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Robotic Cytology using Extra-Fine Needles
-Proposal of Puncture Control Strategy for Increasing Collection Amount-

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***Abstract*— Fine needle aspiration cytology requires accurate needle insertion into a tumor and sufficient amount collection of samples, which highly depends on the skill of the physician. The advantage of the diagnosis is to minimize the tissue damage with the fine needle, while, when the amount of the sample sucked from the lesion is not enough for the definite diagnosis, the procedure has to be repeated until satisfying them. Although numerous research reported a robot-assisted insertion method to improve the accuracy of needle placement with fine needles, there was less research to address the efficient tissue collection. Ideally, the amount of the samples can be satisfied for the diagnosis even if an extra-fine needle (e.g. 25-gauge) is used. This paper proposes a novel needle insertion method for increasing the amount of the tissue sample with the extra-fine needle. The proposed insertion method comprises the round-trip insertion motion and trajectory rerouting with the nature of the bevel-tipped needle. The phantom study's result showed the equivalency of the aspiration amount between a physician's manual procedure with a 22-gauge needle and the proposed method with a 25-gauge needle (4.5 ± 1.0 mg vs 5.1 ± 0.7 mg). The results suggested that the proposed robotic aspiration method can increase the sampling amount with the extra-fine needle in the fine needle aspiration cytology.**

I. Introduction

Fine needle aspiration cytology is a cancer diagnosis method by aspirating cells from the lesion and obtaining microscopic findings on the morphology of the cells. This method often uses to diagnose lesions suspected of being thyroid or breast cancer [1], [2]. For satisfying the reliability of the diagnosis, it is important to collect samples accurately from the lesion and to obtain sufficient amounts of samples that can make a definite diagnosis by pathologists [3]. Thus, clinicians are required to insert the needle into the lesion accurately under image guidance such as ultrasound imaging and suck it with a certain time.

For assisting the accurate fine needle insertion, numerous robotic needle insertion system has been widely developed [4], [5]. Particularly, as mainstream in this research field, a needle steering method that enables control of the path trajectory with a flexible bevel-tipped fine needle can enhance the reachability of the needle tip by avoiding anatomical obstacles [6], [7]. Also, we proposed a needle insertion control method and preoperative path planning to minimize needle deflection with a 25-gauge needle focusing on multi-layered tissues and organs such as the lower abdomen [8]–[10]. Although most of the previous research focused on the accurate placement into the target, less research is focusing on the adequacy of the tissue sampling after reaching the needle tip into the lesion. The advantage of fine needle aspiration cytology is to minimize tissue damage by using a fine needle. Meanwhile, when the amount of the sample sucked from the lesion is not enough for the definite diagnosis, the procedure has to be repeated until satisfying them, which leads to the patient's trauma significantly. This is a trade-off, as a smaller needle size results in less tissue damage, but a fewer amount of samples. Needles finer than 22-gauges are commonly used for the fine needle aspiration cytology, while the use of finer needles resulted in reducing the amount of cell collection [1], [11]. Ultimately, it is ideal that the amount of the samples can be satisfied for the diagnosis even if an extra-fine needle (e.g. 25-gauge) is used. Thus, there is a critical demand for the method to enable improving sucking the amount of the samples with the extra-fine needle.

This study develops a novel robotic insertion method for sucking enough amount of the tissue sample with the extra-fine needle. As the contribution of this paper, 1) we performed an experimental analysis on the relationship between variable insertion control parameters and the sucked amounts of the tissue sample, 2) based on the experimental analysis, we proposed a needle insertion control method for combining a round-trip needle insertion and an adjustment of the rotation angle for enhancing the amount of the samples. Roud-trip needle insertion means the back and forth movement of the needle in the direction along the puncture path. Finally, the proposed method was validated by comparing the amount of the sample performed by the clinician's procedure and the proposed method with a gelatin phantom and porcine liver.

