

Controllable Motorized Devices for Accurate Percutaneous Needle Placement in Soft Tissue Target

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Abstract: Some mechanisms for accurate percutaneous needle placement in soft tissue target are presented in this paper. The mechanisms ensure the rotation of the needle simultaneously with the translation. The devices can be used with fluoroscopy, X-ray or CT (CAT-scan, or computed tomography) guidance in image guided surgery, biopsy as well as interventional therapy. Introduction of needle rotation simultaneously with translation motion significantly reduces the needle insertion force into soft tissue, which results in less needle deflection

Keywords: Mechanism, Rotation, Translation, Needle

1 Introduction

Precision percutaneous needle placement in inhomogeneous soft tissue is a fundamental enabling problem in clinical delivery of percutaneous therapy and needle biopsy. The accuracy of delivery is dependent both on accurate targeting and on precise driving of the needle on the target. Targeting accuracy often greatly exceeds driving accuracy primarily because of needle deflection, due to tissue inhomogeneities, organ deformation, and respiratory or cardiac motion. Furthermore, a wide spectrum of novel treatment methods (e.g. local injections of therapeutic agents, tissue ablation with radio-frequency or focused ultrasound) require that we hold the needle firmly in the target location for a considerable period while the patient may be in respiratory or muscular motion.

Current robotic needle drivers for percutaneous therapies use a friction transmission to achieve translational motion to guide a needle into a soft tissue target [2, 7, 8, 9]. A robotic device for percutaneous access to kidney, attached to a passive mechanical arm [5], is presented in [2].

The force necessary for penetration into the tissue target is greatest at the initial point of entry, and then the force experienced by the needle is significantly reduced following initial penetration. High needle insertion forces result in deflection of the needle, which leads to the needle

deviating away from the planned target [1]. Moreover, the friction transmission of the needle has limitations in its tracking of translational position. Needle slippage occurs when the force experienced by the needle is greater than the product of the preloaded contact of the needle to the transmission, and the dynamic coefficient of friction. Slippage results in loss of encoding which, in turn, results in loss of accurate positioning of the needle in the translation axis. It has been demonstrated through experiments that the introduction of needle rotation simultaneously with translation significantly reduces the amount of force necessary to penetrate a soft tissue target (Figure 1) [4]. The reason of this diminution of force is the conversion of static friction to dynamic friction between two sliding surfaces.

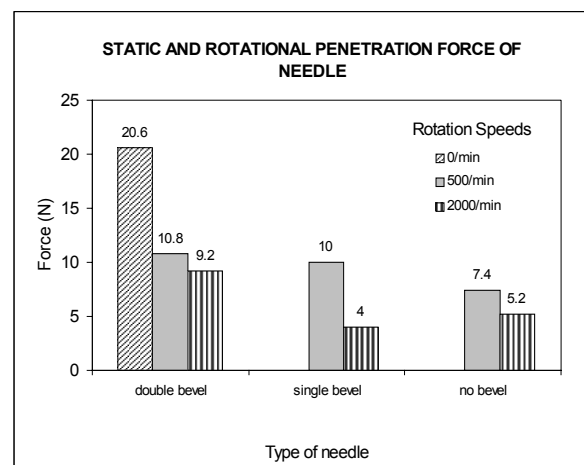


Figure 1. The penetration force in experiments with needle rotation

This reduction in penetration force results in a reduction in needle bending, which leads to more accurate final positioning of the needle into its target. Practitioners generally do not favor rotation of needle due to higher

trauma in the region of penetration. Some sources [6] recommend rotation during initial part of needle insertion.

To solve these problems we have developed some mechanisms for percutaneous delivery of needles by means of rotation and simultaneous translation of the needle [3, 4, 10]. The design criteria of these devices were such that they would have: X-Ray or CT compatibility, easy sterilization, independent control of twisting and translating motions, repeated release and grasp of needle without loss of encoding, one-touch release of the needle in case of emergency, sudden patient motion, or power outage, and easy connection to the Remote Center of Motion robot (RCM) [7].

2 Mechanisms design

The first rotating needle driver [4] is comprised of two arms (each arm is comprised of two fingers), a transmission arm and a needle guide arm (Figure 2).

