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The Impact of Drilling Guide Length of a Surgical Guide on Accuracy of Pre-Drilling for Miniscrew Insertion

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Abstract: Background: Temporary anchorage devices (TADs) are broadly used in orthodontic treatment. TADs must be placed accurately to avoid collision against tooth roots. To place miniscrews with a higher accuracy, a digitally designed surgical guide was proposed in previous studies. However, to our knowledge, there have been no articles that have assessed the minimal required length to achieve good drilling accuracy. The objective of the present study was to evaluate the accuracy of pre-drilling using computer-aided designed surgical guides with different lengths. Methods: A typodont model was scanned, and surgical guides of 3.0, 4.5, and 6.0 mm were designed. Duplicated typodonts and the surgical guides were printed with a 3D printer. Using these models and surgical guides, pre-drillings were performed. Freehand drilling was also conducted for the control. The drilled models were scanned with micro-computed tomography to evaluate the accuracy. Results: The mean errors at the tip of the drill were 0.44 mm, 0.61 mm, 0.41 mm, and 0.24 mm for the freehand drilling, and 3.0, 4.5, and 6.0 mm for the surgical guide, respectively. Conclusion: The results suggested that a longer surgical guide was recommended to achieve good insertion accuracy for a narrow interradicular space, and that 3.0 mm was enough when an error of 1.0 mm was acceptable for the insertion site.

Keywords: temporary anchorage device; TADs; miniscrews; CBCT; pre-drilling; orthodontic anchor screws; surgical guide

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1. Introduction

Temporary anchorage devices (TADs) are widely used in orthodontic treatment for expanding the boundaries of tooth movement. TADs are used to obtain skeletal anchorage to move teeth, and make it possible to achieve absolute anchorage, to distalize or mesialize molars, to intrude molars, or to rotate the occlusal plane without the patient's compliance.

Two types of temporary anchorage devices are used in orthodontics, namely, miniplate appliances and miniscrew appliances. The miniplate appliances are more stable than the miniscrew appliances because they are supported by two or more screws, but flap surgery is required to insert and remove them, which causes swelling and discomfort in patients. Although the miniscrew appliances are less stable than the miniplates, they show clinically acceptable success rates, and can be placed without flap surgery. Thus, the miniscrew appliances are the most common temporary anchorage devices nowadays.

While the insertion of miniscrews is much easier than that of miniplates, there are limitations regarding placement sites. Since the head of the miniscrew needs to pass through the attached gingiva to avoid patient discomfort, the position of the placement cannot be as deep as that of the miniplates. Thus, the miniscrews often need to be placed in the interradicular space whey they are placed in the buccal region, which may result in the proximity of miniscrews to the tooth roots.

The proximity of the miniscrew to the roots of the adjacent teeth is a major cause of the failure of miniscrews [1]. Many previous studies have reported that a higher failure rate was observed when the proximity of the miniscrews occurred. It was reported that when the body of the miniscrew was overlaid onto the lamina dura, the success rate was only 35%, while the overall success rate was more than 80% [2]. A finite element analysis showed the excessive stress was caused by the occlusal force around a miniscrew when a miniscrew is too close to the adjacent root [3]. Thus, the miniscrew must be placed with high caution when it is positioned in the interradicular region.

Furthermore, in the worst-case scenario, the tooth roots can be injured during the insertion of the miniscrews [4]. If a miniscrew touches the root of the adjacent tooth, it may damage the root surface. Most root injuries are resolved spontaneously with restorative cement formation after the removal of the miniscrews. However, root perforation was outlined in a previous report, and permanent changes are sometimes caused, such as nerve damage, lesions of the dentin-pulp complex, or periapical periodontitis, and endodontic or surgical treatment might be required.

Cone-beam computed tomography (CBCT) is useful to assess the root direction and bone quality of the placement site of the miniscrews [5]. Using CBCT, clinicians can measure the distance between the roots more accurately than using other 2D X-ray methods such as panoramic X-ray, dental X-ray, or cephalograms. By viewing CBCT images, they can find the best place for miniscrew insertion, where there is enough interradicular distance and enough cortical bone thickness.

However, if no surgical guides are utilized, the accuracy of the insertion depends on the clinical proficiency of a doctor. The doctor must put great effort into matching the CBCT image and the patient's mouth and estimating the position of the roots from the crown portions. Also, they must hold the screwdriver precisely during the insertion. Previous studies have reported that freehand insertion showed a large deviation in the position and direction of the miniscrews [6].

