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Deflection modeling for a needle actuated by lateral force and axial rotation during insertion in soft phantom tissue☆

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ABSTRACT

In prostate brachytherapy, radioactive seeds are implanted into the prostate for treatment of early-stage localized cancer. A major issue is seed displacement due to needle deflection, which is difficult to control as the needle is inserted manually. To address the problem and automate needle insertion, robotic systems, mathematical models for estimation and prediction and control algorithms have been developed. The method of choice for robotic steering of beveled-tip needles is predominantly intermittent axial needle rotation since this re-aligns the beveled tip and thus re-directs the needle. In this work, we present a method for needle steering to supplement axial needle rotation. A point force applied laterally to the needle near its point of insertion into tissue is used to displace the needle perpendicularly relative to its insertion axis. An advantage of this method is that the lateral force provides a continuous control input and thus continuous deflection control as opposed to axial needle rotation by 180 degrees in the 2D case of planar needle steering. Further, more control over deflection is possible as the lateral force provides direct shape change for the needle and improves the under-actuated nature of the needle. In order to predict and estimate needle deflection during insertion while applying both lateral force and axial rotation, a mechanics- and energy-based model for needle deflection is developed. Both single-layer and multi-layer tissue can be modeled if the tissue layer thickness is known. The accuracy of the model is validated experimentally. A comparison between the measured tip deflection and the model-based estimate shows only a small error. Moreover, control and sensitivity studies are carried out through insertion simulations using the model. The studies show the potentials and limitations for needle deflection reduction with various combinations of lateral force application and intermittent 180 degrees axial needle rotation.

1. Introduction

Needle insertion is a minimally invasive procedure commonly used in biopsy, drug delivery, therapy, and ablation. One of the therapeutic procedures in which needles are inserted for the purpose of radiation therapy is prostate brachytherapy (from Greek “short distance” therapy). A schematic depicting the procedure is shown in Fig. 1. In order to implant the seeds into the prostate, the needle is loaded with rice-grain-sized seeds and inserted into the prostate. When the final insertion depth is reached, the seeds are deposited by being pushed out of the needle as it is retracted. Multiple needle insertions are carried out at different locations on a 5 mm grid template (see Fig. 1) such that seeds are distributed across the prostate volume affected with cancerous tissue. For the radiation emitted by the seeds to be distributed efficiently throughout the prostate, it is important for the seeds to be deposited at their pre-planned locations. The target locations are registered with the template holes and, therefore, it is essential for the needle to remain on a straight path during insertion. Due to the cutting-related asymmetric forces acting at the beveled tip of the needle during insertion, however, the needle naturally deflects from a straight trajectory, thus causing the seeds to be deposited away from their pre-planned location. The tip of brachytherapy needles is beveled for facilitation of seed deposition and tissue cutting. Moreover, the beveled needle tip provides some control over needle deflection as the direction of the bevel can be changed through axial needle rotation. Thus, in order to steer the needle back to a straight trajectory, the brachytherapist may rotate the needle about its axis of insertion by 180°. Rotation is done intermittently throughout insertion to avoid tissue damage and out-of-plane deflection. Intermittant 180° axial needle rotation reverts the bevel’s direction and, therefore, the asymmetric

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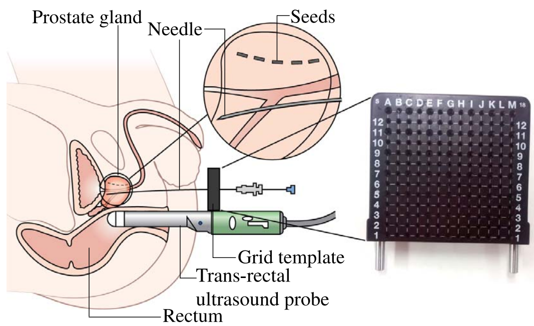

Fig. 1. The radiation therapy procedure prostate brachytherapy. Radioactive seeds are inserted into the prostate with a needle guided by a grid template. The needle tip position is observed with a trans-rectal ultrasound (TRUS) probe (source: Cancer Research UK / Wikimedia Commons).

force's direction and steers the needle in the opposite direction.

The above-mentioned method for needle steering and trajectory control can be automated using robotic assistance in order to aid the surgeon during needle insertion procedures. For improving the efficiency of seed deposition in brachytherapy or, more generally, steering of the needle tip towards a desired target, extensive research has been conducted in modeling needle-tissue interactions, sensing, estimation and prediction of needle deflection, and control algorithms for needle steering using axial rotation as the control action. Fundamental interactions between needle and tissue such as friction, and cutting-related tip forces were investigated [1–5]. Several contributions were made in further investigating needle-tissue interactions and proposing mechanics-based models for needle deflection [5–17]. Others proposed kinematics-based models [18–22], e.g., based on bicycle kinematics, which are less directly associated with tissue properties.

