Modeling of geometry and insertion force of a new lancet medical needle

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Abstract

Lancet needle is a typical medical treatment device. Its tip consists of two lancet planes and one bevel plane. When the lancet needle is inserted into soft organ tissue, the insertion force may influence the needle cutting direction and treatment effect and increase the pain. One of the main factors affecting this insertion force is the geometry of the needle tip. Based on the research on the shape and processing method of the conventional lancet needle, a new lancet needle tip geometry was obtained by adjusting the relative position of the grinding wheel to the needle. A mathematical model of this new lancet needle was established. The relationship between processing parameters and needle shape was analyzed, and the needle insertion force was predicted. Compared with the conventional lancet needle, the new lancet needle is sharper, and the insertion force on the cutting edge is smaller. However, this change in the grinding position of the needle lancet plane has a great influence on the shape of needle tip near the intersection of the bevel plane and the lancet plane. Some special second bevel angle and rotated angle will cause a large change in the specific force at the intersection place, which is not conducive to reducing the insertion force.

Keywords

Lancet needle, insertion force, cutting edge geometry, grinding, mathematical model

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Introduction

Medical needles are widely used in medical treatment for injection or blood sampling purposes.1–3 When the needle is inserted into a human organ, an insertion force is generated between the needle and the organ tissue. This force may influence the needle inserting direction3–5 or increase pain.5–10 Therefore, it is important to reduce or minimize it for achieving better medical treatment. The sharpness of the needle tip is closely related to the insertion force. Li et al.11 polished the needle using the magnetic abrasive finishing technique and then measured the axial force—including tip cutting force, inner friction force, and outer friction force—during insertion of a hollow needle into a tissue-mimicking sample. The results showed that unpolished needles had a tip cutting force 22% higher than polished needles. Needle insertion in soft tissue is essentially similar to a knife cutting. The insertion force greatly depends on the needle tip’s cutting-edge geometry.12–23 On the basis of the geometry of the needle tip and its fabrication method, two parameters—inclination angle and rake angle—are used to develop the mathematical models of needle.12,14–18 Many studies have been conducted about the insertion force of needle.21–31 Moore et al.20 developed a predictive force model based on the inclination angle and the rake angle of a needle’s cutting edge to predict the insertion force and studied a novel needle cutting-edge geometry for end-cut biopsy and curved needle tips based on rake and inclination angles.13–15 The rake angle is the angle of the rake face with respect to the perpendicular to the cut surface. It is believed that a larger inclination angle will lead to a lower cutting force and a larger rake angle will lead to a sharper needle edge.10,14,15,17,21

Currently, there exists a wide variety of needle tip geometries. Lancet needle usually has complicated cutting edges,16,18,24 which are generated by the intersection of the needle tube surface and the bevel plane or the needle tube and lancet plane. A rake angle together with the inclination angle and edge radius properly describes the cutting edge.17,24 Studies have been conducted to investigate the effects of needle tip geometry on the insertion force and needle sharpness.12–18,25–31 Chebolu et al.25 investigated the relationship between the insertion forces and the cutting-edge geometry and proposed two novel needles. Wang et al.24 described the fabrication procedure of the conventional lancet needle and developed a mathematical model to calculate the inclination and rake angles along the cutting edge of this needle.

In this article, after gaining an in-depth understanding of the definition of lancet needle geometry and the relationship between needle fabrication parameters and insertion force, based on the studies of the conventional lancet needle, a new lancet needle tip geometry was proposed in order to achieve a smaller insertion force. The fabrication parameters of this new lancet needle were described and its mathematical models were developed to calculate the inclination and rake angles along the cutting edges. The shape of this new lancet needle was studied. The specific forces on the cutting edge were calculated. The insertion force is the sum of the specific force in the cutting edge and leading edge. The insertion force of the new lancet needle was studied, and it is found that the insertion force produced by this new
lancet needle during insertion into tissue is lower than that produced by the conventional lancet needle with the same fabrication parameters.

**Needle geometry**

There are three main parameters in processing a lancet needle—bevel angle, second bevel angle, and rotated angle. The conventional lancet needle, as shown in Figure 1, is fabricated in four steps. In step 1, the needle tube is grinded along a bevel angle $\delta$. Point $P$ is the highest point of the intersection line of the first grinding plane and the needle tube outer surface. In step 2, the grinding plane rotates to a secondary bevel angle $\varphi$ and the grinding wheel touches the needle tip point $P$. In step 3, the grinding plane rotates along the needle tube centerline by an angle $\beta$ and the grinding wheel is moved down by an offset distance $l$ to grind the first lancet (this $l$ is a value along the needle tube centerline, not the $l$ in Wang et al.24). In the fourth step, the grinding plane rotates along the needle tube centerline by an angle $2\beta$ in the opposite direction and the grinding wheel is ground at the same height to grind the second lancet. The tip point $C$ is the intersection of the third grinding plane, the fourth grinding plane, and the outer tube of needle. And point $C'$ is the intersection of the third grinding plane, the fourth grinding plane, and the inner tube of needle.

