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Accuracy of three-dimensional movement tracking of digital dental models with optical scanner and target tracking system

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Accuracy of three-dimensional movement tracking of digital dental models with optical scanner and target tracking system

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먼저, 본 연구논문이 완성되기까지 좋은 연구주제를 발굴할 수 있도록 해주시고, 아낌없는 지도를 베풀어주신 심준성 교수님께 감사와 존경의 말씀을 드립니다. 또한, 부족한 논문에 많은 가르침을 주시기 위하여 바쁘신 와중에도 귀중한 시간을 내어주시고, 논문의 부족한 부분에 대하여 소중한 조언과 충고를 해주신 이근우 교수님, 문홍석 교수님, 최성호 교수님, 김광만 교수님께 진심으로 감사 드립니다. 부족한 제게 보철학의 더 깊은 경지를 가르쳐 주시고 많은 깨달음을 주신 정문규 명예교수님, 한동후 교수님, 박영범 교수님, 김선재 교수님, 이재훈 교수님, 김지환 교수님께 감사 드립니다.

실험을 진행할 수 있도록 많은 지원과 아이디어를 주셨던 고려대학교 장민호 교수님과 메디트의 이수복 소장님, 그리고 실험 전체과정을 함께 고민하고 진행하며 도움을 주신 메디트 임성빈 연구원님께도 감사의 말씀을 드립니다.

멀리 부산에서 늘 응원해 주시고 기도로 함께해 주시는 아버지, 어머니, 잘 챙겨드리지 못함 에도 뵐 때 마다 격려를 아끼지 않으시는 장인어른과 장모님께 감사드립니다. 하루가 다르게 에너지가 넘치는 두 아들을 혼자 감당하고, 묵묵히 저를 지지해 주는 사랑하는 아내 박지현과 귀여운 동갑내기 두 아들 선우, 선재에게 고마운 마음을 전하며, 이 기쁨을 함께 나누고 싶습니다.

마지막으로, 저에게 지혜와 명철을 주시고, 변함없는 사랑과 은혜로 제가 가는 길을 인도해 주시는 하나님께 감사 드립니다.

2017 년 12 월 김종은

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Abstract

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This study is an *in vitro* study evaluating the accuracy of tracking the movement of the mandible by means of an optical scanner and a target attached to the tooth and to find optimal conditions. The null hypotheses of this study were as follows. 1. There is no difference in the stability of tracking depending on the type and arrangement of the target. 2. There is no difference between the conventional cumulative motion data using wax, digital cumulative motion data, and digital cumulative motion data with mesh gap filling.

In this study, a structured-light 3D scanner and target materials attached to the anterior tooth region were used to track mandibular movements. Nine groups were constructed according to the three types of target arrangement and three target types. The extraoral template was designed as a control group to evaluate the stability of tracking by arranging the target most widely. Full-mouth conventional cumulative motion data with function wax and digital-based cumulative motion data were obtained using a structured-light 3D scanner and a target-tracking system. Root mean square (RMS) value, + Average (AVG) value, -AVG value, and tolerance value between the two data sets were obtained using reverse engineering software.

The tracking results of the maxillary target area confirmed that the stability of the 3-mm donut target was higher. The tracking stability of the Type III arrangement, which was widely distributed to the canine, was about 7.1 μm, which was not significantly different from the value of 7.4 μm in the control group. In the mandibular anterior target and maxillary and mandibular posterior tracking points, the 3-mm donut target-Type III array was the most stable and showed similar tracking stability as in the control group. Conventional cumulative motion data showed a very large RMS value of 170.3 μum. Even in the case of a tolerance value based on 50 μm or less, only 34.9% was satisfied. In the case of digital cumulative motion data, the original data produced using an optical scanner showed an RMS value of 42.4 μm. The RMS value was 42.0 μm when the mesh-filling process was performed once, and 41.8 μm when the mesh-filling process was performed twice.

Based on the results of this study, the donut-shaped target with the diameter of 3 mm was the most stable during tracking, and the tracking stability was the highest when the target was arranged wide to the canine. In addition, the digital method using the target-tracking system is more predictive than the conventional technique using wax for generating cumulative motion data. It was confirmed that mandibular movements can be reproduced at a high level, even when there is no additional mesh correction process when the optical scanner records at 50 frames per second.

Key words: CAD/CAM; cumulative motion; functional generated path; mandibular movement; optical scanner; target tracking

Accuracy of three-dimensional movement tracking of digital dental models with optical scanner and target tracking system

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(Directed by Professor June-Sung Shim, D.D.S, Ph. D)

I. INTRODUCTION

Due to recent advances in digital dentistry, a variety of software has been developed and made available to allow the fabrication of prostheses and the diagnosis of occlusion. The need for development of tools to provide accurate information to software in order to obtain predictive treatment results is increasing. This includes equipment and software for precisely tracking the mandibular movement path, which is crucial for automating and simplifying procedures for prosthodontic restoration.

1. Current status of the articulator for reproducing mandibular movement

The three-dimensional movement of the mandible is determined by occlusal relationships and posterior elements, such as the temporomandibular joint (TMJ), muscles, and ligaments (Nishigawa et al. 1991). Many clinicians and researchers have long attempted to record the patient's actual mandibular movement as closely as possible (Mesqui, Kaeser, and Fischer 1986; Mohl et al. 1990; Otake et al. 2006). The most commonly used equipment for diagnosing the correct occlusal relationship and manufacturing dental prosthesis is a mechanical articulator, which reproduces the relative movement of the maxilla and mandible (Hindle and Craddock 2006). Since dental prostheses are generally made via an indirect method, through impression taking and gypsum model-making, it is necessary to implement the mandibular movement and occlusal relationship of the patient in the articulator in order to produce a precise prosthesis that is harmonious with the existing patient occlusion

For mechanical articulators, a face-bow is used to establish the relationship between the maxilla and the patient's transverse hinge axis (THA) (Borgh and Posselt 1958; Long 1970; Razek 1981). The face-bow uses an ear-piece instead of a tool that can designate a true hinge axis point for ease of use. It has been pointed out that an error occurs when the vertical position of the articulator changes (Palik, Nelson, and White 1985). The adjustment of the articulator condylar element is then made through the checkbite. Although the information at the specific point at which the checkbite is taken can be transferred accurately, the motion that is reproduced may differ, depending on the recording position of the checkbite, even in the same patient (Utz et al. 2002). The articulator is characterized by a linear representation of the curved mandibular movements, and importantly, it is not accurate at all points of mandibular movement (Weinberg 1963).

Many equipment and techniques for transferring the patient's mandibular movements to a fully adjustable articulator using a kinematic instrument have been tested (Beard, Donaldson, and Clayton 1986; Chang et al. 2004). However, achieving this required the use of more complex, bulky, and expensive equipment, such as a pantograph, and was time-consuming. In addition, these methods were not reliable, and the results differed according to the proficiency of the clinician.

Depending on the case of prosthesis restoration, it is still debated which articulator should be used and how accurate a recording should be made to minimize occlusal interference and to meet acceptable tolerance limits (Proschel, Maul, and Morneburg 2000).

