Published in final edited form as:

IEEE Trans Med Robot Bionics. 2020 November ; 2(4): 557–560. doi:10.1109/tmrb.2020.3030532.

Body-Mounted Robotics for Interventional MRI Procedures

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Abstract

This paper reports the development and initial cadaveric evaluation of a robotic framework for MRI-guided interventions using a body-mounted approach. The framework is developed based on modular design principles. The framework consists of a body-mounted needle placement manipulator, robot control software, robot controller, interventional planning workstation, and MRI scanner. The framework is modular in the sense that all components are connected independently, making it readily extensible and reconfigurable for supporting the clinical workflow of various interventional MRI procedures. Based on this framework we developed two body-mounted robots for musculoskeletal procedures. The first robot is a four-degree of freedom system called ArthroBot for shoulder arthrography in pediatric patients. The second robot is a six-degree of freedom system called PainBot for perineural injections used to treat pain in adult and pediatric patients. Body-mounted robots are designed with compact and lightweight structure so that they can be attached directly to the patient, which minimizes the effect of patient motion by allowing the robot to move with the patient. A dedicated clinical workflow is proposed for the MRI-guided musculoskeletal procedures using body-mounted robots. Initial cadaveric evaluations of both systems were performed to verify the feasibility of the systems and validate the clinical workflow.

Index Terms—

MRI-guided intervention; body-mounted robot; musculoskeletal procedure; arthrography; chronic pain management

I. Introduction

IMAGE-GUIDED procedures involving the musculoskeletal (MSK) system are essential part of interventional radiology [1]. Commonly performed procedures range from steroid injections to arthrograms. Conventional musculoskeletal procedures use X-ray, i.e. CT or fluoroscopy, to provide guidance, which involves ionizing radiation exposure to both patients and physicians. Magnetic resonance imaging (MRI) is able to provide real-time high-contrast soft tissue visualization of musculoskeletal anatomy without exposing patients or clinicians to ionizing radiation. This benefit of the MRI is especially crucial in pediatric and pregnant patients. Therefore MRI is an ideal imaging modality and is often used for many diagnostic questions in musculoskeletal procedures. However, the strong magnetic and radio frequency field, and narrow scanner bore lead to significant challenges to the development of robots that can operate in the MRI environment.

To overcome these challenges, several robotic systems have been developed by researchers to assist with procedures in the MRI environment. MRI-guided robots can be classified as table-mounted and body-mounted systems based on the mounting approach. Table-mounted robots are fixed to the scanner table and the patient has to remain still during the procedure to maintain position with respect to the robot. Table-mounted robotic systems have been used for MRI-guided procedures including stereotactic neurosurgery [2], [3] and prostate cancer therapy [4], [5]. Nonetheless, patient motion is inevitable, especially for procedures that require a longer time. Therefore, mechanical fixtures, such as the Leksell frame utilized in stereotactic neurosurgery, are usually used to restrict patient motion. Contrarily, body-mounted robots are attached to the patient directly using straps or other methods, which can attenuate influences of patient motion by moving with him/her. Because dedicated supporting frames are not required, body-mounted robots could be devised with lightweight and compact structures. Body-mounted robotic systems have been used for MRI-guided renal cancer interventions [6] and abdominal interventions [7].

While several systems have been developed to assist MRI-guided procedures, a unified approach to develop robotic systems with high accuracy, modularity and robustness which can operate inside a closed-bore MRI scanner is still demanding. In this paper, we present our work in developing and validating an integrated robotic framework to support the clinical workflow of interventional MRI procedures. Based on this framework we developed two body-mounted robots for musculoskeletal procedures. The first robot is a 4 DOF (degree of freedom) system called ArthroBot for shoulder arthrography in pediatric patients [8]. The second robot is a 6 DOF system called PainBot for perineural injections used to treat pain in adult and pediatric patients [9], [10]. The major contributions of this paper include: 1) development of a unified robotic framework to support the clinical workflow of interventional MRI procedures with modular design principles, 2) creation of a dedicated clinical workflow for MRI-guided musculoskeletal procedures using body-mounted robots, and 3) verification of the feasibility of the framework and validation of the clinical workflow with initial cadaver torso studies using both ArthroBot and PainBot.

