Enabling Helical Needle Trajectories with Minimal Actuation:
A Screw-Based Approach to Concentric Tube Needle Deployment

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INTRODUCTION

The clinical need for needle-based therapies capable of accessing tissues unreachable by conventional needles has motivated substantial research into steerable needles (see [1] and [2] for a review of these technologies). In particular, it has been observed that curved paths can be useful in percutaneous procedures [3]. Gilbert, *et al.*, showed that helically pre-curved concentric tube nitinol needles can be deployed in a follow-the-leader (FTL) fashion, such that the needle shaft follows the path traced out by the tip [4]. Further information on concentric tube robots and the mechanics-based models that govern their motion can be found in [5] and [6].

The motivating application for helical needles in [4] was minimally invasive treatment of epilepsy—a neurological disorder that causes debilitating seizures. We have been developing a needle-based procedure for this application that involves delivering thermal energy to the hippocampus with both guidance and thermometry from magnetic resonance imaging (MRI) [4][7][8]. Figure 1 illustrates this application, in which a helical concentric tube needle is used to deliver therapy to the curved structure of the hippocampus through an occipital burr hole in the skull.

A principal challenge to executing FTL deployment of a helical concentric tube needle in soft tissue is the requirement for precise coordination of needle rotation and translation necessary to achieve a smooth "corkscrew-like" motion. To address this, Comber, *et al.*, developed an MRI-compatible needle-driving robot for the aforementioned epilepsy application [7], and Pitt, *et*
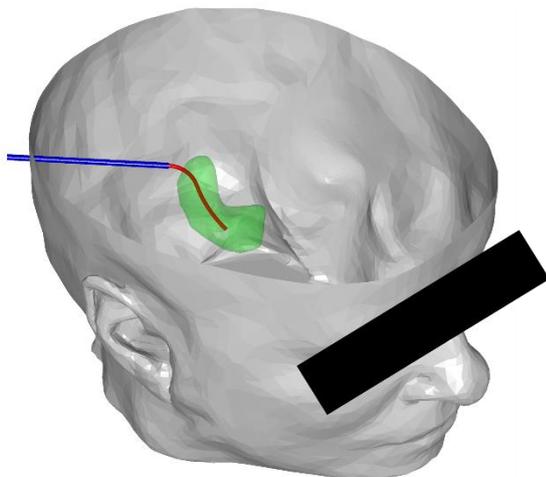
al., demonstrated the same robot's ability to accurately achieve FTL deployment of a helical needle [8].

The motivation for our current paper comes from the observation that FTL deployment requires the two actuation degrees of freedom to move at a fixed rate relative to one another, meaning that deployment is actually a single degree-of-freedom operation. Thus, in this paper we mechanically couple the two traditional actuation degrees of freedom through a screw mechanism. The benefit of this approach is that one actuator can be eliminated from the robotic system, making it simpler and less expensive. A further benefit of the approach is that manual insertion of a helical concentric tube robot becomes straightforward, allowing a human operator to deploy the needle in a FTL path by pushing linearly on the back of the screw mechanism. This paper is the first to demonstrate FTL deployment of a helical concentric tube needle by manual actuation.

MATERIALS AND METHODS

Figure 2 shows the screw mechanism and helical needle, assembled in the experimental setup. The prototype screw was manufactured by fused deposition modeling of acrylonitrile butadiene styrene (ABS) using a Stratasys Dimension 768SST. The process of shape setting the helical needle is described in [9].

The superelastic nitinol helical needle is grasped at its base by a collet in the tip of the screw mechanism. The needle is deployed through a fixed, straight, rigid outer cannula. When retracted within the cannula, the needle straightens; however, as the needle deploys from the end of the cannula, the deployed portion of the needle returns to its pre-curved helical shape due to the superelastic properties of nitinol. Achieving FTL deployment requires that the base of the needle be rotated (simultaneously with translation) at a rate equal to the
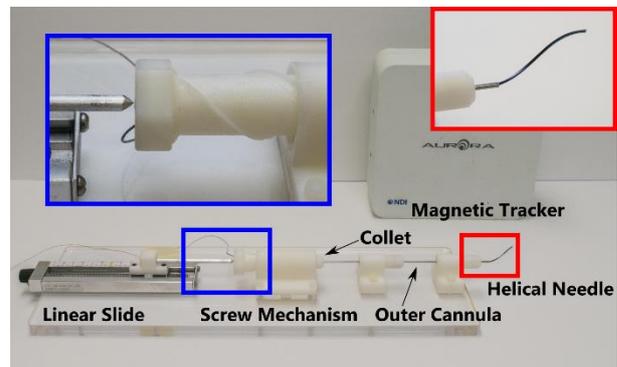

Fig 1. Minimally invasive, helical needle-based treatment of epilepsy. A helical needle (red) deployed from an outer cannula (blue) delivers therapy to the hippocampus (green).