2. Recent studies on individual pattern of condylar movement

There have been many studies on the movement of the patient's TMJ region. It is known that when a patient opens their jaw, it typically involves pure rotational hinge movement during the early opening, and translational movement during the posterior opening. However, some studies have shown that the early opening period does not only involve pure rotation (Mapelli et al. 2009; Torii 1989). Rather, each patient demonstrated a slight translational movement during the rotational movement section, such that the relation between the maxilla and mandible, according to the change in vertical dimension, is very unique for each patient (Mapelli et al. 2009; Torii 1989). In addition, the anatomical characteristics of the TMJ and the position of the disk may cause deviation in mandibular movement. Since the patients' mandibular movements vary widely, it may not be possible to reproduce all aspects of an individual's mandibular movement through mechanical devices, such as articulators.

3. Conformative approach and the functionally generated path technique

The most frequent cases for dental prosthesis treatment are the single crown, bridge, or short-span implant-fixed prosthesis. In these cases, it is important to make a prosthesis that is in harmony with the patient's existing occlusion. Whether the prosthesis is attached or not, it is essential that the occlusion of the adjacent teeth does not change and that occlusal dysfunction does not occur (Wiskott 2011; Yip, Smales, and Kaidonis 2004).

This is commonly referred to as conformative occlusion, where occlusal contacts of adjacent teeth are either untouched or experience only minor alterations (Mehl and Blanz 2005; Mehl, Blanz, and Hickel 2005; Wiskott 2011; Yip, Smales, and Kaidonis 2004).

In the case of such conformative restorations, a digital approach for tracking and recording the patient's mandibular movements and accumulating their trajectory data may be helpful. This technique can be used to check the occurrence of interference in prosthesis manufacturing and reflect it in the design. This concept was introduced in 1959 by Meyer et al. as the functional generated path (FGP) technique (Meyer 1959). The FGP technique is used to make a dental prosthesis in the traditional way. It involves putting the recording material in the space between the prepared teeth and the opposing teeth for preparation of the restoration and records the accumulated actual movements of the opposing teeth in the patient's mouth. FGP techniques have been implemented in a variety of ways by various researchers, and is known to save time in producing restorations and to allow the production of quality prostheses without the need for complex equipment (Kafandaris 1981; Mehl, Blanz, and Hickel 2005; Minagi et al. 1998; Pankey and Mann 1960). Since the most accurate articulator is the patient him or herself, the FGP technique is considered a practical technique (Lin et al. 2017). However, the conventional FGP technique has the disadvantage in that the process is cumbersome and requires much additional laboratory work.

4. Development of digital dental technology and limitations of the virtual articulator

Computer-aided design/computer-aided manufacturing (CAD/CAM) technology, which began in the 1980s, has continued to evolve ever more rapidly with the recent development of many types of scanning equipment, CAD software, and milling machines (Duret et al. 1988). CAD/CAM technology has helped to overcome the shortcomings of existing manufacturing methods for dental prostheses and intraoral devices and has shortened the manufacturing process (Christensen 2009). However, most of the dental prostheses that are digitally fabricated have been based on static intercuspal position alone and do not reflect the actual occlusal motion of the patient. Thus, error could only be detected at try-in or delivery time, and a long chair time was required (Mehl 2012; Park et al.2017).

Recently, a variety of products have been introduced to digitalize the patient's mandibular movements and various studies have been performed. Recent approaches have involved digitally recording the relative motion of the upper and lower mandibles with techniques such as ultrasound, voltage division, optoelectronic technology, and simulate motion in software (Kordass et al. 2013). However, most of them are digitally to acquire the patient's movements digitally, and then to obtain setting values that can be placed in a mechanical articulator or a virtual articulator. In addition, since it does not utilize the existing patient's model or CBCT data, it is limited in terms of obtaining the setting value only by the movement of the tracking device (Kobs et al. 2007; Wieckiewicz et al. 2014).

The implementation of mandibular movements by acquiring the value of the condylar element has the drawback that it cannot overcome the limitations of the movement representation of the articulator device itself, in both mechanical and virtual articulators (Szentpétery 1997). It is also bulky and expensive, making it difficult for clinicians to use it (Solaberrieta et al. 2015a). There are, thus, only a few studies that have evaluated the accuracy of digital recording of mandibular movements, but the need for accuracy assessment is increasing, in order to facilitate reliable treatment.

5. Previous studies

The author and collaborators have developed a technical approach to digitalize mandibular movement through tracking a target attached to an anterior tooth and using an optical scanner in various ways. This approach utilizes procedures for constructing occlusal splints by adjusting the vertical dimensions within the opening and closing pathways of the patient, by implementing opening and closing motions during target tracking (Kim et al. 2017). In this approach, FGP data can be produced using a digital approach, and the value of the posterior element can be obtained and applied to the condylar element of the articulator.

As the field of digital dentistry is expanding and gaining increasing attention, the technology of digitally recording mandibular movements and evaluating occlusion will become increasingly utilized and its importance will continue to escalate. However, no studies have been performed to evaluate the accuracy of mandibular motion using a target-tracking system to date.

6. Purpose of this study

This study is an *in vitro* study evaluating the accuracy of tracking the movement of the mandible using an optical scanner and a target attached to the tooth, and to optimize the relevant conditions.

The null hypotheses of this study were:

1. There is no difference in the stability of tracking depending on the type and arrangement of the target.

2. There is no difference between the conventional cumulative motion data obtained using wax, digital cumulative motion data, and digital cumulative motion data with mesh gap-filling.

II. Materials and methods

1. Study model preparation

Maxillary and mandibular study models without tooth loss or inadequate occlusal relationship were made with gypsum plaster (Snowrock die stone premium; DK Munkyo, Gimhae, Korea). The upper and lower stone models were scanned with a tabletop scanner (Identica hybrid; Medit, Seoul, Korea) and the data were converted into Stereo Lithography (STL) format data (Figure 1). The stone model was mounted on a mechanical articulator (Articulator PROSTAR evo 9; KaVo Dental, Bieberach, Germany).

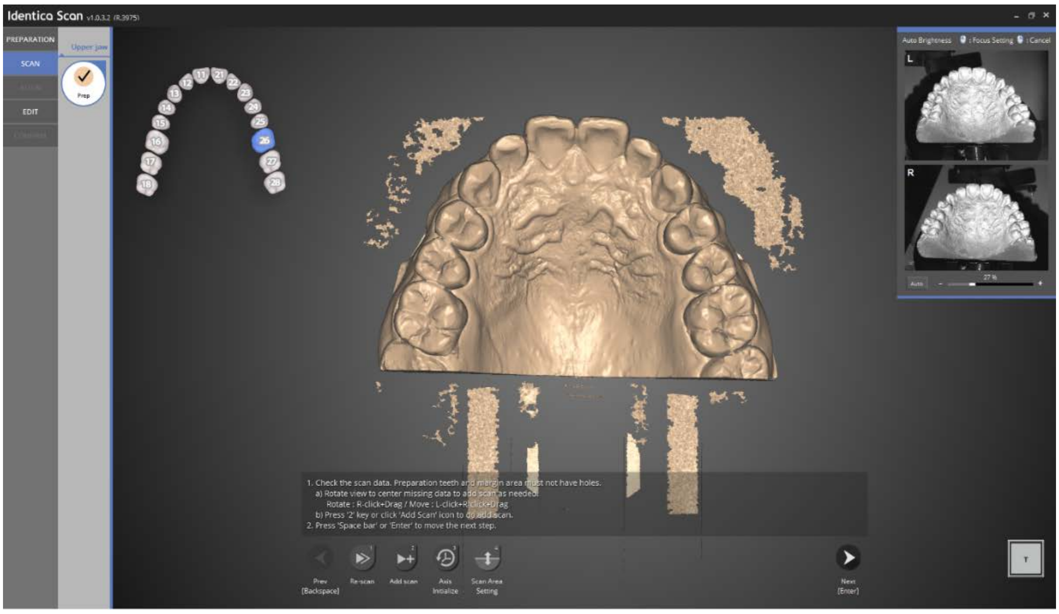

Figure 1. Creating digital data in STL format using a tabletop scanner.

