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MECHANICS OF SCORPION-INSPIRED CURVED TIP NEEDLE MOVING IN SOFT TISSUE

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ABSTRACT

Soft tissue biopsy is a necessary diagnostic and therapeutic procedure, but traditional biopsy needles can cause harm to the patient, including tissue damage, bleeding, and pain. These can compromise the accuracy of the sample and negatively impact the patient's well-being. Hence, there has been a growing interest in developing bio-inspired surgical needles that are safer, more effective, and more comfortable for the patient. The scorpion-inspired curved tip needle study focuses on analyzing the mechanics of needle-tissue interaction and creating needles that travel through soft tissue with minimum resistance at the tip. An essential aspect of the study is the mechanics and geometry of the needle tip, which plays a crucial role in its performance. The study incorporates structures of curved scorpion's stinger to balance between penetration and minimal needle-tissue interaction forces. In this study, various parameters of curved tip geometry are explored to decrease the insertion and extraction forces. Tests are initially performed on brain tissue mimicking medical gelatin with Young's modulus of 2kPa. It is observed that the insertion force with curved tip needles is decreased by up to 21.7%, and the extraction force is decreased by up to 28.2%. This study shows that a scorpion-inspired tip design can minimize insertion and extraction forces, leading to less tissue damage and deformation. Furthermore, the proposed tip design has great potential to improve surgical needles for more effective minimally invasive percutaneous procedures with various applications such as biopsy, brachytherapy, tumor ablation, and drug delivery to the brain.

Keywords: bioinspired needle, insertion force, extraction force, curved-tip needle

1. INTRODUCTION

Needle insertion is vital in minimally invasive surgery (MIS), used for procedures such as biopsies, blood sampling, and

brachytherapy. Minimally invasive procedures are known for less intrusive and reduced post-operative complications compared to traditional open surgeries, resulting in faster recovery times, lower risk of infection, and occasionally shorter treatment periods [1]. However, the precision of needle insertion is crucial for successful diagnosis and treatment. Surgeons often need to make multiple insertions to reach the target area during the procedure. Each penetration can cause additional damage to the surrounding tissues, leading to complications and longer patient recovery time. Several factors, including insertion force, tissue deformation, and tissue damage, can affect the accuracy of needle insertion [1]. To improve this, researchers are studying steerable needles to enable them to reach the target area in a single pass. In contrast, others are motivated to reduce insertion force and tissue damage by modifying the needle body or tip designs [2]. The insertion force is a combination of puncture, cutting, and friction force, which can be affected by needle body and tip geometry, tissue materials, insertion speed, and insertion dynamics, such as rotation and vibration.

The effects of needle tip geometries and aspects of needle-tissue interaction has been well discussed throughout the year. Jushiddi et al. [3] investigate various angles of bevel tip needles by measuring deflections and insertion forces. It shows that the angle of the tip plays a significant role. As the tip angle increases, the needle deflects less, the needle puncture force is increased, and the total insertion force is decreased. Wang et al. [4] study different geometry of lancet point needles by changing angles for grinding setup and shows that reduction of insertion force compared to bevel tip needle. Podder et al. [5] focus on the effects of three different tip geometry: bevel, diamond, and conical tip. It concludes that the conical tip results in the highest insertion force due to weak cutting geometry but has a minor deflection. The bevel tip shows the least insertion force but the highest deflection.

Scorpions use their stinger for intraspecific competition, self-defense, hunting, mating, and to inject venom into other substances. Especially their penetration mechanical performance is exceptionally developed as an advanced survival skill. As shown in Figure 1, the scorpion's stinger has a sharp tip with a curved shape for quickly penetrating hard materials such as the exoskeleton of insects and mammal skin and a hollow structure for venom delivery. Scorpion's stinger is known for its excellent mechanical properties, such as high stiffness, strength, toughness, and structural stability. It can also be applied to needle designs, requiring small puncture and insertion forces [6].

This work introduces a curved tip design inspired by a scorpion to learn reduction in insertion and extraction forces compared to bevel tip needles. The curved and bevel tip needles are 3D printed with Acrylonitrile Butadiene Styrene (ABS) plus polymer with a length of 180mm and diameter of 3mm. The insertion and extraction tests are done in brain tissue-mimicking phantom, with Young's modulus of 2kPa. Each needle's insertion force, extraction force and deflection are experimentally investigated.

