Characterizing Tissue Damage and Optimizing Material Properties of Tape Spring Based Steerable Needles

Megan Santamore, Princeton University, Department of Electrical Engineering *SUNFEST Fellow*
Mark Yim, Ph.D. Department of Mechanical Engineering and Applied Mechanics
Omar Abdoun M.D. Ph.D., Department of Bioengineering

Abstract— **Often physicians must deliver treatment or take biopsies from difficult to access regions of the body. With traditional straight-shaft needle designs, tough tissue areas and bones blocking the needle's path can complicate the process. Nontraditional steerable needle prototypes have thus been proposed as potential solutions to this problem, providing physicians more flexibility as they steer the needle to a precise treatment location. This paper outlines the material modifications made to a novel tape spring steerable needle prototype that allows for the design of a steerable needle that minimizes the necessary insertion force into tissue through a pointed, sharp-tipped tape-spring based needle with vibrational capabilities. In the future, this improved needle prototype will be refined by assessing its performance when inserted in real tissue of nonhomogeneous stiffness, similar to the conditions such needles would face in the human body.**

Index Terms— **ablation, biomedical engineering, biopsy, heat treatment, medical instruments, medical needles, precision medicine, shearing, steering systems, springs,**

I. INTRODUCTION

Conventional medical needles are constrained by their design, as traditional needle models with straight shafts and subsequently direct trajectories often prevent needles from being able to access hard-to-reach areas of the human body, such as tissue behind bones like the rib cage or more sensitive tissue of nonhomogeneous stiffness. Thus, steerable needles that are able to bend and alter their trajectory through a patient's body would allow physicians to access these difficult areas of the body for procedures such as biopsies, ablations, and targeted drug delivery more easily, subsequently improving the outcome of these medical procedures in the process [1]. In recent years, a number of research investigations have been conducted regarding the design of different steerable needle models. Previous steerable needle prototypes have been designed to have flexible needles with asymmetric "bevel-tips" that allow for both curved and straight trajectories depending on how the needle is inserted [2]. However, such "bevel-tip" needles, along with other current steerable needle designs, have resulted in needle prototypes that have too large a turning radius to be useful for the accurate, precise steering necessary when reaching secluded parts of the body. In fact, a survey of interventional radiologists revealed that these physicians have a minimum and maximum allowable placement errors of 2.7mm and 5.3mm respectively [10]. Thus, direct, targeted needles are necessary for appropriate medical treatment and would prove a valuable asset to the interventional radiology field.

To this end, a new model of steerable needles utilizing the physical properties of tape springs, which are long, thin curved elastic sheets of metal that are able to be bent without plastically deforming [3], that has a significantly smaller turning radius and low energy requirement for turn propagation throughout the needle has been proposed as an improved steerable needle model [4]. However, these tape spring-based steerable needle prototypes have a main mode of failure: unintentional buckling, which is when a bending moment is applied to the tape spring which causes it to reversibly bend or curve. Thus, for these needles to be clinically useful and more broadly applied, this prototype must be improved upon by minimizing the insertion force necessary to insert the needle into tissue so as to ensure the needle will not buckle when steered into or throughout the body.

The goal of the experiments discussed in the rest of this paper is to develop standard procedures regarding the material treatment of the steel tape-spring needle, in regard to the hardness, sharpness, and geometry of the needle's tip as well as the elasticity and oscillatory motion of its shaft. Specifically, two 3 mm wide and 8.5 cm long tape spring needle prototypes were developed. One needle had an intentionally dull tip with a rounded needle tip geometry and the other had an intentionally sharp tip with a pointed tip geometry. Each of these needles had a 16000 RPM motor attached to the bottom of the shaft to assess the effect of the needle shaft's oscillation on minimizing insertion force. 76 kPa gels were created and positioned vertically on top of a force transducer to measure the insertion and cutting force as the steerable needle was inserted into the gel when the needles were experiencing no vibration, low vibration, and high vibration. Due to time constraints these experiments were not able to be conducted in real tissue, but this will be done in the future. These trials were visually recorded, which was later analyzed to find the insertion force of the steerable needle into the gel at one second intervals.

Further research will expand upon these experiments by assessing insertion force, under varying vibrational conditions, in real tissue, such as liver or muscle, that is ideally less homogenous than the gels used for these experiments. This will allow for a more thorough assessment of the tape spring-based needle's effectiveness in real, nonhomogeneous tissue and will indicated if such sharpness, geometric, and vibrational material alterations affect the needle's trajectory in more human-like tissue samples.