To overcome this issue, several methods to fabricate surgical guides have been proposed. Suzuki and Suzuki [7] used a prefabricated adjustable guide for placing miniscrews. The guide consisted of metal vertical arms of different lengths, and a Gurin lock for fixing the guide to the archwire and the guide sleeve. Miyazawa et al. [5] proposed another method, in which they adapted light-curing splint resin over the occlusal and insertion area of the cast, then a hole for a guide sleeve was made. Both articles reported that higher accuracy could be achieved with this method than by using freehand insertion. However, in these methods, clinicians needed to take X-rays before and after positioning the surgical guide to ensure the sleeve was accurately positioned. That was because neither the intra-oral scanner nor the desktop model scanner were common in orthodontic practice at that time, and the superimposition of CBCT and dental geometry was not performed in the planning stage. Since intra-oral scanners have become more common in orthodontic practice in the past decade, and 3D printers are also increasingly common, methods using these devices have been proposed recently [8–10]. The overall designs of these methods are similar to those of a previous study that used light-curing splint resin, but it was designed using CAD software based on the CBCT and 3D models of the patient's dentition and printed with stereolithography (SLA) or digital light processing (DLP) 3D printers. As the superimposition of the CBCT and the 3D dental model was completed before designing the surgical guide, these methods did not require X-ray validation after making the surgical sprint.

The surgical guides for miniscrews are designed either for the self-drilling or the self-tapping methods. Self-drilling is a method in which the miniscrew makes the hole and thread by itself, and the self-tapping method is a method in which a drill bit is used to make the hole, and a miniscrew is used to make the thread in the hole.

Although the self-tapping method requires more steps than the self-drilling method, it has some advantages over the self-drilling method. Previous research has suggested that the self-drilling method tends to cause more bone damage around the hole, and that more bone cracks were observed than when using the self-tapping method [11]. Although a systematic review concluded that their success rate was not significantly different, it was also reported that the self-drilling method shows a higher failure rate when root proximity occurs [12]. Another advantage of the self-tapping method is that it can reduce insertion torque. Previous research has suggested that the insertion torque may exceed a yield torque of miniscrews during the placement with a driver without a torque limiter [13]. Pre-drilling before insertion can reduce the insertion torque and reduces the risk of a fracture.

However, to our knowledge, no research has been performed for determining the best parameters of surgical guides for the self-tapping method. As of now, most research relating to surgical guides has been about the accuracy of surgical guides for the self-drilling method, and only a few studies have been conducted about the self-tapping method.

The objective of this study was to assess the effect of the length of surgical guides on the accuracy of drilling using the self-tapping method. A longer surgical guide should restrict the direction of the drill more tightly, but a longer guide is less easy to handle. In this study, we assessed the accuracy of the hole position and the direction using a model experiment to find the minimal lengths that can achieve acceptable accuracy.

2. Materials and Methods

A typodont model (Nissin, Kyoto, Japan) was scanned using a desktop scanner (Identica hybrid, Medit, Seoul, Republic of Korea), and was saved as a standard triangle language (STL) file. The direction and position of a miniscrew was determined using custom-developed software, and the miniscrew was placed between the estimated roots of the second premolar and the first molar.

The 3D models of surgical guides were generated by thickening a part of the typodont model and subtracting the original model. The undercuts of the model were removed so that the surgical guide could be removed after the placement. The surgical guide was designed to cover the first premolar and the first molar. The length of this part was set at 2.0 mm. The guide hole for the drilling of the 1.0 mm diameter was placed in the planned position. Three different lengths were tested for this part, namely, 3.0, 4.5, and 6.0 mm. A higher level of accuracy was expected with a longer guide (Figure 1).

