Remotely Actuated Needle Driving Device for MRI-Guided Percutaneous Interventions: Force and Accuracy Evaluation*

Di Wu¹, Gang Li¹, Niravkumar Patel¹, Jiawen Yan¹,
Gyeong Hu Kim¹, Reza Monfaredi², Kevin Cleary², and Iulian Iordachita¹

Abstract—This paper presents a 2 degrees-of-freedom (DOF) remotely actuated needle driving device for Magnetic Resonance Imaging (MRI) guided pain injections. The device is evaluated in phantom studies under real-time MRI guidance. The force and torque asserted by the device on the 4-DOF base robot are measured. The needle driving device consists of a needle driver, a 1.2-meter long beaded chain transmission, an actuation box, a robot controller and a Graphical User Interface (GUI). The needle driver can fit within a typical MRI scanner bore and is remotely actuated at the end of the MRI table through a novel beaded chain transmission. The remote actuation mechanism significantly reduces the weight and size of the needle driver at the patient end as well as the artifacts introduced by the motors. The clinician can manually steer the needle by rotating the knobs on the actuation box or remotely through a software interface in the MRI console room. The force and torque resulting from the needle driver in various configurations both in static and dynamic status were measured and reported. An accuracy experiment in the MRI environment under real-time image feedback demonstrates a small mean targeting error (<1.5 mm) in a phantom study.

I. INTRODUCTION

Pain in the lower back is a common symptom in both adults and children. A study of Global Burden of Disease (GBD) indicated that low back pain is a problem of epidemic proportions and among the top 10 diseases causing disabilities [1]. The lifetime prevalence of lower back chronic pain is estimated at 80% [2]. Lower back pain can interfere significantly with daily activities. Needle-based interventional pain management is one treatment technique for low back pain. Local anesthesia medications and steroids can be injected to achieve temporary or long term pain relief [3]. Clinicians also inject phenol and ethanol to destroy the nerves that transmit pain signals [4]. When targeting the anatomy, the bevel-tip needle can allow for manipulation around anatomic features because of the asymmetric force experienced by needle tip [5]. Currently, these injection procedures rely on the use of radiological imaging such as Computed Tomography (CT), fluoroscopy and ultrasound guidance to manipulate the needle. However, these imaging

Fig. 1. Robotic system for MRI-guided percutaneous pain injections. The 2-DOF needle driver for needle steering is remotely actuated by the actuation box at the end of MRI table through a novel beaded chain transmission. It can be mounted on a 4-DOF base robot, constituting a fully actuated 6-DOF robotic platform.

modalities suffer from ionizing radiation (CT, fluoroscopy) and poor nerve visualization (Ultrasound).

We developed a body-mounted robotic systems to assist with precise pain injections under MRI guidance. MRI provides excellent cross-sectional imaging capabilities and superior visualization of nerves and surrounding tissues without ionizing radiation. Free-hand MRI-guided interventions can be time-consuming, consisting of several contiguous steps where the patient is moved in and out of the scanner bore to reposition the needle and reconfirm the needle position with repeated imaging [6].

Robotic assistance for MRI-guided intervention could achieve more precise needle targeting and significantly reduce the overall time of the procedure. MRI-conditional robots have been designed for various interventional procedures such as prostate biopsy [7], [8], and neurosurgery [9]. To minimize the influence of the electronic elements on the imaging, a few researchers studied remote needle placement. Burkhard et al. developed a 1-DOF system for needle teleoperation using hydrostatic transmission and reported an average position error of <1 mm [10]. The NeuroBlate[®] system for the laser ablation of tumors employs umbilical cables to transmit the power from master to slave [11]. A hydraulic driving stereotactic neurosurgery robot designed by Guo et al. demonstrated a targeting error of <1.73 mm in simulated deep brain needle insertion [12].

