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Effect of vibration on insertion force and deflection of bioinspired needle in tissues

Sai Teja Reddy Gidde[1,3], Alexandra Ciuciu[2,3], Neha Devaravar[2], Rafael Doracio[2], Kian Kianzad[1] and Parsaoran Hutapea[1,4]

1 Department of Mechanical Engineering, Temple University, Philadelphia, PA, United States of America
2 Department of Bioengineering, Temple University, Philadelphia, PA, United States of America
3 These two authors contributed equally to this work.
4 Author to whom any correspondence should be addressed.

E-mail: hutapea@temple.edu

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Abstract

The design of surgical needles used in biopsy procedures have remained fairly standard despite the increase in complexity of surgeries. Higher needle insertion forces and deflection can increase tissue damage and decrease biopsy sample integrity. To overcome these drawbacks, we present a novel bioinspired approach to reduce insertion forces and minimize needle-tip deflection. It is well known from the literature, design of bioinspired surgical needles results in decreasing insertion forces and needle-tip deflection from the needle insertion path. This technical note studies the influence of vibration on bioinspired needle to further reduce insertion forces and needle-tip deflection. Bioinspired needle geometrical parameters such as barb shapes and geometries were analyzed to determine the best design parameters. Static and dynamic (vibration) needle insertion tests were performed to determine the maximum insertion forces and to estimate needle-tip deflection. Our results show that introducing vibration on the bioinspired needle insertion can reduce the maximum insertion force by up to 50%. It was also found that the needle-tip deflection is decreased by 47%.

1. Introduction

Needles are commonly used in medical procedures such as biopsy, brachytherapy and blood sampling. The effectiveness of a needle insertion in these procedures is highly dependent on the insertion accuracy [1]. The most important factors contributing to needle misplacement are tissue deformation and needle deflection [2, 3]. These drawbacks are directly related to the force experienced by the needle, and results in high insertion force and tip deflection from the insertion path [4, 5]. To minimize the needle placement errors and tissue damage, a practical approach is to reduce insertion force. Decreasing insertion force could also help with less pain, trauma and edema caused to the patients, such that it allows the patient to recover in a shorter time [6].

The insertion force occurs when the needle first breaks through the tissue, and a high insertion force leads to more tissue damage [7]. The parameters that affect the insertion force are needle geometry, needle-tip and speed of insertion [1, 8–11]. Needle-tips have been designed to decrease the insertion force, but inadvertently create an uneven distribution of force on the tip causing needle deflection. The needle deflection also depends on the speed of insertion, in which it reduces the needle bending [12]. Also, studies have shown that vibration-assisted needle insertion helps in increasing the needle placement accuracy [13] and reducing the cutting forces [14–16], ultimately decreasing insertion forces.

Many research efforts to mimic insect stingers are ongoing with penetration mechanisms such as honeybee [17–19] and mosquito [20] to help facilitate better needle insertion. Insect stingers hold promise for modernizing needle design, as the stingers have evolved and become adept at entering human tissue through various mechanical and dynamic insertion techniques [21]. In particular, a mosquito inspired vibration has gained interest due to its penetrating technique in reducing insertion forces with minimal pain [22–24]. The penetrating process of the mosquito vibration to the bioinspired needle in this study was investigated experimentally.