II. Experimental Analysis of Collectible Samples

To increase the amount of sucked samples efficiently, we hypothesized that it would be effective to provide a dynamic motion to the needle so that the tissues are broken and increased its fluidity to facilitate suction collection. Based on the hypothesis, an experimental analysis of the suction sampling amount under applying 1) needle rotation motion and 2) a round-trip needle insertion motion was conducted.

A. Experimental Setup

The suction collection was performed while applying those two needle insertion motions to gelatin with two types of Young's modulus. For deciding the stiffness of the gelatin used in this experiment, the stiffness of a porcine liver was referred. A compression test with a 6-axis force/torque sensor

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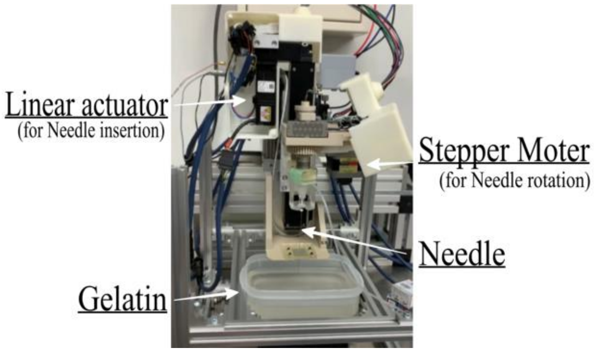


Fig. 1 Experimental sestup overview

Table I Needle operating conditions

No.	Number of round trips	Round trip speed [mm/s]	Section distance [mm]	Rotational speed [rpm]
1	2	10	10	0
2	2	10	10	100
3	2	10	10	250
4	2	200	10	0
5	0	0	0	0
6	4	10	10	0
7	6	10	10	0

(Nano17, ATI industrial automation, USA) to the porcine liver resulted in Young's modulus was about 6.3 to 55 kPa when the strain was 0 to 0.2. Then, referring to the result, the gelatin with two types of stiffness was created with volumes of 2.0 and 4.8 wt% at about 5 ^{o}C. With those gelatins, the needle insertion and tissue suction were performed using a previously developed robotic needle insertion system [10]. The experimental overview is shown in **Fig. 1**. The needle insertion control parameters are shown in **Table I**. The experimental protocol is as follows:

① The weight of the needle was measured using an analytical balance (1-1726-01, AS-ONE Cooperation, Japan).

② The needle was connected to the vacuum device and attached to the needle insertion unit.

③ Needle inserted into gelatin about 10 mm with 10 mm/s.

④ Needle operation was performed under each condition of No.1 to No.7 while applying negative pressure for 20 s using a solenoid valve (VDW20DA, SMC Corporation, Japan), and aspiration sampling was performed.

⑤ After releasing the negative pressure, the needle was pulled out at 10 mm/s.

⑥ The needle was removed from the needle insertion unit and vacuum device.

⑦ The weight of the needle after aspiration was measured. The difference from the measured value in advance was used as the collected amount value.

Six trials were performed for each condition. In step 4, the needle movement was operated immediately after applying negative pressure. The rotation operation was performed as a bidirectional rotation in which the rotation direction is switched for each one rotation [12].

