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Feasibility study on a robot-assisted procedure for tumor localization using needle-rotation force signals

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ABSTRACT

Accurate tumor localization is critical to early-stage cancer diagnosis and therapy. The recent force-guided technique allows to determine the depth of a suspicious tumor on the insertion path, while the spatial localization is still a great challenge. In this paper, a novel force-guided procedure was proposed to identify spatial tumor location using force signals during needle rotation. When there is a harder tumorous tissue around the needle rotation, an abnormal force signal will point to the location of the suspicious tissue. Finite element simulation and phantom experiment were conducted to test the feasibility of the procedure for the tumor localization. The simulation results showed that the harder tumorous tissue made a significant difference on the stress and deformation distributions for the surroundings, changing the needle-rotation force signals when the needle rotated towards the harder tissue. The experimental results indicated that the direction of the tumor location can be identified by the rotation-needle force signals. The intersection point of the two identified directions, derived from force signals of twice needle rotations, determined the tumor location ultimately. Also, parametric sensitivity tests were performed to examine the effective distance of the tumor location centre and the needle insertion point for the tumor localization. This procedure is expected to be used in robot-assisted system for cancer biopsy and brachytherapy.

1. Introduction

Effective early-stage diagnosis and therapy of cancer is critical to prevent its development. Although digital rectal examination (DRE) has been used to detect suspicious tumor tissue, needle biopsy is still the only method for a definite diagnosis of cancer. In the biopsy procedure, the suspicious tissue is removed by needle for a further examination [1]. Also, as an effective treatment for the early-stage cancer, brachytherapy needs to place radioactive sources commonly used as an effective treatment for the in which are d close to the tumor location for radiotherapy [2]. Thus accurate localization of the tumor is important to cancer diagnosis and therapy.

Recent advances in robot-assisted minimally invasive surgery (MIS) provided intelligent technology for tumor localization. Guided by Transrectal ultrasound (TRUS) or magnetic resonance imaging (MRI), a needle can be driven by a robotic manipulator to reach the target location [3–8]. Although image-guided technology has many appealing merits, there are still great challenges for the accurate localization. TRUS, for example, is limited by its poor imaging quality, reducing the detection rate significantly [9,10]. MRI can provide higher spatial solution, but a metal needle inevitably generates a susceptibility artifact that would misguide the needle insertion and probably damage the normal tissue [11,12].

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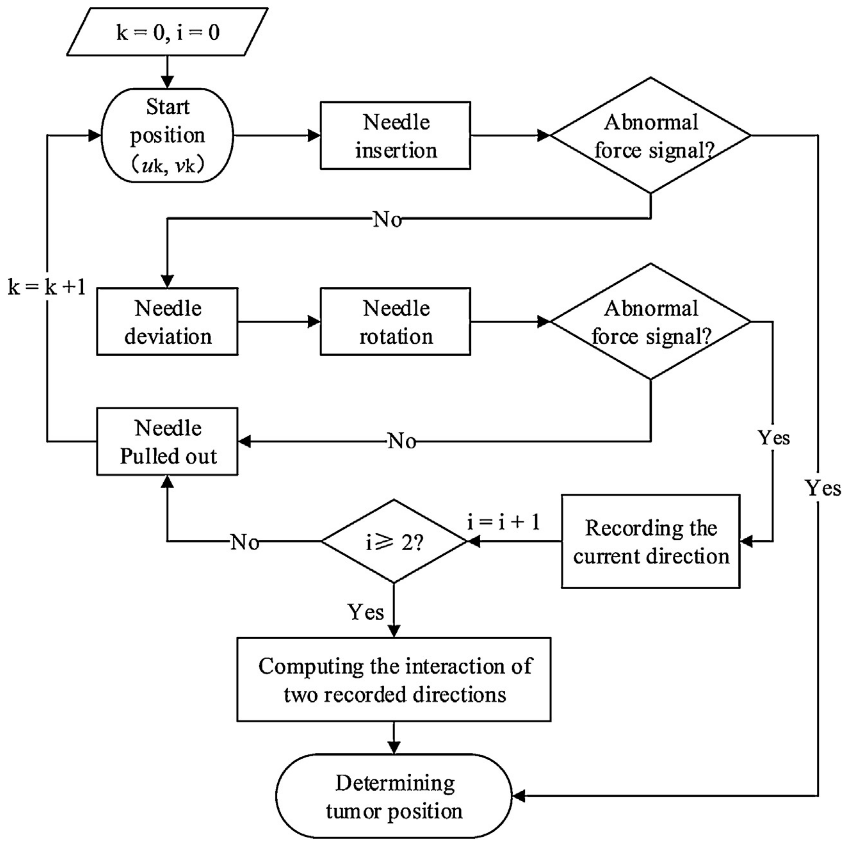

