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Survey on Current State-of-the-Art in Needle Insertion Robots: Open Challenges for Application in Real Surgery

Inko Elgezua*, Yo Kobayashi, Makatsu G. Fujie

Graduate School of Advanced Science and Engineering, Waseda University. TWIns, 03C201, Wakamatsu-cho, Shinjuku , Tokyo, 162-8180 Japan
* Corresponding author. Tel.: 81 3-5369-7330; fax: 81 3-5369-7330. *E-mail address*: ielgezua@asagi.waseda.jp.

Abstract

Minimally invasive percutaneous treatment robots have become a popular area in medical robotics. Minimally invasive treatments are an important part of modern surgery; however percutaneous treatments are a difficult procedure for surgeons. They must carry out a procedure that has limited visibility, tool maneuverability and where the target and tissue surrounding it move because of the tool. Robot technology can overcome those limitations and increase the success of minimally invasive percutaneous treatment. In this paper we will present a review of the current state-of-the-art in robotic insertion needle for minimally invasive treatments, focusing on the limitations and challenges still open for their use in clinical application.

Selection and/or peer-review under responsibility of Professor Mamoru Mitsuishi and Professor Paulo Bartolo

Keywords: Needle insertion robot; steerable needle; flexible needle; tissue modeling; minimally invasive percutaneous treatment.

1. Introduction

Since the beginning of the popularisation of laparoscopic surgery in the 1980s, minimally invasive treatments have won an important role in modern surgery. Nonetheless, they provide several advantages versus traditional open-surgery. They cause less trauma to patients and as result, there are less complications after surgery and stay in hospital is shorter.

Initially, many of the robots intended to be used in surgery were adaptations of industrial robots. Clear examples are Da Vinci [1] or MIRO [2], which use anthropomorphic robots to manipulate surgical tools.

Advances in minimally invasive treatments have brought new types of robots specifically designed for a particular type of surgery. For instance, needle insertion robots are becoming popular among roboticists for minimally invasive percutaneous treatment.

Percutaneous treatments include: biopsies and other cancer treatments such as brachytheraphy, radio frequency ablation (RFA), cryoablation or chemotherapy.

This type of treatment consists in the introduction of a needle into a cancerous area, then one of the techniques mentioned above are applied to kill the cancer, or obtain a sample. Because the treatment is localized in the cancerous region only this area is affected. This approach has advantages over traditional chemotherapy or radiotherapy, were the effects of the treatment affect the whole body.

However, this is a complex procedure for physicians. On one hand surgeons have to guide the needle into the target using only US image, which is noisy and it is difficult to distinguish the needle in it unless a good alignment between US probe and needle is kept.

On the other hand, human tissue is soft and easily deformable. When a needle is inserted, tissue will deform and target moves. With limited visibility, tool maneuverability, needle deflection and tissue variability, surgeons must relay in tactile feedback and experience.

In this paper we present an overview of the state-of-the-art in percutaneous treatment robots with an special focus in open challenges and limitations.

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It is not the goal of this paper to explain in detail each solution or system, but to provide an overview to readers who are not familiar with the field of needle insertion robots. For detailed explanation, the reader can refer to [3-4] or the original papers cited in the bibliography.

1.1. Needle tissue cutting

When a needle cuts tissue, the process follows a distinctive pattern that can be divided into two phases.

First the needle pushes the tissue increasing the insertion force steadily. During this phase the tissue deforms until the stress limit is reached. Then, the needle punctures the tissue and advances into it followed by tissue relaxation, this is the second phase. A puncture is observed as a sharp drop in insertion force. This process repeats itself as long as the needle is inserted with another series of pushing and puncturing (Figure 1).

Deformation and force needed to puncture a particular tissue depend on: tissue properties, needle insertion speed, needle size and tip shape [3-9].

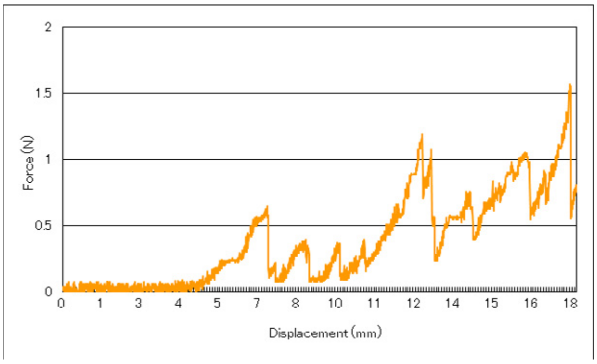

Fig. 1 Tissue punctures are easily observed in a force-displacement graph with a characteristic saw shape. Peaks correspond to the force necessary to puncture the tissue.

It is the first part of the needle insertion process that deforms the tissue and displaces the target. Minimize this deformation will reduce the amount the target is displaced and increase accuracy.