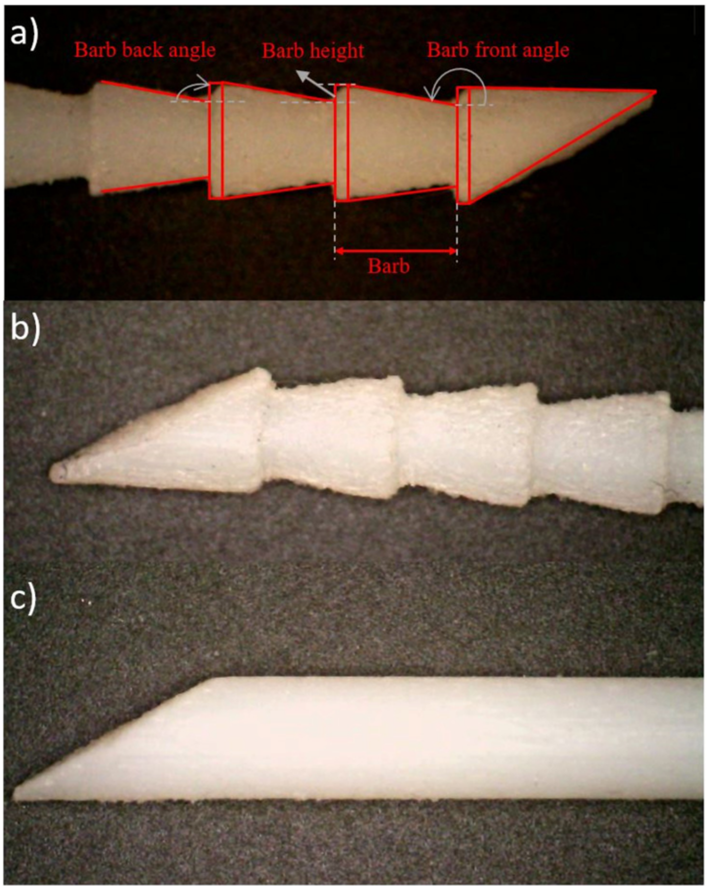


Figure 1. (a) A schematic representation of the bioinspired needle with final design parameters as length of the needle = 180 mm, diameter = 4 mm, barb front angle = 165°, barb height = 0.5 mm, barb thickness = 0.15 mm, barb back angle = 90° and no of barbs = 10, (b) microscopic view (magnification:16×) of bioinspired needle and (c) standard bevel-tip needle.

To further study how vibration reduces the insertion force during its penetration into tissue, Huang *et al* [14] showed 28% reduction in peak insertion forces using hypodermic needle (27-gauge needle), Clement *et al* [25] showed 73% reduction in peak insertion forces using hypodermic needle (25-gauge needle). The reduction in insertion forces were also achieved by applying axial vibration on microneedle [26], and ultrasonic vibration on hypodermic needles [14]. These forces were tested by varying frequencies and amplitudes in optimizing the vibration on tissue cutting [27]. Furthermore, to improve the needle position accuracy, Bi and Lin [13] studied vibration effect during needle insertion to reduce deflection. Through this study, the mechanical and procedural facets of mosquito-inspired vibration were implemented in novel bioinspired needle design.

The aim of our work is to study the effect of vibration on bioinspired needle to decrease insertion forces and to minimize needle-tip deflection. The outline of this paper is as follows: the *materials and method* section discussess the bioinspired needle design, experimental procedure and needle deflection analysis to study needle-tip deflection. The *results and discussion* section provides bioinspired needle parameter analysis such as barb height, barb front angle, vibrational frequency and lastly, effect of vibration on bioinspired needle insertion force and deflection. Finally, the *conclusion* section demonstrates the importance of the new needle design to reduce insertion forces and minimize needle-tip deflection.

2. Materials and methods

2.1. Bioinspired needle design

The insect inspired for this biomimetic needle design were barbs and vibration. The honeybee stinger is covered in asymmetric barbs [19] that lay flush against the body of the stinger. These barbs have shown to lower the insertion forces of the stinger, but increase the extraction forces to about 70 times that of the acupuncture needle [17, 28] and is caused by the asymmetric distribution of barbs along the needle body. Considering this drawback of barbed needles, the design of the final needle used symmetric barbs surrounding the circumference of the tip of the needle. Also, studies have shown that needles with scaled-up diameter have an average insertion force of 1.45 N [29] and an average of 4 N [19] for PVC with Young's Modulus of 3.5 kPa [30]. It has also been shown that bevel-tip needles have less insertion force compared to conical needles [12]. The final com-

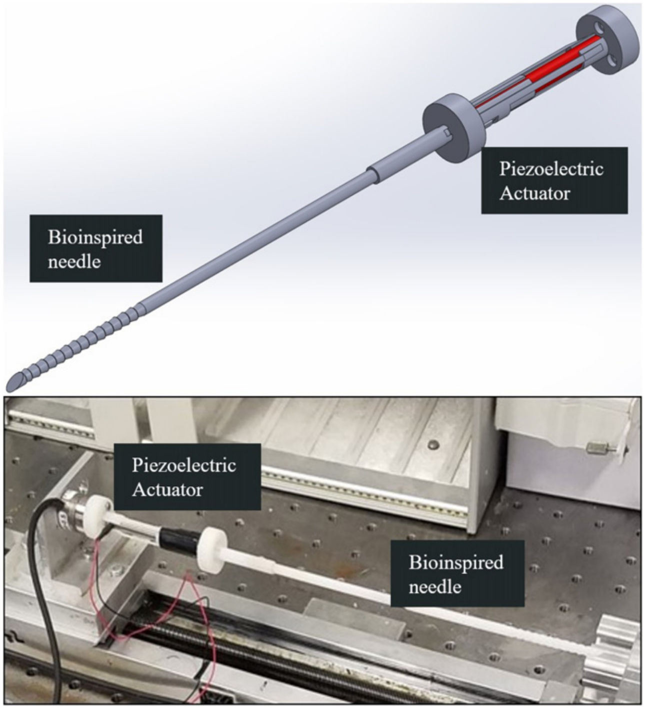


Figure 2. CAD model (top) and 3D printed (bottom) bioinspired needle with piezo actuator.

