An Efficient Needle Injection Technique and Radiological Guidance Method for Percutaneous Procedures

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Abstract. This paper presents a simple radiological image guidance method and robotic system optimized for percutaneous procedures. This simplicity is achieved by combining the proven guidance procedure normally employed by practicing surgeons with a simple and cost-effective needle injection device. The needle injector exhibits an extremely low radiological profile while providing actuated needle motion. The mechanical manipulator is designed to be used stand-alone in existing operating rooms without additional computers or personnel.

1 Introduction

As an alternative to traditional open surgery, percutaneous surgery significantly reduce morbidity and recovery time. However, percutaneous needle access may be difficult and requires extensive experience due to the lack of three-dimensional information provided to the surgeon by the imaging device. To overcome this problem several groups have proposed robotic systems to assist in needle placement. Potamianos and Davies [1],[2] use a stereopair of two x-ray views registered to a common fiducial system with a 5DOF instrumented passive linkage to position a passive needle guide. Bzostek et al [3] propose an active robot for similar purposes. Although these systems successfully address issues of image-to-robot registration and provide convenient means for defining target anatomy, in their present state of development they can be moderately expensive and cumbersome in the operating room. Further, at least for the current implementation of [3], the radiological profile of the end-effector may interfere with a clear view of the kidney.

Our goal was to rapidly develop a system to improve surgical success rate for percutaneous renal access procedures. To achieve this we focused on: (1) needle placement accuracy, (2) procedure duration, (3) patient safety, (4) sterility,

and (5) surgeon radiation exposure. After extensive observations of urologists performing surgical needle insertion, we sought to develop a system that mimics and improves upon the surgeon's standard technique. The key advantages of this approach are that it employs a proven radiological needle alignment procedure, improves accuracy in comparison to purely manual placement, and enables lateral fluoroscopic monitoring of the needle without necessitating computer-based vision and robotic systems.

Percutaneous renal access procedures are often performed in radiology suites where sophisticated imaging devices are available. Performing the renal access in the operating room (OR) significantly reduces cost, improves availability, and allows the surgeon to have full control over the entire procedure. The imaging commonly available in the OR is uni-planar fluoroscopy provided by a "C-arm". An inexpensive robotic system for the OR utilizing existing C-arm imagery would be widely and immediately deployable.

2 Superimposed Needle Registration

Manual renal access normally proceeds as follows: The urologist positions the C-arm over the collecting system, chooses the target calyx and the skin insertion site. Then the C-arm is positioned ("frogged") to align the desired needle entry point and the needle target so that they are superimposed in the image. This alignment defines the needle trajectory and is memorized by the locked orientation of the C-arm. Next, the urologist manually holds the needle in position and orientation along this trajectory line. The needle, the entry point, and the target (calyx) should then be superimposed as a single point in the image. The surgeon inserts the needle by hand into the patient, while viewing the superimposed C-arm image to maintain the prescribed alignment. A lateral view is not simultaneously available because the C-arm is used to maintain axial needle alignment. In consequence, no needle depth imagery is available. To gain access to the renal collecting system the depth of insertion is determined by the surgeon's experience, as well as trial and error.

We are developing a system that mimics this surgical technique of superimposed registration. In this system the C-arm and needle are aligned as before. The needle axis is then mechanically locked on the desired line of insertion by a robotic manipulator. In this way the insertion line is memorized by the locked position of the manipulator, enabling the surgeon to "frog" the C-arm to obtain a lateral view. The insertion depth and needle path can then be observed directly. Direct observation of the insertion depth allows the surgeon to compensate for the soft tissue deflection of the kidney and surrounding tissue. In comparison to the purely manual procedure, this technique will improve both safety and accuracy.

Note that the proposed method does not require image correction and calibration. By superimposing the needle, the entry point, and the target, the image distortions are identical and, therefore, they are relatively zero. Furthermore, the method only requires direct observation by the surgeon, and does not require

computer-based image processing, thereby significantly reducing operative time and expense.