Fig. 1. The setup of robot-assisted tumor localization procedure using needle force signals.

To allow more accurate localization, force-guided technique has been proposed to assist TRUS and MRI navigation in robotic MIS [13–16]. This technique is based on the biomechanical theory that tumor tissue increases its induration, becoming harder than the normal tissue [17–20]. The harder tumorous tissue would make a difference on the needle force signal, which can be used to identify the tumor location. The needle-tissue force interaction has been investigated in the previous studies. Brett et al. [21,22] performed pioneering work on characterization of needle force to identify the type of tissue on the needle insertion path. Kataoka et al. [23] measured tip and friction needle forces when a needle is penetrating into a prostate. Okamura et al. [24,25] developed a mathematical model to simulate needle insertion, in which tissue stiffness, needle friction and puncture were computed synchronously. Majewicz et al. [26] evaluated needle insertion forces using various needle types in ex vivo and in vivo experiments. Yan et al. [27,28], for the first time, proposed a force-guided technique for tumor detection using insertion forces in the prostate brachytherapy. Validated by patients' experiments, they confirmed the effectiveness of the force-guided technique for cancer detection.

However, the recent force-guided technique can only determine the depth of the suspicious tumor which is just on the path of insertion. Spatial tumor localization using needle force signals has still been a great challenge. In this paper, we proposed a novel robot-assisted procedure for tumor localization using needle-rotation force signals. This procedure can be used to predict the spatial location of a suspicious tumor. The feasibility of the robot-assisted procedure for tumor localization was validated using finite element simulation and phantom experiments. Also, we evaluated the effective range of needle-rotation localization in several parametric tests. The proposed procedure is expected to use in robot-assisted guidance system for tumor localization.

2. Materials and methods

2.1. Procedure description

The procedure of the force-guided tumor localization refers to needle motions involvng vertical insertion, planar deviation and 360° rotation. The needle forces in three directions (F_x, F_y and F_z) are recorded during the needle motion. The tumor's location can be determined according to the force signals. The setup of the tumor localization procedure is illustrated in Fig. 1.

The main steps in the tumor localization procedure is elaborated as follows.

Step 1: A needle is driven to be inserted a suspicious tissue vertically (Fig. 2a). When abnormal (changing rapidly) signals is found in the insertion force (F_z), it is considered that the tumor is located on the path of the insertion. The method for analyzing and determining the depth of the tumor can be found in the literature by Yan et al. [28].

Step 2: If there is no indication of abnormal signal during the insertion (Fig. 2b), the needle is then driven to perform a deviation in *x*-*y* plane (Fig. 2c), followed by a 360° rotation around the insertion axis (Fig. 2d). Normally, the resultant force ($F_r = \sqrt{F_x{}^2 + F_y{}^2}$) is almost consistent with the needle rotation. If there is a harder tumorous tissue around the needle, an abnormal (increasing rapidly) force signal could be found when the needle rotates close to the tumor's location (Fig. 2e). The direction of the tumor's location relative to the insertion position can be identified according to the orientation of the abnormal signal (Fig. 2e).

Step 3: The needle is pulled out and driven to insert the suspicious tissue at a different position (2nd insertion position), repeating Step 1. If there is no harder tumorous tissue on the path of needle insertion, the needle is then driven to perform a deviation