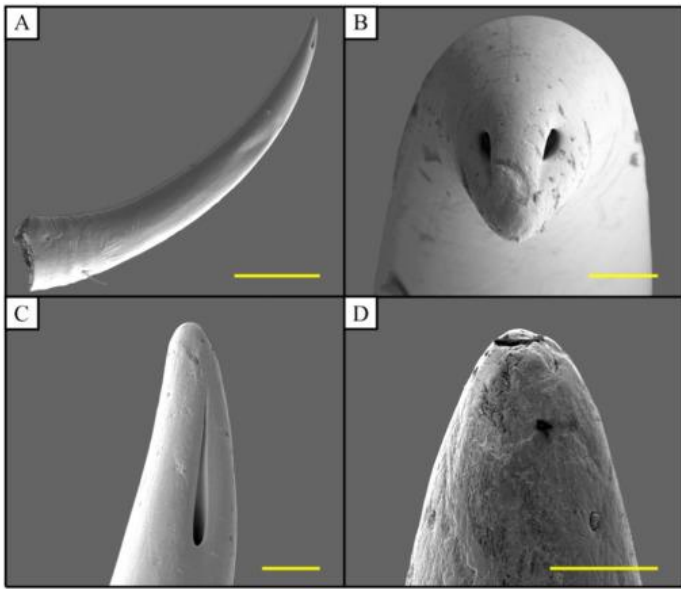


FIGURE 1: Anatomy of Scorpion's Stinger: (A) Lateral view, (B) Front view with a pair of venom pores, (C) Magnified view of the stinger tip with venom pore, (D) Magnified view of a stinger apex. Scale bars = 500 μm (A), 50 μm (B,C), and 20 μm (D). Adapted with permission from Elsevier (Materials Science and Engineer: C), Copyright (2016) [6]

2. MATERIALS AND METHODS

This section has two subsections. The first section includes the design of the curved tip with a detailed drawing and prototype fabrication. The second section explains in detail about experimental setup and measuring process of insertion and extraction forces and deflection of the needles.

2.1 Design and manufacturing of scorpion-inspired needle

The scorpion's sharp tip stinger geometry is considered for designing a curved-tip needle. In addition, bevel-tip needles are widely used in the medical field, and the research shows that it causes less insertion force than needles with different tips, such as conical, blunt, or diamond tips. For this reason, the curved shape is added to the bevel tip, and the same angle of the bevel and curved tip needles are compared. Figure 2 shows that is the bevel angle and the curve is created by constraining the central angle of the arc as 2. The preliminary results show that the angle of 15° and 30° curved tip needles reduced insertion force compared to bevel tip needles [7]. Therefore, this work selects four different angles between 15° and 30° to analyze the mechanics of needle-tissue interactions focusing on the insertion force and needle deflections in brain tissue-mimicking gel. The needle tip shape is radial symmetrical since the asymmetrical needle design causes an undesirable and unbalanced force. Between 14 gauge (14G-outer diameter of 2.109mm) and 16 gauge (16G-outer diameter of 1.651 mm), surgical needles are used for brain biopsy and brachytherapy. However, due to manufacturing limitations, the prototype curved tip and bevel tip needles are scaled up with an outer diameter of 3mm and a length of 180mm. Both tip needle types are generated using Computer-aided Design (CAD) software. Eight different needles: four different angles of both bevel and curved tip needles are manufactured using a high-resolution 3D printer (J35 Pro, Stratasys, Inc., Eden Prairie, MN, USA). The material used for needle prototypes is ABS plus polymer, with Young's modulus of 2.1-2.8 GPa.

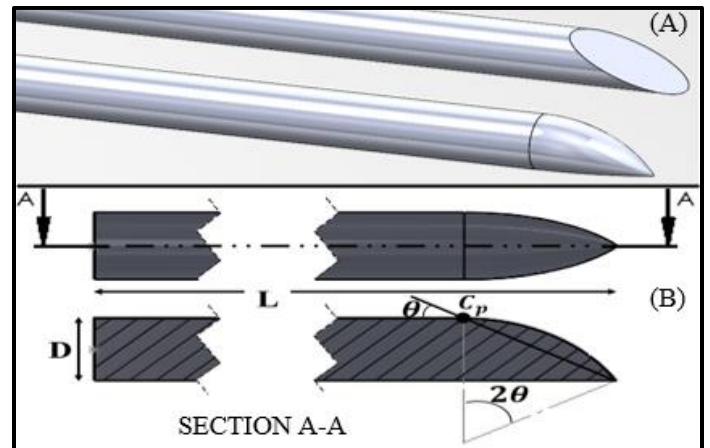


FIGURE 2: (A) 3D models of the bevel and curved tip needles, (B) The schematic of the scorpion-inspired needle in this study with the parameter as an angle (θ) of 15°, 20°, 25°, 30°, length of the needle (L) of 180 mm, curved arc starting point (C_p), and diameter of the needle (D) of 3 mm.