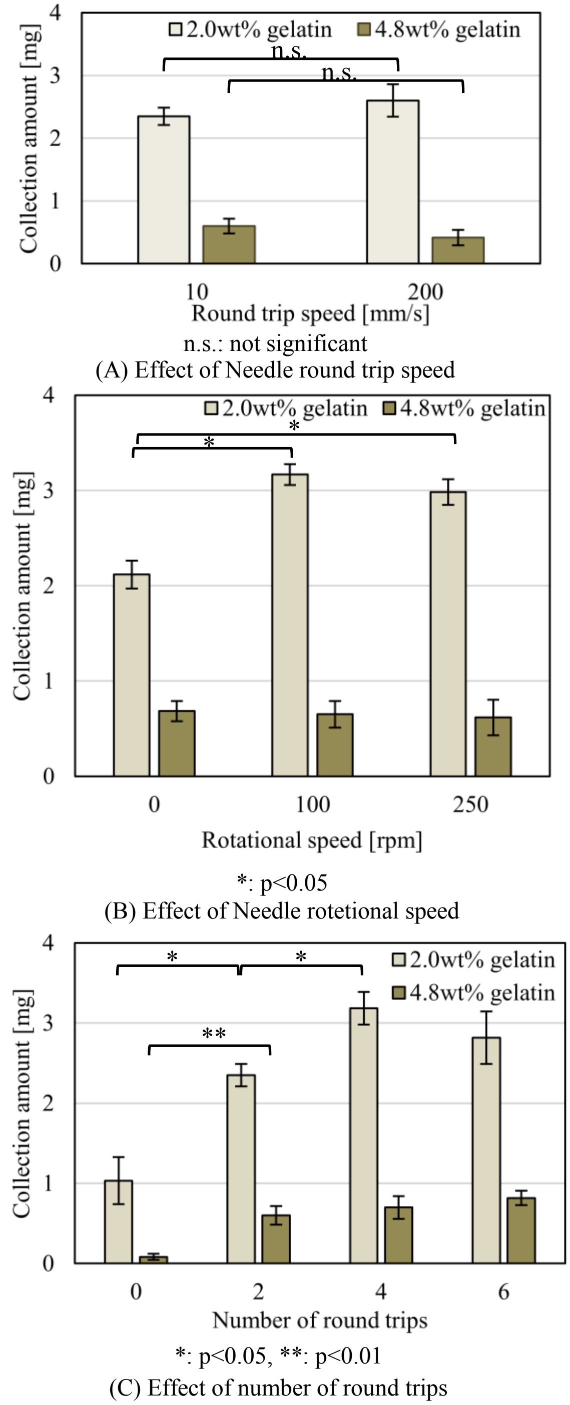


Fig. 2 Collection amount in varying insertion conditions

B. Result

Fig. 2 shows the difference in the amount of samples collected under each condition. The effects of each parameter were compared and analyzed using a statistical test. The Steel–Dwass test was used for No.1, 2, and 3 for comparing the effect of the rotational speed to the amount of the collected samples. The Mann–Whitney *U* test was used for No.1 and 4 for comparing the effect of the round-trip speed to the amount of the collected samples. For comparing the effect of the number of round trips to the collected samples, Steel–Dwass test was used for No.1, 5, 6, and 7.

In the case of softer 2.0 wt% gelatin, the collection amount increased significantly by applying the rotational motion ($p < 0.01$). There was no significant difference in the collection amount between the rotational speeds of 100 and 250 rpm. In the case of harder 4.8 wt% gelatin, even if applying the rotation motion, there was no significant difference between and without the rotation motion. Regarding the round-trip insertion speed, there was no significant difference between each of the insertion speed for either of the gelatin. Regarding the number of round trips, although the collection amount increased due to the increase in the number of round trips up to 4 round trips in the case of 2.0 wt% gelatin, the increase in the collection amount stopped at the 6 round trips. With 4.8 wt% gelatin, the collection amount increased up to 2 round trips.

C. Discussion

As a result, the application of the round-trip insertion motion showed the effect of increasing the collection amount of both gelatins. An increase of 130% was confirmed with 2.0 wt% gelatin and 620% with 4.8 wt% gelatin compared with the case where the round-trip motion of the needle was not added. Particularly with 4.8 wt% gelatin, it was almost unable to suck the sample without needle round-trip motion. Thus, the needle round-trip motion would help the amount of aspiration. Alternatively, when the number of round trips was increased, the collection amount stopped increasing after a certain number of times. This may be because the capability of the suction force attracting the gelatin around the needle tip is related to the stiffness of the gelatin. The amount of 4.8 wt% gelatin attracted by the suction force is small because of its hardness and less fluidity. While the needle round-trip motion promised to improve sucking the amount of the samples, the insertion speed could not contribute to it.In addition, in the case of 2.0 wt% gelatin, an increase in the amount of gelatin collected was observed by the rotating motion. On the other hand, no improvement was observed for 4.8 wt% gelatin, which requires a higher collection volume.

