Medical Engineering and Physics 37 (2015) 617–622

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Design of an actively controlled steerable needle with tendon actuation and FBG-based shape sensing

Nick J. van de Berg*, Jenny Dankelman, John J. van den Dobbelsteen

Department of BioMechanical Engineering, Delft University of Technology, Mekelweg 2, Delft 2628CD, The Netherlands

ARTICLE INFO

Article history:
Received 20 September 2014
Revised 24 March 2015
Accepted 31 March 2015

Keywords:
Needle steering
Shape sensing
Mechanical design
Mechatronics
Automation

ABSTRACT

This work presents a new steerable needle to facilitate active steering toward predefined target locations. It focuses on mechanical aspects and design choices in relation to the observed response in a tissue phantom. Tip steering with two rotational degrees of freedom was achieved by a tendon actuated ball joint mechanism. During insertion, the flexible cannula bends as a result of asymmetric tip–tissue interaction forces. The stylet was equipped with fiber Bragg gratings to measure the needle shape and tip position during use. A PI-controller was implemented to facilitate steering to predefined targets. During the validation study, nine targets were defined at a depth of 100 mm below the gelatin surface. One was located below the insertion point, the others at a radial offset of 30 mm in each of the eight principle steering directions. Per location, six repetitions were performed. The targeting accuracy was 6.2 ± 1.4 mm (mean ± std). The steering precision was 2.6 ± 1.1 mm. The ability to steer with this new needle steering approach is presented and the mechanical characteristics are discussed for this representative subset of steering directions.

1. Introduction

Needles form a minimally invasive alternative to reach deep seated locations within the human body for diagnosis and treatment of diseased tissue. In most of these treatments, e.g. taking a liver biopsy or thermally ablating malignant structures by means of radio frequency ablation, an accurate tip placement is of importance. The operator often works with visual feedback from computed tomography (CT) or ultrasound (US) devices. Nevertheless, the risk of needle misplacement tends to increase with target depth. Placement errors can arise from human errors, imaging limitations, and needle–tissue interactions [1]. While operating flexible needles, the compensation of discovered errors can be difficult and unintuitive [2]. As placement errors become too large, needles are often completely retracted and inserted anew.

1.1. Background

The development of steerable needles is motivated by the desire to facilitate correct placements. In addition, curved paths allow targets to be reached that were formerly inaccessible. As an example, Fig. 1 presents the anatomical location of the liver with respect to surrounding structures. In particular the ribcage [3], and occasionally the lower parts of the lungs can complicate needle access.

For objective validation and comparison of steerable needles, experimental repeatability is required with a stable support, a constant insertion speed [4], an equal environment, and equal control actions. This may be obtained using computer- or robot assistance.

1.2. Related work

In the past decades, several needle steering techniques have been investigated and discussed. DiMaio and Salcudean [5] described base manipulation of unmodified clinical needles. Other passive needle steering techniques include bevel tips [6], occasionally with pre-curve [7], or flexure [8] near the tip. Active steering solutions incorporate combinations of pre-curved concentric stylets and cannulas that can translate and rotate with respect to each other [9–11]. The use of multiple interlocked segments that can individually translate resulted in an actively variable bevel [12,13]. In general, both the optimal control of passive needles and the optimal design of active needles are on-going research fields. In terms of mechanical design, passive needles are much simpler and cheaper. In terms of control robustness, active needles are potentially more adaptive to varying environmental conditions.

The key concern has been the acquisition of kinematic knowledge on non-holonomic steering constraints. Recent research focus is shifting toward practical applicability, covering the inclusion of planning

* Corresponding author. Tel.: +31 15 2782054.
E-mail address: N.J.P.vandeberg@tudelft.nl (N.J. van de Berg).

http://dx.doi.org/10.1016/j.medengphy.2015.03.016
1350-4533/

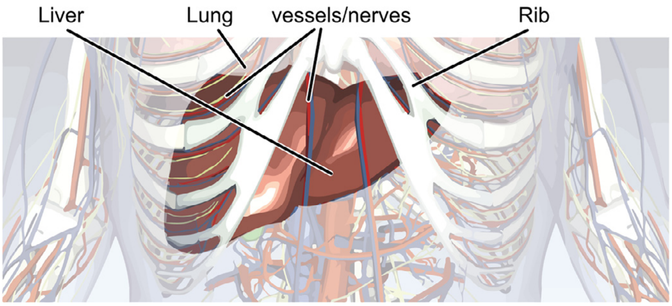

Fig. 1. Human anatomy: illustration of the liver, covered by regions of the ribcage and in variable amounts by the lungs. Image adapted from The Biodigital Human.

uncertainties with respect to tissue variability [14], the consideration of torsional friction [15], and the reduction of model dependencies on a-priori information [16].

1.2.1. Performance metrics

Many needle steering studies have focused on the evaluation of path planners (for a review see [1]). Control actions for these methods are determined a priori and occasionally updated intra-operatively, e.g. [17,18]. Planning paths requires (inverse) kinematic expressions for needle motion. To assess the error build-up of a steering task, some form of trajectory error [19] or end-point error [16,20] is generally reported. For this, position information is acquired by various sensors, such as cameras [21,22], electromagnetic sensors [12], ultrasound probes [23], fluoroscopic X-ray [24], and fiber Bragg gratings (FBGs) [25–27].