2.2 Needle insertion and deflection test setup and procedure

The needle insertion experimental setup is developed to measure the insertion force and tip deflection. It consists of a linear motor, a force sensor, a data acquisition system, and a tissue-mimicking gelatin phantom with graph paper, as shown in Figure 3. The motorized linear slide implements translational

motion, and a force sensor is attached to the linear slide. The force sensor, a six-axis force/torque transducer Nano 17® (ATI Industrial Automation, Apex, NC), is connected to a data acquisition system and attached to the base of the needle. The force data are obtained using LabView software (National Instruments Corporation, Austin, TX). The graph paper is placed under the clear phantom to reference when the deflection values are collected with ImageJ software. Images are captured from the top when the needle is inserted at 100mm, which is the maximum insertion for this experiment. In order to demonstrate a good representation of the needle-tissue interaction for brain tissue, tests are performed on polyvinyl chloride (PVC) with Young's modulus of 2kPa, which is a similar mechanical property of brain tissue. The needle is inserted up to 100mm with a velocity of 2mm/s.

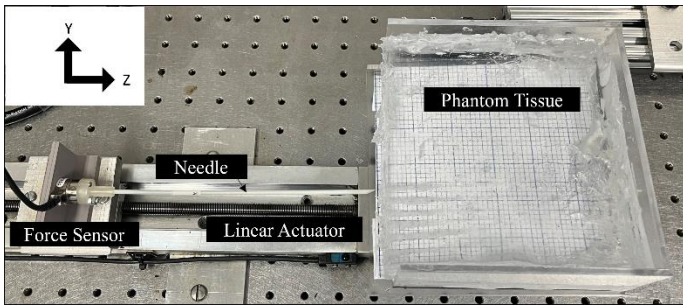


FIGURE 3: Needle insertion and deflection experimental Setup

3. RESULTS AND DISCUSSION

The effect of the curved needle on insertion and extraction forces in the z-direction is studied because the x and y-direction forces are negligible due to small magnitudes compared to z-axial forces. Different angles of curved tip needles are compared to bevel tip needles. Figure 4 shows that the area of the curved needles' graphs is smaller than the area of bevel tip needles' graphs. Most curved tip needles show a reduction in insertion force but a higher reduction in extraction force. The reduction percentage is calculated by observing the difference between two maximum insertion forces, which are measured at 100mm insertion. Angles of 15°, 25°, and 30° do not show significant reduction at 100mm insertion depth. However, at about 60mm insertion, all three curved tip needles show a reduction. For an angle of 20°, the maximum insertion force is reduced up to 21.7%.

The extraction forces are reduced even more than the insertion forces. The reduction percentage is measured by acquiring the maximum magnitude value during extraction. For angle 15°, 20°, 25°, and 30°, extraction forces are reduced by 28.2%, 23.9%, 14% and 21.5%, respectively. The friction force between the needle body and the tissue can affect the extraction force. Also, from the deflected needle, when the needle tries to move straight backward, a cutting force can come from point A, the starting point of the curved arc and bevel (Figure 2). In this work, the needle's outer diameter, materials, and body are identical, which means that both needle's tip geometry and deflection can affect extraction force.

