevertheless, it indicates that the lack of adequate feedback in mode 1 and 2 is not intuitively compensated within five attempts.

Previously, proximity-based haptic feedback has been proposed for ultrasound imaging [11] and endovascular catheterization [12]. However, these approaches provide an insufficient resolution, are not designed to work in-vivo or rely on external imaging that is not typically available in epidural anesthesia. Our proximity sensor with μm resolution can resolve small scale structures like the ES and can be easily integrated into medical needles. Our system does not decouple the needle tip from shaft forces which has been shown to improve needle placement in [8]. However, this requires a more complex needle tip sensor.

In conclusion, we show that our collaborative approach has the potential to improve placement accuracy and highlight the importance of haptic feedback. The haptic response is decoupled from the puncture resistance of the dura and no physical contact is required. Proximity-based haptic feedback is therefore suited to avoid delicate structures and drastically reduces accidental puncture in our phantom study. Further evaluation will address the operation by medical experts and the applicability within real tissue samples.

References

1. Kang, X.H., et al.: Major complications of epidural anesthesia: a prospective study of 5083 cases at a single hospital. *Acta Anaesthesiol. Scand.* **58**(7), 858–866 (2014). <https://doi.org/10.1111/aas.12360>. <https://onlinelibrary.wiley.com/doi/full/10.1111/aas.12360>
2. Bezov, D., Lipton, R.B., Ashina, S.: Post-dural puncture headache: Part I diagnosis, epidemiology, etiology, and pathophysiology. *Headache J. Head Face Pain* **50**(7), 1144–1152 (2010). <https://doi.org/10.1111/j.1526-4610.2010.01699.x>. <https://headachejournal.onlinelibrary.wiley.com/doi/full/10.1111/j.1526-4610.2010.01699.x>
3. Webb, C.A.J., et al.: Unintentional dural puncture with a tuohy needle increases risk of chronic headache. *Anesth. Analg.* **115**(1), 15–25 (2012). <https://doi.org/10.1213/ANE.0b013e3182501c06>. https://journals.lww.com/anesthesia-analgesia/Fulltext/2012/07000/Unintentional_Dural_Puncture_with_a_Tuohy_Needle.22.aspx
4. Manchikanti, L., Atluri, S.: Chapter 152 - lumbar epidural nerve block. In: Waldman, S.D., Bloch, J.I. (eds.) *Pain Management*, pp. 1281–1293. W.B. Saunders, Philadelphia (2007). <https://doi.org/10.1016/B978-0-7216-0334-6.50156-4>. <https://www.sciencedirect.com/science/article/pii/B9780721603346501564>
5. Dhansura, T., Shaikh, T., Maadoo, M., Chittalwala, F.: Identification of the epidural space-loss of resistance to saline: an inexpensive modification. *Indian J. Anaesth.* **59**(10), 677–679 (2015). <https://doi.org/10.4103/0019-5049.167483>
6. Yang, J., et al.: The development of a novel device based on loss of guidewire resistance to identify epidural space in a porcine model. *J. Healthc. Eng.* **2020**, 8899628 (2020). <https://doi.org/10.1155/2020/8899628>
7. Neidhardt, M., et al.: Robotic tissue sampling for safe post-mortem biopsy in infectious corpses. *IEEE Trans. Med. Robot. Bionics* **4**, 94–105 (2022)
8. de Lorenzo, D., Koseki, Y., de Momi, E., Chinzei, K., Okamura, A.M.: Coaxial needle insertion assistant with enhanced force feedback. *IEEE Trans. Biomed. Eng.* **60**(2), 379–389 (2013). <https://doi.org/10.1109/TBME.2012.2227316>
9. Okamura, A.M., Simone, C., O’Leary, M.D.: Force modeling for needle insertion into soft tissue. *IEEE Trans. Bio-med. Eng.* **51**(10), 1707–1716 (2004). <https://doi.org/10.1109/TBME.2004.831542>
10. Latus, S., et al.: Rupture detection during needle insertion using complex OCT data and CNNs. *IEEE Trans. Biomed. Eng.* (2021). <https://doi.org/10.1109/TBME.2021.3063069>

11. Antonello, R., Oboe, R.: Force controller tuning for a master-slave system with proximity based haptic feedback. In: IECON 2014–40th Annual Conference of the IEEE Industrial Electronics Society, pp. 2774–2779 (2014). <https://doi.org/10.1109/IECON.2014.7048900>
12. Dagnino, G., Liu, J., Abdelaziz, M.E.M.K., Chi, W., Riga, C., Yang, G.Z.: Haptic feedback and dynamic active constraints for robot-assisted endovascular catheterization. In: 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 1770–1775 (2018). <https://doi.org/10.1109/IROS.2018.8593628>

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