II. Materials and Methods

The architecture of the robotic framework is illustrated in Fig. 1. The framework is based on modular design principles making it able to support various interventional MRI procedures. The framework consists of five main components: 1) body-mounted needle placement manipulator, 2) robot control software, 3) robot controller, 4) interventional planning workstation, and 5) MRI scanner and control console. 3D Slicer [11], an open source software, is used to visualize the target anatomy and define the interventional plan with intraoperative MR images. The robot control software organizes the dataflow and incorporates the robot kinematics. The robot controller is developed to provide high-precision position control and accurately manipulate the needle using the positioning encoder feedback. The desired needle path is planned on 3D Slicer and transmitted to the robot control software through OpenIGTLink network communication interface [12]. Fiber optic Ethernet is used to transfer data between the robot control software (inside the control room) and the robot controller (inside the scanner room). The fiber optic cable is routed through the patch panel between the control room and scanner room to prevent the electrical noise from being introduced into imaging by excluding transmission of electrical signals.

The modular design of the proposed system framework has the advantage of interchangeability and therefore it could be applied to different applications: each module of this system could be potentially replaced with other modules of equivalent functionality (e.g. it can be used to support both ArthroBot and PainBot) or a simulation at any level to aid in development and validation.

ArthroBot was developed as an MRI-guided needle placement device for diagnostic and interventional procedures such as arthrography. Arthrography requires injection of contrast material within the joint to distend the joint capsule and better visualize the internal structures. The ArthroBot robot is a body-mounted system designed to position and orient the needle under MRI guidance. This robot has 4 DOFs: 2 DOFs for needle translation and 2 DOFs for needle orientation adjustment. The needle insertion is performed manually by the physician. The ArthroBot was designed in a serial structure. The dimension of ArthroBot is 264 mm $\times$ 170 mm $\times$ 127 mm and the weight is 700 g, which is compact and lightweight enough to be attached to the patient's shoulder. A detailed description of the mechanical design was reported in [8].

While ArthroBot was designed for manual needle placement by the physician, PainBot was designed for MRI-guided interventions that require a high level of precision with active needle insertion and rotation such as perineural injections. Perineural injection delivers pain relief medications to the pain source, such as epidural space, facet joint, or spinal nerve root, and it is a typical treatment for chronic pain management. PainBot was designed to provide 6 DOF full motion, which consists of a 4 DOF needle alignment module and a 2 DOF needle driver module as shown in Fig. 2. The 4 DOF needle alignment module was designed in a parallel structure. The dimension of PainBot is 250 mm $\times$ 219 mm $\times$ 265 mm and the weight is 1.5 kg, which is compact and lightweight enough to be attached to the patient's lower back. The 6 DOF fully actuated PainBot can manipulate the needle inside the scanner bore during imaging. Therefore, it can alleviate the need of shuttling the patient in or out of

the scanner bore during the procedure, and thereby, streamline the clinical workflow and reduce the procedure time. The 2 DOF needle driver is remotely actuated by the actuation box placed at the end of scanner table through novel beaded chain transmission. Hence, it can minimize the size and weight of the robot on the patient, as well as reduce the imaging noise generated by the actuation electronics. In addition, the needle driver can be manipulated in the motorized or manual mode by engaging or disengaging the gears transmission of the actuation unit; Therefore, it can increase the safety if the motors fail, and facilitate the learning curve because the clinicians can place the needle manually as they do in conventional clinical practice. A detailed description of the mechanical design was reported in [9], [10].

A custom MR imaging coil was designed and integrated with the robot base to provide augmented imaging quality of patient anatomy. The integrated imaging coil is a single loop coil built inside a circular case and was designed to be utilized independently of robots while acting as a mounting frame for a family of robots. The imaging coil embedded mounting frame includes straps that directly attach it to the patient and a locking ring that enables the robot to be readily attached and detached. This method enables a single robot, or a family of robots such as ArthroBot and PainBot, to be utilized in a variety of MRI scanners with its own imaging coil. To allow the coil to be used with our Siemens 1.5T Aera scanner, a coil interface box was built by the company Stark Contrast (Erlangen Germany). The interface box has a connector that plugs into the Siemens scanner and then eight BNC connectors for custom coils such as ours. We are also able to combine our custom coil with the Siemens table coil for improved imaging.

Clinical workflow design is essential for developing interventional robotic systems, because the workflow reflects the restraints of the clinical environment and presents requirements for the design of robots. The clinical workflow was designed through consultation with our clinical leads on the basis of the current freehand MRI-guided procedures. As illustrated in Fig. 3, the proposed workflow is composed of eight major steps. Depending on the specific mechanical design of ArthroBot (manual needle insertion) and PainBot (remote needle insertion), the clinical workflow can be adapted for both systems. For ArthroBot, because of the manual needle insertion and long scanner bore (about 1.5 m), the radiologist has to move the patient out of the scanner bore to insert the needle. Therefore, the radiologist can not use real-time MR images and has two options: 1) use the depth scale on the needle to advance to the measured depth from the planning images or 2) use advance and check strategy under intraoperative MRI guidance. For PainBot, because of remote needle actuation, the needle insertion can be done with patients remained inside the scanner bore. Therefore, the radiologist can take advantage of real-time MRI and perform real-time needle path correction and confirmation.