In this article, we fabricate the needle tip geometry by changing the third and the fourth grinding plane positions. As shown in Figure 2, in step 1, the needle tube is grinded along a bevel angle $\delta$, as described in Figure 1. In step 2, point $P$ is moved along the $Z$ direction $l$ distance to point $C$ and grinding needle tube along the second bevel by angle $\varphi$. In step 3, the grinding wheel rotates along tilt line $CC'$ by angle $\beta$ to grind the first lancet. Tilt line $CC'$ is the intersection of the second grinding plane and needle tube. In step 4, the grinding plane rotates along the tilt line $CC'$ by an angle $2\beta$ in the opposite direction to grind the second lancet.
Mathematical model and parameter analysis of new lancet needle

Mathematical model

The parameter $\gamma$ marks the angular position of a point on the cutting edge in the $xy$-plane measured from the $x$-axis, as shown in Figure 3(a). The inclination angle $\lambda$ is defined as the angle between the tangent to the cutting edge and the plane
perpendicular to the cutting direction, as shown in Figure 3(a). The rake angle \( \alpha \) is defined as the angle between the plane perpendicular to the cutting direction and the plane of the needle tip face surface measured in the plane with normal vector that tangent to the cutting edge. Vector \( a \) is the intersection line of plane \( Pn \) and \( Pr \), and vector \( b \) is the intersection line of plane \( Pn \) and \( Ar \). \( Pr \) is the plane at the cutting point and parallel to the \( xy \)-plane. \( Ar \) is the face plane of the needle tip surface. \( Pn \) is a plane with a normal vector \( s \), vector tangent to the cutting edge.

As mentioned by Han et al., the parametric equation of the first grinding plane with a needle of radius \( r \) is given by

\[
x = r \cos \gamma \\
y = r \sin \gamma \\
z = r(1 - \cos \gamma) \cot \delta
\]

For the second grinding plane, its parametric equation can be given by

\[
x = r \cos \gamma \\
y = r \sin \gamma \\
z = z_c - r(1 + \cos \gamma) \cot \varphi \\
z_c = 2r \cot \delta - l
\]

From the parametric equation of the first and the second grinding planes, the normal vector of the first plane at a point on the cutting edge is \( n_f = [\cos \delta, 0, \sin \delta] \) and the normal vector of the second grinding plane at a point on the cutting edge is \( n_s = [\cos \varphi, 0, \sin \varphi] \).

According to the principle of graphic transformation, the normal vector \( n_t \) of the third grinding plane at a point on the cutting edge is given by

\[
n_t = n_s \cdot T
\]

\[
T = T_y \cdot T_z \cdot T_y'
\]

\[
T_y = \begin{bmatrix}
\cos \varphi & 0 & -\sin \varphi \\
0 & 1 & 0 \\
\sin \varphi & 0 & \cos \varphi
\end{bmatrix}
\]

\[
T_z = \begin{bmatrix}
\cos \beta & \sin \beta & 0 \\
-\sin \beta & \cos \beta & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
T_y' = \begin{bmatrix}
\cos(-\varphi) & 0 & -\sin(-\varphi) \\
0 & 1 & 0 \\
\sin(-\varphi) & 0 & \cos(-\varphi)
\end{bmatrix}
\]
Therefore

\[
n_t = \begin{bmatrix} \cos \phi & 0 & -\sin \phi \\ 0 & 1 & 0 \\ \sin \phi & 0 & \cos \phi \end{bmatrix} \begin{bmatrix} \cos \beta & \sin \beta & 0 \\ -\sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos(-\phi) & 0 & -\sin(-\phi) \\ 0 & 1 & 0 \\ \sin(-\phi) & 0 & \cos(-\phi) \end{bmatrix}
\]

\[
= [\cos \beta \cos \phi, \sin \beta, \cos \beta \sin \phi]
\]

(10)

Then, the parametric equation of the third grinding plane is given by

\[
x = r \cos \gamma
\]

(11)

\[
y = r \sin \gamma
\]

(12)

\[
z = -\left(\frac{r \cos \beta \cos \phi \cos \gamma + r \sin \beta \sin \gamma + r \cos \beta \cos \phi + z_c \cos \beta \sin \phi}{\cos \beta \sin \phi}\right)
\]

(13)

The tangent vector at a point on the lancet plane cutting edge can be expressed as

\[
s = \begin{bmatrix} -\sin \gamma, r \cos \gamma, -r(\cos \gamma \sin \beta - \cos \beta \cos \phi \sin \gamma) \\ \cos \beta \sin \phi \end{bmatrix}
\]