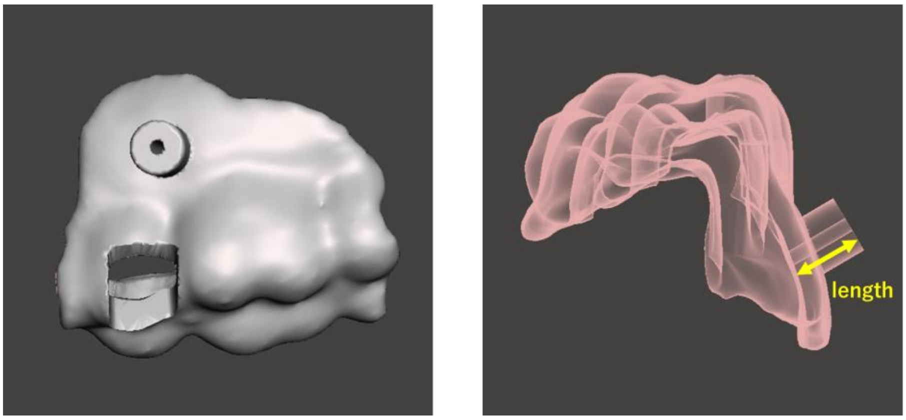

Figure 1. The design of the surgical guide. The second premolar was partially exposed to check the fitting to the teeth. The length of the surgical guide is the distance from the gingival surface to the top of the guide tube.

The 3D models of the surgical guides and the typodont were printed using a digital light processing (DLP) 3D printer (ASIGA MAX UV, Asiga, Alexandria, Australia) and a clear resin (DentaGUIDE, Asiga, Alexandria, Australia). A layer thickness of 0.1 mm was used for the printing configuration. Five surgical guides were printed for each length. Thus, 15 surgical guides were printed for the test.

The drilling tests were performed on duplicated typodonts (Figure 2). The part of the typodont model, which was close to the surgical guide, was extracted and duplicated using the same 3D printer and an accurate resin for the dental model (DentaMODEL, Asiga, Alexandria, Australia). We printed 20 duplicated typodont models. A layer thickness of

0.05 mm was used to print the models. The surgical guides were placed on the duplicated typodont, then the holes were drilled using a micro-motor (Ultimate XL, NSK Nakanishi, Tochigi, Japan) at 1000 rpm. The drill was a double flute drill of 1.0 mm made of high-speed steel (PROXXON, Osaka, Japan). Drilling without using surgical guides (freehand drilling) was also performed as a reference. The drilling depth was set to be 6.0 mm.

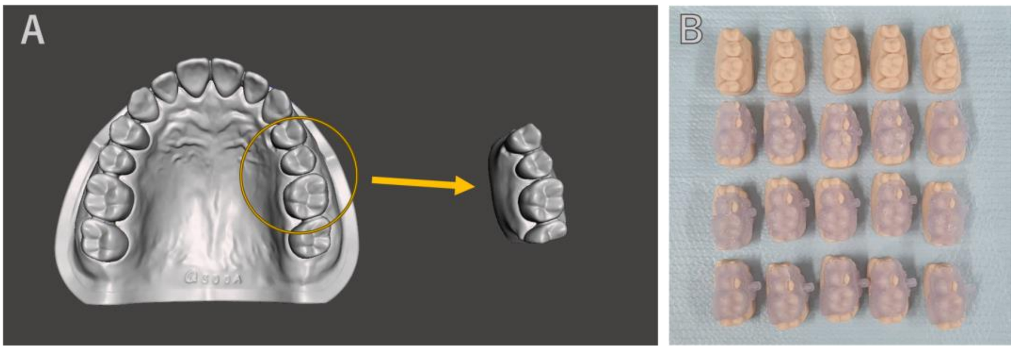

Figure 2. (**A**) The partial typodont model extracted from the original model. (**B**) The printed partial typodont and the surgical guides placed on the typodont. The first row, second row, third row, and fourth row are for freehand drilling, with surgical guides of 3.0 mm, 4.5 mm, and 6.0 mm, respectively.

After the drilling, the surgical guides were removed, then the drilled typodonts were scanned to make 3D surface models. All typodonts were scanned using micro-computed tomography (micro-CT) (R-mCT, Rigaku, Tokyo, Japan). The voxel size and voltage of the X-ray tube were 50 µm and 90 kV, respectively. The volume data of the micro-CT were exported in a Digital Imaging and Communications in Medicine (DICOM) format and converted to 3D surface data using the marching cubes algorithm.

The 3D surface model of the drilled typodont was superimposed onto a reference model to evaluate the accuracy of the drilling (Figure 3A). The surface data of the original typodont model were used as a reference, and the superimposition was calculated by using the iterative closest-point algorithm with custom-developed software. After the superimposition, we measured the distance from the opening of the hole to the ideal insertion vector, the distance from the bottom of the hole to the ideal insertion vector, and the angular difference between the drilled direction and the ideal insertion vector (Figure 3B).

