Retraction

Retraction: Research on Force Analysis and Path Planning of Flexible Needle Puncture Bending Modelling (J. Phys.: Conf. Ser. 1952 042058)

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1. Shi Kaiming 2019 Research on Movement Modeling and Path Planning of Flexible Cannula Needle Based on Finite Deformation Theory PhD Thesis Harbin University of Science and Technology, China (https://t.cnki.net/kcms/detail?v=zDWWPgpj7XNIYVmjPzotLQqrqE5suL8UT58pa0cYSzNWTc6cTneXhheuT3eZOa2hfsihncE2errhfb11---WQrpYCErNwN730qt90Gb_CdjKxkPFYC1Ppuj1cZoBQyYGNMZRph70O-WGDNoSWGdk1rHYrxJSM&uniplatform=%20NZKPT)

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Research on Force Analysis and Path Planning of Flexible Needle Puncture Bending Modelling

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Abstract. Through the force analysis of the flexible needle puncture process, the corresponding mechanical model is established, and the main factors that cause the flexible needle bending deformation are analysed, and the bending model of the flexible needle puncture process is initially established. By discretizing the bending model, combined with experimental verification, a relatively complete bending model is obtained. Based on the RRT algorithm, the goal guidance algorithm, the optimal path selection algorithm, etc. are proposed, combined with the bending model of the flexible needle, and an improved RRT algorithm suitable for the flexible needle insertion method is established. Through simulation analysis and combined with experimental verification, it is concluded that path planning based on the improved RRT algorithm can bypass important human organs and soft tissues more flexibly, accurately puncture the target position, and achieve relatively safe surgery.

Keywords: Mechanical Modeling, Bending Modeling, Path Planning, Soft Tissue Puncture.

1. Introduction

Targeted puncture in minimally invasive surgery is to puncture a puncture needle into a designated position in the body, and perform tissue sampling, fixed-point drug delivery, or short-distance radiotherapy [1]. At present, the puncture needle widely used in clinical practice is a rigid straight needle. Because the diameter of the rigid needle is large, and the puncture force during the puncture process is relatively large, it is easy to cause large deformation of the soft tissue, which affects the accuracy of the operation, and the rigid needle in the process of puncture, it is very easy to puncture important tissues such as nerves and blood vessels, which aggravates the patient's pain [2]. Flexible needle puncture is very different from rigid needle puncture. Because the rigidity of the flexible needle is relatively small, the soft tissue damage is relatively small during the puncture process, and important nerves and blood vessels can be avoided relatively easily during the puncture process. Such important soft tissues have improved the safety and accuracy of targeted puncture [3].

The research on rigid needle puncture has been carried out relatively early. C. Simone et al used rigid needles to puncture isolated bovine liver through experiments, and studied the force distribution during the puncture process, and divided the puncture process into two parts: before puncture and after puncture
stage [4]. The force received during the puncture process is decomposed into three parts: surface stiffness force, cutting force and friction force, and an improved Karnopp friction model is used to model the friction force [5]. But there is no detailed analysis of the cutting force. Simon P. DiMaio et al studied the influence of rigid needle speed on force during puncture, and concluded through experiments that the cutting resistance at the tip of the needle is a concentrated force, which is basically not affected by the speed of puncture [6].

For the research of flexible needle puncture, Alhassan et al analyzed the influence of the puncture needle on the puncture force and the size of soft tissue deformation when the puncture needle is rotated, and proposed a more reasonable rotation needle control strategy to achieve a smaller puncture force and tissue deformation [8, 9]. Konh et al used LS-DYNA simulation analysis software to establish a simulation model for puncturing soft tissues, and obtained the relationship between the radius of curvature of the puncture needle and the bevel angle of the needle tip [10, 11].