II. BACKGROUND

A. Tape Springs

Tape springs are most commonly used for applications such as measuring tapes, solid state hinges, and deployable space structures [5]. One of their unique properties most applicable to steerable needle applications is that tape springs are stiff when straight but can be buckled when a bending moment is applied [6]. While tape springs require more force to initiate a bend, the force required to sustain that bend is much lower, close to zero.

B. Tape spring-based steerable needle design

An ideal steerable needle design would be stiff enough to be successfully inserted into the tissue without breaking or buckling and maintain navigational control, while simultaneously being flexible enough to make tight turns while navigating throughout the human body [4]. Thus, because of their specific properties, tape-springs prove an effective new model for steerable needle designs. The flexibility of tape springs allows the tip of a tape spring-based steerable needle device to be actuated in a desired direction and for the shaft of the device to follow the path of the needle tip as it is pushed further into the tissue.

As for the design of this tape spring based steerable needle to be improved upon, the needle design allows the user to control the direction and angle of bending of the tip**.** Thus, the user controls the trajectory of the needle in tissue or gel in a manner similar to how catheters are steered, where the tip of the needle is bent in a certain direction, forming a bend that will remain as the needle is further inserted, allowing the needle to proceed in the direction of the tip.

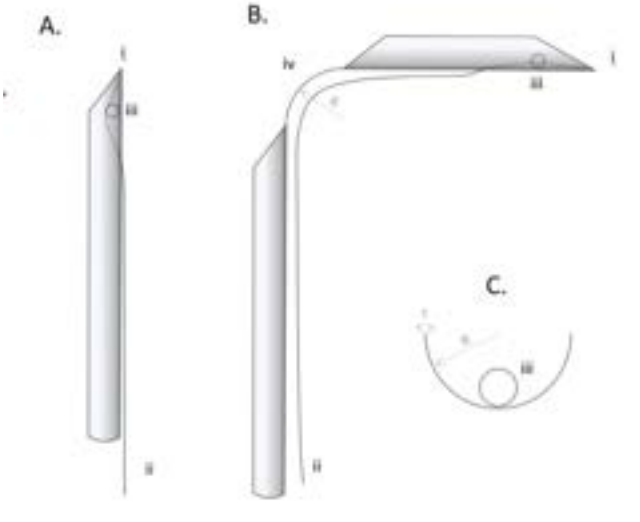

Fig. 1. Tape spring steerable needle where i is the tip of the needle, ii is the cable that facilitates needle steering, iii is the lever arm, iv represents a bend in the tape spring needle. Part A of the figure shows a straight instance of the tape spring needle while part B of the image shows the tape spring needle with a bend. Part C shows a head-on view of the tape spring where R is the traverse radius of curvature, t is the thickness of the shaft, and iii is the lever arm [4].

The material properties of the tape spring steerable needle are crucial because of the forces that the steerable needle will encounter as it is inserted into human tissue. In order for the needle to be successfully inserted into the tissue, the needle has to overcome the insertion force ($\mathrm{F}_{\mathrm{insertion}}$). Tape springs can occasionally buckle unintentionally if the force necessary to insert the needle into the tissue is too high and the tape spring needle is too compliant [4], thus improvements to the strength of the needle tip are necessary for the needle to overcome this insertion force.

Additionally, as the needle steers through the body, the tip of the needle has to continually cut through the tissue as it works its way to its target location. Thus, the tip of the needle must be sharp enough to slice through nonhomogeneous tissue of various thicknesses without the progress of the needle being halted prematurely.

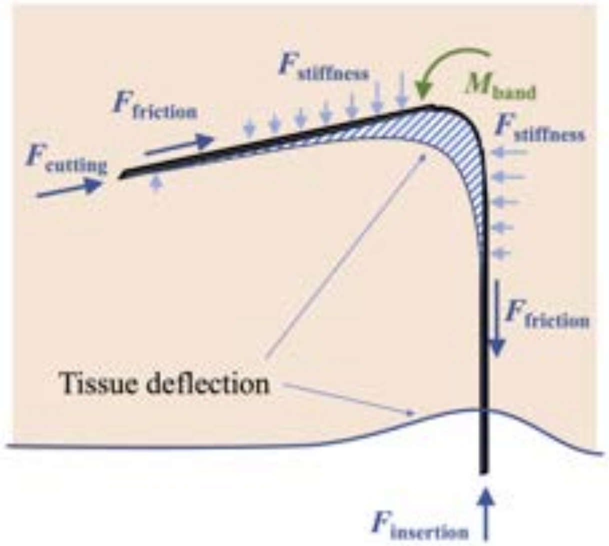

Fig. 2. External forces acting on the tape spring steerable needle. In this image tissue deflection is greatly exaggerated for visualization purposes [4].