ponents of bioinspired needle design are labeled as follows: the bevel tip angle (35°), the length and diameter of the needle body (180 mm and 4.0 mm, respectively). The typical medical needle for our application is approximately 1.5–2 mm in diameter. Due to the manufacturing complexity of the true-scale design, the diameter of the needle was chosen to be 4 mm (about 2 times of a typical needle size) to study the influence of vibration on the insertion force of bioinspired needle. From our previous study [19], barb back angle of 90°, barb tip thickness of 0.15 mm and the number of barbs of 10 were considered constant throughout this study as shown in figure 1. However, the barb front angle and barb height were experimentally studied due to its significant contribution in reducing insertion forces. 3D model of the barbed needle was generated using CAD software and was 3D printed (see figure 2) using Connex350 3D printer. Additionally, the final needle was combined with a piezoelectric actuator (Physik Instrumente, Auburn, MA) that vibrated needle in the axial direction with a sinusodial waveform at a frequency ranging from 60–100 Hz. Furthermore, a digital microscope (Dino-Lite, AnMo Electronics Corporation, New Taipei City, Taiwan) was used to take images with a magnification of 16× (see figures 1(b) and (c)) of bioinspired and standard bevel-tip needle.

2.2. Dynamic needle insertion test procedure

The dynamic needle insertion setup (see figure 3) of this experiment included a horizontal linear insertion motor with a six-axis Force/Torque Transducer Nano17® (ATI Industrial Automation, Apex, NC) connected to a data acquisition system (National Instruments Corporation, Austin, TX). The force sensor was used to record the insertion forces and these force data were acquired using programable data acquisition system utilizing LabVIEW software. The needle guider was used to steer the needle and decrease the buckling of the needle. The tissue phantom was housed in a 3D printed gel mount. Additionally, a piezoelectric actuator, and an amplifier were added to the setup as shown in figure 3. The insertion tests were done using PVC gel phantoms (1.8 kPa) which is commonly utilized to mimic soft tissues. The PVC and softener were combined to mimic the viscoelastic properties of the tissue. This solution was heated until it became an activated solution and cooled using a freezer till it turns to a thick solidified solution. Additionally, a gelatin was used to study needle-tip deflection. To create a gelatin phantom, 111 grams of gelatin powder was mixed with 225 ml of de-ionized degassed water in a sanitized container before adding ten drops of vyse defoamer solution (Vyse Gelatin Co., Schiller Park, IL, USA). The mixture (evaporated milk/water of 500 ml and 275 ml of de-ionized water) was heated to 80 °C and added into gelatin/water mixture where it was thoroughly stirred. This mixture was allowed to cool to 40 °C before transfering into a phantom mold. The main objective of the dynamic insertion system was to vibrate the bioinspired needle at a frequency, and amplitude, that would mimic the mosqutio on a larger scale and reduce the insertion force. The maximum insertion depth during needle insertion was 5 cm both in PVC gel and chicken breast.

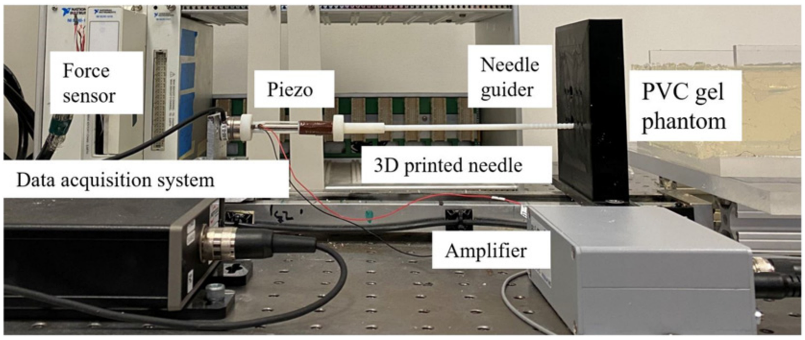


Figure 3. Dynamic needle insertion test setup.

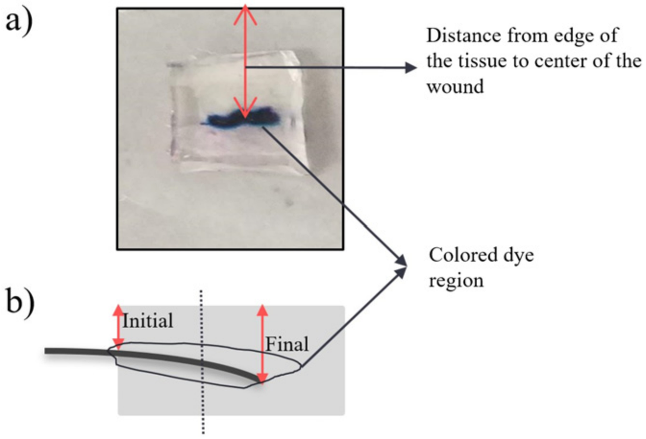


Figure 4. The distance from edge of the tissue to centre of the wound: (a) top view showing the initial section and (b) a schematic representation (side view) of the needle deflection inside the gelatin with coloured dye region.

