Effect of Needle Geometry on Insertion Force of Different Hair Implaners

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**Abstract** Surgeons insert approximately 3000 hair implants in a single hair restoration surgery, and the needle shape critically affects surgical performance including surgical time, survival rate, and the surgeon’s fatigue. There are several experimental studies on the relationship between needle shape and performance; however, there are no studies on hair implant needles, which are different from other medical needles as they have a comparatively short bevel. This study compared several hair implant needles to determine the relationship between needle shape and insertion force. Eight hair implant needles with the same diameter were collected, and their geometrical data were visually measured. The insertion force and total work of each needle were measured using custom-made force measurement equipment; the results were statistically compared, and their correlation was analyzed. Moreover, a qualitative comparison was made. The needle insertion force ranged from 1.30 to 2.97 N, and the total work ranged from 8.15 to 10.97 mJ. The primary bevel and acute angles showed a moderate positive correlation with the total work. A longer point length, smaller primary bevel, and acute angle decrease the total work of hair implant needles. As per the results of the qualitative comparison, we found that the surgeons can identify the differences in needle insertion force among various hair implant needles, and their grading was consistent with the grading according to the total work of needle insertion.

**Keywords:** needle insertion force, hair implanter, hair restoration surgery, correlation analysis.

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1. **Introduction**

Hair plays an important role in an individual’s social life, so maintaining hair and preventing hair loss are major concerns of people with androgenic alopecia. Androgenic alopecia (male pattern baldness) is a prevalent hair disorder, occurring in approximately 15%–20% of adults in Korea [1]. Autologous hair transplantation is a permanent solution to androgenic alopecia [2]. Surgical techniques are classified based on hair extraction and implantation techniques. The most commonly used hair extraction techniques are follicular unit transplantation (FUT) and follicular unit extraction (FUE) [3]. In FUT, follicles are obtained using microscopic graft dissection from a donor strip located on the occipital region of the scalp [4]; whereas in FUE, a small circular incision is made on the skin around a follicular unit, and each follicle is individually separated from the surrounding tissue using a punching needle. The process is repeated until sufficient follicles are obtained [5]. FUE has recently gained popularity, although FUT is still widely performed. Especially in Korea, FUT is the gold standard for hair restoration surgery.

Typical hair implantation techniques are the slit and hair implanter methods. In the slit method, the surgeon makes an incision first using a blade or a needle and then implants the graft using forceps. However, the surgery time is long and the possibility of graft damage is high. In the hair implanter method, the surgeon injects a hair implant needle into the graft site, simultaneously piercing the skin and inserting the graft. The hair implant needle is then withdrawn, leaving the graft inside the incision [6, 7]. The hair implanters used currently are shaped
like a pen (Fig. 1). The hair implanter comprises the needle, guide hook, and cases. The needle part has a slit, and the hair follicle is inserted into the slit for implantation. While the needle with a hair follicle is inserted into the skin to create a transplant site and control the insertion depth, the guide hook pushes the hair follicle to implant it (Fig. 2).

Although the hair implanter method is technically demanding, it is easy to control the direction of hair follicle insertion, resulting in a natural hair curl. The hair implanter method is commonly used in South Korea and Japan and is now being used in other countries as well.

In the hair implanter method, many harvested hair follicles are transplanted one by one using hair implanters. The surgeon implants approximately 3000 hair follicles in a single hair restoration surgery [8], and four or more hair implanters are used in turn.

Different manufacturers have different hair implant needle designs. The hair implanter performance and insertion force depend on the hair implant needle design. A large insertion force generated by the hair implant needle sometimes causes previously implanted hair follicles to pop up, and continuous insertion with a large force increases the surgeon’s musculoskeletal fatigue, thereby increasing surgery time, which is closely related to the survival rate of hair follicles [9].

Therefore, it is important to minimize the needle insertion force of the hair implant needle. Several studies on the relationship between hair implant needle design and insertion force used simulation to improve procedure

![Fig. 1](image1.png)  
**Fig. 1** Configuration of hair implanter. (a) hair implanter (b) components of hair implanter (A = needle, B = guide hook, C = cases).