Human tissue is a viscoelastic material, property that can be used to minimize its deformation. Experimental results indicate that higher needle insertion speeds reduce deformation and insertion force. For an example see Mahvash *et al.* [5]. However, only robots can use high needle insertion speeds safely. Manual insertion requires lower speeds.

Needle rotation during insertion was proposed to minimize tissue deformation and needle deflection [6-8], but experimental results indicate that it increases trauma in patients due to the cutting done by the tip of needle.

2. Needle-Tissue interaction: Models

Needle tissue interaction is important for needle insertion robot control. Deflections of the needle can cause the robot to miss the target [13], friction has to be compensated, or in a higher control level, these models will be useful to detect puncture events or distinguish different types of tissues.

Living tissues present a viscoelastic, anisotropic, nonlinear behavior. This behavior needs complex tissue models that are not easy to develop. Fung [43] developed living tissue models based on rheological models, which is a basic reference in the field.

The work by Okamura *et al.* also deserves especial mention. In [9] force acting in a needle in bovine liver is modeled as:

$$f_{needle}(x) = f_{cutting}(x) + f_{friction}(x) + f_{stiffness}(x)$$

Where $f_{stiffness}$ is the force necessary to puncture the capsule and x is needle position. After the capsule is punctured the forces acting on the needle are those in the tip and friction.

In the same work they also investigated the effect of type of needle, bevel-tip angle and diameter. Bevel-tip angle seems not to affect insertion force, however insertion force increases with needle diameter and tip type: triangular, bevel and cone shape.

Extensive literature exits in needle tissue interaction [10-13, 29, 34-35]. Although in most cases they are either variations on Fung's models, or Okamura's equation.

It has to be remarked that mechanical properties of tissue change from person to person, organ, age, gender, mass, temperature, etc. Therefore, values that can be found in valid models might not be valid for other tissue than the ones used for the validation.

To find real values of mechanical properties for a given tissue, researches have proposed different methods for parameter online estimation. Barbé *et al.* [14] proposed to use curve fitting with rheological models, whereas Asadian *et al.* [15] proposed Kalman filters to estimate the real value starting from an initial value.

But online methods are used operatively when insertion force can be measured. For tissue deformation simulation, these values have to be known in advanced.

Therefore it is necessary to use stochastic models to compensate for these differences [42], or use non-invasive methods to measure the mechanical properties of a particular patient in a pre-operative phase.

Salcudean *et al.* [16-17] proposed to use vibro-elastography to determine the contour of bladders for prostate brachytherapy, and to measure viscoelastic parameters of tissue surrounding the bladder. Whereas Hoshi *et al.* [18] proposed an algorithm to adjust mechanical properties of tissue combining inverse FEM with US image.

It is also common to validate tissue models using phantoms. Although mechanical properties of phantom materials are similar to living tissue, phantoms don't behave in the same way as real living tissue, therefore those models have to be treated with caution.

3. Calculation of needle trajectory

Because needles deform the tissue they are inserted into, the position of the target will change; therefore, the initial needle trajectory might not be able to reach the target, and a new one has to be calculated.

Two approaches are used to solve this problem. One uses mechanical simulation to calculate a trajectory that will be successful at hitting the target, and a second that changes the needle trajectory in real-time to compensate for target motion.

3.1. Needle trajectory based on mechanical simulation

In order to calculate trajectory, given an initial trajectory, it is possible to simulate the final position of a target due to the deformation caused by the needle. Later the system will iterate until a new trajectory of the needle converges with the target displacement.

Examples of this approach are the palpation needle insertion robot for breast cancer treatment developed by Kobayashi *et al.* [20] (Figure 2), and the robot to implant radioactive seeds for prostate brachytheraphy created by Salcudean *et al.* [21].

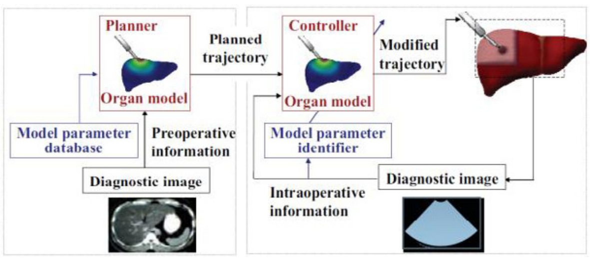

Fig. 2 Block diagram of Needle Insertion robot for Breast Cancer by Kobayashi *et al.*

Two methods are commonly used to simulate tissue deformation caused by the needle: FEM and mass-spring-damper models.

FEM provides high accuracy but it is computationally expensive and only valid for small linear deformations. Because they require long time to find a solution, FEM methods cannot be used in real-time for needle insertion control. Therefore, simulations have to be done in a pre-operative phase.

Mass-spring-damper models are computationally light and can be easily solved by GPUs. However, they have a lower accuracy than FEM, cannot handle volumetric constrains and are difficult to model.