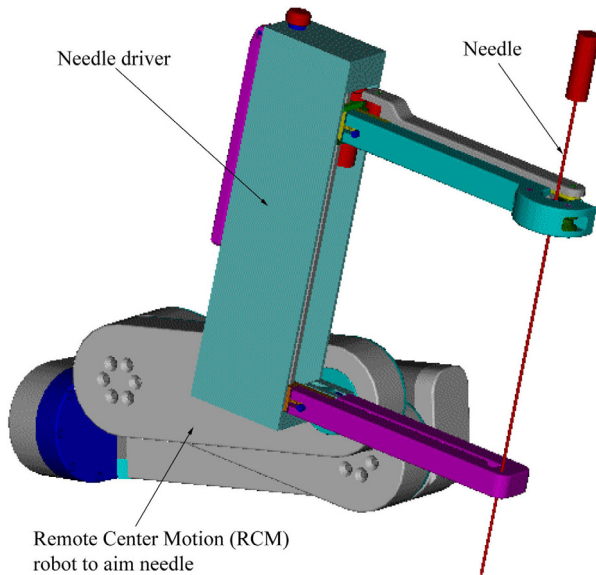


Figure 2. Rotating needle driver (upper arm – two fingers)

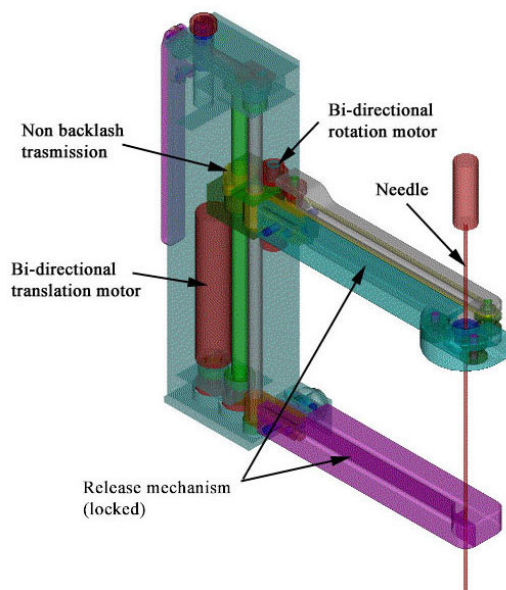


Figure 3. Needle driver in locked position

The needle to be used in a procedure is equipped with a sterilizable-disposable plastic wheel, affixed to the shaft at the distal end from the needle tip. The needle driver fingers open and close mechanically or electro-mechanically (operated by a solenoid). The needle is placed inside an upper and lower radiolucent catch arm and the revolving fingers of the arms are turned into a closed position. The needle catch fingers will remain closed as long as there is power supplied to the driver (Figure 3). The fingers automatically release the needle if the power is cut off from the device (Figure 4).

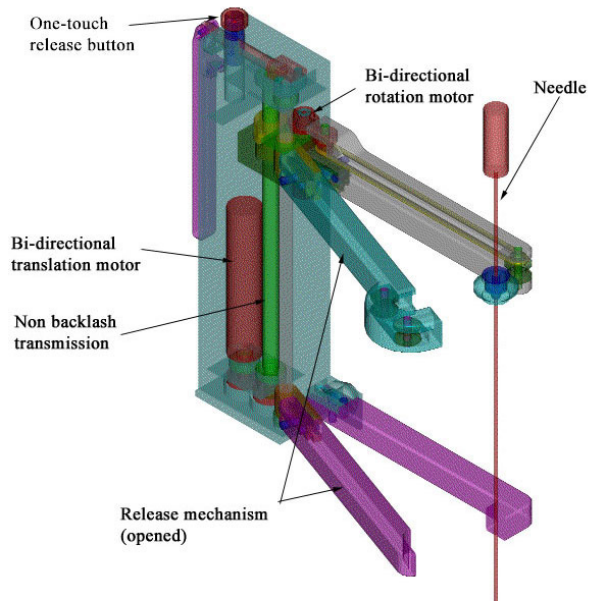


Figure 4. Needle driver in released position

This fail-safe feature ensures that the device will release the needle when the release button is actuated. The needle wheel is encased in the upper arm, where it makes contact (a friction-based transmission) with another wheel actuated by a belt transmission that delivers the rotation to the needle (Figure 5).

