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Estimation of the cutting force using the dynamic friction coefficient obtained by reaction force during the needle insertion.

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Abstract

To decrease human error during the needle insertion, authors aimed to develop force visualization system. The purpose was to elucidate a method of determining the dynamic friction coefficient and estimating the cutting force.

The elastic force was obtained by pressing a test piece with a stick. The needle inserted twice to the test piece. The dynamic friction coefficient and the cutting force were calculated based on the elastic force and the second needle insertion force.

The experimental and the theoretical cutting force wave forms were consistent qualitatively. The cutting force could estimate by obtaining the elastic force and the dynamic friction coefficient.

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1. Introduction

In recent years, there has been an increased focus on QOL-conscious minimally invasive surgery. Examples of minimally invasive surgery are laparoscopic surgery, radiofrequency ablation and brachytherapy. In these minimally invasive types of surgery, the insertion of the needle has a low degree of invasiveness. However, the needle insertion depends on the physician's skill, and thus it involves human error. A number of researchers have used the finite element method (FEM) to reduce the degree of human error involved in needle insertion. For example, Kobayashi *et al.* [1][2] have developed a viscoelastic and nonlinear liver model for needle insertion using the FEM. Dehghan *et al.* [3] have developed a model that leads to accurate placement of the needle during a prostate brachytherapy procedure that uses the FEM. The FEM, however, needs to model the target organs, and it is not versatile method. Washio *et al.* [4] have developed a coaxial needle that is divided into an inner needle and an outer needle.

The coaxial needle can separate the needle tip force (the cutting force) and the dynamic friction force exerted by the force of insertion. It can also detect the penetration of the tissue by the separation of the inner needle and the outer needle. However, the coaxial needle requires a special outer needle.

In this study, the authors aimed to develop a force visualization system that can obtain the tip force by subtracting the modeled friction force from the total insertion force. The dynamic friction force is considered to be dominant to the reaction force during needle insertion. In this paper, the purpose was to elucidate a method of determining the dynamic friction coefficient and estimating the cutting force.

2. Estimation of dynamic friction coefficient

2.1. Methods

2.1.1. Experimental equipment

White chicken meat (breast tender) was employed as the test piece for the insertion. The needle used was an intravenous cannula that is used for dialysis (18G, Nipro). The needle was set in a motorized stage (SGSP26-100, Sigma Koki). The force during the needle insertion was sensed by a force sensor and recorded by a data recorder at a frequency of 400 Hz. (MEMORY HiCORDER 8808, HIOKI). The experimental equipment is shown in Fig. 1.

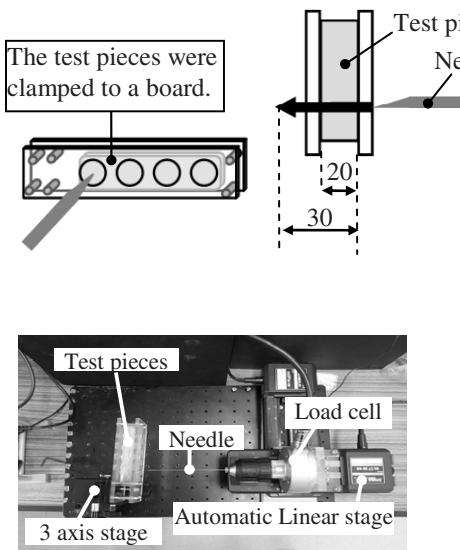


Fig. 1. Experimental equipment

2.1.2. Determination of dynamic friction coefficient

The dynamic friction force F_r can be approximated by the following equations:

$$F_r = \mu P S_t \quad (1)$$

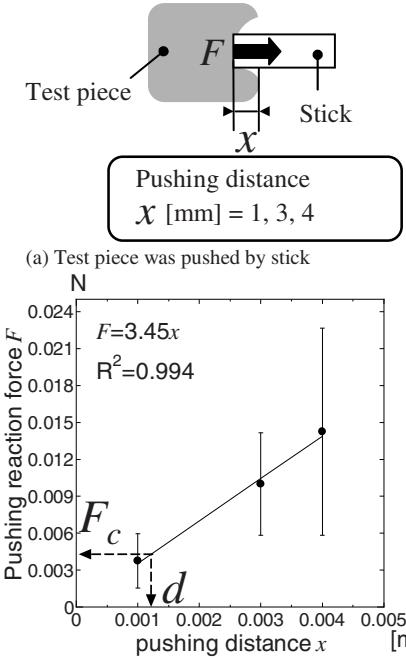
$$P = \frac{F_c}{S_c} \quad (2)$$

$$S_t = d \pi I_d \quad (3)$$

Here, μ is the dynamic friction coefficient, P is the pressure on the needle exerted by the surrounding test piece, S_t is area of contact between the needle and the test piece, F_c is the clamping force exerted on the needle by the test piece, S_c is the cross-sectional area of the stick, d is the diameter of the needle, and I_d is the insertion depth.