This was accomplished using a piezoelectric actuator with an amplitude of 5 μm and insertion speed of 10 mm s^{-1}.

A mosquito vibrates its stinger within the range of 15–30 Hz [20] during its insertion into human skin and a scaled-up vibration frequency was also studied and showed that it is ideal for mimicking mosquito proboscis vibration [22, 31]. This frequency for needle to vibrate was found to be 60 Hz (see results section 3.3), with an amplitude of 5 μm in sinusodial waveform and addressing the problems of high insertion forces with traditional needles in a distinctive dual bioinspired approach. The number of test trials for each parameter were five using PVC gel phantom and three using chicken breast. The average and the standard deviation (SD) of these trials were calculated and presented. Firstly, the parameters that contribute major changes in insertion force were studied i.e. the front barb angle and barb height with no effect of vibration. All the other additional parameters such as barb back angle of 90°, barb tip thickness of 0.15 mm and the number of barbs of 10 were constant throughout this study. Secondly, the vibration frequencies were studied with the parameters that showed less maximum insertion force for the bioinspired needle. Finally, the influence of vibration on the insertion force of bioinspired needle were performed and compared with standard bevel-tip needle.

2.3. Needle deflection analysis

The needle deflection analysis to study needle-tip deflection on gelatin tissue was studied to quantify the position of the needle throughout the insertion and measure deflection. The insertion tests as shown in figure 3 were performed into gelatin to study the needle-tip deflection. In this method, the insertion path in the gelatin sample was categorized as 'wound' within the tissue, and the spreading of dye within this wound allowed for visualization of the damage to surrounding tissue as shown in figure 4. This damage was quantified for the final needle to understand the effect of the design decisions outside of insertion force. The damaged wound of the gelatin sample was sliced into sections (see figure 4(a) for sample section) and a colored dye was used to spread across the sample sections. A digital camera was used to image the initial and final sections of the gealtin sample. A schematic representation of how the needle deflected inside the tissue was shown in figure 4(b)). The needle insertion path was located on this colored dye sections and dis-

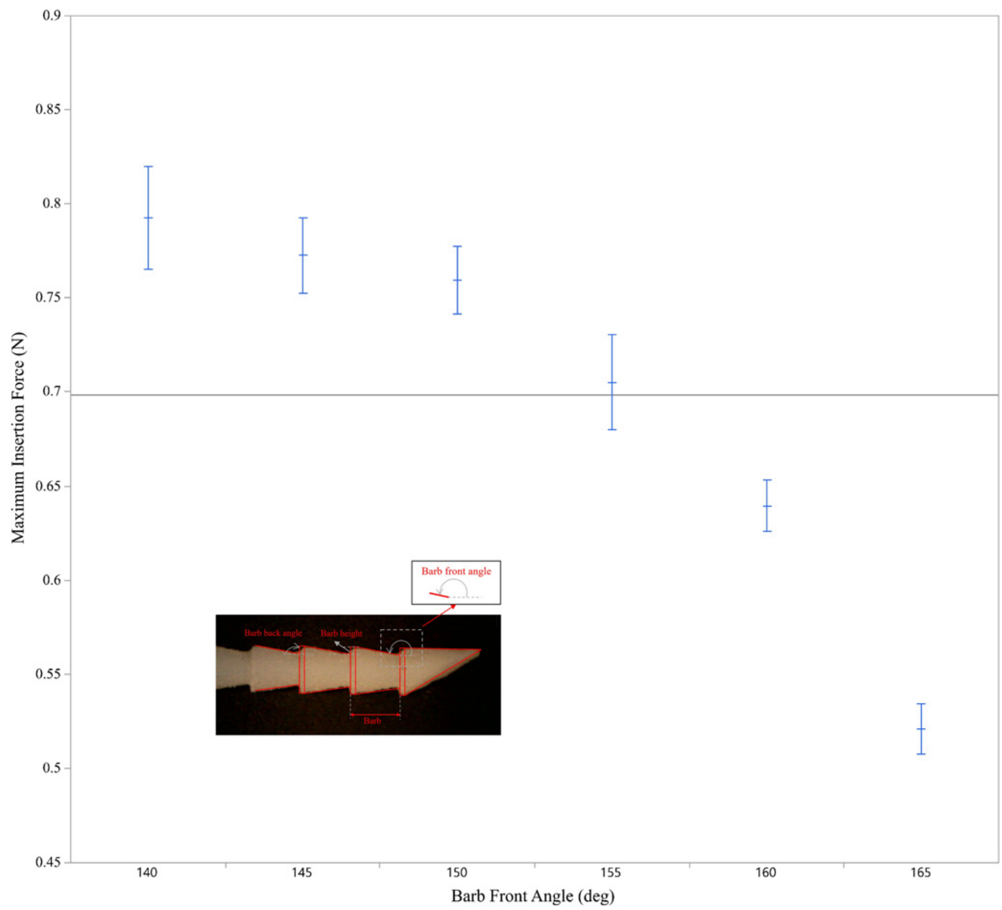


Figure 5. Effect of different barb front angles on bioinspired needle (without vibration) insertion force.

tance from edge of the tissue to centre of the wound was measured using ImageJ software.