C. Previous tape spring-based steerable needle work

Previous assessments of this tape spring steerable needle have been conducted in order to characterize a number of the physical attributes of this prototype such as the needle's turn radius in different surrounding mediums, the external forces acting on the needle that affects its motion as it steers throughout tissue, and the static forces acting on the needle prototype that may cause the needle to buckle or fail.

This paper is a continuation of this previous work that presents several physical and material modifications made to these needles and experimentally assesses the performance of these modified steerable needle prototypes,

III. METHODOLOGY

The following experiments helped determine the effect of different physical conditions and material properties in minimizing the insertion and cutting force exerted by these steerable needle prototypes. First, the needle manufacturing procedure is outlined. Then, the material alterations made to these fabricated needles are described. This is followed by a description of the process by which needle insertion experiments were conducted to determine the insertion and cutting force exerted by the needle as it cut through 76 kPa gels.

A. Creation of base of tape spring-based needle prototypes

For the creation of these needle prototypes, strips of 50 um thick 301 blue spring steel were cut and then pressed into an aluminum mold with a cylindrical hole that allowed the steel needle shaft to have the necessary tape spring curvature [4]. The mold with the steel sheets were then placed in a 475 degree oven for an hour, after which the mold containing the steel needles was immediately quenched in water. This heat treatment allowed the steel sheet to be formed into a tape spring shape with the necessary curvature and heat treatment for the steel needle shaft to obtain the optimal tape spring shape and elastic properties.

B. Heat treatment, shaping, and sharpening of needle tips

After making two of the needle tape spring bases, one of the needle tips was cut with scissors to have a simple rounded tip while the other was cut to have a more pointed 45 degree angle tip. After the tape spring needle tips were shaped, it was necessary for them to be hardened; first, the tips were tempered at extremely high temperatures of around 1100 degrees Fahrenheit by heating the tip of the tape spring, focusing especially on the edges, with a blow torch for 30 seconds at a time. Once the metal tape spring tip was glowing, it was quenched in water. This process was repeated approximately 5 times for each needle or until the tape spring tip has been appropriately hardened, which can be assessed by touching the tip of the needle. After the needle tips were shaped and hardened, the needle with a pointed tip was sharpened using a belt sharpener at a 120 grit.

The *Edge-On-Up Industrial Edge Tester* from Sharpening Supplies was utilized to ensure that the rounded, unsharpened needle was quantitatively less sharp than the pointed, sharp needle. This device measures the force in grams necessary for an object to cut through a string. To test the sharpness of both the dull and sharpened needles, the needles were individually positioned so that their edge was parallel to the string, which was set on top of a force transducer, and then the needle was slowly pressed downwards onto the string until the string ultimately broke. At this point, the device would recognize that string had broken and would display the force exerted in grams when the string broke.

Fig. 3. The *Edge-On-Up Industrial Edge Tester*

Once it was found that the dull and sharpened needle prototypes were far apart enough in sharpness, according to this sharpness testing device, then a 6900 RPM motor was attached to the base of each needle and the prototypes were ready to be assessed in gels resemblant of human tissue.

C. Resonance Experiments

Since the motors were attached to the tape spring needles with the intent of determining the effect of needle vibration on cutting force, it was necessary to determine what the voltage supplied to the motors should be in order to achieve such oscillations. To this end, some initial investigations were conducted where the voltage supplied was increased linearly in 0.1V intervals and the level of oscillations were qualitatively rated. The voltages for each needle, above the baseline of 1V, that resulted in the most mild and most chaotic oscillations would be selected for further experimentation into which type of needle tip vibration would work to minimize the needle insertion force.