Typically, kinematic expressions rely on shape assumptions, such as a piecewise constant radius of curvature [28]. Therefore, radius of curvature is an often used metric to characterize kinematic models [7,29–31]. The validity of constant radius path approximations, however, has in the past been debated for certain needle–environment combinations [6,32].

For needles that require rotations to select a steering plane, torsion may affect target reachability and is typically assessed [33,34]. In analogy, for needles that do not rotate, a representative subset of steering planes should be selected to investigate directional symmetry in actuation. Kinematic responses may differ due to various imperfections in the designing, machining and assembling process. In a study of Burrows et al. [35], the eight principal steering directions (every 45°) of an adaptable bevel tip needle were evaluated. Kinematic differences were found and attributed to variations of the needle's flexural rigidity for different tip configurations.

1.3. Aim

This article presents a novel actively steered needle and focuses on its mechanical design. The needle is composed of a flexible cannula and has a conical tip that can rotate with two orthogonal degrees of freedom. During insertion, the needle will deflect as a result of asymmetric reaction forces at the needle–tissue interface. In order to track the needle shape and tip location, FBGs have been integrated in the stylet. This stylet can be withdrawn after placement, leaving the cannula as working channel. The characteristics of the shape-sensing stylet have been analyzed for various configurations and deformations [26,36]. Since the insertion stroke is considered constant, 2D targeting errors (top view) are presented for the eight principal steering directions. To the author's knowledge, this is the first study to combine an active needle steering method with FBG-based shape feedback. The obtained shape information can ultimately provide an overlay on static or dynamic visual information from CT or ultrasound devices, in order to continuously update the tip position with respect to the target.

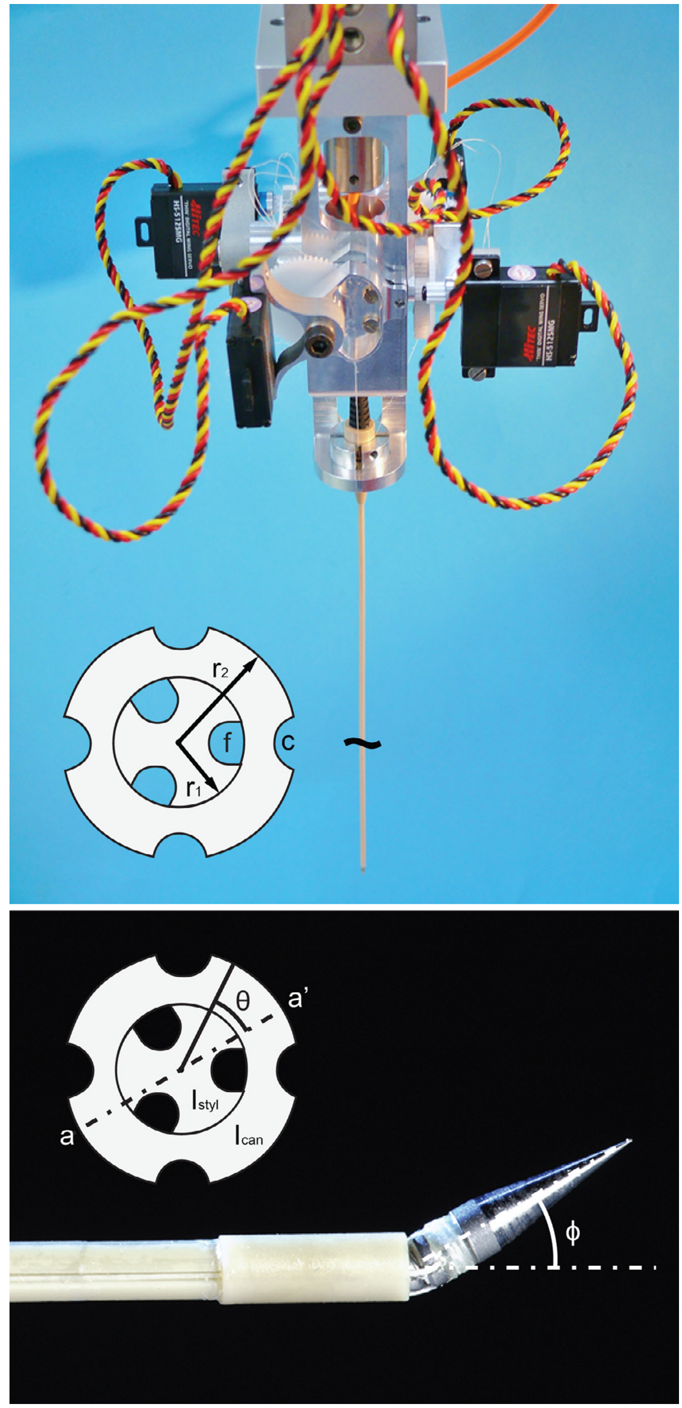

Fig. 2. The tendon-driven needle consists of a stylet with radius r_1 and grooves for optical fibers (f), and a cannula with radius r_2 and grooves for the actuation cables (c). Steering is achieved by four servo motors located at the needle base. This results in tip rotations with a magnitude (ϕ) up to 20° in any orientation (θ).

2. Methods

2.1. Mechanical needle design

The steerable needle used in this study is shown in Fig. 2. It is composed of a flexible cannula, a retractable sensorized stylet and a 5 mm long conical tip (apex angle of 20°) placed on top of a ball joint. The ball joint is tendon driven and actuated by 4 rotary servo motors (Hitec HS-5125 MG) working in complementary pairs. By alteration of the servo positions, the needle tip can rotate with 2 orthogonal