Thus, the results indicated that the tissue in a certain range from the needle tip can be effectively sucked by applying the round-trip motion. To further increase the suction amount, we assume that the needle tip position is needed to be adjusted finely inside the targeted lesion for expanding the collectible area.

III. Proposed Method and Experimental Results

A. Needle Trajectory Rerouting

From the observation of the experimental analysis, adjusting the needle tip position for expanding the suction area can increase the collection amount. Meanwhile, a one-dimensional insertion motion, such as the monotonous round-trip motion performed in the limits of the previous experiments to expand the sampling range because the needle tip trajectory is almost the same every round-trip motion. To address this limitation, it is considered effective to change the needle tip trajectory every round-trip motion and expand the collectible range two- or three-dimensionally. Considering the burden and invasiveness of the patient, it is inappropriate to completely pull out and reinsert the needle, and it is preferable to change the trajectory of the needle in or near the lesion. The bevel-tipped fine needle is easily deflected during the insertion into tissues due to the asymmetric interaction force loaded at the needle tip [13]. Then, the needle trajectory can be changed by manipulating the direction of the needle tip. For instance, when the needle is inserted into the 4.8 wt% gelatin with this rerouting method, the needle trajectory was divided into two directions (**Fig. 3**). Repeating to reroute the needle trajectory is expected to expand the reachability of the needle tip within the lesion without fully pulling out the needle and inserting it again from another position.

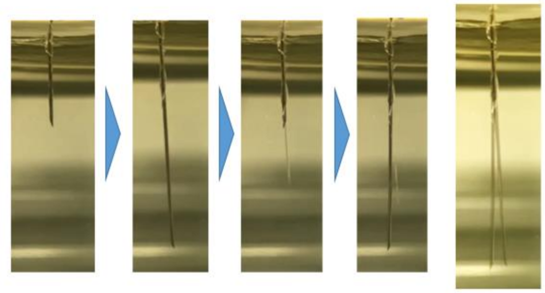


Fig. 3 Puncture route change by the proposed method

Table Ⅱ Needle operating conditions in evaluating test

Method	No.	Phantom	Number of round trips	Suction time [s]
Simple round trip	1	gelatin	4	20
	2	Pig liver	8	40
Proposed method	3	gelatin	2 × 2 way	10 × 2 way
	4	Pig liver	4 × 2 way	20 × 2 way

B. Verification Experiment

For evaluating the efficacy of needle trajectory rerouting during the round-trip insertion motions for improving the collection amount, we compared the amount of the sucked samples between the round-trip insertion with and without the needle trajectory rerouting. Additionally, to demonstrate the feasibility of the proposed insertion method, we compared the amount of the sucked samples between the proposed needle insertion method with the 25-gauge needle and the conventional clinician's manual operation with the 22-gauge needle. The comparison between the round-trip motion with and without rerouting the needle trajectory was performed on a phantom using 4.8 wt% gelatin and porcine liver. **Table II** shows the operation conditions. The procedure is as follows:

① The weight of the needle was measured using an analytical balance.

② The needle was connected to the vacuum device and attached to the needle insertion unit.

③ At a needle insertion speed of 10 mm/s and a rotation speed of 100 rpm, the phantom was inserted by 10 mm.

④ The rotation was stopped

⑤ In simple round-trip motion, negative pressure was applied, and 4 or 8 round-trip motions were performed on the same route. In the proposed method, negative pressure was applied after the needle is inserted by 10 mm additionally, and round-trip motions were performed 2 or 4 times. Releasing the negative pressure, the needle was pulled 10 mm and rotated 180 degrees to change the needle tip direction. After inserting the needle 10 mm again and applying negative pressure, round-trip motions were performed 2 or 4 times on the second route.

⑥ Negative pressure was released, and the needle pulled out with 10 mm/s.

⑦ The needle was removed from the needle insertion unit and vacuum device.