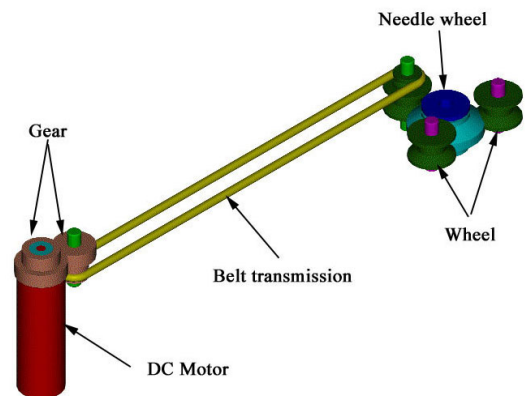


Figure 5. The rotation mechanism

The needle wheel is firmly fixed to the needle, and the needle wheel is encased in the upper finger, therefore there is no slippage in the translating axis. This results in accurate and controllable encoding of the needle for insertion. The needle needs to have a high preload force against the friction wheel, similar to the high preload force that is required to translate the needle in the PAKY driver [8]. The preload force is not desirable since the material

used for the fingers must be radiolucent (e.g. a plastic). It became imperative to develop a method to rotate the needle with little, or no preload force. Future design work includes development of steerable needles where rotation will be encoded.

The motor located in the upper arm is responsible for delivering rotational motion to the needle. This motor is not encoded since the transmission between the motor and needle is achieved with an o-ring pulley belt. Slippage may be experienced in the pulley, resulting in a loss of encoding.

The introduction of needle rotation simultaneously with translation motion significantly reduces the needle insertion force into soft tissue is expected to reduce needle deflection. Needle driver configuration is slip-less in the bi-directional translational axis, which results in accurate and controllable encoding. The translation motion is achieved ball screw moving the upper arm, driven by an encoded motor (Figure 6).

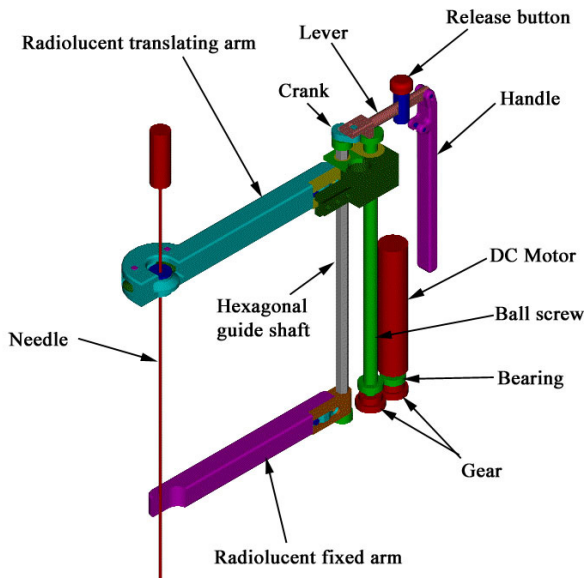


Figure 6. The translation and closing mechanism

The ball screw offers anti-backlash between the motor and the arm, for accurate and controllable position encoding. A low screw pitch diameter was selected such that the motor will experience relatively constant force feedback when the needle passes through different regions of anisotropic soft tissue, or experiences patient movement such as organ motion and respiration. A hexagonal guide shaft is placed next to the ball screw. The purpose of the hexagonal guide shaft is to carry the majority of the moment load experienced when the needle is penetrating the tissue. The ends of the hexagonal guide shaft are supported by ball bearings to minimize frictional losses in the rotation power translation. The encoded motor includes a planetary gear reduction head (4:1 reduction) so that maximum translational speed can be controlled.

The closing mechanism is comprised of a handle, a lever, a crank located in the upper end of the hexagonal guide shaft and two revolving fingers (Figure 6). To encase the needle and the needle wheel the handle is manual actuated. To release the needle, the release button is actuated and a spring opens the mechanism.

Other needle driver, similar with the above one, is presented in [3]. Also, this device is comprised of two arms, but the transmission arm (the upper arm) is comprised of three fingers and the needle guide arm (the lower arm) is comprised of two fingers (Figure 7).

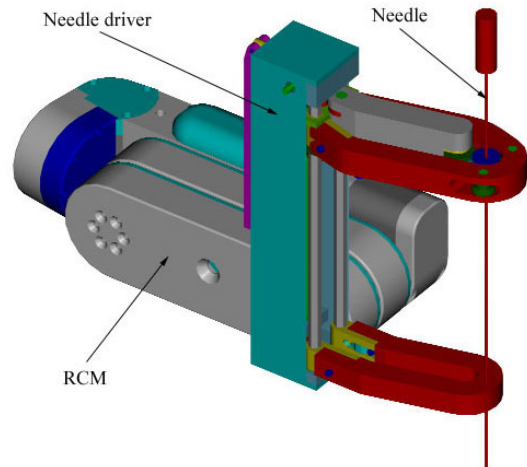


Figure 7. Rotating needle driver (upper arm – three fingers)

Although, this device is more complicated than the first one, it has the advantage of a large release space for the needle (Figure 8).