![Fig. 2](image2.png)  
**Fig. 2** Diagram explaining the functions and usage of hair implanter.
accuracy by evaluating the insertion force of the biopsy needle or trocar system [10–12]. Okamura et al. [10] analyzed the needle insertion process using computerized tomography data and investigated the needle insertion force based on differences in needle diameter and tip geometry. The larger the needle diameter, the larger was the needle insertion force shown by the needle bevel’s triangular geometry. Moreno et al. [11] analyzed the difference in insertion force according to the type of trocar used in laparoscopic surgery. Different types of trocars were inserted into the anesthetized porcine abdominal wall to evaluate the insertion force and depth, and statistical analysis was performed to confirm the mean difference. The blade and conical trocars showed a large insertion force [11]. Meyer et al. [12] compared the insertion force of commercial trocar systems for pars plana vitrectomy. They established a standardized experiment in compliance with the International Organization for Standardization (ISO) standards and compared the needle insertion force based on needle geometry under the same experimental conditions. The lancet and back bevel-type needles showed a low insertion force [12]. Results showed that the sharper the needle tip, the lower was the insertion force. van Gerwen et al. [13] investigated the influence of various factors on needle insertion force by reviewing literature for experimental data. They found that the needle diameter, insertion velocity, and different needle tip shape had a relevant effect on insertion force. However, the significance of the needle insertion force according to the bevel angle of the needle was insufficient to be applied to the hair implanter.

A hair implant needle is similar to an injection needle, but the bevel length is limited. The reason is that the bevel length is related to the insertion depth. The insertion depth influences the level of implantation (Fig. 2). This eventually affects the survival rate of hair follicles. If the surgeon inserts the hair implant needle too deep, it may cause tissue damage and pain. To maintain a constant insertion depth, the surgeon’s technique is vital, but the limit of the bevel length of the needle should be prioritized.

However, there are no studies on the needle design for hair implanters. This study quantitatively analyzed the needle insertion force of hair implanters. We compared several hair implant needles to determine the relationship between hair implant needle shape and insertion force. First, we developed a standardized laboratory setting. Second, we measured the hair implant needle geometry and insertion force. Third, we analyzed the correlation between hair implant needle geometry and insertion force to determine the most suitable needle for hair restoration surgery. Finally, we compared experimental results with human sensing. The results will help surgeons select an optimal hair implanter. Moreover, the results could be used as primary data for developing a hair implant needle.

2. Materials and Methods

2.1 Materials

Eight frequently used hair implanters with the same diameter (1.0 mm) were systematically analyzed following ISO standards (ISO7864; sterile hypodermic needles for single use—requirements and test methods). Images of the hair implant needles were taken using a microscope and transferred to dedicated software to manually measure the length and angles (Fig. 3). We measured each value thrice and averaged them to decrease the measurement error.

![Fig. 3](image-url)  
**Fig. 3** Needle geometry measurements. (a) Length of the hair implant needle ($A =$ bevel point length; $B_1 =$ primary bevel length; and $C_1 =$ secondary bevel length). (b–d) Angles of the bevel ($\alpha =$ primary bevel angle; $\Phi =$ secondary bevel angle; $\beta =$ tip angle; $\lambda =$ acute needle angle).
The mean point length (A) of the hair implant needles was 2.90 ± 0.29 mm, and the mean secondary bevel length (C₁) was 1.37 ± 0.08 mm. The primary bevel angle (α) was 16.22° ± 1.59°, and the secondary bevel angle (Φ) was 26.54° ± 1.88°. The tip (β) and acute angles (λ) were 28.80° ± 3.03° and 63.56° ± 7.59°, respectively. Details are listed in Table 1.