(14)

As shown in Figure 3(b), vectors \( a \) and \( b \) are defined using the cross-products of the normal vectors \( s \) and \( n_t \). The plane \( Pr \) is parallel to the \( xy \)-plane and has a normal vector \( v = [0, 0, 1] \). The rake angle for a lancet needle is the angle between vectors \( a \) and \( b \):

\[
\alpha = \arccos \frac{a \cdot b}{||a|| ||b||}
\]

\[a = s \times n_t\]

\[b = s \times v\]

The inclination angle and rake angle along the cutting edge of the new lancet needle are given below:

In Section 2 (lancet plane)

\[
\alpha = \pi - \arccos \left(\frac{c}{\sqrt{d}}\right)
\]

(15)

\[
c = \left|(\cos \gamma \cos^2 \beta \cos^2 \phi + \sin \gamma \sin \beta \cos \beta \cos \phi - \cos \gamma)^2\right|
\]

\[
+ \cos^2 \beta \sin^2 \phi |\sin \gamma \sin \beta + \cos \gamma \cos \beta \cos \phi|^2 + |\cos^2 \beta | \cos \beta \sin \gamma - \cos \gamma \cos \phi \sin \beta |^2
\]

\[
d = (\cos^2 \gamma \cos^2 \beta \cos^2 \phi - \cos^2 \beta \sin^2 \gamma - \cos^2 \gamma + 2 \cos \gamma \cos \beta \cos \phi \sin \beta \sin \gamma)\]
\[
\lambda = 90 - \arccos\left(\frac{\mathbf{v} \cdot \mathbf{s}}{||\mathbf{v}|| \cdot ||\mathbf{s}||}\right) = \arcsin\left(\frac{\mathbf{v} \cdot \mathbf{s}}{||\mathbf{v}|| \cdot ||\mathbf{s}||}\right)
\]

\[
= - \arcsin\left(\frac{\cos\gamma \sin\beta - \cos\beta \cos\phi \sin\gamma}{\sqrt{\cos^2\gamma \cos^2\beta \sin^2\phi + \sin^2\gamma \cos^2\beta \sin^2\phi + \cos^2\gamma \cos^2\beta \phi}}\right)
\]

(16)

In Section 1 (bevel plane)

\[
s = [-\sin\gamma, r \cos\gamma, r \sin\gamma \cot\delta]\n\]
\[
n_t = n_f = [\cos\delta, 0, \sin\delta]
\]

\[
\alpha = \arccos\left(\sqrt{\cos^2(\gamma - \beta) \sin^2\phi + \sin^2(\gamma - \beta)}\right)
\]

\[
\lambda = \arcsin\left(\frac{\cot\phi \sin(\gamma - \beta)}{\sqrt{1 + \cot^2\phi \sin^2(\gamma - \beta)}}\right)
\]

(17)

(18)

As shown in Figure 4, line \(EF\) is the intersection of the lancet plane and the bevel plane or the intersection of the third grinding plane and the second grinding plane. Line \(PB\) (the intersection of the first grinding plane and the \(xz\)-plane) and line \(CD\) (the intersection of the second grinding plane and the \(xz\)-plane) cross at point \(D\).

The function of line \(PB\) is \(z = (r - x) \cot\delta\);

The function of line \(CD\) is \(z = z_c - (r + x) \cot\phi\);

Therefore, the coordinate of point \(D\) is

\[
x_D = \frac{r \cot\delta - z_c + r \cot\phi}{\cot\delta - \cot\phi}
\]

(19)

\[
y_D = 0
\]

(20)

\[
z_D = \left(\frac{r - r \cot\delta - z_c + r \cot\phi}{\cot\delta - \cot\phi}\right) \cot\delta
\]

(21)

The direction \(n_m\) of line \(DE\) is the cross-product of normal vectors of the first grinding plane \(n_f\) and normal vectors of the third grinding plane \(n_t\) in the \(XYZ\) coordinate

\[
n_m = n_f \times n_{th} = \left[\sin\delta \sin\beta, \frac{\sin(\delta + \beta - \phi)}{2} - \frac{\sin(\delta - \beta - \phi)}{2}, -\cos\delta \sin\beta\right]
\]

(22)

Then, the slope \(m\) of the intersection of the first grinding plane \(n_f\) and third grinding plane \(n_t\) in the \(xy\)-plane can be expressed as the ratio of the second element to the first element of vector \(n_m\)
\[ m = -\frac{\sin(\delta + \beta - \varphi) + \sin(\delta - \beta - \varphi)}{2\sin\delta \sin\beta} \] (23)

Since line \( FE \) passes through point \( D \), the function of line \( FE \) in Figure 4(b) can be expressed as \( y = (x - x_D)m \).