In the research of path planning, Alperovitz et al used finite element software to divide the constructed human soft tissue model into a triangular mesh, and hypothesized and simulated the force on the soft tissue during the puncture process and the deformation model of the soft tissue and the puncture needle, and simulated different soft tissue puncture paths [13]. Regrettably, no experimental verification was performed on this model, only simulations were performed. Davneet S. Minhas et al realized the linear trajectory puncture by continuously rotating the needle shaft during the insertion of the flexible needle. Through experimental research, it is concluded that different needle entry trajectories can be achieved by changing the duty cycle of the rotating torque applied on the needle shaft [15, 16, 17].

Considering the complex biomechanical properties of soft tissues and organs, this article simplified the treatment of soft tissues: (1) The soft tissue is considered to be uniform and continuous; (2) It is isotropic; (3) During the puncture process, the process of soft tissue deformation is linear; (4) soft tissue has viscoelasticity; (5) quasi-incompressible. Comprehensive consideration of various factors, in order to simulate soft tissue as much as possible, and to make the experiment have a certain observability, in the choice of experimental materials, a transparent agar glue is used.

2. Establishment of mechanical model

2.1. Force analysis of flexible needle puncture

The force analysis of the flexible needle puncturing the soft tissue is relatively complicated. During the puncture process, the root of the flexible needle is subjected to the feeding force $F$ applied by the feeding mechanism. In order to ensure the smooth insertion of the needle and avoid the deformation of the puncture needle before puncturing the soft tissue, additional support is required at the needle insertion site, so additional support force $F_s$ and support friction force $F_{s,f}$ will be generated. Since the soft tissue has a clamping effect on the needle shaft, it will bring clamping force $F_n$ and clamping friction force $F_{n,f}$. The needle tip is subjected to the cutting reaction force $F_c$ and cutting friction force $F_{c,f}$ brought by the soft tissue when the soft tissue is cut, as shown in Fig.1. During the puncture process, part of the force will change as the puncture progresses.
Figure 1. Force analysis of the puncture needle

As shown in Fig. 2, it is the analysis of the local force at the needle tip of the puncture needle. During the puncture process, due to the asymmetric force received at the needle tip and the rigidity of the puncture needle itself is relatively small, it will be generated after the needle is inserted. Bending deformation, the needle tip deflection angle $\beta$ is the deflection angle of the tangential direction at a certain point on the needle shaft relative to the needle insertion direction, and $\alpha$ is the oblique angle of the needle tip.

Figure 2. Analysis of the local force on the needle tip

When the puncture needle material and soft tissue properties are fixed, the cutting reaction force $F_c$ can be regarded as a fixed value. During the puncture process, its direction has been changing, but in the local coordinate system at the needle tip, the direction of the cutting reaction force is always perpendicular to the inclined plane at the needle tip. Therefore, a model of the cutting reaction force $F_c$ is established:

$$ F_c = C $$

Where $C$ is a constant greater than zero.

The component forces of the cutting reaction force $F_c$ in the $X$ and $Y$ directions are:

$$ \begin{align*}
F_{c,x} &= F_c \sin(\alpha + \beta) \\
F_{c,y} &= F_c \cos(\alpha + \beta)
\end{align*} $$

Where $F_{c,x}, F_{c,y}$ are the component forces of the cutting reaction force in the $X$ and $Y$ directions respectively; $\alpha$ is the bevel angle of the needle tip; $\beta$ is the deflection angle at the needle tip.

According to Coulomb's law, a model of cutting friction $F_{c,f}$ is established:
\[ F_{c,f} = \mu F \]  

Where \( \mu \) is the friction coefficient between the soft tissue and the puncture needle, which is about 0.55.