2. Optical scanner and target-tracking system

In this study, a structured-light 3D scanner (Rexcan DS2; Medit, Seoul, Korea) and target materials (Target sticker; Medit, Seoul, Korea) were used to track mandibular movements. The optical scanner was set to record data at 50 frames per second for evaluating tracking accuracy. The following method was used to track the target. Four target stickers were attached to the anterior tooth region of a vacuum-forming template as a carrier on the study model, and the scan was performed with the target carrier mounted on the study model. The scanned study model without the target carrier and the scan data with the target carrier were aligned using the common shape of a gypsum model base. The positional relationship between the tooth and the target materials was defined using this data (Figure 2). Since the positional relationship between the target position and the tooth is set, it is possible to track the movement of the upper and lower model by tracking only the movement of the target in real time in order to track the movement of the articulator.

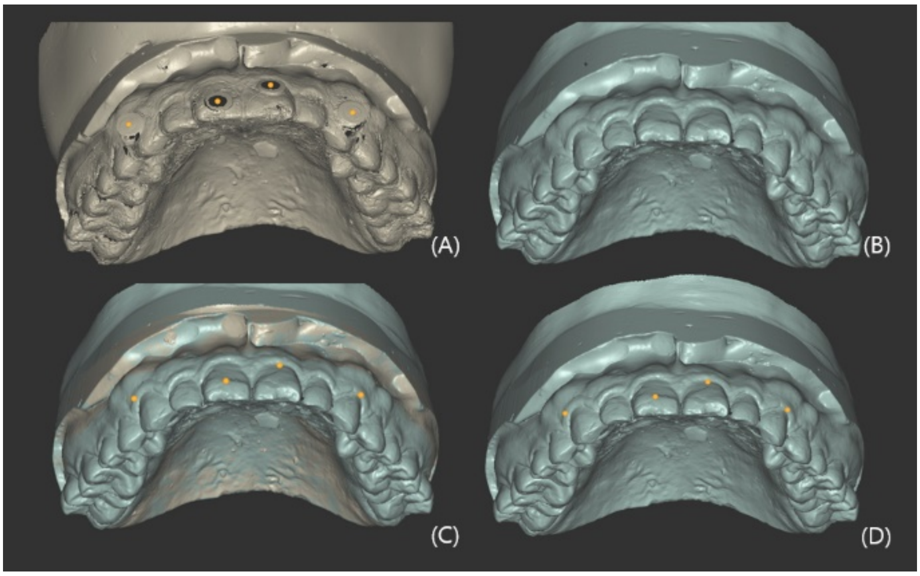

Figure 2. Process of alignment between the target and full arch model. Scanned model with a target carrier (A) and without a target (B). The target position is indicated by the orange dot. (C) The three-dimensional relationship between the gypsum model data with and without a target is aligned by superimposition. (D) The final relationship between the target and the gypsum model is aligned.

3. Measurement the stability of target tracking on the static model

The purpose of this experiment was to determine the shape, size, and arrangement of the target that allows the most stable tracking of the movement. Various sizes, shapes, and arrangements of the targets were evaluated. First, three types of targets were prepared to evaluate the stability of tracking according to the size and shape of the target. Three-millimeter diameter reflective targets and donut-shaped targets of 3-mm and 5-mm diameters, with a black border, were made (Figure 3).

Figure 3. Three types of targets produced for the study. The target on the left is a reflection target, the center target is a donut target with a diameter of 3 mm, and the target on the right is a donut target with a diameter of 5 mm.

In order to evaluate the effect of the target arrangement on the stability of occlusal motion tracking, three types of arrangements were also employed.

- Type I: Arranged in a line on the four anterior teeth
- Type II: Arranged in a zigzag pattern on the four anterior teeth
- Type III: Arranged on the central teeth and canines

Thus, nine groups were constructed according to the three types of target arrangement and three target types (Figure 4). The extraoral template was designed as a control group to evaluate the stability of the tracking by arranging the target most widely (Figure 5). This was designed by CAD software and output to a 3D printer (3Dwox, Sindoh, Seoul, Korea).

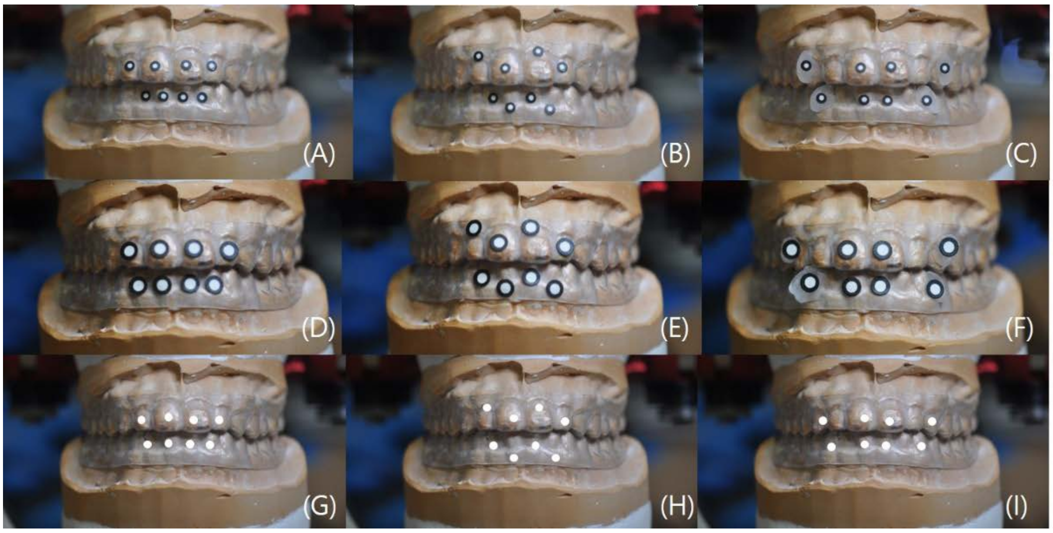

Figure 4. Evaluation of the tracking stability according to the target arrangement. (A, D, G) Arrangement of targets in a line on the four anterior teeth (B, E, H) Arrangement of targets in a zigzag pattern on the four anterior teeth (C, F, I) Arrangement of targets on the central teeth and canines.