3. Results and discussions

The insertion tests into tissue-mimicking PVC gels (Young's modulus (E) of 1.3 kPa) [32] was carried out using barbed needle. Before performing the dynamic needle insertion, analysis on bioinspired parameters (such as barb front angle, barb height and vibration frequency) are done experimentally and statistically studied (with 5% significance level) to choose the best design for testing, and to study the maximum insertion forces of bioinspired needle.

3.1. Effect of barb front angle on bioinspired needle insertion force

The insertion forces were measured with different barb front angles of the bioinspired needle. The average maximum insertion forces of five trials of barb front angles for bioinspired needles with barb height of 0.5 mm are shown in figure 5. The maximum insertion force decreases with increase in barb front angle. The comparison of barb front angle showed that the needle with 165° angle have significant lower maximum force compared to the needles with 140°, 145°, 150°, 155° and 160° angles. Furthermore, increasing the barb angle showed reduction in maximum insertion forces, which means removal of extra material from the needle results in less frictional force and thus decreasing insertion forces.

3.2. Effect of barb height on bioinspired needle insertion force

The insertion tests were done into PVC gels to study the barb height parameter. Since larger barb height results in removal of extra material, ultimately resulting in less insertion forces due to less friction. The other parameters considered for this needle are barb front angle of 165° barb. There was statistical difference between the insertion forces of different barb height groups, and the 0.5 mm barb height group presented the lowest maximum insertion force with a mean of 1.1 N with no effect of vibration. Furthermore, the maximum insertion force for the bioinspired needle with barb height of 0.5 mm is less than the smaller barb heights. Based on these results, the barb height was chosen to be 0.5 mm (see figure 6) along with 165° barb front angle (result from previous section) for the next parameter study.

3.3. Effect of vibration frequencies on bioinspired needle insertion force

The final parameter analyzed to the needle design was mosquito inspired vibration and is discussed on