The component forces of the cutting friction \( F_{c,f} \) in the X and Y directions are:

\[
\begin{align*}
F_{c,f,x} &= \mu F_{cx} \cos(\alpha + \beta) \\
F_{c,f,y} &= \mu F_{cy} \sin(\alpha + \beta)
\end{align*}
\]  

Since the puncture direction is constantly changing during the puncture process, in the local coordinate system of the needle axis, the clamping friction force is always along the axial direction, but in the world coordinate system, the direction of clamping friction is always changing. Assuming that the clamping friction force per unit length is \( f, \beta(x) \) is the deflection angle of the puncture needle at a certain point, and the clamping friction force per unit length \( f \) can be expressed as:

\[
\begin{align*}
f_x &= f \cos(\beta(x)) \\
f_y &= f \sin(\beta(x))
\end{align*}
\]  

Integrating the length with the above equation, the component force of the clamping friction force \( F_{n,f} \) in the X and Y directions can be obtained as:

\[
\begin{align*}
F_{n,f,x} &= \int_0^L f_x \, ds = \int_0^L f \cos(\beta(x)) \, ds \\
F_{n,f,y} &= \int_0^L f_y \, ds = \int_0^L f \sin(\beta(x)) \, ds
\end{align*}
\]  

Where \( L \) is the depth of the puncture needle inserted into the soft tissue; \( F_{n,f,x} \) and \( F_{n,f,y} \) are the component forces of the clamping friction in the X and Y directions respectively; \( ds \) is the unit length of needle shaft.

The puncture needle is analyzed when puncturing and withdrawing from the soft tissue, and the mechanical equilibrium equations of the two processes are established:

\[
\begin{align*}
F &= (F_{c,x} + F_{c,f,x}) + F_{n,f} + F_{s,f} & \text{puncturing} \\
F' &= F_{n,f} + F_{s,f} & \text{withdrawing}
\end{align*}
\]  

Where \( F \) is the feed force applied during puncture; \( F' \) is the external force applied during withdrawal; \( F_{c,x} \) and \( F_{c,f,x} \) is cutting reaction force \( F_c \) and cutting friction force \( F_{c,f} \) component force in the X direction; \( F_{n,f} \) is the clamping friction force; \( F_{s,f} \) is the support friction force.

### 2.2. Cutting reaction force measurement

Since it is not convenient to measure the cutting reaction force in the case of bending deformation, other methods are used for measurement. When the puncture needle material and soft tissue properties are certain, the cutting reaction force is basically a certain value. Here, a combination of rigid needle and flexible needle is used for measurement.

The outer diameter of the selected and rigid needle is equal to the inner diameter of the flexible needle. The rigid needle is placed inside the flexible needle to play a supporting role, ensuring that the
flexible needle does not deform during the puncture process, but the tip of the flexible needle is still involved in cutting soft tissue, the force analysis is shown in Fig. 3.

![Figure 3. Force analysis of cutting reaction force measurement](image)

Establish the force balance equation when puncturing and withdrawing from the soft tissue:

\[
\begin{align*}
F &= (F_{e,x} + F_{c,f,x}) + F_{n,f} & \text{puncturing} \\
F' &= F_{n,f} & \text{withdrawing}
\end{align*}
\]  

(8)

Where \( F_{e,x} = F_c \sin \alpha \), \( F_{c,f,x} = \mu F_{e,x} = \mu F_c \cos \alpha \). Substituting equation (8) to get:

\[
\begin{align*}
F &= (F_c \sin \alpha + \mu F_c \cos \alpha) + F_{n,f} & \text{puncturing} \\
F' &= F_{n,f} & \text{withdrawing}
\end{align*}
\]  

(9)

Subtracting the force during puncture and withdrawal can get:

\[F - F' = F_c \sin \alpha + \mu F_c \cos \alpha\]  

(10)

Based on equation (10), the feedback force during puncture and withdrawal of the puncture needle at a puncture depth of 20 mm was measured, as shown in Fig. 4 and Fig. 5. Fig. 4 shows the feedback force during the puncture process, and Fig. 5 shows the feedback force during the withdrawal process.

By comparing and analyzing the data in Fig. 4 and Fig. 5, the difference between the two parts of the data can be obtained, that is, the value of \( F - F' \), as shown in Fig. 6. Combining equation (10) can get the cutting reaction force \( F_c \) during the puncture process. Since the cutting reaction force \( F_c \) in the puncture process is basically a certain value, processing the obtained data, it can be concluded that the cutting reaction force is about 0.3N.
2.3. Factors that cause bending deformation

Although the force applied during the entire puncture process is more complicated, after detailed analysis of each force, it is found that the force causing the bending deformation of the needle shaft is concentrated at the needle tip, and the needle shaft is subjected to clamping forces from all directions of the soft tissue. The vector sum is zero, which basically does not affect the bending of the needle shaft.