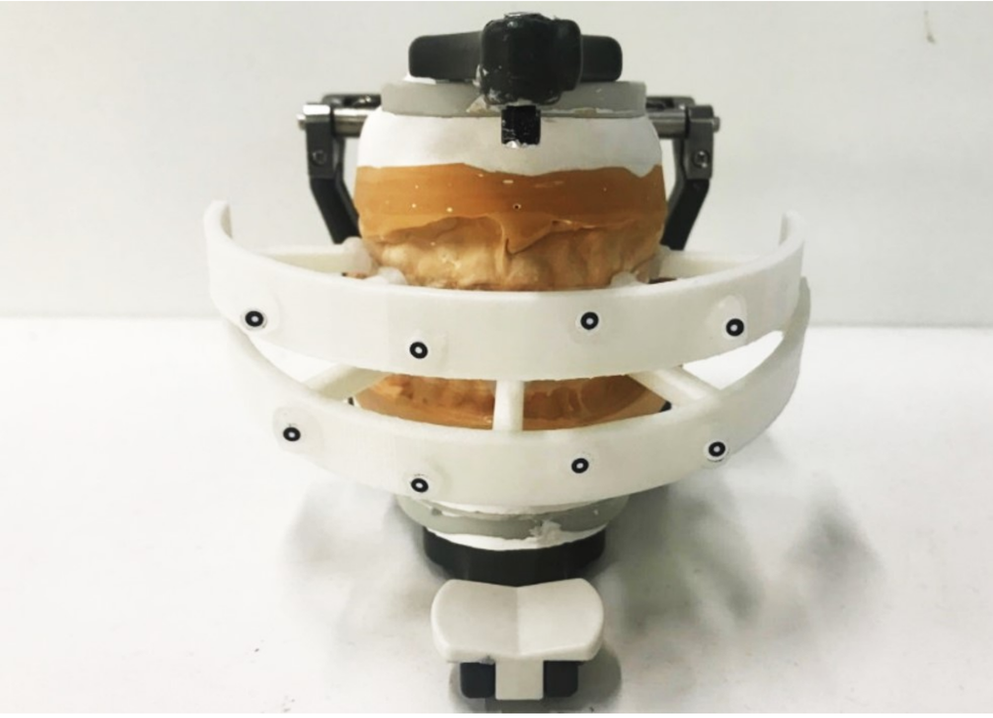

Figure 5. Extraoral template designed as a control group.

For target-tracking stability experiments, four additional points were traced in addition to the eight targets attached to the upper and lower anterior tooth. The tracking stability of both the mesiopalatal cusps of the maxillary second molar and both the distobuccal cusps of the mandibular second molar were evaluated (Figure 6). Data from 350 frames were acquired for 7 seconds, at 50 frames per second, using an optical scanner, while the upper and lower gypsum models were positioned at the maximum intercuspation position (MICP). The target itself and the tracking points in the upper and lower molar regions were evaluated for the degree of error created in the three-dimensional XYZ coordinates while tracking targets were attached to the upper, lower anterior tooth, and extraoral template, in real time. The average position in the 50–150 frame interval was set as the reference point, and the error was evaluated by measuring the average distance between the reference point and the position generated during the total of 350 frames (Figure 7, 8). The tracking stability of each region was calculated by analyzing the representative values of the four regions, including the maxillary anterior target, the mandibular anterior target, the maxillary posterior tracking point, and the mandibular posterior tracking point, by calculating an average value for each region.

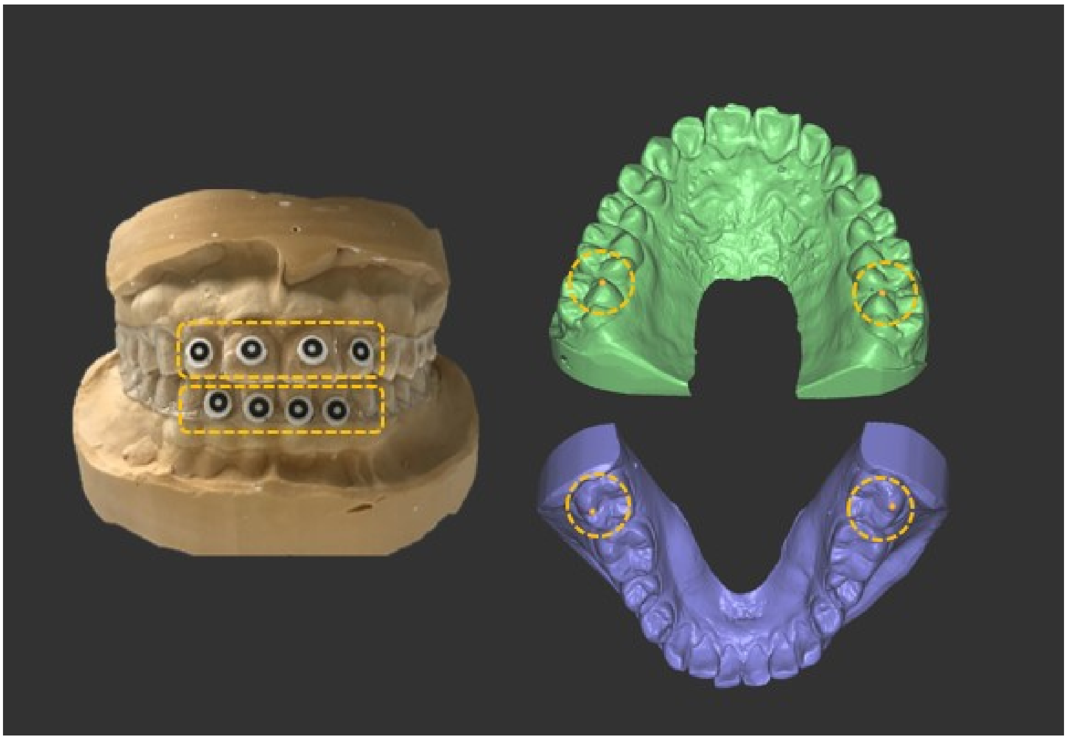

Figure 6. Sites used for evaluation of target tracking stability. The tracking stability of the mesiopalatal cusp of the maxillary second molar and that of the distobuccal cusp of the mandibular second molars were evaluated, in addition to the eight targets attached to the upper and lower anterior tooth.

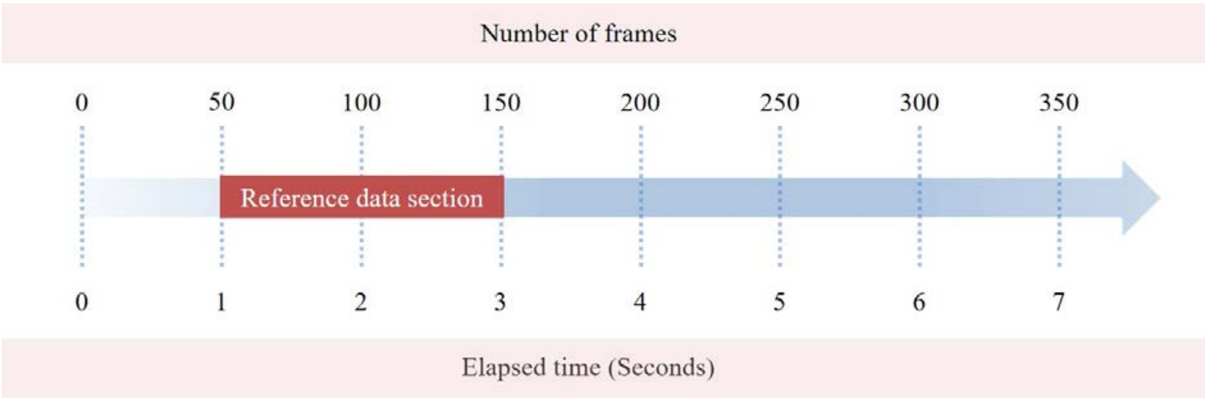

Figure 7. Process of setting the reference point. Coordinate data of a total of 350 frames were acquired for 7 seconds, and the degree of scatter was evaluated. The average position of 100 coordinate data points between 50–150 frames was used as reference data.