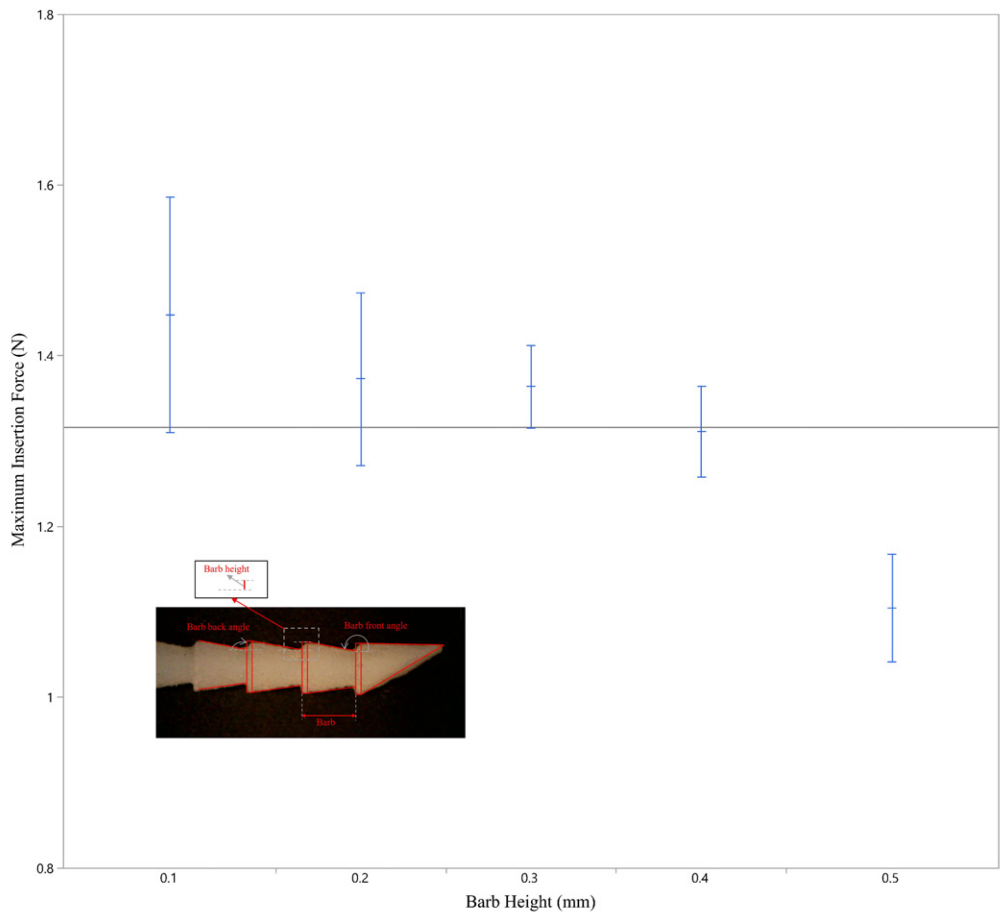


Figure 6. Effect of different barb heights on insertion force of the bioinspired needle without vibration.

what vibration frequency effect can reduce the insertion force of a bioinspired needle. Since a mosquito vibration ranged between 15–30 Hz [20, 22, 31] and increasing frequency resulted in higher forces. But, in order to mimic this on a larger scale, empirical testing was done to determine the lowest frequency that had an effect on the insertion force measurements, while still being below 100 Hz to be representative of the mosquito. Between the vibartional frequency of 15 and 60 Hz, there is little difference on the insertion forces. This is because the diameter of the needle is higher and the vibration effect is small: therefore, the vibration frequency ranging from 60–100 Hz with an amplitude of 5 μm was studied. The results for this analysis are shown in figure 7, and it was found that there was significant difference between the frequencies from 60–100 Hz on the bioinspired needle and frequency with 60 Hz showed less mean insertion forces compared to other frequencies. There was a close relationship between the frequency parameter and insertion force, this force increased with increase in frequency, and is due to the effect of high vibratory actuation on cutting tissues [31]. Furthermore, signal to noise ratio during needle insertion shown to be higher and reliable at 60 Hz with an amplitude of 5 μm.

3.4. Effect of vibration on the insertion force of bioinspired needle

Now with all the parameters statistically analysed, the effectiveness of the vibration on bioinspired needle is evaluated with barb front angle of 165°, a barb height of 0.5 mm and vibration frequency of 60 Hz with an amplitude of 5 μm. The performance of the vibratory bioinspired needle in PVC gel (see figure 8) and chicken breast (figure 9) was demonstrated by comparing the maximum insertion force of the bioinspired needle (with and without vibration) and standard bevel-tip needle without vibration as shown in figure 8. The final maximum insertion force of a dynamic needle insertion obtained was 1.99 N. The maximum insertion force of the vibratory bioinspired needle insertion force was qualitatively lower than the bioinspired needle without vibration. The maximum insertion force of the bioinspired needle (without vibration) was found to be a mean of 3.24 N, whereas the final net insertion for the bioinspired needle (with vibration) was 1.99 N. Lastly, the maximum insertion force of a standard bevel-tip needle found was 3.96 N, which is significantly higher than the bioinspired needle. The PVC gel phantom in this study is close to tissue-mimicking material [32]. The insertion tests into PVC gel showed higher insertion forces