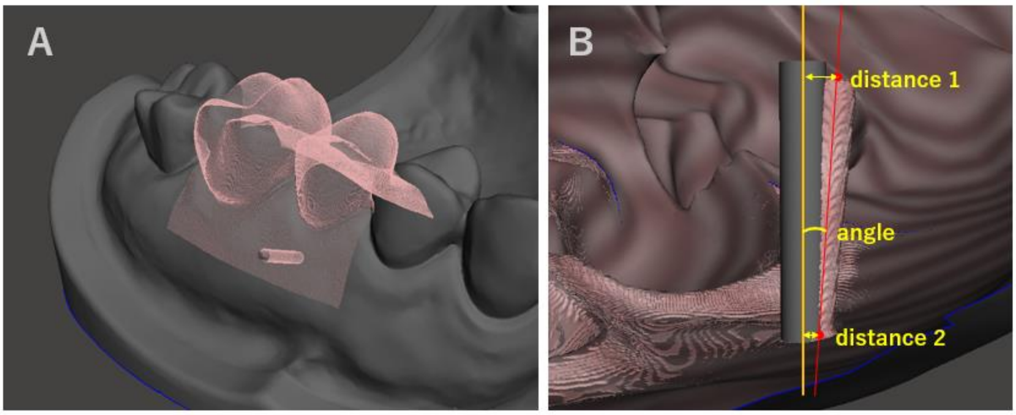

Figure 3. (**A**) The superimposition of the original typodont model and the reconstructed surface data from the micro-CT image. (**B**) The yellow line shows the ideal insertion vector, and the red line shows the actual direction of the drilled hole. Distance 1 is the distance between the ideal path and the bottom of the actual hole. Distance 2 is the distance between the ideal path and the opening of the actual hole. The angle between the yellow line and red line was also measured.

The regression analysis was performed on the assumption that the error was inversely proportional to the length of the guide: the error was supposed to be distributed using the following formula, and coefficient α and constant β were calculated.

$$error = \frac{\alpha}{length} + \beta$$

This assumption was based on a calculation using ideal geometry with a fixed gap between the guide and the drill. We also tested the significance of the regression coefficient for the coefficient α to validate whether the length of the guide had a significant impact on the error. The null hypothesis was that the true value of α was zero, which meant the length of the guide had no effect on the error. The test was performed by calculating t-statistics and p-values based on the estimated coefficient and their standard errors. The regression analysis and the test of significance were performed with a Python and SciPy package.

The number of samples was determined so that it was 15 times more than the number of independent variables for regression analysis according to a previous study [14].

The dedicated software for positioning miniscrews was developed by Unity 2021 (Unity Technologies, San Francisco, CA, USA), which allowed us to visualize 3D data easily, and the CGAL 5.0 library was used to generate the 3D data of the surgical guide as it provides many basic and advanced algorithms for mesh operations.

3. Results

Figure 4 shows the positional error at the bottom of the hole and the regression curve. The mean errors and the standard deviation were 0.44 (±0.22), 0.61 (±0.26), 0.41 (±0.21), and 0.25 (±0.15) mm for freehand, and the guides were 3.0 mm, 4.5 mm, and 6.0 mm in length. The regression coefficient α was 2.13 and constant β was −0.08. As for the significance of the regression coefficient, the length of the guide had a statistically significant impact on the error and the p-value was 0.0153 ($p < 0.05$).