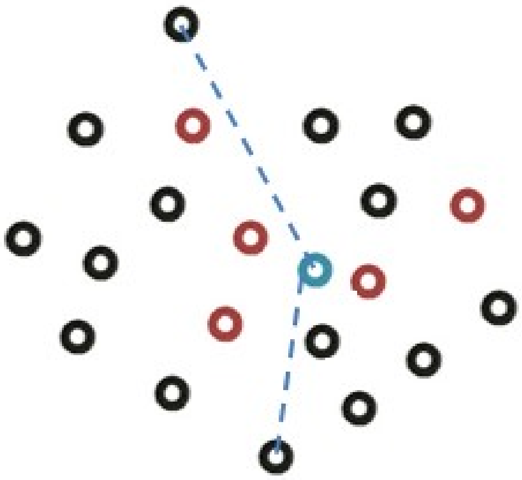

Figure 8. Depiction of the process of setting up a reference point. The red dots are the positions of coordinates of the reference data section. The blue dot is the average position of the hundred of red dots and it is the final reference position.

4. Measurement of precision of digital-based full-mouth cumulative motion data

Digital-based full-mouth cumulative motion data were obtained using a structured-light 3D scanner and a target-tracking system. Conventional incisal guide pins mounted on the articulator can make the target attached to the anterior part invisible, and thus, a customized incisal guide pin was made, which does not interfere with movement tracking (Figure 9). For production of the customized guide pin, a selective laser melting (SLM) alloy with a Cr-Co component (EOS Cobalt Chrome SP2; EOS GmbH, Krailing, Germany) and an SLM machine (EOSINT M270 system; EOS GmbH, Krailing, Germany) were used. For the acquisition of full-mouth digital cumulative motion data, the customized guide pin was raised by 4 mm and the condylar guidance and Bennett angle were set at 30 and 15 degrees, respectively. A customized incisal guide table was made with chemically cured acrylic resin (Pattern resin LS™, GC America, Alsip, IL, USA) to follow a constant path when moving the articulator. The movement path, which is approximately 5 mm to the buccal cusps on the balancing side, reached a similar position in the left and right lateral excursion.

Figure 9. A customized incisal guide pin was made to avoid interfering with movement tracking.

The optical scanner took 50 frames per second and moved the articulator left and right for 4 seconds. Thus, digital cumulative motion data with a total of 200 frames was generated. The lateral movement of the articulator was operated at a constant speed, and seven digital cumulative motion data sets were generated.

Since the data is stored in the continuous recording method, there was a blank interval between the data points. In this blank section, post-processing was performed by applying an algorithm by which the matrix rotation and matrix shift components of the coordinate values of each data point are extracted, and the transformation matrix of each step is calculated and applied to fill the blank section. Through this process, seven mesh-filled data sets and seven two-step mesh-filled data sets were also created.

The reproducibility of the data in each group was calculated by superimposing two data sets pairwise, using the best-fit algorithm (*n* = 28). Then, in order to obtain the precise measurement reproducibility of the test object, the RMS value, + AVG value, -AVG value, and tolerance value between two data sets were obtained, using reverse engineering software (Geomagic Control X, 3D Systems, Rock Hill, SC, USA). The RMS value was calculated to extract the error value between the data sets using following equation:

$$\mathrm{RMS} = \frac{1}{\sqrt{n}} \cdot \sqrt{\sum_{i=1}^{n} (e_i - \hat{e_i})^2},$$

where e_i is the measurement point of the reference data, and $\hat{e_i}$ is the measurement point of the comparison data, and *n* is the total number of measurement points used in the analysis.

5. Measurement of precision of the conventional full-mouth cumulative motion data

Conventional full-mouth cumulative motion data were obtained with the same articulator setting, with 4-mm spacing of anterior teeth. To obtain the cumulative motion data, which is a cumulative movement path of confluence, an occlusal template made using a 3D printer (Zenith; Dentis, Seoul, Korea) was prepared on the mandibular occlusal surface, and a special wax (S-U-FGP-FUNKTIONS-WAX; Schuler Dental, Ulm, Germany) was used for performing the cumulative motion data procedure on the template. The FGP wax was softened in water at a softening temperature of 75°C to allow modeling, and was then applied to the upper surface of the template. The FGP wax was attached well to the template and lateral movement of the articulator was then performed according to the movement trajectory set in the customized incisal guide table. The cumulative movement path of the upper gypsum model recorded in the FGP wax was scanned with a tabletop scanner to generate a file in STL format, and the data were inverted to complete the conventional cumulative motion data.

For recording data using the conventional procedure, since the shape of the outer part of the wax differed, only the data of the actual functional area was obtained by trimming before analysis. Seven conventional cumulative motion data sets were obtained in the same procedure, and the precision was evaluated by using the best-fit algorithm in the same pairwise manner (n = 28).

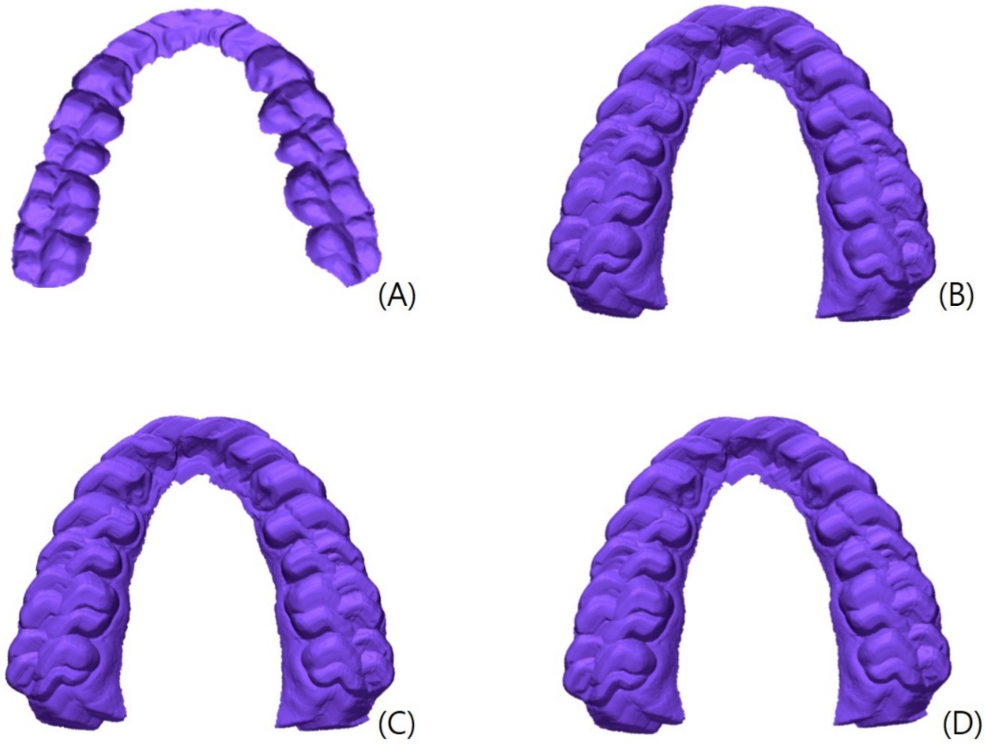

Figure 10. Four groups used for analysis of cumulative motion data. (A) Conventional cumulative motion data obtained using FGP function wax, (B) original digital cumulative motion data, (C) data obtained with the mesh-filling process for the digital cumulative motion data, and (D) data obtained with 2-step mesh filling. As the mesh-filling process progresses, the surface became smoother.