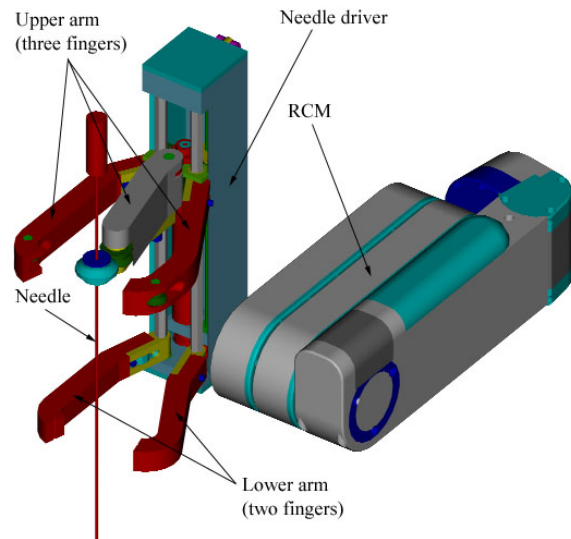


Figure 8. Needle driver in released position

The mechanism for the needle rotation is similar with the above showed one (Figure 5). In this case, the belt transmission that delivers the rotation to the needle is inserted into the central finger of the upper arm. The lateral fingers of the upper arm and the two fingers of the lower arm perform the needle catch. Therefore, the closing mechanism of this device is comprised of a handle, a lever, two cranks located in the upper end of the carcass, two hexagonal guide shafts and four revolving fingers (Figure 9). To operate the closing mechanism the handle is manual actuated. To release the needle, a release button is actuated and a spring removes the lever, which opens the mechanism.

The needle driver presented in [10] achieves the same functions. This device is comprised of two arms, too

(Figure 10). The needle to be used in a procedure is equipped with a plastic gear, affixed to the shaft at the distal end from the needle tip.

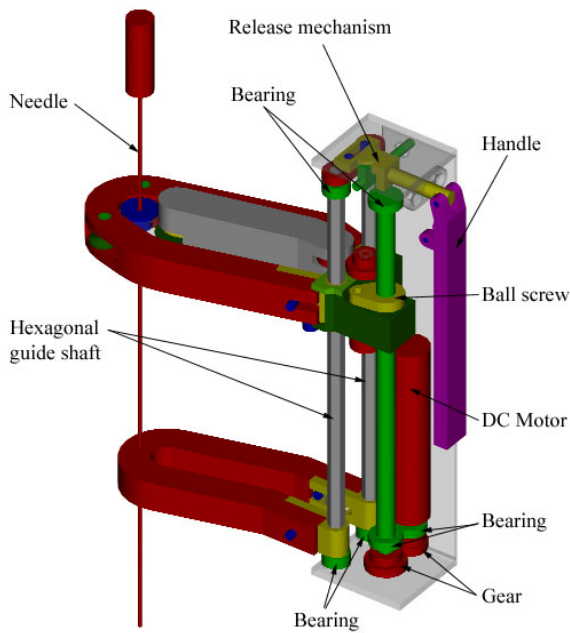


Figure 9. The translation and closing mechanism

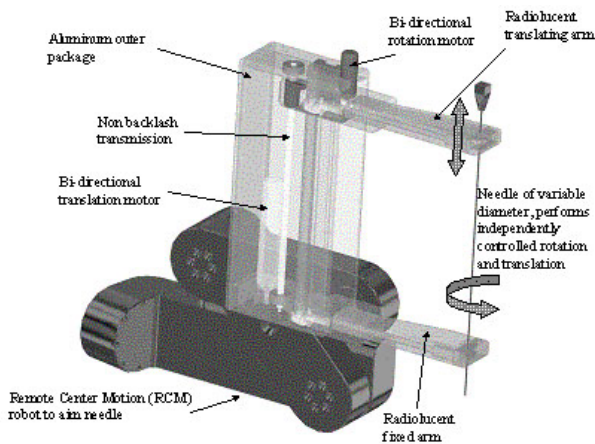


Figure 10. Electromechanical needle driver

The needle driver arms open and close electro-mechanically (operated by a solenoid). The needle is placed inside an upper and lower radiolucent catch arm and the arms are pressed into a closed position. The needle catch arms will remain closed as long as there is power supplied to the driver (Figure 11). The fingers automatically release the needle if the power is cut off from the device (Figure 12). This failsafe feature ensures that the device will release the needle when the release button is actuated. The needle gear is encased in the upper arm, where it makes contact with another gear transmission that delivers the rotation to the needle. The needle gear is permanently fixed to the needle, and that the needle gear is encased in the upper finger, therefore there is no slippage in the translating axis. This results in accurate and controllable encoding of the needle for insertion.