### Table 1 Geometrical data of hair implant needles 1–8 with 1.0 mm diameter.

| Classification | Primary bevel length (B₁) | Secondary bevel length (C₁) | Point length (A) | Primary bevel angle (α) | Secondary bevel angle (Φ) | Tip angle (β) | Acute needle angle (λ) |
|----------------|---------------------------|-----------------------------|------------------|-------------------------|--------------------------|--------------|---------------------|
| Needle 1       | 1.70                      | 1.44                        | 3.18             | 15.43                   | 24.04                    | 26.83        | 62.19               |
| Needle 2       | 1.64                      | 1.46                        | 3.10             | 14.78                   | 24.78                    | 24.29        | 66.02               |
| Needle 3       | 1.46                      | 1.21                        | 2.65             | 17.58                   | 27.42                    | 29.08        | 67.67               |
| Needle 4       | 1.33                      | 1.42                        | 2.70             | 16.73                   | 26.22                    | 28.55        | 60.53               |
| Needle 5       | 2.01                      | 1.36                        | 3.41             | 13.15                   | 27.54                    | 35.03        | 52.82               |
| Needle 6       | 1.35                      | 1.43                        | 3.06             | 15.59                   | 24.26                    | 27.14        | 57.18               |
| Needle 7       | 1.23                      | 1.24                        | 2.52             | 18.59                   | 28.89                    | 29.22        | 81.50               |
| Needle 8       | 1.42                      | 1.40                        | 2.84             | 16.38                   | 26.05                    | 32.34        | 63.26               |
| Mean±SD        | 1.49 ± 0.24               | 1.37 ± 0.08                 | 2.90 ± 0.29      | 16.22 ± 1.59            | 26.54 ± 1.88             | 28.80 ± 3.03 | 63.56 ± 7.59       |
| Min            | 1.23                      | 1.21                        | 2.52             | 13.15                   | 24.04                    | 24.29        | 52.82               |
| Max            | 2.01                      | 1.46                        | 3.41             | 18.59                   | 28.89                    | 35.03        | 81.50               |

The mean point length (A) of the hair implant needles was 2.90 ± 0.29 mm, and the mean secondary bevel length (C₁) was 1.37 ± 0.08 mm. The primary bevel angle (α) was 16.22° ± 1.59°, and the secondary bevel angle (Φ) was 26.54° ± 1.88°. The tip (β) and acute angles (λ) were 28.80° ± 3.03° and 63.56° ± 7.59°, respectively. Details are listed in Table 1.

### 2.2 Needle insertion force evaluation

#### 2.2.1 Needle insertion force experimental setup

We developed a needle insertion force measuring device, complying with ISO standards (ISO7864; Sterile hypodermic needles for single use-requirements and test methods) [12] (Fig. 4). The needle insertion speed was set at 1.6 mm/s during all trials using a motorized stage (KYC06020-G, Suruga Seiki Co., Ltd., Shizuoka, Japan), and the needle insertion force was measured at 8000 Hz and 1/320 N resolution using a Nano17 force sensor (ATI Industrial Automation, Apex, NC, USA). Figure 5 shows the system configuration and its control timing. The XY stage is responsible for horizontal (forward and backward) movement; it represents needle insertion and removal motion. First, the system moved forward and inserted the needle into a polyurethane (PU) foil; this process was recorded using the force sensor data. The stage automatically moved to the side when the needle was removed from the foil. We manually changed to a vertical insertion position after three automatic insertion data acquisitions. The PU foil with a thickness and shore hardness of 0.40 mm and 85 ± 10, respectively, was used as a specimen, and hair implant needles were perpendicularly inserted into the specimen. We tested each hair implant needle eight times.

#### 2.2.2 Analysis of needle insertion force

Previous studies have shown a typical insertion force pattern when a needle is inserted into a specimen [10–15]. In our study, most patterns coincided with the typical pattern shown in Fig. 6, although some patients are exceptional. The typical pattern of needle insertion force was classified as follows:

- The piercing force ($F_0$) appeared when the PU foil was not penetrated but was pierced, at which time the force rapidly increased and then decreased slightly.
- The cutting force ($F_1$) increased further until the secondary bevel ($C_1$) cuts the PU foil. It showed the maximum force from cutting resistance.
- After that, the penetration force ($F_2$) appeared when the primary bevel ($B_1$) passed through the PU foil, and then it decreased slightly.
- After the entire bevel passed through the PU foil, the
friction force ($F_3$) appeared.