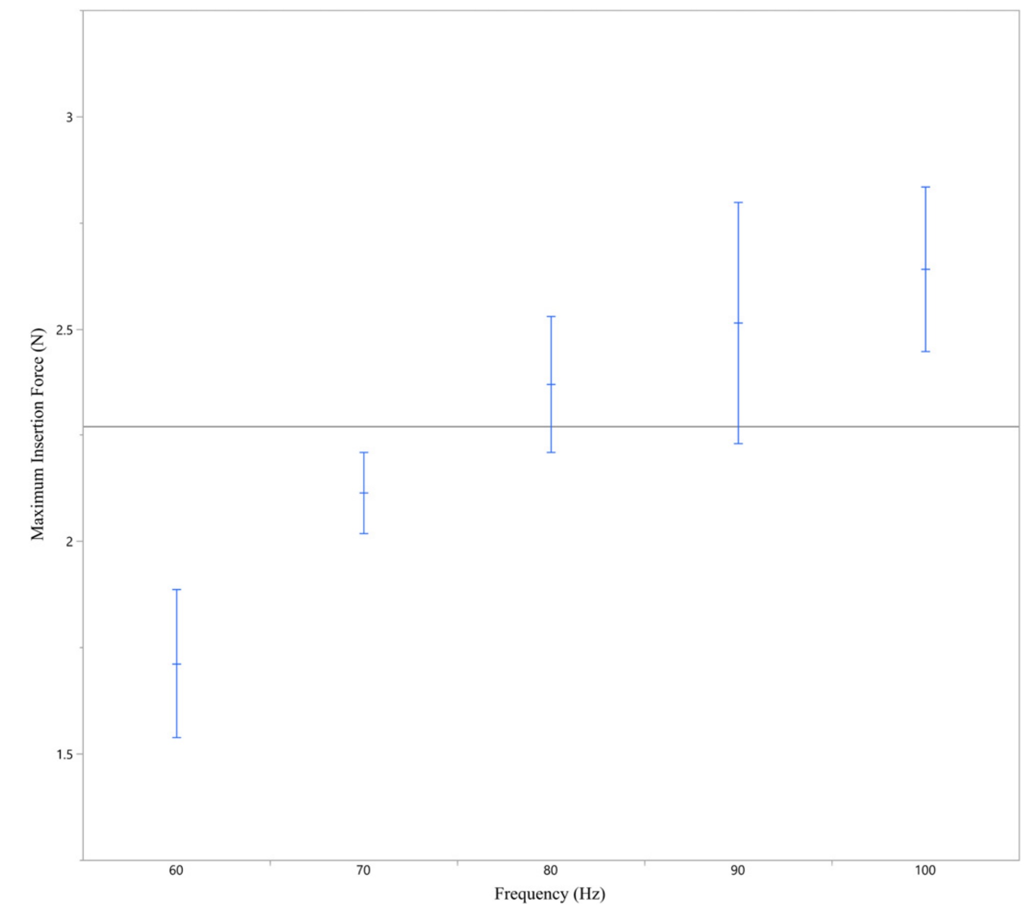


Figure 7. Effect of vibration frequencies on maximum insertion force of the bioinspired needle with barb front angle = 165°, barb height = 0.5 mm.

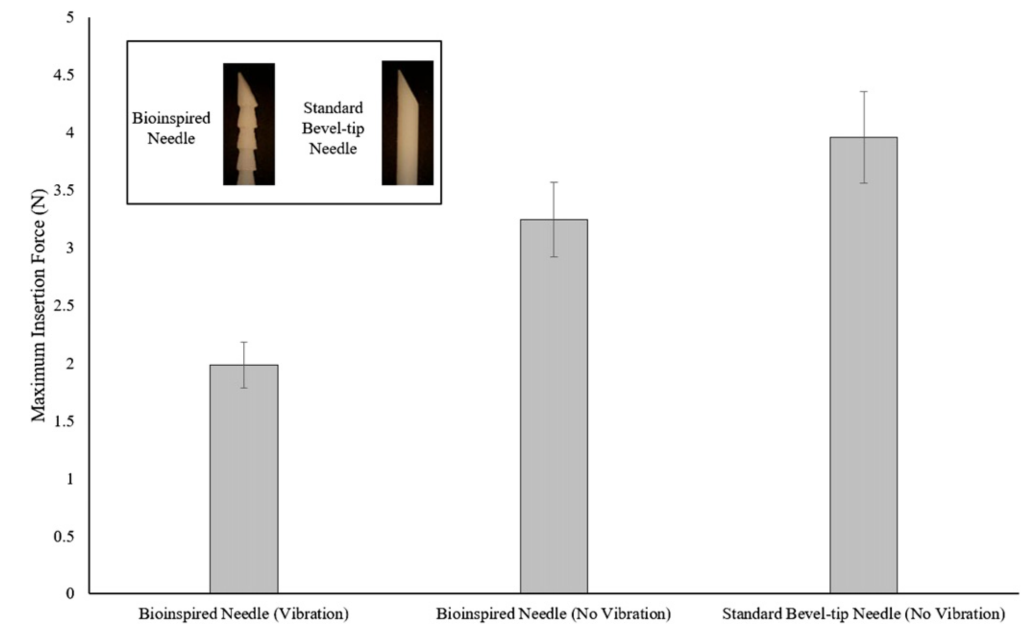


Figure 8. The maximum insertion forces obtained for bioinspired needle (with and without vibration) and standard bevel-tip needle (without vibration) from insertion tests into PVC gels.

for a tissue with $E = 1.3$ kPa was due to the diameter of the needle. This study focuses on influence of vibration on the insertion force of bioinspired needle. Therefore, our experiments were performed in both PVC gel phantom to study the influence of vibration. Additionally, the insertion tests into higher tissue