To obtain pressure P from the white chicken meat, the white chicken meat was pushed x [mm] by a stick

(diameter: 10 mm) (Fig. 2 (a)). The pushing reaction force F exerted by the stick was measured. The relational expression between F and pushing distance x was estimated by the least squares method. The estimated relational expression and an F - x graph are shown in Fig. 2 (b).



(b) Relationship between pushing distance and pushing reaction force

Fig. 2. Explanation of the elastic force

The clamping force exerted on the needle by the test piece F_c was obtained by the needle diameter, which was substituted into the relational expression between F and x in Fig. 2(b). The pressure P can be obtained with Equation 2, using the cross-sectional area of the stick, S_c and F_c .

The needle was inserted twice at the same place to estimate the dynamic friction coefficient (Fig. 3(a)). The 1st insertion force F_{1st} is determined by adding the needle tip force F_{tip} and the friction force F_r . The 2nd insertion force is composed of F_r . The effect of the cutting force and the pushing force from the white chicken meat were omitted in the second insertion, F_{2nd} . The relational expression between F_{2nd} and product pressure P and the contact area between the needle and test piece S_t are shown in Fig. 3 (b).

The dynamic friction coefficient is the slope of the relational expression in Fig. 3(b). The experimental conditions are shown in Table 1.

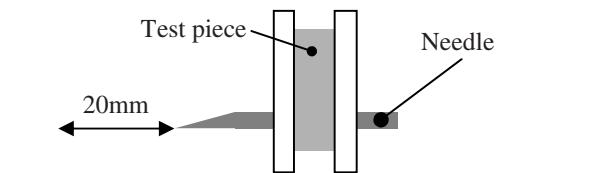
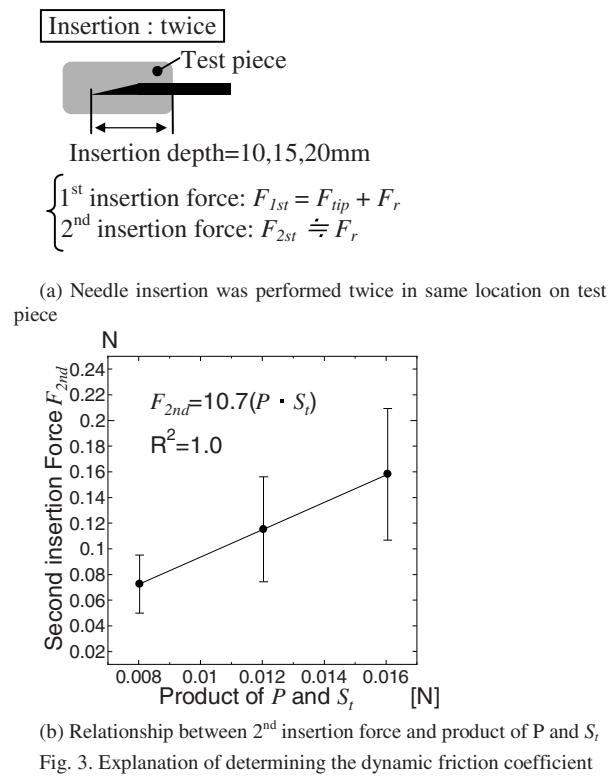


Fig. 4. Determination of dynamic friction coefficient using method of the test piece penetration

Table 1. Experimental conditions for determining dynamic friction coefficient used in 2nd insertion

Needle diameter d[mm]	1.27
Cross-sectional area of stick $S_c[\text{mm}^2]$	785
Insertion speed [mm/s]	2, 2.5, 3, 3.5, 10, 20, 30, 40, 50
Test piece	White chicken meats (breast tender)

The needle tip force cannot be reduced to exactly zero by inserting the needle twice. The needle tip force is expected to include error for two insertions of the needle. For comparison, the dynamic friction coefficient was determined using the method of Simone *et al.* [5]. To obtain pressure P from the test piece, the test piece was pushed by a stick, as it was in the method that inserted the needle twice. The test piece was penetrated by the needle, and the needle was then moved back and forth 20 mm three times (Fig. 4). The measured force is the

dynamic friction force F_r . The dynamic friction coefficient was obtained by using Equation 1. The experimental conditions are shown in Table 2.

Table 2. Experimental conditions for determining dynamic friction coefficient using method of test piece penetration

Needle diameter d[mm]	1.27
Cross-sectional area of stick $S_c[\text{mm}^2]$	785
Insertion speed [mm/s]	2, 2.5, 3, 3.5, 4, 6, 8, 10, 12, 14, 16, 18
Test piece	White chicken meats (breast tender)

2.2. Results

The dynamic friction coefficient and the standard deviation obtained using two methods are shown in Table 3. The dynamic friction coefficient obtained by the method in which the needle was inserted twice was 10.7; with the needle penetration method, the coefficient was 9.82.

The relationship between the insertion speed and the dynamic friction force in the method of needle penetration is shown in Fig. 5.

In the experiment, no correlation was shown to exist between the dynamic friction force and the insertion speed.

Table 3. Dynamic friction coefficient of the white chicken meats obtained by the two methods.