This registration method has certain limitations. By mimicking the surgeon's technique, in special cases difficulties may arise due to the positioning of the C-arm. Body habitus may limit patient positioning on the OR table so that the C-arm may not be maneuvered into a position for superimposed registration to occur. One may also note that, in the first superimposition step, the heavy structure of the C-arm may not be accurately positioned resulting in misalignment of the entry and target points. To overcome this problem, the second superimposition should be performed for the needle and target only. While this results in an entry point error, the targeting remains accurate.

3 Robotic Design

As previously implied, superimposed registration requires neither a fully actuated robot nor position feedback sensors. For cost-effectiveness we are employing a passive manipulator arm to maintain the end-effector (needle) position. To minimize the surgeon's radiation exposure and minimize disturbances in the needle trajectory, we have developed a novel needle insertion mechanism (see Fig. 1). The passive manipulator component is an FDA approved Leonard Arm (Leonard Medical, Inc.). This arm is a six degree of freedom manipulator with three rotational and one spherical joint. The joints are spring-loaded to compensate for gravitational loading. The joints are not equipped with motors or position encoders. They may be simultaneously locked in the desired position by vacuum operated breaks. A custom designed rigid side rail is mounted on the OR fluoroscopic table to provide a sturdy base for the robotic arm. This is critical in order to maintain the needle trajectory under the insertion force. The active insertion mechanism is attached to the distal end of the passive arm. The needle insertion is actuated by a variable speed DC motor which the surgeon regulates via joystick control. The insertion mechanism is constructed of plastic, and could be inexpensively manufactured as a disposable unit. It can be easily sterilized and is almost completely radiolucent. This enables surgeon to monitor the injection with an unimpeded fluoroscopic image.

A novel feature of the insertion device is that it grasps the barrel of the needle, not the needle head. This significantly reduces the unsupported length of the needle during insertion, thus minimizing the lateral flexure of the unsupported needle under insertion loading.

4 Conclusion

We have addressed a particularly difficult surgical task by designing a simple and cost-effective robotic system that can be rapidly transferred to the clinical setting. The advantage of this robotic system for percutaneous renal access is its uncomplicated mimicry of the urologist's technique while improving both the

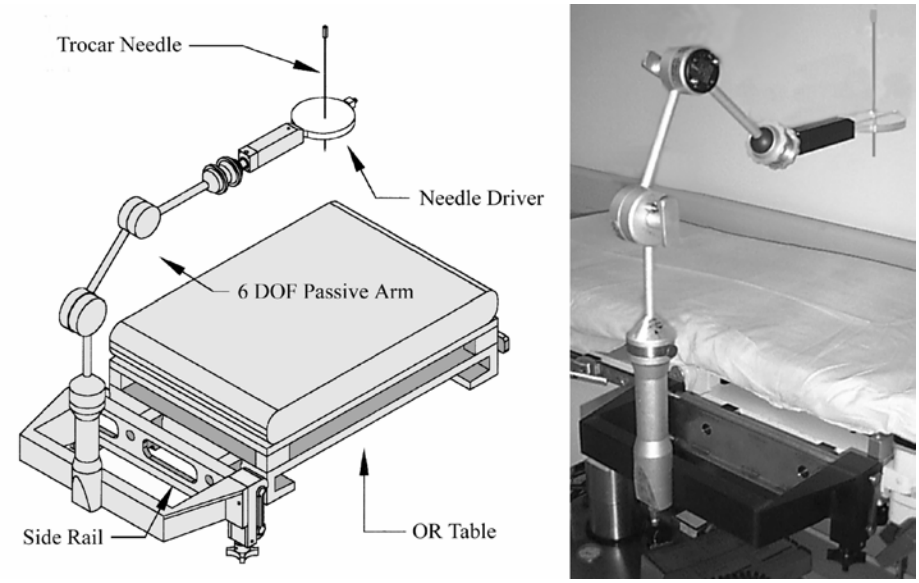

Fig. 1. The robotic system for percutaneous renal access: Schematic and photograph

safety and accuracy of the procedure. The system is fully compatible with, but does not require a computer-based vision system or a fully actuated robot with joint position feedback.

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