D. Insertion force

The experiments that assessed the amount of force that the needles needed to exert as they were inserted into the gels under these sharpness and vibration conditions were conducted as follows. First, two 76 kPa gels were made and placed in plastic containers that had holes cut out on the side so that needles could be easily inserted. For each needle insertion trial, one of these gels would be placed vertically on top of a force transducer, with the holes for needle insertion at the top. A tape measure was also positioned vertically alongside the gel so that the needle's insertion depth could accurately be seen during video analysis the footage of these insertion force trials. To this end, a video camera was positioned in front of this experimental setup so that video footage of these trials could be obtained for later force and insertion length analysis. A power source was positioned to the side so that the voltage supplied to the motors attached to the tape spring needles could be adjusted, so as to assess the effect of needle vibration on cutting force. First, the dull needle was attached to the power supply, which initially supplies 0V, and then held vertically above the gel. Then, the needle was inserted slowly into the gel, while the camera recorded the force supplied by the needle, displayed on the force transducer, as well as the needle's insertion length throughout. Then the voltage supplied to the needle was increased to the voltage previously determined to result in a low, more controlled vibration based on the resonance experiments (3.5V and 2.0V for dull and sharp needles respectively) and the insertion process was repeated for several trials at that voltage. Lastly, the voltage supplied by the power supply was increased to the voltage previously determined to result in rapid, more chaotic vibration based on the resonance experiments conducted previously (3.9V and 2.5V for dull and sharp needles respectively) and then the insertion experiments were conducted for several trials at this voltage. This insertion process at three different supplied voltages was repeated for the sharpened, pointed needle as well.

Fig. 4. Image of the testing setup for the tape spring-based needle insertion tests. The 76 kPa gel is positioned vertically above the force transducer, currently measuring a force of 30.4 N. The tape measure on the left, as well as the centimeter lines drawn on the needle itself are used to determine the insertion depth from the videos taken during these experiments. The power supply on the right supplies a voltage of 2.5V to the motor attached to the base of the tape spring needle.

E. Video Analysis

Videos from these needle insertion experiments would be uploaded to a video player platform such as VLC Media Player so that the footage could be analyzed frame by frame. First, for each individual trial, the initial insertion force, characterized by when just the tip of the needle cuts into the gel, would be read from the value printed on the force transducer and the initial insertion depth, as measured by the tape measure positioned vertically next to the gel, would be recorded. After the initial insertion force and insertion depth were recorded, the footage would be stepped forward second by second, recording the updated insertion force and insertion length at each depth. This recording process is continued for the needle's entire insertion into the gel or until the needle buckles.

IV. EXPERIMENTAL RESULTS

Results from the straight insertion of the dull, unsharpened needle and pointed, sharpened needles at different vibrations are included below.

A. Needle Sharpness

1.5 cm Blue Spring Steel Needle	
Trial Number	Force Measured (g)
1	1499
2	1221
3	1555
4	1693
5	1492
6	1119
7	1840
8	1628
9	1255
10	1682
Average	1498.4
Standard Deviation	232.9636118

Sharpened 1.5 cm Blue Spring Steel Needl	
Trial Number	Force Measured (g)
1	341
2	494
3	717
4	461
5	535
6	357
7	282
8	321
9	465
10	269
Average	424.2
Standard Deviation	138.3616838

The results of the sharpness tests using the *Edge-On-Up Industrial Edge Tester* from Sharpening Supplies shows that the dull, unsharpened needle had an average sharpness of 1498.4 g, while the average sharpness of the sharpened, pointed needle was 424.2 g (in terms of grams of force needed to be exerted by these needles to cut through the sharpness device's string testing medium). This roughly means that the unsharpened needle had about the same sharpness as a bent edge, while the sharpened needle was only slightly duller than new high-end cutlery.

B. Insertion force trials

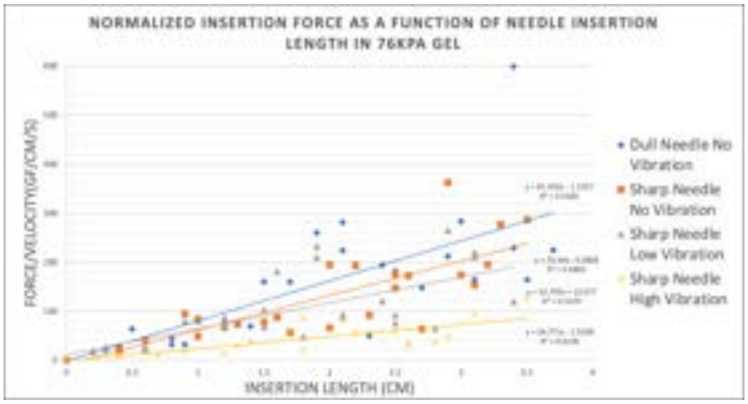

Fig. 5. Graph of the force per velocity at each insertion length of the needle into the gel