The mechanical design of the needle driving device is presented here. Preliminary evaluations including tracking accuracy, backlash, bench-top phantom study under real-time camera imaging feedback, and functionality validation in MRI environment of the needle driving device were presented in our previous study [13]. Its transmission error was smaller than 0.35 mm and backlash was smaller than 0.1 mm after compensation. As the needle driver is designed to be attached on top of the base robot [14], [15], the

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¹D. Wu, G. Li, N. Patel, J. Yan, G. Kim, and I. Iordachita are with the Laboratory for Computational Sensing and Robotics, Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218. D. Wu is also with Technical University of Munich (TUM), Garching, 85748, Germany. [dwu39, gli22, npatel89, jyan18, gkim64, iordachita]@jhu.edu

²R. Monfaredi, and K. Cleary are with the Children's National Medical Center, 111 Michigan Avenue, NW Washington, DC 20010 [rmonfare, kcleary]@childrensnational.org

force and torque that the needle driver applies on the base robot should be minimized. Moreover, we need to further evaluate the system accuracy in MRI environment. In this paper, we present the force/torque assessment and accuracy study under intra-operative MR image feedback. The primary contributions are: 1) Evaluate the force and torque applied by the needle driver on the base robot while the needle driver is still and performing manual and motorized needle manipulation and 2) Evaluate the system accuracy under real-time MR image feedback.

II. ROBOTIC SYSTEM DESCRIPTION

The needle driving device is composed of a 2-DOF needle driver, a beaded chain transmission and an actuation box (Fig. 1). The needle driver is remotely actuated by the actuation box through a 1.2 m long beaded chain. With such a remote actuation, there are no electronic elements (such as motors and encoders) on the needle driver. Thus this design can not only avoid introducing artifacts on MR imaging, but also reduce the weight and size of the needle driver on the patient.

The needle driver is the end-effector of the device that resides inside the MRI scanner bore and could be attached on our previously designed serial [14] and parallel base robot [15]. Its overall length is 186 mm, so it can fit into a standard MRI scanner bore (Fig. 1). The maximum insertion depth it can achieve is 150 mm. Its translation motion is implemented by a lead screw mechanism and rotation motion is directly actuated by the beaded chain.

The actuation box is placed at the end of MRI table. The box contains all the electronic elements such as motors and encoders. Two piezo motors (LR 50, PiezoMotor Co., Upsala, Sweden) were used initially for actuation [13]. Their speed ranges from 0 - 16.7 rpm and maximum torque is 50 mN·m. Because of the slow speed, it took about 8 minutes to complete a 120 mm insertion. To speed up the insertion, we replaced the piezo motor for translation with an ultrasonic motor (USR 30-S4, Shinsei Corporation, Japan), which is faster (speed range: 0 - 250 rpm) and more powerful (max. Torque: 0.1 N·m).

The beaded chain transmission has two primary functions: 1) Bridging the needle driver and actuation box and 2) Enabling the positioning and orienting of the needle driver around needle entry point. This flexible transmission method can transmit rotary motion between the needle driver and the actuation box. The beaded chain goes through plastic tubing, which works as a guiding sleeve and provides necessary tension on the chain for reducing the backlash.

Most of the parts on the needle driver are made of 3D printed plastic except for the aluminum lead screw, the ceramic ball bearings, plastic beaded chain, nylon tubing and carbon fiber guiding rails. By using similar materials as the patient-mounted robot (see [16]), in which the signal-to-noise ratio study was already carried out, our device is considered to be MRI-conditional.

Fig. 2. Force/torque assessment setup: (a) The needle driver is mounted on a 6-DOF F/T sensor to measure the force and torque of the needle driver in free space. (b) The force and torque of needle driver is measured while the needle is inserted into a phantom. The F/T sensor is clamped on a 3-DOF base mount, which is employed to configure various insertion angles.

III. EXPERIMENTS

The 2-DOF needle driving device can be attached on the 4-DOF base robot to constitute a fully actuated 6-DOF robotic system. The needle driver may have different positions and orientation with respect to the actuation box, which results in shifting forces and torques on the base robot. To ensure that the base robot is able to hold the needle driver at various configurations, we carried out a force/torque assessment both in free space and during insertion into a phantom. The previous phantom study under camera image feedback showed a small targeting error < 1.5 mm [13]. To evaluate the system accuracy in the MRI environment, an accuracy study under intra-operative MR image feedback was conducted.