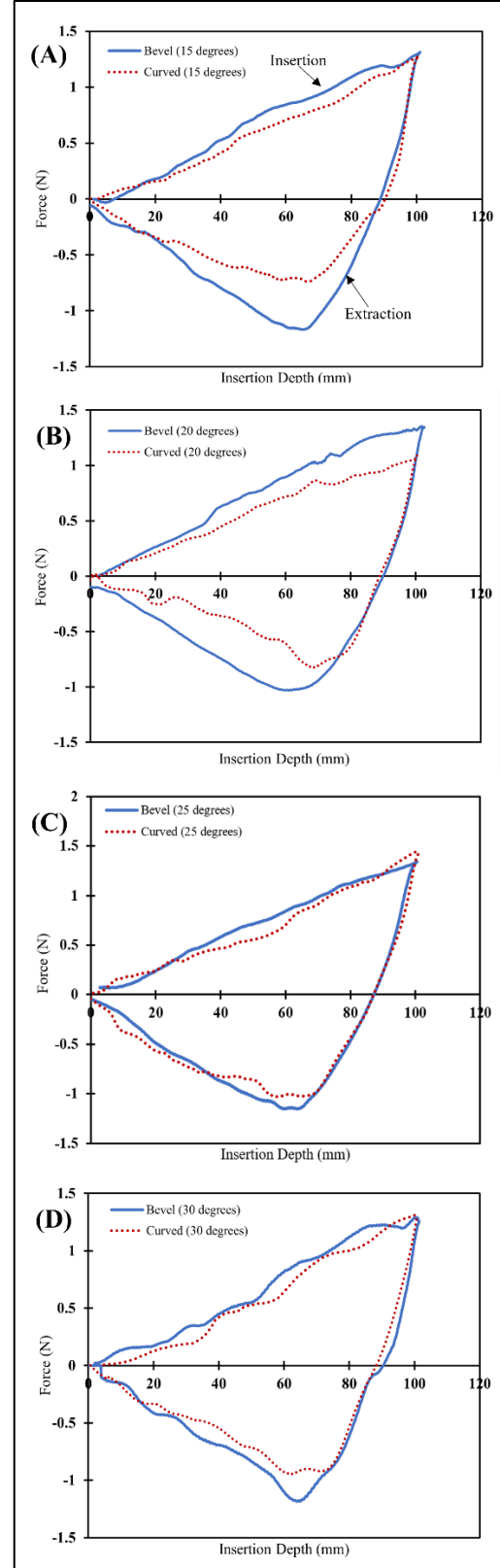


FIGURE 4: The average insertion and extraction force for the bevel tip and curved tip needles of angle: (A): 15°, (B): 20°, (C): 25°, and (D): 30° with needle insertion depth of 100mm and velocity of 2mm/s.

Table 1: Maximum insertion force (insertion depth of 100mm), maximum magnitude of extraction force, and deflection of needle tip at 100mm insertion with standard deviation (SD). Experiments are repeated 3 times each.

Needle Type	Insertion Force (N)	± SD	Extraction Force (N)	± SD	Deflection (mm)	± SD
Bevel 15°	1.31	0.02	1.34	0.046	8.594	0.623
Bevel 20°	1.35	0.145	1.32	0.318	6.494	0.717
Bevel 25°	1.34	0.007	1.38	0.014	5.004	0.251
Bevel 30°	1.29	0.047	1.18	0.153	4.851	0.641
Curved 15°	1.31	0.146	0.97	0.225	6.629	0.508
Curved 20°	1.06	0.106	1.01	0.202	6.054	0.427
Curved 25°	1.44	0.28	1.19	0.073	5.469	0.639
Curved 30°	1.32	0.005	0.95	0.063	4.013	0.814

To investigate further, deflections at the 100mm where extraction starts are recorded. This study assumes that needles deflect on the x-z plane. As shown in Figure 5, standard deviation error bars overlap moderately for angles of 20°, 25°, and 30°, leading to the conclusion that the difference is not statistically significant. However, an angle of 15° shows a significant difference between the bevel and curved tip needle. As a result, the curved tip needle can achieve a smaller needle-tissue interaction force for the same deflections. Table 1 lists the values of insertion forces and tip deflection at 100mm insertion depth and extraction forces at the maximum magnitude with standard deviation.

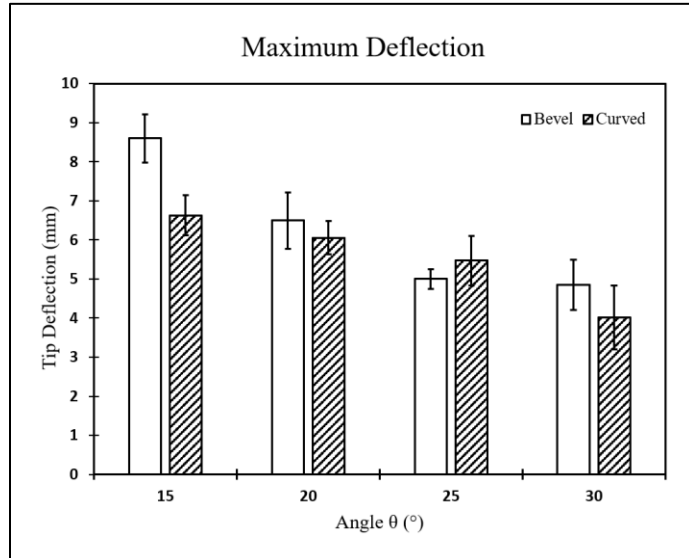


FIGURE 5: The average deflection of needle tips at insertion depth of 100mm with standard deviation for each angle.

4. CONCLUSION

The mechanics of the new curved tip design inspired by the scorpion's stinger moving into brain-mimicking tissue are studied. The curved tip needles reduce insertion force by up to 15.2% and extraction force by up to 28%. Therefore, curved tip needles have the potential to improve performance on needle insertion by reducing insertion and extraction force, which can lead to less tissue damage and tissue deformation. Currently, the computational analysis for the proposed shape is being worked on to support experimental study. Further investigation is needed for an angle of 25° because it has the slightest reduction in needle-tissue interaction forces. Moreover, true-scale needles such as 14G and 16G could be tested in real brain tissue to ensure the practicality of the proposed design.

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