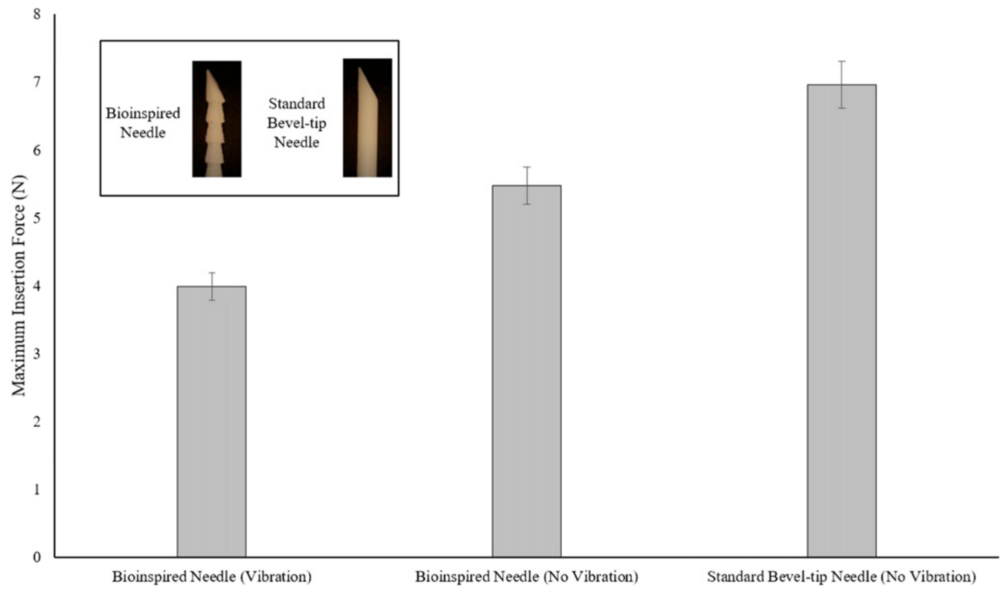
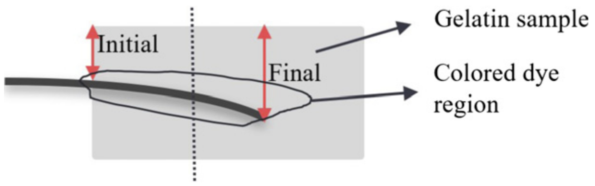


Figure 9. The maximum insertion forces obtained from insertion tests into chicken breast.

Table 1. Bioinspired needle insertion (with and without vibration) deflection values for distance from edge of the tissue to centre of wound.

Distance from edge of the tissue to centre of wound in sliced gelatin sample



Group	Initial deflected distance (mm)	Final deflected distance (mm)	Total distance (mm) = initial − final
With vibration	9.31 ± 0.08	7.87 ± 0.03	1.44 ± 0.10
Without vibration	9.56 ± 0.02	6.84 ± 0.05	2.72 ± 0.03

properties such as chicken breast [33] were performed to study the influence of vibration on bioinspired needle. The applying of vibratory actuation during bioinspired needle insertion reduces the amount of force required for bioinspired needle penetration.

From the results, it shows that having barbs decreases friction forces and ultimately reducing insertion forces. Furthermore, it has been demonstrated that having vibration actuation during needle insertion reduces maximum insertion force by up to 50% in PVC gel and 43% in chicken breast compared to needle insertion without vibration.

3.5. Effect of vibration on the deflection of bioinspired needle

In addition to insertion force measurements, needle-tip deflection was done in gelatin (4.2 kPa) to determine the effect of vibration on the deflection of the bioinspired needle. The maximum insertion forces in gelatin with vibration was 2.94 ± 0.08 N and without vibration was 3.44 ± 0.07 N. Due to viscoelastic properties in PVC [32], lack of tissue damage was seen compared to gelatin in this method. Therefore, the damage analysis was done on gelatin with higher Young's modulus to study the bioinspired needle deflection with and without vibration. The initial and final distance (see figure 4) measured values and the standard deviation values for distance from edge of the tissue to centre of wound are presented in table 1. The results obtained from this method for three trials of experiments showed that the average deflection of the vibratory bioinspired needle was 1.44 mm and without vibration was 2.72 mm. Thus, the fabrication test proved that the decisions made for bioinspired needle with vibration were capable of decreasing deflection significantly by 47%.

4. Conclusions

In this work, the effect of mosquito-inspired vibratory actuation on the bioinspired needle insertion force was studied. Results showed significant decrease in insertion force of bioinspired needle during its insertion into PVC gels. Analysis was done on the bioinspired parameters such as barb front angle, barb height and vibration to determine the best design that reduces the insertion forces. The maximum insertion force for the final bioinspired needle with 60 Hz vibration is reduced by up to 50% in PVC gel and 43% in chicken breast than the force without vibration. Furthermore, the bioinspired needle-tip deflection with the vibration showed 47% reduction compared to the needle without vibration. The vibratory actuation for the bioinspired needle mentioned above helps to precisely control the needle during insertion and reduce the forces. In future research, *in vivo* tests will be performed to acquire detailed knowledge about the influence of vibration on bioinspired needles for clinical applications.

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ORCID iDs

Sai Teja Reddy Gidde https://orcid.org/0000-0003-3153-3902
Parsaoran Hutapea https://orcid.org/0000-0001-6917-1252

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