A. Static Force/Torque Assessment

The goal of this assessment was to measure the force and torque applied by the needle driver on the base robot in static status without any needle movement. The needle driver was attached to a 6-DOF force/torque sensor (Nano 25-E, ATI Industrial Automation, North Carolina, USA) and the sensor was mounted on a 3-DOF base mount. The experimental setup is shown in Fig. 2a. In this experiment, the transmission length (Fig. 2), which is the distance between the actuation box and needle driver, was set to 110 cm and 85 cm to simulate 2 insertion locations on the lower back. At each transmission length, five different orientations (i.e. vertical, north, south, west, east, Fig. 2) were set and the measurements were repeated five times at each configurations. During the measuring period, the needle remained static at the home position. The sampling rate is 62.5 Hz. We skipped 50 samples before acquiring the data and then at least 500 samples were collected.

B. Dynamic Force/Torque Assessment

The dynamic force and torque assessment was carried out when the needle was inserted into a phantom (Fig. 2b). The artificial phantom was made of liquid plastic and plastic hardener (M-F Manufacturing Company, TX, US) with a ratio of 5:1. The assessment was carried out when the transmission lengths was set at the maximum distance of 120 mm and at the same 5 orientations. At each configuration, we completed several 120 mm motorized insertions and 120

Fig. 3. Accuracy experiment under MRI-guidance: (a) Manual insertions: the user manipulate the needle inside the scanner room by rotating the knobs on the actuation box and observing imaging feedback projected on a screen. (b) Motorized insertions: the user steer the needle in the MRI control room through GUI under real-time imaging feedback. (c) The homogeneous phantom is supported by an acrylic frame and is located at the center of the scanner bore to achieve a better imaging quality.

TABLE I
RESULTS OF STATIC FORCE/TORQUE ASSESSMENT (FORCE ARE IN N AND TORQUE ARE IN N·M)

Transmission Length	Orientation	F _{x_avg}	F _{y_avg}	F _{z_avg}	F _{avg}	T _{x_avg}	T _{y_avg}	T _{z_avg}	T _{avg}
110 cm	Vertical	0.067	0.537	-0.992	1.130	-0.026	-0.020	-0.216	0.218
	North	0.932	0.524	-0.774	1.320	0.022	0.029	-0.210	0.213
	West	0.444	-0.862	-2.586	2.762	0.498	-0.135	-0.054	0.054
	South	-0.652	0.988	-0.523	1.294	-0.210	-0.013	-0.253	0.329
	East	0.085	1.536	-0.476	1.611	-0.310	0.057	-0.447	0.547
85 cm	Vertical	-0.084	0.533	-0.144	0.559	-0.195	0.041	-0.236	0.309
	North	0.629	0.496	-0.242	0.837	-0.088	0.043	-0.220	0.241
	West	0.110	1.116	-0.694	1.318	-0.026	-0.018	-0.172	0.174
	South	-0.556	0.528	-0.058	0.769	-0.337	0.032	-0.102	0.353
	East	-0.121	0.037	0.050	0.136	-0.302	0.029	-0.197	0.361

mm manual insertions. The variations of force and torque were recorded during the whole insertion procedure.

C. Accuracy Study under Real-Time MR Imaging Feedback

Accuracy study in the MRI environment was carried out to further evaluate the needle steering accuracy of the improved device. This study was carried out in a 1.5 Tesla Siemens Aera[®] scanner. The needle was a 20 Ga MRI-safe bevel tip needle. The homogeneous phantom was made of liquid plastic and plastic hardener (M-F Manufacturing Company, TX, US) with a ratio of 5:2 to simulate soft tissues. The phantom was molded in a cuboid acrylic box with a few openings on the side as pilot holes for needle insertion. Several 3D printed rods with a diameter of 3 mm were inserted in the phantom as targets (Fig. 3c). The phantom could be translated on the acrylic frame to switch the holes for insertions and fixed by two brass thumb screws. The needle driver was attached vertically with respect to the phantom, and the actuation box resided at the end of the MRI table. The MRI scanner ran continuously during the needle insertion to create real-time imaging (flip angle :45°, TR: 228.5ms, TE:1.4ms, slice thickness: 8mm, pixel spacing: 1.9mm x 1.9mm, image frequency: 1.45 Hz) serving as visual feedback for the user.