	Needle insertion twice	Needle Penetration
μ	10.7 ± 3.20	9.82 ± 2.70

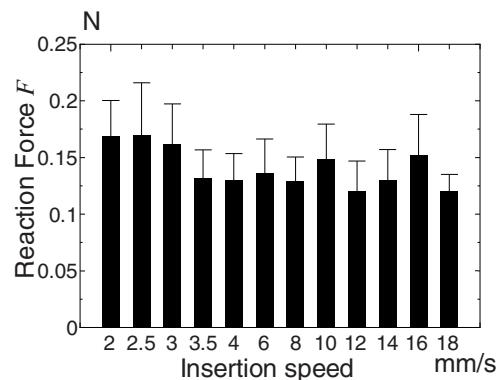


Fig. 5. Relationship between insertion speed and friction force

2.3. Discussion

In the experiment of determining the dynamic friction coefficient, which was performed by Simone *et al.* [5], the dynamic friction coefficient was zero. This result is

attributable to the lubricating quality of the blood contained in the liver. The dynamic friction force was dominant in this experiment because white chicken meat did not contain blood.

In the method in which the needle was inserted twice, the measured dynamic friction coefficients can be considered with the error between the method in which the needle is inserted twice, and the needle penetration method, owing to the effect caused by the difference in the place of insertion and the component force of the needle tip. There was no significant difference between the two methods

3. Estimation of needle tip force

3.1. Methods

The needle tip force was estimated using two methods. In one method (hereafter referred to as the experimental tip force), the tip force was estimated by subtracting the total insertion force from the second insertion force. In the other method (hereafter referred to as the theoretical tip force), the tip force was estimated by subtracting the total insertion force and the friction force that calculated with the product of the dynamic friction coefficient, the pressure from the tissue and the contact area between the needle and the tissue. (Equation 1).

3.2. Results

Figure 6 shows the variation in the insertion force and the cutting force during needle insertion obtained by both methods. The heavy lines indicate the 1st insertion force (the total insertion force). The solid lines indicate the experimental tip force. The dotted lines indicate the theoretical tip force.

The two estimated cutting force waveforms were consistent qualitatively. When the needle penetrated the white chicken meat (10~23 mm), the maximum value of the estimated cutting force was different.

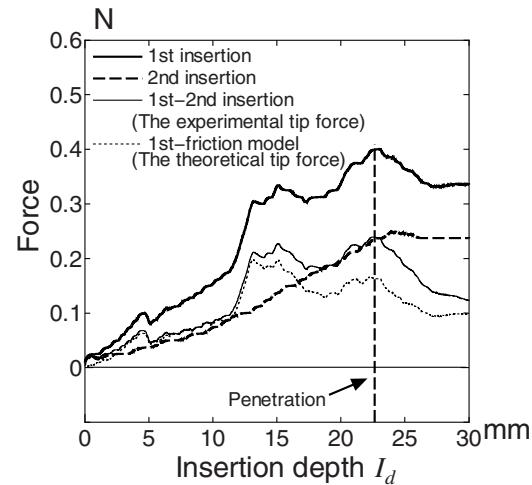


Fig. 6. Comparison of cutting force for theoretical tip force and experimental tip force

3.3. Discussion

The reason for this is that the pressure on the needle inside the white chicken meat was not even. When the needle penetrated the fibrous tissue, the needle surrounding tissue was pulled and deformed by the needle. This movement varies the pressure P in Equation 1. The 2nd insertion force is shown in Fig. 7.

The slope of the 2nd insertion force changed at an insertion depth of 10 mm. It is thought that at this point, the pressure P in Equation 1 is changed by the tissue, which has a stronger elastic force than the muscle tissue.

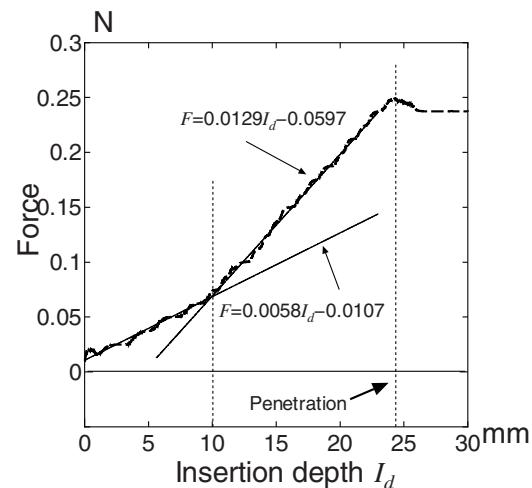


Fig. 7. Variation in slope of 2nd insertion force during needle insertion

4. Discussion

To estimate the penetration of tissue from the tip force, it is necessary to elucidate whether the penetration can be detected by the needle tip force. The method for determining the dynamic friction coefficient presented in this paper, however, is not a realistic method for clinical use. Therefore, in the future, a method for determining the dynamic friction coefficient in real time needs to be developed.

The dynamic friction coefficient was one of the quantitative properties employed in developing a force visualization system. It was found that the needle tip force could be estimated from the dynamic friction coefficient.

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