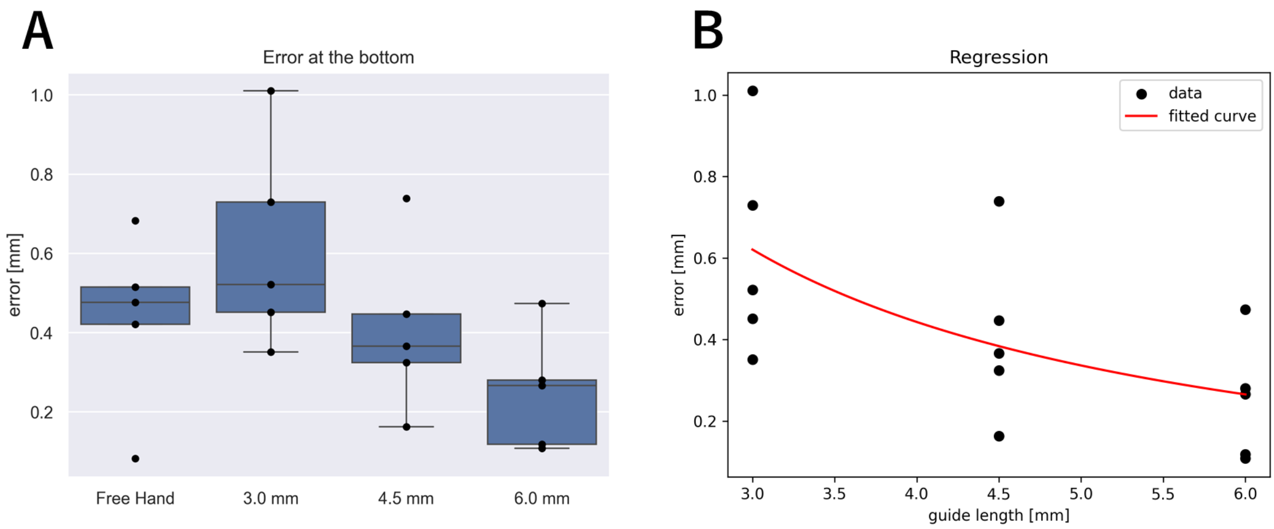

Figure 4. (**A**) A boxplot of the error at the bottom of the hole. The black dot represents each sample. (**B**) A regression curve of the error.

Figure 5 shows the positional error at the opening of the hole and the regression curve. The mean errors and standard deviations were 0.90 (±0.27), 0.16 (±0.10), 0.10 (±0.04), and 0.08 (±0.03) mm for freehand, and the guides were 3.0 mm, 4.5 mm, and 6.0 mm in length. The regression coefficient α was 0.48 and the constant β was 0.00. For the significance of the regression coefficient, the length of the guide did not have a statistically significant impact on the error, and the p-value was 0.0709 ($p > 0.05$).

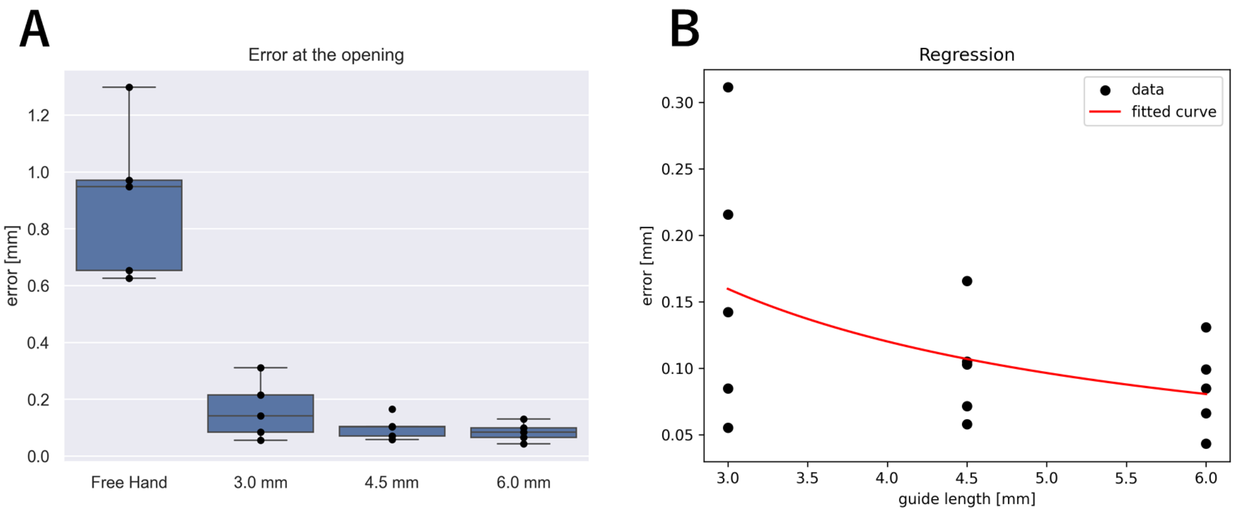

Figure 5. (**A**) A boxplot of the error at the opening of the hole. The black dot represents each sample. (**B**) A regression curve of the error.