In general terms, FEM are used for precise simulation of organ deformation in a pre-operative stage for real needle insertion, and mass-spring models are used for needle insertion simulators thanks to their computational speed and low requirement in accuracy.

In both cases, FEM or mass-spring-damper, nonlinear models are used to match human tissue behavior.

As stated in previous section, mechanical properties of tissue change between persons and depend on several other factors, to obtain accurate simulation results real values of a particular tissue are necessary. Because of this variability simulation based needle trajectory robots are not always successful.

3.2. Active tissue deformation

Mallapragada *et al.* [23] proposed to use tissue deformation for needle insertion. In this case, instead of calculate a new needle trajectory based on how the target it is going to move, it calculates a tissue deformation to move the target into the needle trajectory.

This approach also allows avoiding obstacles, since it is possible to deform the tissue to move one obstacle outside the needle trajectory (Figure 3).

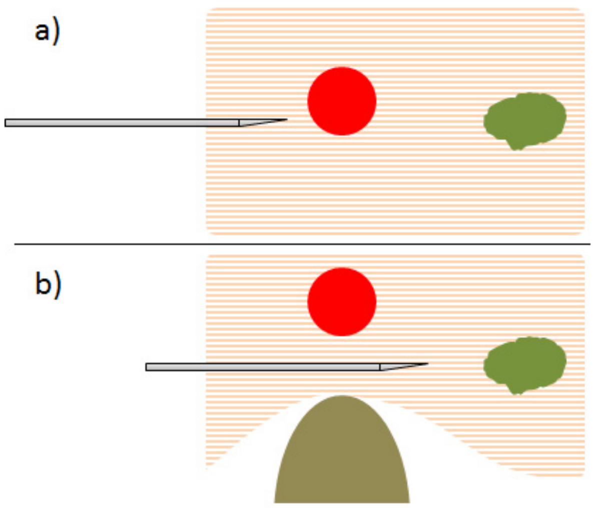

Fig. 3 a) An obstacle (circle) is in the trajectory of the needle. b) By deforming externally the tissue the obstacle is moved out of the trajectory of the needle.

Although physicians already use this same technique manually, there aren't many examples of such robotic systems.

3.3. Steerable needles

Contrary to trajectories planned in a pre-operative phase, steerable needle robots adjust the trajectory of the needle in real-time depending on the target displacement or to avoid obstacles.

The most basic system consists in moving the base of the needle perpendicularly to the needle motion. This movement rotates the needle over the entry point changing its direction. But the force necessary to change needle's direction increases as insertion depth increases, thus, when the needle is deeply inserted this method loses its effectiveness.

A new type of needles, called flexible needles, make intentional use of needle deflection due to asymmetrical forces on bevel-tip needles to steer the needle into the desired path. Flexible needles can follow more complex paths than rigid needles what makes possible to avoid obstacles or sensitive areas.

To control the direction of the needle, flexible needles are rotated through their axis. With this rotation the force acting on the surface of the bevel-tip changes direction and the needle is bent accordingly [25].

Modeling tissue needle interaction and needle model [36] are open problems of flexible needles. Trajectory planning [27, 37] - challenging because they cannot follow straight lines - as well as guidance are new challenges [40].

Although experimental results show the feasibility of flexible needles for obstacle avoidance and target motion compensation, most of them are preliminary works done with phantom materials. Further *in-vitro* and *in-vivo* validation is necessary.

Furthermore, because of their small diameter, about 0.05 mm, they have no real application in clinical use yet.

3.4. Contribution to the field

In section 1.1 we explained the cutting process of needle insertion and a typical force-displacement graph. However, when a needle is inserted in real tissue, force displacement graphs present different shapes. Compare Figure 1 and 4. This is due to different types of tissues as well as the puncture of veins.

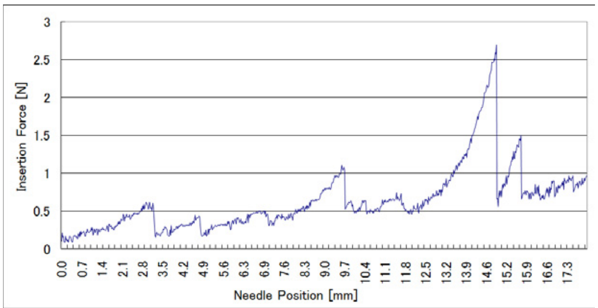

Fig. 4 Example of vein puncture in force-displacement in pig liver. The big peak in the centre corresponds with a vein being punctured.

As stated before, mechanical simulations rely on the accuracy of mechanical properties of human tissue. A combination of simulation based needle trajectory with image guided needle can overcome this problem, however, US images are not always clear and identification of veins, arteries, tissue or needle are not always possible or accurate. Furthermore, image processing is generally slow compared to force control constraints.

