LABORATORY INVESTIGATION

Endpoint Accuracy in Manual Control of a Steerable Needle

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ABSTRACT

Purpose: To study the ability of a human operator to manually correct for errors in the needle insertion path without partial withdrawal of the needle by means of an active, tip-articulated steerable needle.

Materials and Methods: The needle is composed of a 1.32-mm outer-diameter cannula, with a flexure joint near the tip, and a retractable stylet. The bending stiffness of the needle resembles that of a 20-gauge hypodermic needle. The needle functionality was evaluated in manual insertions by steering to predefined targets and a lateral displacement of 20 mm from the straight insertion line. Steering tasks were conducted in 5 directions and 2 tissue simulants under image guidance from a camera. The repeatability in instrument actuations was assessed during 100 mm deep automated insertions with a linear motor. In addition to tip position, tip angles were tracked during the insertions.

Results: The targeting error (mean absolute error ± standard deviation) during manual steering to 5 different targets in stiff tissue was 0.5 mm ± 1.1. This variability in manual tip placement (1.1 mm) was less than the variability among automated insertions (1.4 mm) in the same tissue type. An increased tissue stiffness resulted in an increased lateral tip displacement. The tip angle was directly controlled by the user interface, and remained unaffected by the tissue stiffness.

Conclusions: This study demonstrates the ability to manually steer needles to predefined target locations under image guidance.

ABBREVIATION

SD = standard deviation

During needle interventions such as percutaneous biopsy, fluid aspiration, and radiation or ablation therapy, an accurate tip placement is crucial for the success of the procedure. However, there are numerous conceivable needle–tissue interactions that disrupt the alignment with the target, including unforeseen movements and deformations of the needle or tissue.

The liver is subjected to quasiperiodic motions in the superior–inferior direction of 5–25 mm (1). Breath-holding techniques are often used during percutaneous liver interventions to approach static conditions, but require a substantial amount of patient cooperation. In addition, lesion displacements may originate from the puncture event itself (2) as a result of the insertion forces acting on the complex set of interconnected and sliding tissue structures. In many cases, eg, under computed tomography (CT) guidance, visual feedback is updated periodically. The physician's situational awareness depends on the quality and the frequency of information updates.

Incorrect needle positioning may be reduced by improving the preoperative needle–target alignment (3), and by using larger-diameter needles that deflect less in tissue. Although these techniques help for preplanning, they do not facilitate path corrections. Needle steering has been studied to achieve direct control over insertion paths. The envisioned use of steerable needles is to correct for errors in the direction of the insertion path (ie, needle heading) by means of small curvatures and low tissue loads or to increase the working range of the intervention by means of highly curved paths (4).

Manual needle steering demands instruments that can be controlled in an intuitive manner. Instruments have been developed that use tendon-actuated needle deformations (5,6) or protruding precurved stylets (7,8).

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Appendices A–E and Table E1 are available online at *www.jvir.org*.

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To our awareness, only one study (6) has presented data on manual insertion paths; the assessment of repeatability in manual steering has not yet been investigated.

The present work introduces a manually steered, tendon-actuated needle. The aim of the study is to determine whether a human operator can minimize the tip-positioning error when inserting a needle toward predefined targets. This task represents the intraprocedural correction of the needle heading. In addition, automated insertions have been conducted in a reference experiment with fixed tip angles to evaluate the needle steering functionality in terms of path reproducibility.

MATERIALS AND METHODS

The experimental runs consisted of automated and manual insertions. The setup used included a steerable needle, a tissue simulant, a camera, and a linear motor.

Needle Specifications

Needle deflections in tissue result from asymmetric interaction forces, which often originate at the instrument tip (9). The needle used in the present study has a conical (symmetric) tip (Fig 1). It consists of a rapid prototyped handle with a thumb controller, a nitinol cannula with removable stylet, and a tendon-actuated flexure joint near the tip. The cannula and stylet are fixed with a conventional Luer taper and have a combined bending stiffness that resembles that of a fine 20-gauge hypodermic needle (Appendix A [available online at www.jvir.org]). After needle placement, the handle and stylet are retractable, leaving the cannula on site as an open working channel. The handle consists of a controller, a body, and a cover (Appendix B [available online at www.jvir.org]).