Fig 2. Experimental setup for characterizing deployment of a helical needle using a screw mechanism

needle's pre-curved torsion [4]. A simple screw mechanism is ideally suited to maintain the required constant relationship between translation and rotation. For the system presented here, the helical needle had radius 4.84 mm and pitch 62.38 mm, and the screw mechanism had pitch 69.39 mm.

To assess the quality of the FTL trajectory during insertion and retraction, the path of the needle tip through 3D space was compared to the helical pre-curved shape of the needle. A total of 20 experiments (10 insertions and 10 retractions) were performed in free space. Needle behavior in soft brain tissue should not be expected to differ significantly from behavior in free space, given the high relative stiffness of the needle compared to brain tissue. In all experiments, actuation of the screw mechanism was performed manually. Needle tip position was measured with a Northern Digital, Inc. Aurora magnetic tracking system; insertion distance (deployed arc length) was measured using digital calipers and an aluminium probe mounted to a linear slide (see Fig. 2). During each experiment, needle tip position was measured at 5 mm increments of deployed arc length. To determine the position and orientation of the needle's known (i.e. pre-shaped) helical curve in the robot's base frame, a point based registration was carried out between all measured data points and the points at corresponding arc length locations on the needle curve.

RESULTS

Figure 3 shows the results of one insertion experiment and one retraction experiment. In an ideal FTL deployment, the position of the needle tip would lie exactly on the curve at all times. For a given arc length, the distance between the measured tip position and the point on the curve at the same arc length is a measure of FTL error. Figure 4 shows the FTL error as a function of arc length.
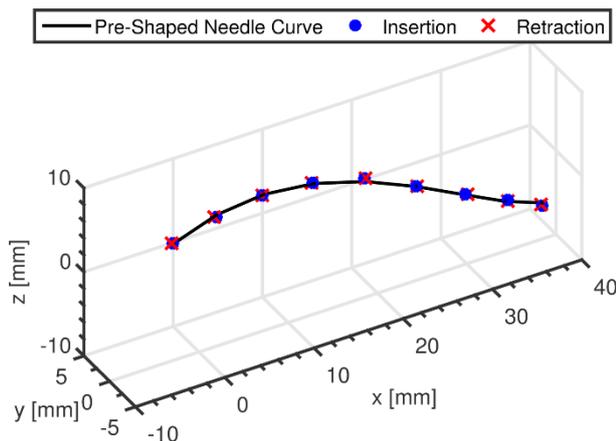

Fig. 3 Point-based registration between measured needle tip positions and the pre-shaped needle curve.

DISCUSSION

The results presented here demonstrate that follow the leader deployment of a helical concentric tube robot can be achieved manually using a screw mechanism to mechanically couple the translational and rotational degrees of freedom. These results provide for the first

time a straightforward method to manually insert helical concentric tube needles through a FTL trajectory. Additionally, these results enable a reduction in the cost and complexity of a robot designed to achieve FTL deployment of a helical concentric tube needle by eliminating one actuator.
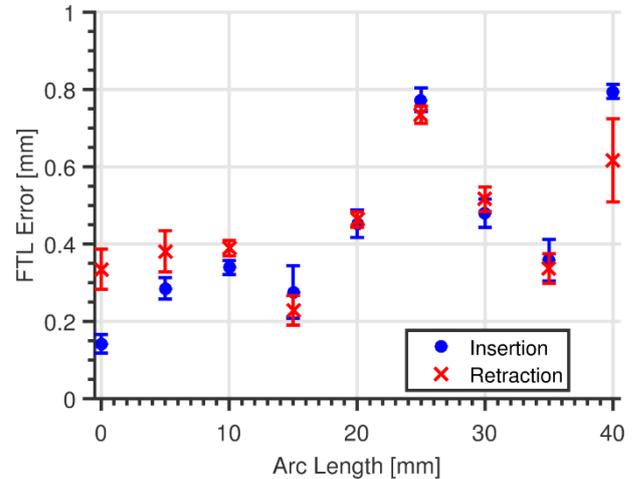

Fig. 4 FTL error versus arc length for insertion and retraction. Reported values represent mean FTL error for all experiments. Error bars represent average absolute deviation from the mean for all experiments.

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