Re-analyze the force on the needle tip, and re-decompose the cutting reaction force $F_c$, and the cutting friction force $F_{c,f}$ into component forces along the radial and axial directions, as shown in Fig. 7.
Figure 7. Force analysis at the tip of the needle

According to the force balance:

\[
\begin{align*}
F_{c,a} &= F_c \sin \alpha \\
F_{c,r} &= F_c \cos \alpha \\
F_{c,f,a} &= \mu F_{c,r} = \mu F_c \cos \alpha \\
F_{c,f,r} &= \mu F_{c,a} = \mu F_c \sin \alpha \\
P &= F_{c,r} - F_{c,f,r} = F_c \cos \alpha - \mu F_c \sin \alpha
\end{align*}
\]

Where \( P \) is the resultant external force in the radial direction.

It can be seen from the force analysis that the axial component forces \( F_{c,a} \) and \( F_{c,f,a} \) at the tip of the needle only exert a compressive effect on the puncture needle, the resultant force \( P \) of the two radial components \( F_{c,r} \) and \( F_{c,f,r} \) is the main factor causing the deflection of the puncture needle.

The bending stiffness \( B \) is:

\[
B = EI = \frac{M}{1} = \frac{M}{k}
\]

Where \( E \) is the modulus of elasticity; \( I \) is the moment of inertia; \( k \) is the curvature; \( r \) is the radius of curvature; \( M \) is the bending moment; \( M = Pl \).

Therefore, the curvature calculation formula is:

\[
k = \frac{Pl}{EI} = \frac{F_c (\cos \alpha - \mu \sin \alpha)l}{EI}
\]

Where \( F_c \) is the cutting reaction force; \( l \) is the bending length of the needle shaft; \( \alpha \) is the bevel angle of the needle tip.

From equation (15), it can be seen that under the condition of constant cutting reaction force, the arc of the needle shaft deflection is an arc of constant curvature.
3. Establishment of mechanical model

According to the previous force analysis, in the world coordinate system, the force direction at the tip of the needle will change as the puncture progresses. If the entire flexible needle is calculated by the bending model, it will cause a big error. Since the feed of the puncture needle is uniform and slow during the entire puncture process, the entire puncture process can be regarded as quasi-static, so the entire puncture process can be discretized.

If the whole process of puncture is discretized, each segment can be regarded as a new cantilever beam structure, and the end of each segment can be regarded as a new needle insertion point, and the direction of the needle is the same as the direction of the needle axis at that position. Because of the clamping force of the soft tissue, the new needle entry point can also be regarded as having the same support. As shown in Fig. 8 and Fig. 9, they represent the discrete process of needle penetration depths of $\Delta L$ and $2\Delta L$ respectively in the case of discrete processing.

Let the coordinates of the origin (needle entry point) $O_0$ in the world coordinate system $XOY$ be $p_0(x_0, y_0)$, and the position of the needle tip in the world coordinate system $XOY$ after deformation is the coordinate $p_1(x_1, y_1)$:

$$p_1 = \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} x_0 + \Delta L - u \\ y_0 - \omega \end{bmatrix}$$

(16)

For the convenience of calculation, the world coordinate system $XOY$ is coincident with the local coordinate system $X_0Y_0Z_0$ at the needle entry position. At this time, the position coordinate of the needle tip in the world coordinate system $XOY$ after deformation is $p_1(x_1, y_1)$:

$$p_1 = \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \begin{bmatrix} \Delta L - u \\ -\omega \end{bmatrix}$$

(17)

In each subsequent process, the puncture end point of the previous section can be used as the new needle entry point, and the corresponding local coordinate system can be established. Take the second puncture section as an example, and the end point of the first puncture section as the new needle entry point and establish a local coordinate system $X_1Y_1Z_1$.