The intersection point \( E \) in the \( xy \)-plane is given by

\[
\begin{cases}
  y = (x - x_D)m \\
  x^2 + y^2 = r^2
\end{cases}
\]

Therefore

\[ \gamma_E = \arccos\left(\frac{x_E}{r}\right) \] (24)

\[ x_E = x_D m + \sqrt{r^2 - m^4 x_D^2 + m^2 r^2 \over 1 + m^2} \] (25)

For the conventional lancet needle, the inclination angle \( \lambda \) and the rake angle \( \alpha \) for cutting edge in Section 1 and Section 2, respectively, are\(^{11}\)

In Section 1

\[ \lambda = \arcsin \left(\frac{\cot\delta \sin\gamma}{\sqrt{1 + \cot^2\delta \sin^2\gamma}}\right) \] (26)
\[ \alpha = \arccos \sqrt{\cos^2 \gamma \sin^2 \delta + \sin^2 \gamma} \]  

In Section 2

\[ \lambda = \arcsin \frac{|\cot \varphi \sin (\gamma \pm \beta)|}{\sqrt{1 + \cot^2 \varphi \sin^2 (\gamma \pm \beta)}} \]  

\[ \alpha = \arccos \sqrt{\cos^2 (\gamma \pm \beta) \sin^2 \varphi + \sin^2 (\gamma \pm \beta)} \]  

\[ m = \frac{\cos \delta \sin \varphi - \sin \delta \cos \beta \cos \varphi}{-\sin \delta \sin \beta \cos \varphi} = \frac{\cos \beta - \cot \delta \tan \varphi}{\sin \beta} \]  

\[ \gamma_e = \arccos \left( \frac{1 - m^2}{1 + m^2} \right) \]  

Parameters analysis

The shape and size of the new lancet needle are determined by parameters used to fabricate it. The change in the inclination angle and the rake angle on the cutting edge reflects the effect of fabrication parameters on the size and shape of the needle tip. In this part, the relationship between needle mathematical model, needle shape, size, and fabrication parameters will be discussed. The inclination angle curve and the rake angle curve of cutting edge of the new lancet needle and the conventional lancet needle will be drawn based on the derived equations.

Offset distance \( l \). Figure 5 shows the needles fabricated with different offset distance \( l \). The needle tip geometry is composed of two kinds of plane: bevel plane and lancet planes. With the decrease of \( l \), the needle tip length and the bevel plane length increase and the length of leading edge \( CC' \) decreases. A small portion of the bevel plane appears besides point \( C' \) when \( l \) is smaller than 0.9785 mm. Distance \( l \) significantly affects the size of the needle tip geometry but slightly affects the shape of the lancet plane.
Bevel angle $\delta$. The $\delta$ can affect the shape and length of the needle bevel plane. Figure 6(a) shows the lancet needles fabricated with various $\delta$, and Figure 6(b) and (e) shows the rake angle for the new lancet needle and the conventional needle. Based on the research results derived by Moore et al.\textsuperscript{13–15} and Wang et al.,\textsuperscript{24} a larger inclination angle will lead to a small insertion force and a larger rake angle $\alpha$ represents a sharper cutting edge. The rake angle along the cutting edge in Section 2 and the area of the lancet plane of the new lancet needle is larger than that of the conventional needle. The new lancet needle is sharper than the
conventional needle when they are fabricated with same $\delta$. With the increase of $\delta$, the length of the bevel plane and cutting edge $EF$ increases and the length of the leading edge $CC'$ decreases, as shown in Figure 6(a) and (d). $\delta$ affects the position of transition point $E$. Correspondingly, the inflection point on the rake angle curve and the inclination angle curve moves forward. The $\gamma$ values for transition point $E$ of different new lancet needles are $75^\circ$, $87^\circ$, and $94^\circ$ for $\delta = 13^\circ$, $15^\circ$, and $16^\circ$, respectively. This leads to that the lancet plane becomes smaller. Relatively, $\delta$ has a little effect on the position of transition point of the conventional lancet needle, as shown in Figure 6(e) and (f). The inclination angle along the cutting edge of the new lancet needle in Section 2 is larger than that of the conventional lancet needle. $\delta$ has a larger effect on rake angle than inclination angle in Section 1, but no effect on both angles in Section 2. Therefore, $\delta$ can affect the size of the needle bevel plane and the lancet plane but does not have a larger effect on the inclination and rake angle of the needle. The rake angle of the new lancet needle is obviously larger than the rake angle of the conventional lancet needle when they have same bevel angle.