We defined the hair implant needle insertion evaluation as needle insertion force (N) and total work (mJ). In needle insertion force, the cutting force ($F_{cut}$) and the maximum force ($F_{max}$) were recorded. $F_{cut}$ appeared when the primary bevel was inserted and cut the PU foil, $F_{max}$ was the maximum force in the entire insertion process, and $W_{total}$ was the integration of the entire insertion process. In a few hair implant needles, $F_{cut}$ was consistent with $F_{max}$. $W_{total}$ was calculated in terms of the needle insertion force.

2.2.3 Qualitative comparison of needle insertion

Five volunteers, including two surgeons, provided written informed consent before the experiment. We selected needles 1, 6, and 7 listed in Table 1 and marked them as A, C, and B, respectively, for de-identification. The volunteers inserted each needle into porcine tissue, including the skin layer, and determined which needle was easy to insert, depending on the feeling. Results were compared with quantitative data obtained from the experiment described in Section 2.2.2.
2.3 Statistical analysis
Correlation between hair implant needle geometry and insertion force was statistically analyzed using SPSS Statistics v.25.0 (IBM Corporation, Chicago, IL, USA). According to Pearson correlation, \( r > 0.8 \) means a strong, positive linear correlation. In this study, \( r > 0.4 \) and \( p \leq 0.05 \) indicated a statistically significant correlation.

3. Results
3.1 Needle insertion force evaluation results
Figure 7 shows \( F_{\text{cut}} \) and \( W_{\text{total}} \) for needles 1–8. Needle 8 had the lowest \( F_{\text{cut}} \) (1.30 N), whereas needle 2 had the highest \( F_{\text{cut}} \) (2.97 N); there was a 56% difference between the two needles.

Moreover, needle 8 had the lowest \( W_{\text{total}} \) of 8.15 mJ, whereas needle 2, which had the highest \( F_{\text{cut}} \), did not show the highest \( W_{\text{total}} \). Instead, needle 3 showed the highest \( W_{\text{total}} \) of 10.97 mJ. Therefore, the results of \( F_{\text{cut}} \) and \( W_{\text{total}} \) did not coincide with each other, but some needles with low \( F_{\text{cut}} \) had low \( W_{\text{total}} \).

3.2 Correlation analysis
There was no significant correlation between needle geometry and insertion force. However, we found some moderate correlation between needle geometry and total work (Table 2). Detailed relations are shown in Fig. 8.

\( W_{\text{total}} \) showed a moderate negative correlation with \( A \), with a Pearson’s correlation coefficient of \(-0.576\) and statistical significance \((p = 0.003)\). \( W_{\text{total}} \) also showed a moderate positive correlation with \( \alpha \) and \( \lambda \) \((r = 0.569\) and \(0.528\), respectively; \(p < 0.005)\).

3.3 Qualitative comparison results of needle insertion
Overall qualitative comparisons made by the five volunteers were in the order of C, A, and B. Three of the five volunteers described a slight difference in the needle insertion force between needles C and A, and felt a greater difference between needles A and B (Table 3). When comparing the volunteers’ qualitative grading of needle insertion force with the needle insertion force quantitatively measured in Section 3.1, the qualitative grading was consistent with the grading according to \( W_{\text{total}} \) of needle insertion.

4. Discussion
The eight hair implant needles selected in this study had small variations in geometric parameters. The total bevel length showed a 10% variation in average length \((SD/\text{AVE} \times 100)\), and most angle variations were <10%. Because the dermis of the scalp is thin, the bevel length of the hair implant needle has to be shorter than other medical needles.

Before analyzing the results of needle insertion force experiments in Section 3.1, we investigated whether the results were reliable. As shown in Fig. 9, each hair im-
The eight hair implant needles showed a deviation of approximately 5% in each experiment. We observed a similar trend in each hair implant needle, which was also confirmed by the graph. Therefore, we can say that the results are reliable and that the experiments have reproducibility.