The user chose a target on the image and it remained immobile during the needle insertion. In the manual insertions, the user stood next to the MRI table and remotely steered the needle inside the scanner bore by rotating the knobs on the actuation box, while the real-time images of the phantom and needle were projected on a screen (Fig. 3a). In motorized insertions, the user stayed in the MRI console room and manipulated the needle by interacting with the GUI

via keyboard, while the real-time images were displayed on the computer screen (Fig. 3b). In both modes, the user needed to observe the needle trajectory, predict the critical turning point, and reorient the bevel. After needle tip reached the target, a confirmation image (flip angle: 150°, TR: 410ms, TE: 14ms, slice thickness: 3.5mm, pixel spacing: 0.39mm x 0.39mm) was acquired to analyze the targeting accuracy.

IV. RESULTS AND DISCUSSION

A. Static Force/ Torque Experiment

The average force (N) and torque (N·m) in each direction that the needle driver applies onto the base robot in static status are presented in Table I. The coordinate system of the 6-DOF F/T sensor is illustrated in Fig. 2a. The resultant force and torque are calculated and their average values and standard deviations are presented in Fig. 4. In general, the forces at transmission length of 110 cm are bigger than the ones at 85 cm, while the torques at 85 cm are comparatively bigger except at the "east" orientation. Of note, irrespective of the transmission length, the "west" orientation always resulted in the maximum force and the maximum torque was always found at "east" orientation (see Fig. 2). Presumably, both of the aforementioned results could be explained by the layout of the tubing (Fig. 2). When the transmission length is small, the tubing is compressed and bent, thus it imposes more torque on the needle driver. As the transmission length increases, the tubing gets more relaxed, hence the torque applied by the tubing gradually reduces and force increases. The maximum resultant force appeared at the configuration 110 cm - west (2.762 N), and the maximum resultant torque is measured at 110 cm - east (0.547 N·m). These results will be used to carry out Finite Element Analysis (FEA) to

Fig. 4. Average value and standard deviation of the resultant force and torque that were applied by needle driver in static status at various orientations and transmission length.

improve the rigidity and design of the previously reported base robots [14], [15].

B. Dynamic Force/ Torque Experiment

Needle insertion into a phantom is a dynamic process and the maximum force and torque at each configuration that appeared during the entire process are shown in Table II. Similar to the results of the static F/T experiment, the needle driver imposed maximum force and torque at “west” orientation. Moreover, the maximum force and torque by motorized insertion are generally smaller than by manual insertion due to the following two reasons: 1) The average time for the motorized insertions was longer than the manual insertions giving the phantom more time to recover the needle insertion force; 2) motorized insertions were performed as small incremental steps while manual insertions were continuous except when user needed to rotate the needle; 3) the motorized insertion worked more smoothly and uniformly than manual insertion, so there are fewer outliers of motorized insertion. After comparing the variations in force and torque over time at different configurations, we found they shared a similar trend. For simplicity, we choose two typical examples i.e. the motorized and manual insertion at “vertical” orientation and their trends in six directions are shown in fig. 5 and fig. 6. During the insertion process, the force in Z and Y axis varied significantly while the X force and all the torques remain almost the same no matter the insertion approach. In manual insertion, the force in Z axis increased substantially, and it reached the peak (1.51 N) when finishing the 120 mm insertion, then the force decreased to about -0.3 N as the phantom recovered from deflection. By contrast, the force in motorized insertion in Z axis grew gradually from -1 N to 0 N, and finally it dropped to about -0.3 N when completing 120 mm insertion. The force in Y axis by both motorized and manual insertion rose at the beginning and reached a plateau (about 1.3 N) after the insertion depth was larger than 100 mm.

C. Accuracy Study under Real-Time Imaging Feedback

The coordinates (Right, Anterior, Superior) of the target positions were recorded before each insertion. The actual needle tip positions were obtained from confirmation images

Fig. 5. Variations of F_x , F_y , F_z , T_x , T_y and T_z while performing manual needle insertion.

Fig. 6. Variations of F_x , F_y , F_z , T_x , T_y and T_z while performing motorized needle insertion.

using 3D Slicer. In this experiment, we define the targeting errors as the distance between needle tip and target. The errors and duration of each of the ten insertion attempts are listed in Table III. An average duration for each insertion was less than two minutes. Significantly, the insertion time gradually decreased with the number of attempts, which indicated a learning curve for the user. The mean targeting error was 1.24 mm in manual insertions and 1.01 mm in motorized insertions, both of which satisfy our preset requirements (2 mm), thus is sufficient for clinical use. In addition, we could draw a conclusion that the operation modes have almost no influence on the targeting accuracy. Besides, small standard deviations (<0.5) reveal a high repeatability of the experiment.