Second bevel angle $\varphi$. Figure 7(a) shows the new lancet needles with various $\varphi$. $\varphi$ has an obvious effect on the entire length of the conventional lancet needle tip and the shape of both kinds of needles, especially on the shape of the lancet plane. This can be proved by the position change of the transition point $E$ and the inflection point position change on the rake angle curve and inclination angle curve in Figure 7(b) and (c). When $\varphi = 25^\circ$, the curvature of the cutting edge $CC'$ is the largest and the lancet plane is much larger than the other planes, which results in a larger taper of the entire tip. For both the new lancet needle and the conventional lancet needle, the inclination angle of the needle with smaller $\varphi$ is larger than the inclination angle of the needle with larger $\varphi$. However, the inclination angles of all the new lancet needle are larger than those of the normal needles when they have same $\varphi$. For the new lancet needle, when $\varphi = 25^\circ$, the angle $\gamma$ for transition point is about $45^\circ$ and the inclination angle is $-41.125^\circ$, which means that the lancet plane in Section 2 is larger and the curvature of cutting edge $CE$ changes dramatically. A smaller or negative inclination angle means the needle is blunt. When $\varphi = 55^\circ$, the angle $\gamma$ for the transition point is about $108^\circ$ and the inclination angle is $50.304^\circ$. For the conventional lancet needle, when $\varphi$ changes from $25^\circ$ to $55^\circ$, $\gamma$ changes from $77^\circ$ to $83^\circ$, which proves that $\varphi$ has less influence on the position of the transition point. In fact, $\varphi$ has less effect on the inclination angle and the rake angle of cutting edge in Section 1.

Rotated angle $\beta$. Figure 8(a) shows the new lancet needles grinded with various $\beta$. The position of point $E$ on the new lancet needle shows that $\beta$ does not affect the whole length of the needle tip and leading line $CC'$ but affects the position of transition line $EF$. When $\beta$ changes, the shape of the new lancet needle changes significantly. When $\beta = 45^\circ$, $55^\circ$, and $65^\circ$, the angle $\gamma = 82^\circ$, $69^\circ$, and $56^\circ$. The influence of $\beta$ on the inflection point on the curve of the rake angle and the inclination angle of the new lancet is greater than that of the conventional lancet needle, as shown in
In Section 1, $\beta$ does not affect the rake angle and the inclination angle for both kinds of needles. In Section 2, when having the same $\beta$, the inclination angle of the new lancet needle is greater than the inclination angle of the conventional lancet needle and the rake angle of new lancet needle is obviously larger than the rake angle of the conventional lancet needle. For the new lancet needles, when $\beta$ increases, the lancet plane of the needle becomes larger and more of the needle tube is grinded away. The inclination angle near the transition point changes drastically. Therefore, even if most of the points on the new lancet needle cutting edge have a larger inclination angle and the needle is sharper near the needle tip point, it is not
sharper near the intersection of the bevel and the lancet plane. The inclination angle is small near line \( EF \) in Section 2. In short, for the new lancet needle, even a larger \( \beta \) will result in a larger inclination angle and rake angle in Section 2, but it will also result in a very small or negative inclination angle near the transition line. As shown in Figure 8(B), for conventional lancet needle, the position of line \( EF \) on different needles is different, but the angle \( \gamma \) of the inflection point on the inclination curve and the rake curve of different needles only have a small change.

Figure 8. Needles produced with different rotated angles: \( l = 0.9785, \delta = 15^\circ \), and \( \varphi = 35^\circ \). (I) New lancet needles and (II) conventional lancet needles. (a) tip geometry for new lancet needles; (b) rake angle for new lancet needles; (c) inclination angle for new lancet needles; (d) tip geometry for conventional lancet needles; (e) rake angle for conventional lancet needles; (f) inclination angle for conventional lancet needles.
Specific force

It has already been demonstrated that the inclination angle and the rake angle can significantly affect the insertion force.12–16 As shown in Figure 3, when needle moves along the cutting direction, after tip point $C$ is inserted into organ tissue, the leading edge $CC'$ and cutting edge curve $CE$ cut open the tissue, then the cutting curve edge $FF$ of the bevel plane in Section 1 will cut into the tissue16 and the needle tube gets inserted. The size of the wound on the inserted tissue surface is determined by the needle tube size, needle tip shape, and the angle between needle cutting direction and inserted tissue surface. The insertion force consists of two parts: the first is the friction between needle tube outer surface and organ tissue, and the second, more important, is the cutting force of needle tip.17–20 In Section 2, the cutting edge is curve $CE$. In Section 1, the cutting edge is curve $FF$ (the intersection of needle inner tube and first grinding plane). Moore et al.20 proposed a model in equation (31) with inclination angle and rake angle as parameters to predict the specific force of every point on the cutting edge of the needle along the inserting direction based on experiment result

$$f(\lambda, \alpha) = -0.042 + 0.296\lambda + 0.298\alpha - 0.255\lambda^2 - 0.408\alpha$$

$$-0.011\alpha^2 + 0.083\lambda^3 + 0.118\alpha^2 + 0.080\lambda\alpha^2 - 0.059\alpha^3[N/mm] \tag{31}$$