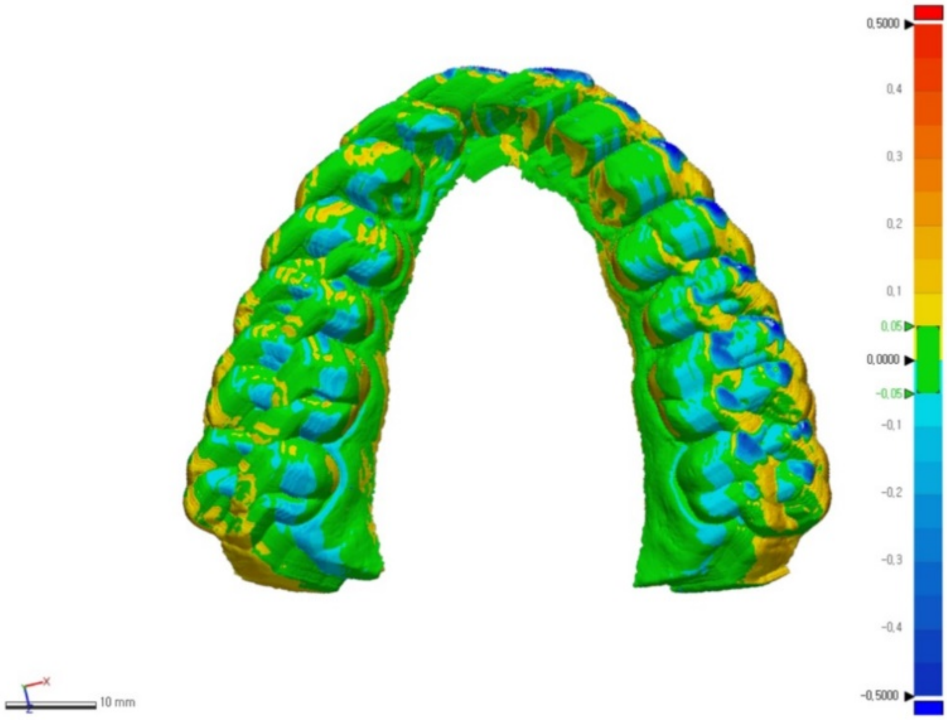

Figure 11. Digital cumulative motion data prepared for precision evaluation

6. Statistical analysis

Analysis of variance (ANOVA) was used to assess the tracking stability of each position according to the target type and arrangement. Post-hoc tests involved Bonferroni adjustment. The same method was applied for RMS, +Avg, -Avg, and the tolerance value of the four groups of cumulative motion data for precision analysis. For statistical analysis, SPSS v22.0 (SPSS Inc., Chicago, IL, USA) was used and a p-value of < 0.05 was taken as indicating statistically significant differences.

III. RESULTS

1. The stability of target tracking

First, in the tracking results of the maxillary target area, it was confirmed that a donut-shaped target of 5 mm diameter had inferior stability, while the stability of the 3-mm donut target was highest. The tracking stability of the Type III arrangement, which was widely distributed to the canine, was about 7.1 µm, which was not significantly different from the value of 7.4 µm of the control group. Moreover, the stability of the zigzag array of type II arrangements does not appear to be consistent across groups. In the 5-mm donut target group, the stability was higher than in the type I arrangement, but the stability was poorer in the other groups. In the case of a reflective target, the stability was highest when it was arranged to the canine, at about 7.2 µm, but the stability was significantly lower than that of the 3-mm donut target in the type I or type II arrangement (Figure 12).

The tracking stability of the mandibular anterior target was similar to that of the maxillary target area, but the 3-mm donut target–Type III arrangement was significantly more stable than that of the control group. As in the case of the maxillary incisor target, the Type III array was found to be highly stable in the 3-mm diameter donut target and the 3-mm reflection target, while the 5-mm donut target was inferior in overall stability (Figure 13).

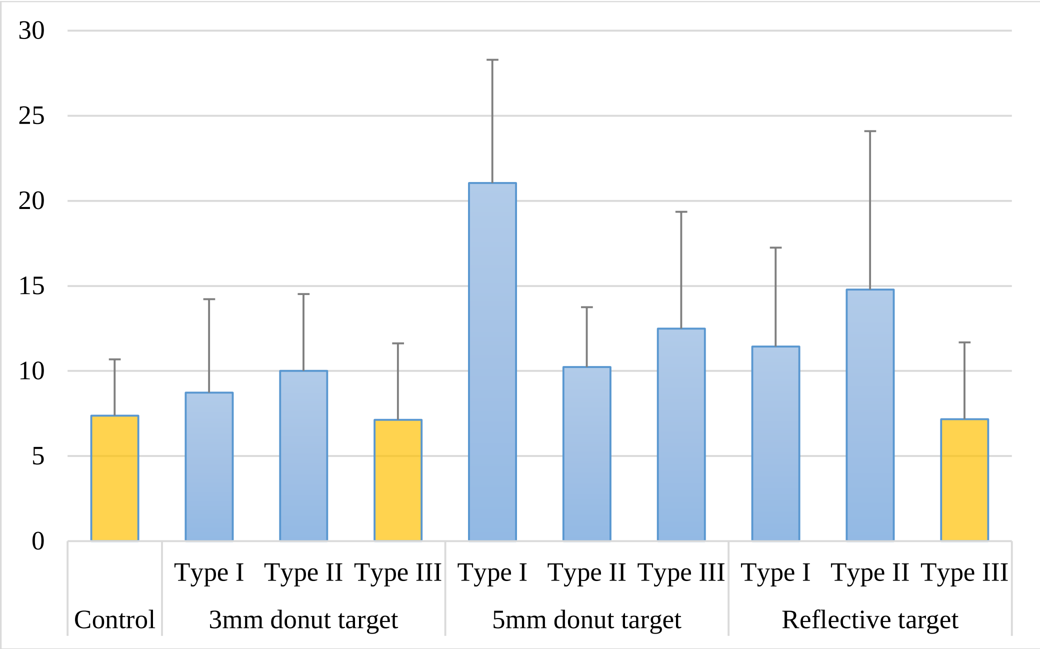

Figure 12. Tracking stability of the maxillary target area. The stability of the 3-mm donut target was the highest. In particular, a Type III arrangement showed the highest tracking stability, i.e., 7.1 μm.