Figure 6 shows the angular error between the ideal insertion vector, actual drilling vector, and regression curve. The mean errors and standard deviations were 5.46 (±2.43), 5.29 (±1.78), 4.38 (±1.72), and 2.83 (±1.47) degrees for freehand, and the guides were 3.0 mm, 4.5 mm, and 6.0 mm in length. The regression coefficient α was 13.81 and the constant β was 0.84. For the significance of the regression coefficient, the length of the guide had a statistically significant impact on the error, and the p-value was 0.0415 ($p < 0.05$).

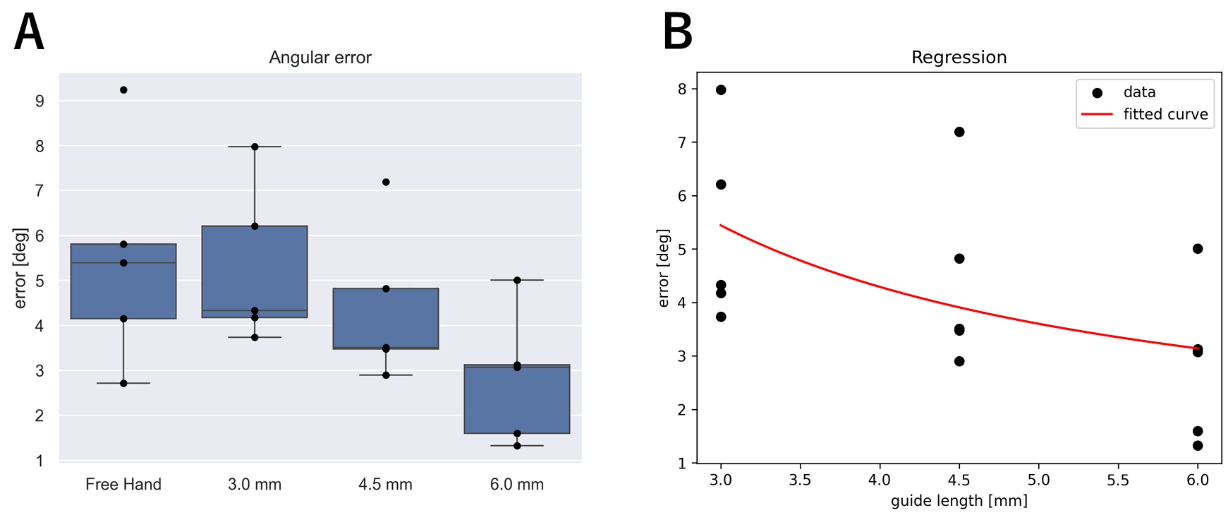

Figure 6. (**A**) A boxplot of the angular error. The black dot represents each sample. (**B**) A regression curve of the angular error.

4. Discussion

According to the regression analysis, the error decreased as the length of the surgical guide increased, which suggested an advantage in using a surgical guide for insertion. With the regression formula we used, the error will diverge at the guide length of zero. However, the angular error and the error at the bottom of the hole will likely converge to a similar accuracy as the freehand insertion, because the driver will be supported by the operator's hand, even if a surgical guide is very thin.

A length of 6.0 mm seemed to be preferable to avoid a collision against the tooth roots. Previous studies have reported that the interradicular distance was 2.4–6.5 mm in the maxillary palatal region and 2.4–3.3 mm in the buccal region [15,16]. As the diameter of miniscrews is usually about 1.5 mm, an error at the bottom of the hole of more than 0.5 mm might be critical. With freehand drilling of 3.0 mm and 4.5 mm in length, errors of more than 0.5 mm were observed, which might cause collision against the tooth roots in a patient. Thus, when a miniscrew is inserted into a narrow interradicular space, a 6.0 mm or longer screw guide is preferable.

As far as acceptable levels of accuracy are concerned, smaller surgical guides are better for handling in an intra-oral environment. Although the surgical guide of 3.0 mm had the worst accuracy regarding the position of the bottom of the hole, its maximum error was 1.0 mm in this study. Thus, when a miniscrew is inserted in a relatively wider space, such as between the palatal root of the upper first molar and the second premolar, a surgical guide of 3.0 mm might be long enough. In addition, a shorter guide is suitable for areas where the soft tissue is thick because if the guide is too long, it consumes the available cutter length of the drill bit, and the hole depth might become too shallow to penetrate the cortical bone.