V. CONCLUSIONS AND FUTURE WORK

To prepare for the integration with base robot, we measured the force and torque applied by needle driver on base robot at various transmission length and orientation both in free space and during insertion into a phantom. We also analyzed and compared the trends of force and torque in manual and motorized insertions. All the forces are smaller than 3 N and torques are less than 0.6 N·m. We also evaluated the accuracy of the presented system in homogeneous phantom experiments under real-time MRI guidance. Manual and motorized insertion were attempted five times respectively,

TABLE II

THE RESULTS OF THE DYNAMICAL FORCE/TORQUE ASSESSMENT (FORCE ARE IN N AND TORQUE ARE IN N·M)

Orientation	Mode	Fx_max	Fy_max	Fz_max	F_max	Tx_max	Ty_max	Tz_max	T_max
Vertical	Motorized	-0.46	1.31	-1.07	1.75	0.09	0.06	-0.29	0.31
	manual	-0.46	1.44	1.51	2.14	0.08	0.11	-0.30	0.33
North	Motorized	0.38	1.32	-1.12	1.77	0.13	0.09	-0.27	0.31
	manual	0.34	1.35	-1.09	1.77	0.14	0.12	-0.28	0.33
South	Motorized	-0.81	1.47	0.49	1.75	-0.18	-0.03	-0.28	0.33
	manual	-0.80	1.68	2.35	3.00	-0.20	0.08	-0.30	0.37
West	Motorized	-0.46	-1.97	-4.66	5.08	0.74	-0.16	-0.12	0.77
	manual	-0.59	-2.39	-4.98	5.55	0.81	-0.15	-0.13	0.83
East	Motorized	-0.94	2.72	0.96	3.03	-0.26	0.12	-0.48	0.56
	manual	-0.83	2.47	1.31	2.91	-0.28	0.07	-0.47	0.55

TABLE III

THE RESULTS OF ACCURACY EXPERIMENT IN MRI ROOM (UNITS ARE IN MM)

		Manual Insertion						Motorized Insertion					
No.		1	2	3	4	5		6	7	8	9	10	
insertion time		1'55"	1'50"	1'42"	1'20"	1'03"		1'31"	1'26"	1'27"	1'20"	1'18"	
Target	R	-6.83	-7.61	-2.72	-3.89	-5.84		-0.90	-0.90	-0.90	-0.90	-0.90	
	A	-11.45	-13.25	-2.40	-7.72	-7.64		6.19	-3.73	-0.38	-9.63	-0.91	
	S	17.47	12.55	3.69	0.30	14.53		-9.73	-6.06	-0.67	-9.28	1.26	
Actual Tip	R	-7.00	-7.40	-2.70	-3.90	-5.80		-0.80	-0.80	-0.80	-0.40	-0.80	
	A	-11.50	-13.20	-2.40	-7.60	-7.70		6.10	-3.70	-0.40	-9.70	-0.90	
	S	19.00	14.40	4.30	1.40	15.60	MEAN	-8.70	-5.10	-0.50	-8.10	2.80	STD
Error	R	0.17	0.21	0.02	0.01	0.04	0.09	0.08	0.10	0.10	0.10	0.10	0.18
	A	0.05	0.05	0.00	0.12	0.06	0.06	0.04	0.09	0.03	0.02	0.07	0.04
	S	1.53	1.85	0.61	1.10	1.07	1.23	0.42	1.03	0.96	0.17	1.18	1.54
	mag	1.54	1.86	0.61	1.11	1.07	1.24	0.43	1.04	0.97	0.20	1.28	1.54

and the average errors in both conditions are 1.24 mm and 1.01 mm respectively, which are sufficient for clinical use.

The future work involves carrying out the finite element analysis on the base robot using the force information obtained in this paper and optimizing the base robot structure for its integration with needle driver. We will also run needle insertion in multi-layer plastic phantom with different stiffness or real tissues e.g. chicken breast and ham to simulate more realistic environment.

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