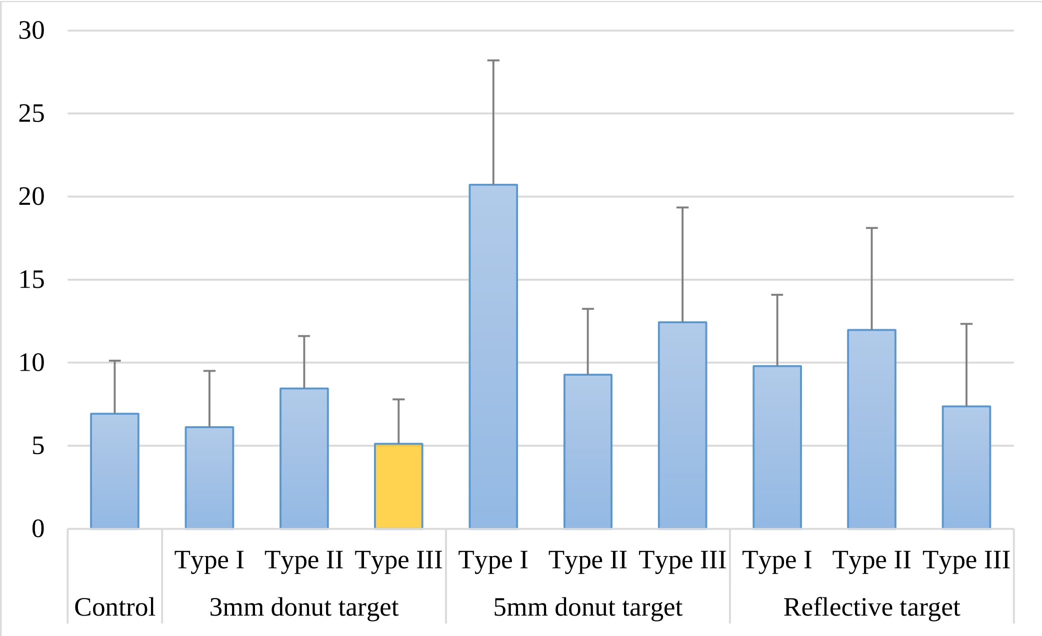

Figure 13. Tracking stability of the mandibular target area. The results were similar to those of the maxilla, and the 3-mm donut target–Type III arrangement group was the most stable.

At the tracking point of the maxillary posterior cusp, the control group showed the highest stability (11.1 µm stability). Next, the type III group of the 3-mm donut target showed a stability as high as 18.9 µm. Similar to the tracking stability results at the anterior target site, the reflection target–Type III array showed stable results, with an error of about 20.7 µm. In the case of type II, which had a zigzag arrangement, the overall tracking stability was poor (Figure 14).

Tracking points in the mandibular posterior cusp were similar and the type III group with the control target group and the 3-mm donut target showed significantly highest stability (Figure 15).

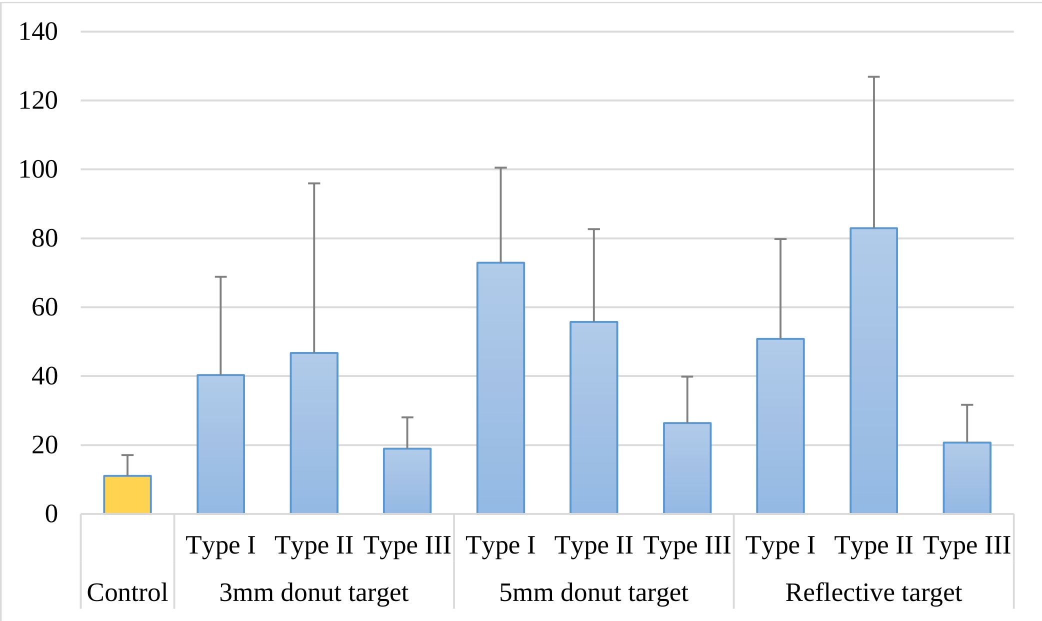

Figure 14. Posterior tracking points of the maxillary molar cusp. The control group showed the most significant stability. Next, the Type III group of 3-mm donut targets showed a high stability (19 μm).

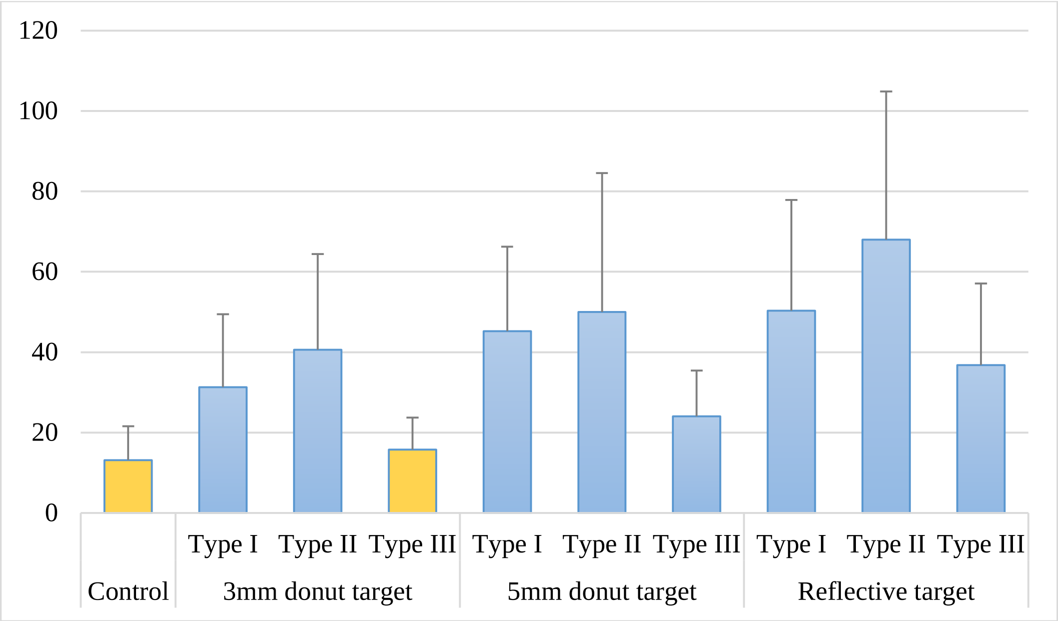

Figure 15. Posterior tracking points of the mandibular molar cusp. A similar pattern was observed in the mandibular posterior cusp as in the maxillary posterior cusp, and the control group and Type III group with a 3-mm donut target showed significantly higher stability.