The length of the guide had no clinically significant effect on the positional error at the opening of the hole. The length of the guide did not have a statistically significant impact on the error, and the p-value was 0.0709 ($p > 0.05$), which might have been because the sample size was too small for detecting the effect of the guide length. However, the difference in mean error was only 0.08 mm between the guides with lengths of 3.0 mm and 6.0 mm, which seemed to be negligible in clinical practice. Thus, there is no point in increasing the number of samples to detect the statistically significant effect of the guide length.

The result of the regression analysis indicated that the fitting of the surgical guide was accurate. The constant β represents an absolute error which is not affected by the length of the guide, and it was 0.00 for the error at the opening of the hole, which meant there would be no error if the guide was long enough. On the other hand, the constant β was 0.84 for the angular error, which meant there was an error of 0.84 degrees, regardless of the length. This angular error was equivalent to 0.09 mm at the depth of 6.0 mm, which was a consistent value with the β of error at the bottom of the hole.

With the self-tapping method, the surgical guides can be thinner and less bulky to handle than using the self-drilling method. Usually, the head of a miniscrew has a larger diameter than its body. Therefore, the guide hole must be larger than the diameter of the head, so that the surgical guide can be removed after the insertion. Furthermore, since the head is held by the screwdriver, the part where the diameter becomes largest is the driver (Figure 7) in the system. A surgical guide for the self-drilling method must cover the part with the largest diameter to maximize accuracy. However, this part is the farthest from the gingival surface, which indicates that the guide hole must be long, and therefore bulky. Such a bulky guide might affect the accuracy of the insertion, due to pressure from the surrounding soft tissue during insertion. On the other hand, in the self-tapping system, since the surgical guide will be removed after drilling, the hole can be the same diameter as the drill bit. Thus, the surgical guide for the self-tapping method can be much thinner, and still achieve the same accuracy. However, in some situations, the self-drilling method has advantages over the self-tapping method. For example, self-drilling is probably preferable for an insertion site with low bone density to obtain enough insertion torque and mechanical retention of the screw. In such cases, surgical guides for the self-drilling method will be needed, and it is our intention to investigate this by comparing the two types of surgical guides in future.

A surgical guide can be more generic when it is designed for self-tapping than for self-drilling. There are numerous miniscrew products in the market, and they all have different diameters, taper angles, head shapes, and drivers for insertion. Thus, surgical guides must be optimized for each product to achieve better accuracy. This can be difficult because manufacturers do not always provide their product's measurements in order to avoid reverse engineering. On the other hand, the parameter of a drill bit is its diameter only. Only the cutter part of a drill bit goes through the surgical guide, and the cutter part does not have a taper. This means that, as long as the hole diameter is configured correctly, a surgical guide will fit any miniscrew system. This is of great advantage for dental laboratories, which often receive various requests from different doctors.

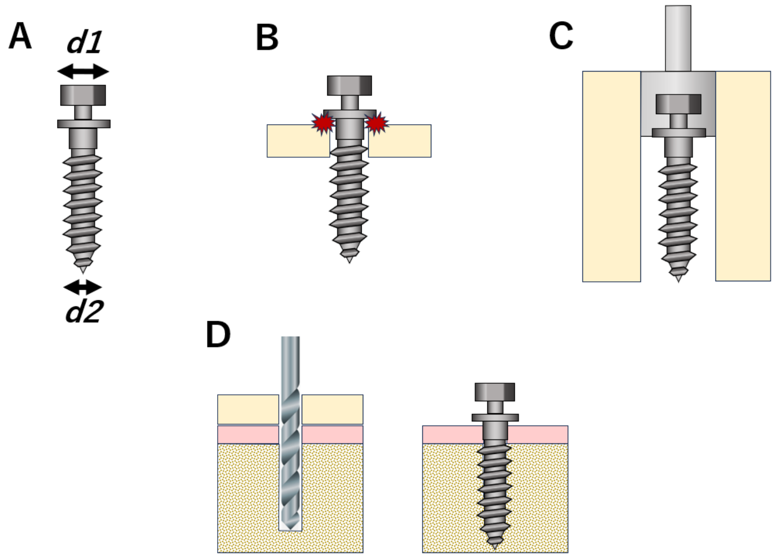

Figure 7. (**A**) The diameter of the neck and the head of a miniscrew (d1) is usually larger than the thread part (d2). (**B**) If the diameter of the guide hole is smaller than d1, the surgical guide cannot be removed after insertion. On the other hand, if the hole is as large as d1, the surgical guide will have too much space, and it will lose accuracy. (**C**) To maximize accuracy, a surgical guide must cover the screwdriver, which will make the surgical guide thicker and bulkier. (**D**) In the self-tapping method, the surgical guide is removed when the miniscrew is inserted. Thus, a guide for the self-tapping method can be much thinner than that for the self-drilling method.

