Influence of Vibration on Bioinspired Surgical Needles for Soft Tissue Biopsy

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Introduction: Design stagnation of traditional surgical needles results in high insertion force and needle tip deflection from the injection path. Higher forces and deflection can increase tissue damage, decrease biopsy sample integrity, and increase patient recovery time. This damage is magnified in softer body tissues, such as brain white matter or breast adipose tissue. Additionally, the traditional tissue phantoms used to simulate human tissue during needle design, often fail to model tissue damage caused by needle injection. Insect stingers hold promise for modernizing needle designs as they have evolved for millions of years, particularly the barbed stinger of a honey bee and the vibratory injection of a mosquito proboscis. Through the analysis of existing surgical needles and various insect stingers, mechanical and dynamic injection features were implemented in a novel needle design to decrease insertion forces and minimize needle tip deflection. Furthermore, this project addressed the gaps in existing tissue phantom simulations of tissue damage through a novel scaled-up tissue phantom histological method.

Materials and Methods: To mimic brain white matter and breast adipose tissue, three tissue phantoms were fabricated. The Young's moduli of the phantoms were measured using compressive testing on an Instron machine to ensure that the tissue phantoms had the same stiffness as breast adipose (E=0.5-25 kPa) and brain white matter (E=1.895 kPa). Polyvinyl chloride (PVC) gels were created with 500 mL plastic hardener and 500 mL softener. A gelatin gel was created with 111 g of 175 bloom gelatin mixed with 1000 mL of DI water. A composite hydrogel required 3% PVA (15 g/500 mL) and 0.75% PHY (3.175 g/500 mL). The needle was inserted into the gel at a speed of 1 mm/sec to a horizontal depth of 35.0 mm. To analyze the damage of the tissue created by the needle, dye was inserted into the injection site and the site was sliced evenly and photographed for image analysis. ImageJ was used to measure the distance from the edge of the tissue to the center of wound to determine needle deflection. A honey bee barbed stinger inspired the design of the needle tip. Symmetric barbs were designed into the circumference of the needle to lower the insertion force of the stinger by decreasing friction forces between the needle surface and the tissue, which also decreased deflection from the injection path. The final barb parameters chosen for the prototype were: a front barb angle of 165˚, a barb height of 0.5 mm, and a total of 10 barbs. To employ vibration similar to a mosquito, a Piezoelectric Actuator (Model P-810.30 PI) was used along with a gain of 10 (Model E-836.1G PI), and a function generator. The final vibrational settings were: a 60 Hz frequency, amplitude of 100 V, and a sinusoidal waveform. The insertion force was to be within the range of 1.45 N, the literature reported value for a metal needle of similar scale, to 3.96 N, the average insertion force of a plastic standard bevel tip (SBT) needle. The success criterion for deflection was taken from an experiment measuring the average deflection of a metal needle of similar scale, and this value was to be within or below the range of 25-30 mm.

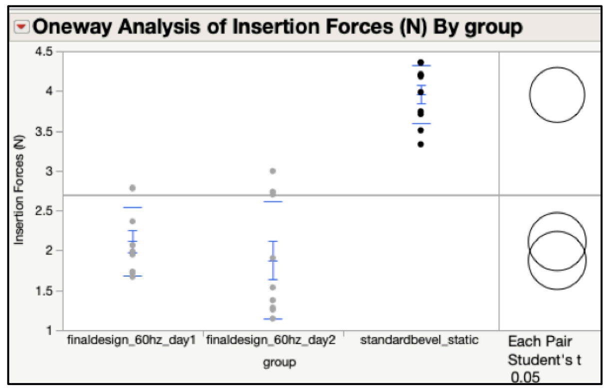

Figure 1: ANOVA analysis of static SBT needle and vibratory final prototype insertion forces.

Results and Discussion: The insertion force data obtained from injection experiments was analyzed in MATLAB and JMP Pro 13 to evaluate the performance of the final needle prototype as compared to the SBT needle (Figure 1). The vibrated final prototype was statistically different from the statically injected STB needle. The final net insertion force of the STB needle was 3.96 N, and that for the prototype was 1.99 N, a decrease of 50% in insertion force. Also, deflection analysis in the scaled-up histology method showed that the average deflection of the final needle prototype was 1.44 mm, which is below the success requirement of 25-30 mm.

Conclusions: The outcome of this project is a bioinspired surgical needle to be used in robotic surgery. The needle itself is barbed, and the operation of the needle includes the application of a uniaxial vibration. Clinical application of this novel design focuses on robotic biopsy procedures. Overall, the needle prototype created in this project performed within the criteria of success, but its performance was evaluated within a specific model environment and limited by a scaled-up, 3D printed prototype, allowing for continued research.