We aim to develop a system to detect specific events in order to provide information to a needle insertion robot.

In the same way that physicians feel if a vein or artery is punctured, there is a change of tissue or the tissue is softer or harder, we aim to replicate such behaviour with our system. This information can be then used to complement data from force sensor and US image.

Experimental data from porcine liver puncture show that exits a difference in force needed to cut regular tissue or puncture a vein. Figure 4 shows a value of about 0.4 N to cut liver tissue whereas to puncture a vein it requires 1 N. This difference in force to cut liver tissue or vein provides two different force distributions. Using Anomaly Detection algorithm we can detect if each peaks corresponds to tissue cutting or vein puncture.

To identify needle insertion force patterns in liver tissue, we performed a series of needle insertions in porcine liver. Each puncture is 15 mm deep and has 5 mm margin to neighbour punctures. We used an 18G–1 1/2'' needle. The number of punctures per liver depends on liver size, ranging between 75 to 150 punctures.

Figure 5 shows the experimental setup. A porcine liver lies flat on a metallic surface and a Cartesian robot punctures it vertically. Force is recorded at 1 kHz with a BL Autotech nano sensor.

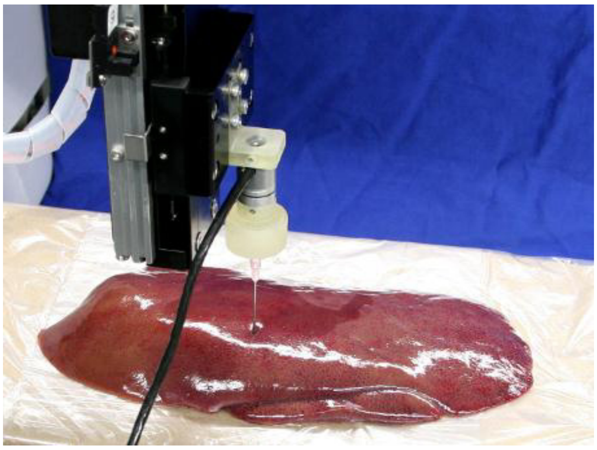

Fig. 5 Experimental setup for force pattern identification of liver puncture.

To study the effect of insertion speed in force pattern, we performed the punctures at insertions speeds between 0.75 mm/s to 6 mm/s. Insertion speeds were distributed randomly over all punctured liver area; with the same number of punctures per insertion speed.

After punctures were completed, the livers were sliced following the puncture path and for each puncture it was checked whether it punctured a vein or not and compared to force-displacement pattern to create force distributions.

Fig. 6 Sliced liver after puncturing. Circles mark where the artery was punctured during the experiment..

Because of the relative simple structure of liver, only two situations are detected: tissue cutting or vein puncture. However, when the feasibility of our proposal is proved after further experiments with more livers, only 2 livers have been used until now, we plan to develop the same system for breast tissue, which is composed of mammary glands, fat, muscle and veins.

4. Vision based needle navigation

Guided needle trajectory control changes the needle trajectory based on the displacement of the target in real-time based on medical image feedback.

Several medical image modalities are available to be used in robotic needle insertion. However, US image is the preferred one over MRI, fluoroscopy or CT.

MRI requires long time to acquire images with enough resolution and cannot be used in real-time, besides, because its use of strong magnetic fields, it imposes strict constraints in use of needle materials.

Fluoroscopy and CT use low levels of radiation and for safety reasons they must be operated by a human.

Finally, US image is generally noisy and manually operated which makes needle detection difficult. There is extensive literature in needle detection in US image. In general, these algorithms combine edge detection with Hough transforms. It is however one of the preferred medical image modalities due to its low cost and safety.

Although experimental results seem to be promising, there are little practical devices developed. One of the possible problems is related to the computational cost of image processing that might not be fast enough for robot control.

Secondly, US image is not always clear and a perfect alignment between US image plane and needle is necessary.

Finally, it is worth noticing that not all needle navigation methods are validated *in vivo* or *in vitro*, but with use of phantoms, which provide a clearer image and are less affected by the deformation caused by the US probe.

5. Conclusion

In this paper we presented a survey on the current state-of-the-art of robots for percutaneous treatment and their problems and challenges for clinical use. To date there is no satisfactory solution to needle insertion for clinical application.

Trajectory planning based on mechanical simulation need to estimate the real value of patient's tissue properties for accurate results, but tissue properties might change between the simulation and procedure.

Online estimation methods can be used during the surgery but their information cannot be used for simulation due to time constraints.

Steerable needles can compensate for target motion and differences between a pre-computed value and the real ones, but they don't have real clinical application due to their small diameter.

Finally, we presented briefly our ongoing contribution to the field in the development in needle insertion force pattern identification for application in intelligent control of needle insertion robot.

Acknowledgements

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