When the needle cuts open organ tissue, the organ tissue will only contact with the lancet cutting edge or contact with both the cutting edge $CE$ of the lancet plane and the cutting edge $FF$ of the bevel plane, which will be determined by the inserting angle (the angle between the needle centerline and cutting direction) and tissue property. Therefore, the insertion force is the sum of the specific force in cutting edge and the leading edge in equation (32)

$$F_N = F_C + F_L = 2S_1 \int_\gamma^\pi f(\lambda, \alpha) r_f d\gamma + 2S_2 \int_\gamma^{\pi-\theta/2} f(\lambda, \alpha) r_b d\gamma + tf(\lambda, \alpha, \beta_2) [N] \tag{32}$$

where $F_N$ is the insertion force, $F_C$ is the force in the cutting edge, and $F_L$ is the force in the leading edge. $S_1$ is the scale factor used to convert the cutting force from straight blade to the lancet’s cutting edge in Section 2 and $S_2$ is the scale factor used to convert the cutting force from straight blade to the bevel’s cutting edge in Section 1. $r_f$ is the needle outer radius and $r_b$ is the $X$ coordinate of the point $C'$. $\gamma = \gamma_f$ and $\gamma_c$ are the transition angles of points $F$ and $E$ between the lancet and bevel cutting edges. $\theta$ is the angle of the contact area between needle and tissue, which is determined experimentally.7 $t$ is the length of the leading edge $CC'$ ($t$ can be equal to or smaller than the thickness of the needle tube). Therefore, the specific force $f(\gamma = 180^\circ)$ and the leading edge’s length $t$ will determine $F_L$. Parameters $S$ and $\theta$ directly affect the accuracy of the prediction of insertion force on the cutting edge. Accurate values of $S$ and $\theta$ can be obtained by experiment. In order to reduce the impact of these experimentally determined parameters on the prediction of
insertion force and to analyze the influence of grinding parameters on the insertion force of the needle, instead of calculating the insertion force, only the specific force was calculated based on equation (31).

Figure 9. Specific force of different needle insertion into tissue. (I) New lancet needles and (II) conventional lancet needles. (a) the specific force of new lancet needles($\delta = 15^\circ$, $\varphi = 45^\circ$, $\beta = 55^\circ$) with different $l$; (b) the specific force of new lancet needles($l = 0.9785$, $\varphi = 45^\circ$, $\beta = 55^\circ$) with different $\delta$; (c) the specific force of new lancet needles($l = 0.9785$, $\delta = 15^\circ$, $\beta = 55^\circ$) with different $\varphi$; (d) the specific force of new lancet needles($l = 0.9785$, $\delta = 15^\circ$, $\varphi = 45^\circ$) with different $\beta$; (e) the specific force of conventional lancet needles($\delta = 15^\circ$, $\varphi = 45^\circ$, $\beta = 55^\circ$) with different $l$; (f) the specific force of conventional lancet needles($l = 0.9785$, $\varphi = 45^\circ$, $\beta = 55^\circ$) with different $\delta$; (g) the specific force of conventional lancet needles($l = 0.9785$, $\delta = 15^\circ$, $\beta = 55^\circ$) with different $\varphi$; (h) the specific force of conventional lancet needles($l = 0.9785$, $\delta = 15^\circ$, $\varphi = 45^\circ$) with different $\beta$. 
Figure 9 shows the predicted specific force when various needles are inserted into the tissue. As stated above, \( l \) can affect the length of the entire needle tip and the length of leading line \( CC' \), but it does not affect the inclination angle and the rake angle for both kinds of needles. Therefore, the specific force curves of needles with different \( l \) almost overlap. \( f \) at different points on the cutting edge of the new lancet needle is smaller than \( f \) at different points on the cutting edge of the conventional lancet needle. For the new lancet needle, the force received at each point on the cutting edge of lancet plane has little change. But for the conventional lancet needle, the difference of the force received at each point on the cutting edge of lancet plane is significant.

For the new lancet needle, the bevel angle determines the shape and size of needle bevel plane but has less effect on the inclination and rake angles. As shown in Figure 9(b) and (f), \( \delta \) has less influence on the specific force at the bevel plane cutting edge and has no effect on the specific force of the lancet plane cutting edge for both the new lancet needle and the conventional lancet needle. Based on the analysis of the relationship between the insertion force and the leading edge and cutting edge of the needle, a larger angle of inclination can produce less cutting force at the leading edge and transition edge.