Four tendons run through the needle lumen and connect the tip to the controller at the base. A flexure joint near the tip allows for active tip angulations (ie, articulations) with two degrees of freedom, meaning that the tip can be articulated to any desired direction (Fig 1). These articulations facilitate the asymmetry needed for steering. The joint design is a product of earlier work on steerable needles and the classification of joint types by Jelínek et al (10). The four principal steering directions of the needle correspond to the four tendons, and are denoted by B, F, L, and R (back,

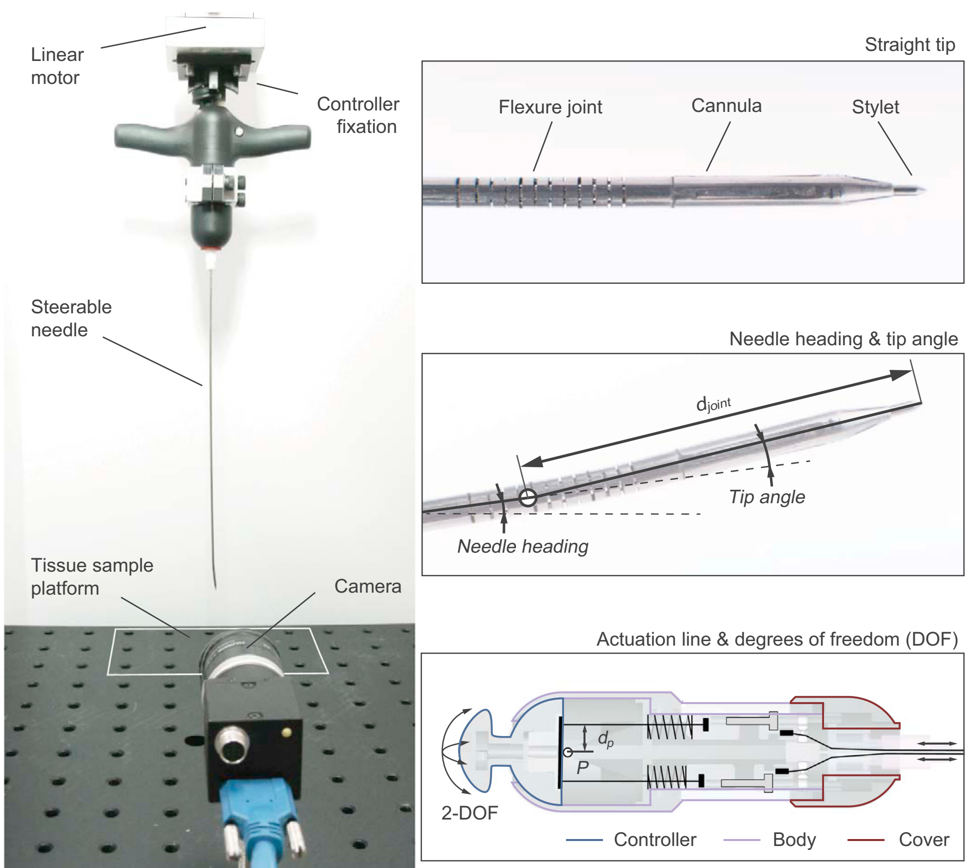

Figure 1. In the automated insertions, the steerable needle was connected to a linear motor and the controller was fixed (left). A tissue simulant was placed underneath the needle, and the tip trajectory was tracked by a camera. The right top image shows the cannula, stylet, and flexure joint. The controller fixation ensured a tip angle of approximately 7° (maximum 10°) at a joint distance d_{joint}. The actuation line is shown in a cross-sectional side view of the needle (right bottom). This relates the controller angle, with a center of rotation P, to a tendon translation, with arm d_p, to a tip angle. During the manual insertions, the controller could be rotated freely to any desired direction, ie, with two degrees of freedom (2-DOF).