In a preliminary experiment, we tested different diameters of holes for the surgical guides and decided to make the holes slightly smaller than the diameter of the drill. As a 3D printer is not 100% accurate, the hole diameter on the printed surgical guide was smaller than the diameter of its original data. Therefore, initially we printed the guide with a hole of 1.1 and 1.2 mm to allow the drill bit of 1.0 mm to pass through the hole. However, it increased the gap between the guide and the drill bit, and the accuracy seemed to decrease. Thus, we set the hole diameter at 1.0 mm in the original data, which was printed slightly smaller than 1.0 mm, then we enlarged the hole diameter using another drill bit of 1.0 mm before the experiment.

It should be noted that the freehand drilling might be less accurate in a real-world patient than in the results of this study. We employed micro-motor and checked the insertion angle from various angles before drilling, which was an easier setting to work in, compared with an intra-oral environment. In a real-life setting, the viewpoints are limited, and the driver is pushed by buccal mucosa. Thus, the accuracy will probably decrease. As the objective of this study was to assess the differences created by the guide lengths, we controlled these environmental factors. However, using phantoms and having the drilling performed by a less experienced doctor should be better for evaluating the effect of a surgical guide.

Drilling using a surgical guide is less sensitive to the skills of a doctor and can reproduce the same results; however, the fit of surgical guide should be inspected carefully before the drilling. If the guide does not fit the tooth surface perfectly, the error will be greater and might be worse than using freehand insertion. To avoid this issue, we designed the guide to expose a part of the crown, so that the gap between the tooth and the guide can be observed.

As the surgical guide is removed in the self-tapping method when a miniscrew is inserted, it is easier for doctors to observe the distance between the neck of a miniscrew and the gingival tissue. With the self-drilling method, the distance between the miniscrew and the gingival tissue cannot be seen because the entire miniscrew is covered by the surgical guide. Therefore, the self-tapping insertion after the drilling means it is easier to position the flange of a miniscrew as close as possible to the gingiva in order to reduce patient discomfort.

Further research needs to be carried out to assess the reproducibility of placing a miniscrew through the hole after the drilling. Although a drilled hole seems to be the most mechanically stable pathway for a miniscrew, to our knowledge, no research has been performed to evaluate the angular error between the drilled hole and the miniscrew placed through the hole. A randomized trial for dental implants showed that using an implant guide after a drilling guide was more accurate than using a drilling guide only [17]. They reported that using the drilling guide only resulted in 1.4 degrees more error. Applying this to a miniscrew, when the miniscrew is inserted to a depth of 6 mm, this would result in an error of 0.15 mm at the tip, which is more acceptable. However, dental implants are much larger than miniscrews, and it is still unclear whether the results can be applied to miniscrews. It might show unacceptable levels of error if the cortical bone thickness is thin or the hole diameter is too large or small compared with the diameter of a miniscrew.

A limitation of this study was that the experiment was performed in vitro and the accuracy in a clinical situation might be lower than in the results shown here. Ultimately, the best way of knowing the actual accuracy in real patients is by comparing the CBCT of actual patients before and after the insertion. However, taking CBCT just for the evaluation is not beneficial for patients because of the radiation risk, especially when the interradicular space is not narrow and a miniscrew looks like it could be inserted successfully. Therefore, for clinical studies, another method with less radiation risk needs to be established, such as superimposing the post-insertion intra-oral scan over the pre-insertion CBCT and estimating the screw position in the bone.

5. Conclusions

A longer surgical guide is recommended when a miniscrew would be inserted into a narrow interradicular space. On the other hand, it is suggested that if an error of 1.0 mm is acceptable for the insertion site, a guide of 3.0 mm in length is sufficient.

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Institutional Review Board Statement: Since no patient's data were used in the present study, ethical approval was not required.

Data Availability Statement: The data presented in this study are openly available in FigShare at https://figshare.com/search?q=10.6084/m9.figshare.24901575.

Conflicts of Interest: The authors declare no conflict of interest.

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