The second bevel angle \( \phi \) mainly affects the shape of the needle near the transition line and the lancet plane. Especially when \( \phi = 25^\circ \), the lancet plane becomes much larger and a higher specific force appears around the transition position of the bevel plane and the lancet plane. For the new lancet needle and the conventional lancet needle, \( \phi \) has a little effect to the specific force on the cutting edge in Section 1 and Section 2. However, the average specific force in Section 2 of the new lancet needle is smaller than the average specific force in Section 2 of the conventional lancet needle. As shown in Figure 9(c) and (g), for needles with various \( \phi \), the difference in specific force at each point on the lancet plane cutting edge of the new lancet needle is small, while the difference in specific force at each point on the lancet plane cutting edge of the traditional lancet needle is relatively large. For both the new lancet needle and the conventional lancet needle, a larger \( \phi \) will lead to a shorter leading edge, a shorter cutting edge, and a smaller inclination angle and rake angle. Since \( F_N \) is the integral of the specific force on the cutting edge and leading edge, the new lancet needle will get a small insertion force during insertion into tissue.

The rotated angle \( \beta \) also has a larger effect on the shape of the needle, especially on the shape of the lancet plane. For both the new lancet needle and the conventional lancet needle, when \( \beta = 65^\circ \), the specific force is the largest on the transition point. The effect of \( \beta \) on the specific force of the conventional lancet needle is greater than on that of the new lancet needle. In Section 2 of both kinds of needle, the \( f \) curve of the new lancet needle is flatter than that of the conventional lancet needle. The average specific force \( f \) of the new lancet needles is smaller (less than 0.1N) than that of the conventional lancet needles. Therefore, in theory, the needle of the 45° rotated angle will have a smaller insertion force.
Conclusion

As a medical device, the insertion force of needle into organ tissue is an important factor affecting the accuracy of needle treatment. Based on the research on the shape and processing method of conventional lancet needle, a new lancet needle tip geometry was obtained by changing the third and fourth grinding plane positions. The mathematical model of this new lancet needle was established. The relationship between processing parameters and needle shape and size was analyzed and the needle insertion force was predicted. Based on the above research, the following conclusions can be drawn:

1. Compared with the conventional lancet needle, the new lancet needle is sharper, and the insertion force on the cutting edge of the lancet plane is smaller.
2. Offset distance $l$ can affect the length of needle tip but cannot affect the insertion force on the cutting edge in the bevel plane and the lancet plane.
3. Bevel angle affects the inclination and the rake angle of the cutting edge on the needle bevel plane and does not affect these angles of the cutting edge on the lancet plane. A larger bevel angle will lead to a larger bevel plane.
4. The second bevel angle and the rotated angle can dramatically affect the shape of new lancet needle. A smaller second bevel angle and a larger rotated angle lead to a larger inclination angle and the needle is sharper.
5. The new lancet needle may have a smaller special force on the cutting edge than the conventional lancet needle grinded with same parameters.

In addition, the shape and size of the needle tip affect not only the puncture force but also the soft tissue cutting profile. Punctures with small puncture resistance, little influence on the cutting profile, or better cutting profile are important for the puncture treatment of sensitive organs. This will be the focus of our next research.