The transformation matrix of the second local coordinate system $X_1Y_1Z_1$ relative to the world coordinate system $XOY$ is:
\[0T = \text{Trans}(P_1) \text{Rot}(z,-\varphi) = \begin{bmatrix}
1 & 0 & 0 & \Delta L - u \\
0 & 1 & 0 & -\omega \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
\cos(-\varphi) & -\sin(-\varphi) & 0 & 0 \\
\sin(-\varphi) & \cos(-\varphi) & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (18)

After the second puncture, the position coordinate \(p_2(x_2, y_2)\) of the needle tip in the world coordinate system \(XOY\) is:

\[p_2 = 0T_2 p_1\] (19)

After \(n\) puncture, the position coordinate \(p_n(x_n, y_n)\) of the needle tip in the world coordinate system \(XOY\) is:

\[p_n = 0T_1 T_2 T_3 \ldots T_n p_1\] (20)

4. Establishment of mechanical model
Since the rapid random number search (RRT) algorithm is a path search based on a polyline, considering the feasibility of the RRT algorithm, the RRT algorithm needs to be improved, and the bending model of the flexible needle is introduced into the RRT algorithm. Replace the polyline path in the RRT algorithm with a circular arc or a straight trajectory, and ensure that the trajectory is continuous and differentiable.

**Target guidance algorithm:** Due to the low efficiency of the search strategy of the RRT algorithm, there is a lot of blindness. The target guidance algorithm is added to the improved algorithm, so that each iteration is moving toward the target position.

**Optimal path selection algorithm:** The choice of the optimal path is not random, but should be selected according to the actual situation. The optimal path must first ensure a certain safe distance from the organs and tissues to be avoided, and secondly, in order to reduce the damage to the soft tissues, under the premise of ensuring a safe distance, the optimal path should be the shortest puncture distance.

The improved RRT algorithm mainly optimizes the polyline path in the original algorithm to make it follow the feasible trajectory of the flexible needle, and adds the target guidance algorithm to make it move toward the target position in each iteration. Combined with the optimal path selection algorithm, the path that causes the least damage to the soft tissue can be accurately planned.

5. Experiment and results
5.1. Bending deformation simulation
This article uses a 25G stainless steel puncture needle with a length of 60mm and a tip angle of 30°. The 25G puncture needle has an outer diameter of 0.5mm and an inner diameter of 0.25mm, and the elastic modulus of the puncture needle is about 134GPa, as shown in Fig. 10.

**Figure 10.** 25G puncture needle

Based on the theories of the first two parts, combined with equation (15) and the discretized bending model, a simulation experiment is carried out. The bending deformation under the condition that the unit discrete length is 4mm, 6mm, 8mm, and 10mm are simulated respectively, as shown in Fig. 11.
5.2. Bending deformation simulation

5.2.1. Selection of experimental materials. At present, the material selected for the simulation of soft tissue must be close to the real soft tissue, and in order to facilitate the observation of the bending deformation of the puncture needle, the material should have a certain degree of transparency. The material selected in this article is transparent agar gel, as shown in Fig. 12.

![Agar gel for experiment](image)

**Figure 12.** Agar gel for experiment

5.2.2. Experimental platform construction and experimental process. First, use a level to calibrate the platform horizontally to ensure that the puncture needle is horizontally punctured into the simulated tissue. As shown in Fig. 13, the 5mm×5mm grid paper is then used for calibration. On the one hand, it is to ensure that the puncture needle is fed along a straight line, and on the other hand, the bending deformation can be clearly measured based on the grid paper.