The proposed models were then used to estimate or predict needle deflection [6–9,13,15,17,18,23,24] in order to inform model-based controllers for needle steering using axial needle rotation [3,8,9,18–21,24–26].

Further research was conducted on designs of robotic needle insertion systems for various clinical applications [27–32]. Specifically for prostate brachytherapy, systems were developed that provide actuated guides that either complement or replace the fixed grid template (see Fig. 1) for needle guidance and deflection manipulation during insertion [33–37]. For a recent and comprehensive literature review on issues in closed-loop needle steering see [38].

While axial needle rotation as a method for steering beveled tip needles has been investigated thoroughly in the past, a further method used by some brachytherapists in a manual fashion has received little consideration. Brachytherapist employing the method apply a force onto the needle perpendicular to the direction of needle insertion for the purpose of needle steering. The perpendicular force can be applied in close proximity to the needle insertion point and will henceforth be referred to as lateral force. It is applied with a finger near the needle's entry point into tissue counter to the direction of deflection in order to correct the needle tip deflection. The force is applied relatively early during insertion in order to force the entire needle shaft inside tissue to be displaced laterally. Towards the goal of utilizing this needle steering method during robot-assisted needle insertion, this paper provides a mechanics-based model that accounts for both steering actions: lateral force and axial needle rotation. A schematic depiction of the proposed method of lateral needle actuation is provided in Fig. 2a. When using lateral force for needle steering, significant benefits exist. As the needle can be regarded as a highly under-actuated manipulator, the application of lateral force near the entry point into tissue provides an additional control input affecting the needle deflection more directly. Naturally, the beveled tip of the needle is constrained to move on a circular trajectory during insertion. This constraint can be significantly relaxed through lateral force as the needle tip can now be directly moved laterally thus increasing the needle tip's dexterity. The lateral force is a continuous input to a deflection control algorithm meaning that also the deflection can be influenced in a more continuous manner as opposed to intermittent axial rotation. If the goal is to keep the needle tip on a straight line (as it is assumed in seed deposition planning during prostate brachytherapy), the axial rotation input needs to be invoked continually to keep the tip deflection under a threshold. This is physically understandable due to the effect of the beveled tip, since as long as the needle insertion velocity is non-zero, its trajectory will diverge from a straight line. Since excessive use of axial rotation results in tissue drilling effects [39], the availability of an additional control input (the lateral force) that can reduce the amount of necessary axial needle rotations is highly beneficial.

A question we seek to answer particularly in the context of prostate brachytherapy is, to what extent can lateral force be used to manipulate the needle curvature for minimizing needle deflection and what are the existing limitations? It is assumed that the effect of the lateral force with respect to steering is reduced with increasing insertion depth. Responsible for this is decreasing resistance to needle bending with increasing needle length and confinement of the needle within tissue during insertion. Therefore, also lateral needle tip displacement caused by the lateral force and thus steerability are reduced at greater depths of lateral force application. This has also been hypothesized by Cowan *et al.* [40]. Moreover, it is of interest to know how lateral displacement and intermittent axial needle rotations should be combined to influence needle deflection and to properly steer the needle.

Due to the needle-tissue system's nonlinearity and constraints (e.g., limited needle maneuverability due to under-actuation and non-holonomic properties), a model-based predictive control approach is necessary, which takes informed decisions based on prediction of needle deflection and on-line path planning. A requirement of controlling needle deflection in a predictive manner is therefore the development of a model, with which the needle curvature can be estimated and predicted based on the lateral needle displacement and axial needle rotation inputs. In this work, we introduce a model for the estimation of needle deflection resulting from a combination of applied lateral force and axial needle rotation. The model is energy-based and quasi-static, and its output is the needle deflection shape that occurs at a given insertion depth d.

1.1. Related work

In order to construct the model, the principle of minimum potential energy is used. This approach has been commonly applied in the past to model needle-tissue interactions and needle deflection during insertion. Misra *et al.* presented an energy-based mechanical model that takes into account needle bending (strain energy), needle-tissue interaction (compression and elasticity) and tip cutting work (tip force and rupture) [5,9]. Roesthuis et al. [11] extended the model proposed by Misra et al. by modeling the resistive force due to tissue compression by a distributed load acting along the inserted needle portion and incorporating needle steering through axial rotation into the model. Another model that used an energy-based approach was proposed by Lee and Kim [17]. Rossa et al. [16] in their version of an energy-based model considered also a cutting-related tip force and a load along the inserted needle portion modeled by a set of elastic springs. The springs model the tissue's resistance to compression. The spring stiffness is the tissue's Young's modulus. To determine the amount of tissue compression at a given position along the needle, the difference between the needle shaft shape and the needle tip trajectory, also referred to as the tip path, is considered. Moreover, the (stationary) grid template commonly used in prostate brachytherapy (see Fig. 1) is included in the model.