Another alternative to a needle-gear transmission system was to use a friction based transmission. This idea was first considered and then disregarded because the needle would need to have a very high preload force

against the friction wheel. As a result, a gear was placed on the needle itself. A gear transmission for the needle provides rotational motion and zero slippage and backlash.

The needle driver is designed for straight needle trajectory when rotation does not need to be encoded. Future design work includes development of steerable needles where rotation will be encoded.

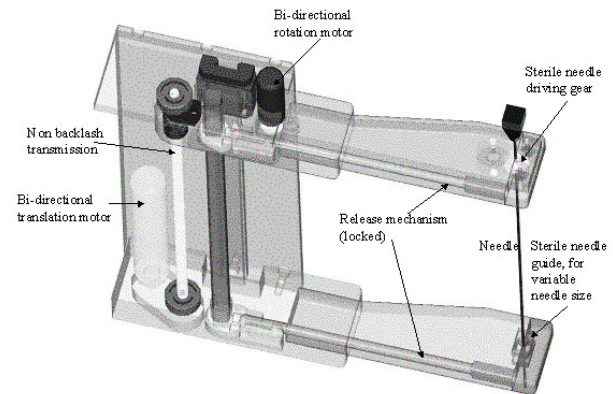


Figure 11. Electromechanical needle driver in locked position

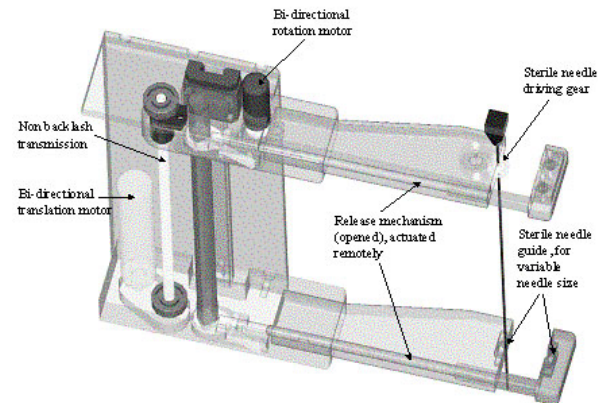


Figure 12. Electromechanical needle driver in released position

The packaging configuration must be very compact and must easily attach to the Remote Center of Motion robot (RCM). The packaging does not have to be radiolucent, since the location of the packaging coincides with that of the RCM, which is not radiolucent. This led to the choice of aluminum for the packaging, which offers high strength, low weight, easy machinability, and low cost. The needle drivers are designed for easy sterilization and to accommodate various sizes of needle diameters.

3 Future Work

Future design iterations of these needle drivers include additional motor encoding, force sensing, enhanced safety features, and MRI compatibility. Adjustable motor encoding for needle rotation will provide constant speed needle rotation when the needle translates through tissue layers of different resistances. Three dimensional needle force sensing will provide feedback to determine if needle trajectory coincides with any obstructions. Enhanced safety features are to include an adjustable safety limit on the maximum allowable needle translation motion. A

surgeon would set an indicator marker on the needle driver, such that the needle driver will stop once the needle reaches a preset penetration depth. For example, in spine surgeries a maximum depth not to exceed would be that at which transition from the vertebrae to the spinal cord occurs. An MRI compatible version of the needle driver is also of interest and will be studied as new material and technologies relating to MRI compatibility become available. The rotating needle drivers are not limited to the applications of percutaneous therapies in soft tissue.

4 Conclusions

The development the rotating needle driver will improve needle placement accuracy in identified soft tissue organs for percutaneous therapies. The principle of constant needle rotation during needle insertion in tissue should significantly reduce needle insertion force and needle deflection. The additional safety enhancement of the one-touch needle release will lower the complications associated with sudden operating room emergencies, and also allow more flexibility in removal and reattachment of the needle during a procedure, without the loss of encoding.

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