The eight hair implant needles showed a difference in design of 10% and a relatively significant difference in insertion force. Needle 2 with the highest $F_{\text{cut}}$ and needle 8 with the lowest $F_{\text{cut}}$ showed a similar tendency in secondary bevel length ($C_1$), primary bevel angle ($\alpha$), and secondary bevel angle ($\Phi$). In needles 1 and 8, which showed the lowest $F_{\text{cut}}$, the geometry, except for the tip angle ($\beta$) and the primary bevel length ($B_1$), was similar. Therefore, it was impossible to determine the specific geometrical parameters of hair implant needles that give low $F_{\text{cut}}$, which is believed to be influenced by a combination of length and angle.

The factor affecting needle geometry and insertion force is $\beta$. Jushiddi et al. [14] reported that $\beta$ ranged from 18° to 27°, prevalently in trocar or biopsy needles, but $\beta$ of the hair implant needles used in our study ranged from approximately 25° to 35°. Jiang et al. [15] reported that $F_{\text{cut}}$ was low when $\beta$ ranged between 10° and 30°. Wang et al. [16] studied the insertion force according to the geometry for the needle tip grinding by adjusting the variation in $\beta$. They found that $F_{\text{cut}}$ decreased as $\beta$ decreased.

However, our results do not coincide with previous studies. The reason is that the hair implant needles we used had a minimal difference in $\beta$ of <10°, and other parameters of the commercial hair implant needles could not be controlled. Moreover, we investigated whether it is possible to keep $\beta$ low to decrease the needle insertion force. However, a low $\beta$ is associated with a large secondary bevel length ($C_1$). $C_1$ is related to the initial insertion depth, thus we believe it is unreasonable to apply it to a hair implanter.

In correlation analysis, $W_{\text{total}}$ showed a significant positive correlation with the primary bevel angle ($\alpha$) and the acute angle ($\lambda$) ($r = 0.569$ and 0.528, respectively). We believe that it is important to adjust these geometric parameters in hair implant needles, where $A$ is limited. Furthermore, this will help find the causal relationship between the geometry and insertion force in regression analysis.

In the qualitative comparison experiment, the volunteers’ subjective grading of the insertion force was the same as the grading based on $W_{\text{total}}$. Therefore, the nee-
dle insertion force felt by the operator may be affected by the entire insertion process, not just $F_{\text{cut}}$. Needle insertion occurs with an instantaneous force within a short period, and each stage of the insertion force cannot be felt. Meyer et al. [12] showed that medical staff could not distinguish $F_{\text{cut}}$ because of the short duration. Above all, it is important to decrease $F_{\text{cut}}$ in order to reduce the popping of implanted hair follicles. However, it is critical to decrease $W_{\text{total}}$ to improve the surgeon’s sensation during needle use.

Fig. 8 Correlation between needle geometry and total work ($W_{\text{total}}$). (a) Bevel point length $A$ showed a moderate negative correlation with $W_{\text{total}}$ ($r = -0.576; p = 0.003$) (b, c) Primary bevel angle $\alpha$ and tip angle $\lambda$ showed a moderate correlation with $W_{\text{total}}$ ($r = 0.569$ and $0.528$, respectively; $p < 0.005$).
This study has some limitations. We used PU foil as a specimen in the experiments, and did not consider tissue deflection, which occurs in real scalp tissue. One hair implant needle is inserted some 600 times in a single hair restoration surgery. Therefore hair implant needle durability is another crucial factor in needle design. We will conduct a durability experiment in our next study.

5. Conclusion

We measured and analyzed the hair implant needle geometry and insertion force in compliance with ISO 7864. The eight needles used in the study had geometric variation of 10%. However, there was a 56% difference between the maximum and minimum insertion forces and a 26% difference in total work. The primary bevel angle ($\alpha$) and acute angle ($\lambda$) correlated moderately with total work, and the values agreed with the qualitative evaluation. A longer point length, a smaller primary bevel, and an acute angle decrease the total work of hair implant needles. In hair implant needle design, the focus should be on $\alpha$ and $\lambda$ to improve quantitative values and the surgeon’s feeling during needle use.

Fig. 9  Results of eight repeated measurements for each hair implant needle, confirming reliability and reproducibility; all needles showed similar tendencies. Panels (a)–(h) refer to needles 1–8, respectively.
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Conflict of interest

There are no conflicts of interest.

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