![Horizontal calibration of the experimental platform](image)

**Figure 13.** Horizontal calibration of the experimental platform

The construction of the experimental platform is shown in Fig. 14, where the puncture needle coincides with the grid line. The main function of the platform is to ensure that the puncture needle will not be deformed before puncturing the soft tissue, play a certain supporting role, and also ensure that the puncture needle is fed in the horizontal direction. The 5mm×5mm grid paper can easily measure the bending deformation. Since the puncture experiment designed in this paper is a puncture on a plane, it is necessary to adjust the orientation of the bevel of the needle tip.
The puncture experiment is carried out by using the built experimental platform. The entire puncture process is a uniform speed process, the puncture speed is 4mm/s, the puncture depth is 60mm, and the bending deformation of each time is measured by the calibration grid through multiple experiments.

5.2.3. Experimental results and analysis. The results of the experiment are shown in Fig. 15. According to the data recorded in multiple experiments, the deflection at the needle tip is about 5mm in the case of a 60mm puncture.

Compared with the simulation experiment, it can be seen that when the discrete length $\Delta l=6$mm, it is the closest to the actual puncture curve, which verifies the feasibility of the bending model.

5.3. Feasibility analysis of path planning

5.3.1. Simulation analysis. Based on the simulation and experiment in the previous section, the simulation is carried out under the condition of discrete length $\Delta l=6$mm. When the puncture needle penetrates 30mm into the agar glue, rotate the puncture needle 180°, change the direction of force at the needle tip, and then continue to puncture, and the simulation results are shown in Fig 16.
5.3.2. Experimental result. During the experiment, when the puncture needle penetrated 30mm into the agar, the puncture needle was rotated 180°. The puncture path obtained through the experiment is shown in Figure 17. Comparing Figure 16 and Figure 17, it is believed that the puncture needle path planning is feasible in actual puncture.

Since the puncture needle used in the experiment has a relatively large stiffness (134GPa), the radius of curvature of the puncture will be large, and the bending deformation will not be very obvious. If a puncture needle with a small rigidity is used, a puncture path with a smaller radius of curvature can be obtained, and the effect of path planning will be more obvious.

5.4. Path planning simulation
The simulation experiment of path planning is carried out in a two-dimensional plane. The set simulation environment range is 300mm×300mm, the position coordinate of the needle entry point is (150, 0), and the position coordinate of the target point is (170, 260). The obstacle coordinates to be set are: (90, 170), (150, 100), (200, 200), and the radii are: 30mm, 20mm, 25mm.

First, the simulation is performed without adding the target guidance algorithm and the optimal path selection algorithm. The simulation path is represented by a thin blue line, as shown in Fig. 18. Each simulation generates a path, a total of 60 simulations are carried out, and all the simulation results are synthesized. It can be seen from the simulation experiment that although the path can also be obtained, it is not the optimal result, and the path has great randomness.

After adding the target guidance algorithm and the optimal path selection algorithm, each iteration of the algorithm is toward the target point, which greatly reduces the randomness of the path. Through experiments, a definite path can be obtained, as shown by the thick red line in Fig. 18.
6. Conclusion
First of all, this paper analyzes the force of the flexible needle puncture soft tissue, establishes the mechanical model of the puncture needle, analyzes the main factors of the bending deformation of the puncture needle, and constructs the bending deformation model of the puncture needle. The bending deformation simulation under different discrete lengths was carried out, and the correctness and accuracy of the bending model was verified through experiments. Then, based on the kinematics model of the flexible needle, the basic RRT algorithm is improved, and the polyline search is optimized to a circular arc search or a straight-line search to ensure the continuous differentiability of the trajectory. And add the goal guidance algorithm, the optimal path selection algorithm, etc., to clarify the direction of the path planning, so that in the search process, the direction is always the location of the target point. Path planning based on the improved RRT algorithm can bypass important human organs and soft tissues more flexibly, accurately puncture the target location, and achieve relatively safe surgery.

Since the experiment in this article is only for the study on the two-dimensional plane, it has not been extended to the three-dimensional space. In the subsequent research, the experiment in the three-dimensional space should also be carried out. The friction caused by the rotation of the needle shaft should also be considered in the new model to establish a complete three-dimensional space path planning model.

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