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References
1. Khadem M, Rossa C, Sloboda RS, et al. Mechanics of tissue cutting during needle insertion in biological tissue. *IEEE Robot Autom Lett* 2016; 2: 800–807.
2. Watkins FH, London SD, Neal JG, et al. Biomechanical performance of cutting edge surgical needles. *J Emerg Med* 1997; 15(5): 679–685.
3. Abolhassani N, Patel R and Moallem M. Needle insertion into soft tissue: a survey. *Med Eng Phys* 2007; 29(4): 413–431.
4. Alterovitz R, Goldberg KY, Pouliot J, et al. Sensorless motion planning for medical needle insertion in deformable tissues. *IEEE Trans Inf Technol Biomed* 2009; 13(2): 217–225.
5. van Gerwen DJ, Dankelman J and van den Dobbelsteen JJ. Needle—tissue interaction forces—a survey of experimental data. *Med Eng Phys* 2012; 34(6): 665–680.
6. Egekvist H, Bjerring P and Arendt-Nielsen L. Pain and mechanical injury of human skin following needle insertions. *Eur J Pain* 1999; 3(1): 41–49.
7. Bjerring P and Arendt-Nielsen L. Depth and duration of skin analgesia to needle insertion after topical application of EMLA cream. *Br J Anaesth* 1990; 64(2): 173–177.
8. Strommen JA and Daube JR. Determinants of pain in needle electromyography. *Clin Neurophysiol* 2001; 112(8): 1414–1418.
9. Kietrys DM, Palombaro KM and Mannheimer JS. Dry needling for management of pain in the upper quarter and craniofacial region. *Curr Pain Headache Rep* 2014; 18(8): 437.
10. Main KM, Jorgensen JT, Hertel NT, et al. Automatic needle insertion diminishes pain during growth hormone injection. *Acta Paediatr* 1995; 84(3): 331–334.
11. Li W, Wang Y, Nteziyaremye V, et al. Measurement of the friction force inside the needle in biopsy. *J Manuf Sci Eng* 2016; 138: 031003.
12. Han P, Che D, Pallav K, et al. Models of the cutting edge geometry of medical needles with applications to needle design. *Int J Mech Sci* 2012; 65: 157–167.
13. Moore JZ, McLaughlin PW and Shih AJ. Novel needle cutting edge geometry for end-cut biopsy. *Med Phys* 2012; 39(1): 99–108.
14. Moore JZ, Zhang QH, McGill CS, et al. Modeling cutting edge geometry for plane and curved needle tips. *Proc Inst Mech Eng Part B: J Eng Manuf* 2012; 226: 861–869.
15. Moore JZ, Zhang QH, McGill CS, et al. Modeling of the plane needle cutting edge rake and inclination angles for biopsy. *J Manuf Sci E: T ASME* 2010; 132: 051005.
16. Wang Y, Chen RK, Tai BL, et al. Optimal needle design for minimal insertion force and bevel length. *Med Eng Phys* 2014; 36(9): 1093–1100.
17. Gao D, Lei Y, Lian B, et al. Modeling and simulation of flexible needle insertion into soft tissue using modified local constraints. *J Manuf Sci Eng* 2016; 138: 121012-1–121012-10.
18. Wang Y and Mei D. Five-plane lancet needle design for soft PVC phantom tissue cutting. *Biodes Manuf* 2018; 1: 195–202.
19. O’Leary MD, Simone C, Washio T, et al. Robotic needle insertion: effects of friction and needle geometry. *IEEE Int Conf Robot* 2003; 2: 1774–1780.
20. Moore J, Malukhin K, Shih A, et al. Hollow needle tissue insertion force model. *CIRP Ann: Manuf Techn* 2011; 60: 157–160.
21. Okamura AM, Simone C and O’Leary MD. Force modeling for needle insertion into soft tissue. *IEEE Trans Biomed Eng* 2004; 51(10): 1707–1716.
22. Towler MA, McGregor W, Rodeheaver GT, et al. Influence of cutting edge configuration on surgical needle penetration forces. *J Emerg Med* 1988; 6: 475–481.
23. Misra S, Reed KB, Douglas AS, et al. Needle–tissue interaction forces for bevel-tip steerable needles. In: Proceedings of the 2008 second IEEE RAS & EMBS international conference on biomedical robotics and biomechatronics (BioRob2008), Scottsdale, AZ, 19–22 October 2008, pp. 224–231. New York: IEEE.

24. Wang Y, Tai BL, Chen RK, et al. The needle with lancet point: geometry for needle tip grinding and tissue insertion force. *J Manuf Sci Eng* 2013; 125: 041010-1–041010-7.

25. Chebolu A, Mallimogga A and Nagahanumaiah. Modelling of cutting force and deflection of medical needles with different tip geometries. *Proc Mat Sci* 2014; 5: 2023–2031.

26. Barnett AC, Lee Y-S and Moore JZ. Fracture mechanics model of needle cutting tissue. *J Manuf Sci Eng* 2015; 138(1): 011005-1–011005-8.

27. Barnett AC, Lee Y-S and Moore JZ. Needle geometry effect on vibration tissue cutting. *J Eng Manuf* 2018; 232(5): 827–837.

28. DiMaio SP and Salcudean SE. Needle insertion modeling and simulation. *IEEE Trans Robotic Autom* 2003; 19(5): 864–875.

29. Kataoka H, Washio T, Audette M, et al. A model for relations between needle deflection, force, and thickness on needle penetration. In: Niessen WJ and Viergever MA (eds) *Medical image computing and computer-assisted intervention* (Lecture Notes in Computer Science), vol. 2208. Berlin: Springer, 2001, pp. 966–974.

30. Alterovitz R, Goldberg K, Pouliot J, et al. Needle insertion and radioactive seed implantation in human tissues: simulation and sensitivity analysis. In: *Proceedings of the IEEE international conference on robotics and automation*, Taipei, 14–19 September 2003, pp. 1793–1799. New York: IEEE.

31. Hirsch L, Gibney M, Berube J, et al. Impact of a modified needle tip geometry on penetration force as well as acceptability, preference, and perceived pain in subjects with diabetes. *J Diabetes Sci Technol* 2012; 6(2): 328–335.

32. Rodrigues EB. Effect of needle type and injection technique on pain level and vitreal reflux in intravitreal injection. *J Ocul Pharmacol Ther* 2011; 27(2): 197–203.

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