Insertion Mechanics of 3D Printed Honeybee-inspired Needle Prototypes for Percutaneous Procedure

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1 Background

Surgical needles are commonly used by medical professionals to reach target locations inside of the body for disease diagnosis or other medical interventions - such as biopsy, brachytherapy, thermal ablation, and drug delivery [1, 2]. The effectiveness of these procedures depends on the accuracy with which the needle tips reach the targets, such as tumors or certain organs/tissues. In procedures, such as deep brain stimulation and prostate brachytherapy, it is impossible to reach the surgical sites via simple needle trajectory because of anatomical constraints. Although needles are considered minimally invasive devices, needle insertion still causes tissue damage of varying degrees so it is desirable to reach multiple targets, or multiple sites on a single target, to obtain multiple high-quality biopsy samples with each insertion [1, 2].

Recently there has been a substantial and growing interest in the medical community to develop innovative surgical needles for percutaneous interventional procedures. The answer to the challenge of developing advanced surgical needles could be found in nature. Insects such as honeybees (Fig. 1), mosquitoes, and horse flies have sophisticated sting mechanics and stinger structures, which they use to steer their stingers to a specific target, such as a human, and to release their venom in a certain path in skin [3]. We are studying these mechanisms, evolved in nature over millions of years, as a basis to develop bioinspired needles.

Surgical needles are typically consisted of a hollow cylindrical component (cannula) and an inner solid cylindrical component (stylet). Our hypothesis is that a surgical needle (stylet) that mimics insect stinger mechanics and structures can be easily controlled for sophisticated needle steering during surgery and can result in more effective and less invasive percutaneous procedures. The focus of this work is to mimic honeybee stinger such as shown in Fig. 1 to design innovative surgery needles.

![Image](https://example.com/image1.png)

**Fig. 1:** An optical microscopy photo of a honeybee stinger (left) and a geometrical sketch from the photo (right)

One of the critical issues in designing surgery needles is the insertion force required to penetrate and to navigate the needle inside the tissue [2]. Larger insertion forces increase tissue damages thus may result in a more painful procedure [2]. Another consideration is the needle trajectory path (needle tip deflection) and the difficulty to control the needle path. The needle deviates from the target and thus it is very difficult to navigate the needle in the tissue. There is a need to design advanced surgery needles that provide smaller insertion force. This can lead to a less invasive procedure, in other words, less tissue damage and pain [3]. The needle trajectory path of these new needle designs must be understood for the needle design optimization.

As stated previously, it is hypothesized that a honeybee-inspired needle can be utilized to reduce the insertion force. In this work, the experimental work to understand the mechanics of bioinspired needles is presented. 3D printing of the needles and their insertion tests are performed to investigate the effect of the needle designs on the insertion force and the needle deflection (trajectory path) curves. Understanding these factors should shed some lights on some design parameters to develop innovative surgery needles.

2 Methods

Four different needles including a conventional needle and three bioinspired needles with barbs are designed by observing honeybee stingers (Fig. 1). Solidworks software (Dassault Systèmes SolidWorks Corporation, Waltham, MA) is utilized to draw these models, Fig. 2(a)-(e). All four needles have the same diameter of 3 mm, the length of 150 mm, and a needle bevel tip angle of 30°. Three needles with barbs have different barb geometries. The dimensions of the barbs are shown in Table 1. The 3D Solidworks models are then manufactured using Objet Connex 350 3D printer (Stratasys, Inc., Eden Prairie, MN), see Fig. 2(f).

![Image](https://example.com/image2.png)

**Fig. 2:** Bioinspired needle design, (a) conventional needle, (b) needle with barbs (h=0.3 mm, \( \theta_2=140^\circ \)), (c) needle with barbs (h=0.5 mm, \( \theta_2=130^\circ \)), (d) needle with barbs (h=0.5 mm, \( \theta_2=110^\circ \)), (e) needle parameters, (f) 3D printed bioinspired needle prototype.

<table>
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<th>Model</th>
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As shown in Fig. 3, needle insertion tests through a phantom material made of plastisol gel (M-F Manufacturing Co., Ft. Worth, TX) are performed using the 3D printed needles. The elastic modulus of the phantom is fabricated to mimic the tissue elastic modulus by the compositions of...
polyvinylchloride suspension and softener. A force sensor, 6 DOF F-T sensor Nano17® (ATI Industrial Automation, Apex, NC), and a high-resolution camera are used to record the insertion force and the deflection of the needles. The needle is inserted into the gel at a constant speed of 1 mm/s by attaching the needle to a motorized linear stage (Velox Inc., Bloomfield, NY, USA) of 6µm resolution. The force sensor is fixed at the needle end and measures uniaxial force of needles. The camera is located on the top to record needle deflection through the gel (Fig. 3, top view).

3 Results

The insertion forces and the deflection curves of conventional and barbed needles are measured as it travels in the gel. As it is shown in Fig. 4, the insertion forces are decreased by 16% to 24% using needles with barbs. Although, the needle size and materials as well the gel phantom materials are different, the insertion force in Fig. 4 is well within the expected range of a typical insertion force in a brachytherapy procedure, which is under 6N in average [2]. It is conjectured that the decrease in insertion force in the needle with bars is due to the decrease in frictional force at the interface of the bioinspired needles and the gel phantom. The decrease in frictional force is due to the reduced contact area of the needle with barbs.

The deflection curves of different needles are presented in Fig. 5. There are two parameters, which affect the deflection; these are the insertion force and the needle bending stiffness. As it is shown in Fig. 4, the insertion force is decreased using a needle with barbs. This is due to the decrease in the bending stiffness of the barbed needles. It can be concluded that by changing barb geometries, the deflection of the bioinspired needles (Fig. 5) could be varied and potentially can be relatively easy to be manipulated.

4 Interpretation

It has been demonstrated that geometrical shape modification of the needles inspired by honeybee stingers could be utilized to significantly decrease the insertion force (Fig. 4). The deflection curves (Fig. 5) of the bioinspired needles show that there is a decrease in the bending stiffness of the needle. As shown in Figs. 4 and 5, it can be concluded that different combinations of barb geometries will result in different deflection curves. Furthermore, the deflection of these needles could be controlled, for example, by embedding active (smart) Nitinol actuators on the needle structures [1].

It should be mentioned that FEA simulation work using LSDYNA (LSTC, Livermore, CA) as shown in Fig. 6 is currently being performed in our laboratory to understand the insertion mechanics, to study the mechanical interactions between the needle and the gel/tissue and to optimize the needle geometry. Additionally, the pull-out mechanism will be studied although at this point it is expected that the pull-out force of the needle will be similar to the conventional needle since the needle cannula will be used to guide the insertion. Future work on needle stylet without the cannula will be presented in a different study. Experimental work is ongoing to perform the insertion tests on real tissues, for example pig livers, to study the influence of tissue anisotropy on the insertion force and the deflection curve.

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References