When the recorded insertion force of the steerable needles was analyzed against the insertion depth of the needle in the 76 kPa gel, it was found that the dull needle with a rounded tip and no vibration required the greatest force as it was inserted into the gel. Meanwhile, the sharp needle with a pointed tip and high vibration required the least amount of force at each centimeter of insertion than the other needles did. The sharp, pointed needle with no vibration and the sharp, pointed needle with low vibration required a similar amount of force, between these two extremes, at each insertion length. However, in the long run the sharp, pointed needle with a low vibration required slightly less force per insertion length to be exerted in order to cut through the gel than the sharp needle with no vibration did.

V. DISCUSSION AND CONCLUSION

Buckling is the primary modality of failure of tape spring steerable needles. Thus, minimizing the insertion force necessary for the needle to cut through tissue is advantageous as it will reduce the likelihood of buckling, minimize damage to surrounding tissue, and allow the steerable needle to cut through more tough, fibrous tissue. Thus, while tape spring based steerable needles already have significant advantages to other current steerable needle designs because of the tape spring based steerable needle's lower turn radius and thus easier navigability throughout the body, in order for these types of steerable needles to be more broadly applied for medical applications, it is necessary to alter the physical and material properties of these needles in a way that will greatly limit or even prevent the needle's buckling.

Fig. 6. The image on the left shows a tape spring based steerable needle being inserted straight into a 76 kPa gel. The image on the right shows an instance of the steerable needle buckling in the gel as the result of the needle's insertion or cutting force not being great enough to overcome the gel or tissue stiffness.

The data shown in this paper indicates that the geometry and sharpness of the tape spring needle play a significant role in minimizing the necessary insertion force and cutting force that must be exerted by the needle as it steers through gels representative of human tissue. Thus, by implementing a more pointed and angled needle tip geometry and ensuring needle sharpness according to the methods outlined above, the cutting force that needs to be exerted by the needle can be lowered, thereby lowering the risk of needle buckling.

It is also worth noting that since velocity and force are correlated, in the case of our needle insertion experiments, this data indicates that the device can be used at higher velocities as well.

Future work for these steerable needle designs will revolve around testing these needles in materials of nonhomogeneous stiffness, more comparable to the human body. Specifically, it would be necessary to characterize the effect of vibration on insertion force in real tissue, such as porcine liver and muscle tissue. Fibrous regions in tissue require large cutting forces, thus testing these new needle prototypes in tissue of nonhomogenous stiffness would assess the effectiveness of the material modifications outlined in this paper.

Also, determining ways to assess the effect of the needle's size on the necessary cutting force would be an important feature of steerable needles to be assessed in future research.

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References

[1] M. Scali, T. P. Pusch, P. Breedveld, and D. Dodou. Needle-like instruments for steering through solid organs: A review of the scientific and patent literature. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 231(3):250–265, 2017.

[2] R. J. Webster III, A. M. Okamura, N. J. Cowan, G. Chirikjian, K. Y. Goldberg, and R. Alterovitz. Distal bevel-tip needle control device and algorithm, Oct. 26 2010. US Patent 7,822,458.

[3] K. Seffen and S. Pellegrino. Deployment dynamics of tape springs. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 455(1983):1003–1048, 1999.

[4] O. Abdoun. A Tape Spring Based Steerable Needle with Small, Tissue Independent Turn Radii, July 2022

[5] K. Seffen and S. Pellegrino. Deployment of a rigid panel by tape-springs. Technical report, Cambridge University Department of Engineering, July 1997.

[6] K. Seffen and S. Pellegrino. Deployment dynamics of tape springs. Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences, 455(1983):1003–1048, 1999

[7] T. L. De Jong, N. J. van de Berg, L. Tas, A. Moelker, J. Dankelman, and J. J. van den Dobbelsteen. Needle placement errors: do we need steerable needles in interventional radiology? *Medical devices (Auckland, NZ)*, 11:259, 2018.