⑧ The weight of the needle after aspiration was measured. The difference from the measured value in advance was used as the collected amount value.

Six trials were performed for each condition. The Mann–Whitney *U* test was used as the statistics for comparison. We also compared the amount of the tissue samples collected by the clinician's manual procedure with a 22-gauge needle and by the proposed method with a 25-gauge needle. The clinician's manual procedure was performed as follows:

① The weight of the needle was measured with an analytical balance.

② The needle was attached to a 20 ml syringe (SS-20LZ, TERUMO, Japan).

③ The physician collected samples from the phantom in the same manner as the conventional procedure.

④ The needle was removed from the 20 ml syringe.

⑤ The weight of the needle after aspiration was measured. The difference from the measured value in advance was used as the collected amount value.

Three trials were performed for the manual operation.

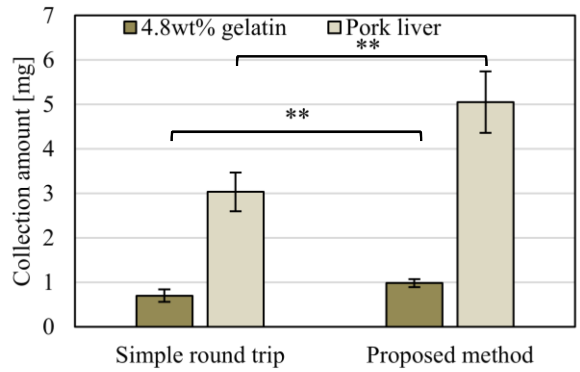
C. *Results*

Fig. 4 shows the result of comparing the amount of the samples collected by the round-trip motion with and without the needle trajectory rerouting. The round-trip motion with the needle trajectory rerouting increased the collection amount by about 40 % for 4.8 wt% gelatin and about 66% for the porcine liver compared to that without the needle trajectory rerouting. There was also a significant statistical difference between the round-trip motions with and without the needle trajectory routing ($p < 0.05$).

Fig. 5 shows the result of comparing the amount of the samples collected by the conventional physician's manual procedure and by the proposed robotic needle insertion method. The average amount collected by the physician's procedure was 4.5 ± 1.0 mg, while the average amount collected with the proposed insertion method was 5.1 ± 0.7mg. Therefore, even with the extra-fine needle, the proposed robotic needle insertion method may have the capability of the suction as same as the physician's conventional procedure with a thicker needle. However, due to the lack of samples, we cannot mention the significant difference.

IV. Discussion

In this study, we focused on developing the robotic needle insertion method for increasing the amount of tissue samples in the fine needle aspiration cytology. Increasing the amount



**: p<0.01

Fig. 4 Change in collection amount by the proposed method

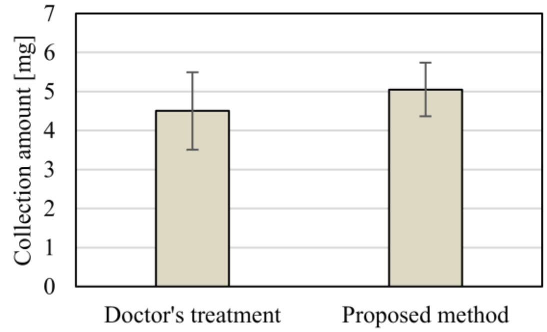


Fig. 5 Comparison of doctor's procedure and proposed method

of tissue samples promises an accurate definite diagnosis. The round-trip insertion motion with the 25-gauge needle under rerouting the needle trajectory enabled to increase in the amount of the collection samples significantly and demonstrated the suction capability equal to the conventional clinician's manual procedure with the 22-gauge needle.

The aspiration with the extra-fine needle becomes difficult due to a decrease in suction force and an increase in the pipe friction force since the inner diameter of a thinner needle is smaller, and then the aspiration amount is decreased. Disrupting the tissue to increase fluidity is effective in increasing the aspirating amount. However, to break the tissue, it is necessary to apply a stress equivalent to or greater than the tissue breaking stress. The main mechanical effects of the needle insertion into the tissue are the cutting force generated at the needle tip and the frictional force generated on the side surface of the needle when the needle is reciprocated or rotated. Whether the stress generated by these reaches the breaking stress may be related to the factor of increasing the aspirating amount.