1. Place the patient on the scanner table and create a sterile environment.
2. Initialize the robot and attach it to the patient with traps.
3. Scan the target anatomy and register the robot with fiducial frame.
4. Define the needle path on the interventional planning workstation.

5. Align the needle with the robotic assistance.
6. Insert the needle manually under intraoperative MRI guidance (ArthroBot) or insert the needle remotely with robotic assistance under real-time MRI guidance (PainBot).
7. Inject contrast or medication under intraoperative MRI guidance and obtain high-resolution diagnostic images.
8. Retract the needle and remove the robot.

III. Results

In this study, we verify the feasibility of the robotic framework and validate the clinical workflow with a human cadaver model using both ArthroBot and PainBot. A cadaver torso provided by Science Care Inc. (Phoenix, USA) was utilized as the biological specimen. This weekend study was permitted by the hospital Office of Infection Control and personnel wore personal protective equipment (PPE). On the first day, shoulder arthrography was performed with ArthroBot. The cadaver torso was placed in the supine position on the MRI table, and the ArthroBot was attached to the shoulder of the cadaver using the mounting mechanism as shown in Fig. 4. On the second day, perineural injections were performed with PainBot. The cadaver torso was placed in the prone position on the MRI table, and the PainBot was attached to the back of the cadaver as shown in Fig. 5. Both procedures were carried out by the same interventional radiologist and followed the clinical workflow designed in Sec. II. Intermittent MR images were obtained for every 2 mm insertion to visualize the needle path and advance towards the target. For the perineural injections, two targets were selected in the epidural space and facet joint. The cadaver torso remained inside the scanner bore throughout the insertions, and the radiologist operated the needle remotely with the actuation box outside the scanner bore. The positioning accuracy of the epidural space insertion was 1.90 mm and of the facet joint insertion was 1.30 mm.

IV. Discussion and Conclusion

This study reports the development and initial cadaveric evaluation of a framework for robot-assisted MRI-guided interventions using body-mounted approach. Based on this framework our research team has been developing two body-mounted MR-Conditional robots for precision needle placement under MR imaging, i.e. a 4 DOF ArthroBot for shoulder arthrography with manual needle insertion and a 6 DOF fully actuated PainBot for perineural injections with remote needle manipulation. Both systems have been tested to date in phantom and cadaver studies. A new clinical workflow was developed and initial results showed acceptable accuracy for both systems. The timing of the initial cadaver study was not measured. We are still at the early stage of development and anticipate that the clinical team will need a learning period to become acquainted with the robotic systems. In addition, sterilization details still need to be addressed. The proposed plan is to first drape the patient and then sterilize the needle guide while covering the rest of the robot with sterile drape. These robots will serve as an enabling platform technology that can be applied to MRI-guided interventions that require a high level of precision.

ACKNOWLEDGEMENTS

We want to thank Ehud Schmidt PhD from Johns Hopkins Medical Institutions for his assistance with integrating the coil with our MRI scanner.

This work was funded by National Institutes of Health grant R01 EB025179 and R01 EB020003

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Fig. 1:
Architecture of the framework for robot-assisted interventional MRI procedures, with PainBot for perineural injections as a demonstrative application.

Fig. 2:

CAD model of the PainBot, a 6-DOF fully actuated body-mounted robot. It shows the degrees of freedom and dimension of PainBot. The bottom part of the robot, including the fiducial frame and mounting frame with imaging coil, is independent of robots and can be used for both PainBot and ArthroBot.

Fig. 3: Clinical workflow of robot-assisted musculoskeletal procedures under intraoperative MRI guidance. Depending on the specific mechanical design of the ArthroBot (manual needle insertion) and PainBot (remote needle insertion), the clinical workflow can be adapted for both systems.

(a)

(b)

Fig. 4:

Experimental setup of the cadaver torso study with the ArthroBot. (a) Mounting frame embedded with imaging coil was attached to the shoulder of torso via straps. (b) The cadaver was placed in the supine position inside the scanner bore. The 4-DOF ArthroBot was attached to the patient through the mounting frame.

(a)

(b)

Fig. 5:

Experimental setup of the cadaver torso study with the PainBot. (a) Mounting frame embedded with imaging coil was attached to the lower back of torso via straps. (b) The cadaver was placed in the prone position inside the scanner bore. The 6-DOF PainBot was attached to the patient through the mounting frame, and the needle driver was remotely actuated by the actuation box via beaded chain transmission.