The breaking stress is calculated from the results of the compression test for 2.0 wt% and 4.8 wt% gelatin. The breaking stress σ can be expressed by the following formula:

$$\sigma = \frac{F}{A_0} \quad (1)$$

Where the cross-sectional area of the columnar sample was A_0, and the axial force at break was F. From equation (1), the breaking stress of 2.0 wt% gelatin was about 13 kPa, and that of 4.8 wt% gelatin was 42 kPa.

Regarding the cutting force, because the needle could insert into the gelatin, the stress generated from the cutting force has reached the breaking stress. Alternatively, regarding the friction force, the shear stress τ due to friction can be expressed as follows:

$$\tau = \frac{dF}{dx}\frac{1}{\pi R^2} \tag{2}$$

Where F is the frictional force, x is the insertion distance, and R is the needle radius. From eq. (2), the shear stress due to friction was 1.6 kPa for 2.0 wt% gelatin and 6.1 kPa for 4.8 wt% gelatin. Since these stresses are smaller than the breaking stress, it is considered that it was difficult for the frictional force to break the tissue. Therefore, the cutting force is effective for breaking tissue and increasing fluidity, which is one of the main factors of increasing the aspiration amount. In addition, the proposed robotic aspiration method is useful for increasing the collection amount, because it is considered that the efficiency of breaking the tissue can be enhanced when a sufficient amount of tissue is present in the traveling direction of the needle.

As a limitation of this study, the quality of the sample collected by the proposed insertion method was not investigated, which is also crucial for an accurate diagnosis. Since this method reciprocated the needle, it may deviate from the lesion during aspiration, which may lead to deterioration of the quality of the sample. It is necessary to select the best needle insertion path that can cover the entire aspiration range within the lesion. To investigate changes in the proportion of impurities such as blood and the effect on diagnostic accuracy when this method is used are also necessary. To investigate changes in the proportion of impurities such as blood and the effect on diagnostic accuracy when this method is used are also necessary. Furthermore, regarding the issue of dissemination of cancer cells in fine needle aspiration cytology, Ito et al. found that the possibility of cancer tumor recurrence in the puncture pathway in conventional puncture aspiration cytology is 0.14%, but it is necessary to investigate the effect of bifurcation of the puncture pathway as in the proposed method [14]. In addition, when using this method, parameters such as puncture speed, distance, and timing of path change should be determined by considering the physical characteristics of the puncture path, size and location of the puncture target. For example, the size of the lesion determines the distance that the needle can reciprocate, and if a sufficient distance cannot be obtained, it is necessary to change the route and expand the aspiration range. If more sampling is required, it will be necessary to consider changing the direction of the needle tip every 120 or 90 degrees and increase the number of routes in 3 or 4 directions. Since this research suggests that the effective number of round trips changes according to the tissue hardness, it can be said that setting the parameters according to the physical properties is necessary.

V. Conclusion

This paper developed a novel insertion method to increase the aspiration tissue amount on the fine needle aspiration cytology with a 25-gauge needle. Based on the experimental analysis of the relationship between the insertion motion and tissue sampling amount, we proposed the robotic aspiration method that combines the round-trip insertion motion and trajectory rerouting with the nature of the bevel-tipped needle. The aspiration amount was significantly increased by the proposed robotic aspiration method. In addition, the aspiration amount equivalent to that of a physician's manual procedure with a 22-gauge needle was obtained by the proposed method with a 25-gauge needle. Therefore, the results suggested that the proposed robotic aspiration method can increase the sampling amount with the extra-fine needle in the fine needle aspiration cytology. Future works will address to validate the efficacy of the proposed method by demonstrating *ex vivo* and *in vivo* evaluations.

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