2. Precision of full-mouth cumulative motion data

Conventional cumulative motion data showed a very large RMS value of 170.3 µm. The +AVG and -AVG values were also relatively large. Even in the case of a tolerance value evaluation based on 50 µm or less, only 34.9% of the total data were satisfied.

In the case of digital cumulative motion data, the target stability experiment demonstrated that the most stable tracking of the intraoral target is possible when the donut target with a 3-mm diameter is arranged up to the canine (Type III arrangement). The original digital data produced using an optical scanner showed an RMS value of 42.4 µm. The RMS value was 42.0 µm when the mesh-filling process was performed once, and 41.8 µm when the mesh-filling process was performed twice.

Tolerance was also 34.9% for conventional cumulative motion data and 79.9% for digital cumulative motion data. When mesh-filling was performed once or twice, the values were higher, at 81.1% and 81.2%, respectively.

When mesh-filling was used, the mesh was entirely smoothened as the mesh was completely filled in. A comparison of the original data with the 2-step mesh-filling data confirmed that the gap was indeed filled (Figure 16).

Table 1. Analysis of conventional and digital cumulative motion data. RMS data obtained using the conventional method of cumulative motion data by employing wax vary widely, and the RMS data from digital method was very low, about 40 µm.

	Conventional motion data (mean ± SD)	Digital motion data (mean ± SD)	Mesh filled data (mean ± SD)	2-step mesh filled data (mean ± SD)	P-value
RMS (㎛)	170.3 ± 67.9[a]	42.4 ± 16.9[b]	42.0 ± 17.4[b]	41.8 ± 17.5[b]	<.05
+AVG (㎛)	124.1 ± 54.7[a]	27.8 ± 7.4[b]	26.3 ± 7.2[b]	26.4 ± 7.1[b]	<.05
-AVG (㎛)	77.6 ± 17.0[a]	35.9 ± 17.4[b]	36.0 ± 18.5[b]	35.5 ± 18.2[b]	<.05
Tolerance (%)	34.9 ± 6.9[a]	79.9 ± 12.9[b]	81.1 ± 12.6[b]	81.2 ± 12.6[b]	<.05

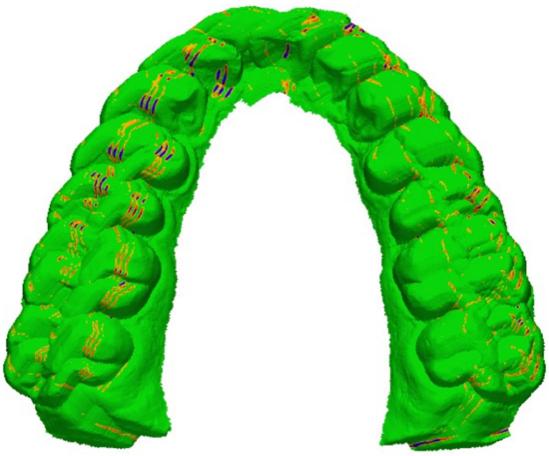

Figure 16. Comparison of the original digital cumulative motion data with the two-step mesh-filling data. By comparing the original digital cumulative motion data with the two-step mesh-filling data using reverse engineering software, the gap areas can be seen to have been filled. Differences in data are distinguished in yellow and blue color.

IV. DISCUSSION

1. Evaluation the stability of target tracking

In this study, we evaluated the tracking accuracy of jaw movement using the target-tracking system. The 3-mm diameter donut target had the highest tracking stability, and the tracking stability was highest when the target was distributed to the canine. Thus, the first null hypothesis of this study was rejected.

The tracking stability of the 3-mm donut target was similar to that of the control group in the maxillary target area and the mandibular molar tracking point, and was more stable than the control group in the mandibular anterior target area. Thus, the optimal combination for tracking mandibular movements clinically using an optical scanner and target-tracking system technology is a 3-mm donut target and a Type III arrangement. The stability of the maxillary and mandibular target sites was 7.1 µm and 5.1 µm, respectively, and the stability was 18.9 µm and 15.8 µm, respectively, at the maxillary second molar and mandibular second molar tracking points, which was suitable stability for clinical application.

Reflectance targets of 3-mm diameter also showed very good tracking stability when applied to the Type III array, but they are not suitable for clinical application because of the relatively large errors in the Type I or Type II array. Relative deviation of the 3-mm donut target according to arrangement method was small, and even if a Type III arrangement was used, distance between the target varied according to patient's tooth size or arch curvature. Therefore, the 3-mm donut target was considered a suitable target for mandibular movement tracking.

On the other hand, the 5-mm diameter target showed relatively low tracking stability, and the instability was too great for the size of the target as compared to the tooth size, and the anatomical shape of the teeth was masked. This may lead to instability in the process of replacing the target location information with the entire stone model data.

2. Evaluation of precision of full-mouth cumulative motion data

In this study, we used conventional FGP function wax to record cumulative motion data, and found an RMS value of about 170 µm. However, the RMS value determined using digital data was as low as 40 µm. Thus, the second null hypothesis was also rejected.

The reason for the large error in the conventional recording method using wax was that the wax tended to move slightly, depending on the movement of the study model. In order to ensure a stable position of the wax when recording cumulative motion in the conventional manner, a 3D printed template was applied on the mandible arch, onto which the wax was applied to obtain cumulative motion data. Despite this measure, the error remained large; movement in the oral environment may be ever greater due to the presence of saliva. In addition, the cumulative path data obtained through the wax may have a large error due to the presence of an empty space in the wax, if the wax is not applied carefully. However, unlike the actual FGP method, this study recorded the path of full-mouth cumulative motion, and thus the actual value obtained by applying this approach to only a small number of teeth in a clinical context may be smaller.

In the case of the digital accumulated path data, the error was as low as 40 µm, showing the possibility of clinical application. In this study, two or more data sets were obtained by modifying the mesh data recorded by the digital method using the algorithm developed here. Considering the setting of the optical scanner, which records at a constant speed, there may be empty space between the meshes. Therefore, precision could be improved by filling the meshes. However, we recorded at very high speed, at 50 frames per second, covering most mandibular movements, and smoother data were obtained; however, it did not lead to an improvement in the RMS value. Therefore, when data at a lower frame per second rate, in order to improve the processing speed, the mesh-filling process may be more useful.

In this study, tolerance was set to 50 µm. For the conventional wax technique, the tolerance was only about 30%, but that of the digital technique approached 80%, and thus the digital technique is promising.

There are few studies in which the motion of the mandible has been tracked with an optical scanner and its accuracy is evaluated, making it difficult to find comparable data. However, Pinheiro et al. reported an error of about 400 μm (Pinheiro et al. 2012) using a similar approach. Fang and Kuo et al. also reported an error of about 177 μm (Fang and Kuo 2008), while Furtado et al. reported an error of about 156 μm (Furtado et al. 2013). Solaberrieta et al. reported the accuracy of positioning a maximal cast in a virtual articulator, using digital equipment instead of a face-bow. They reported an error of 752 μm when the maxilla was placed in the articulator, and the deviation was very large at the time of the operation, with errors of up to 1.49 mm (Solaberrieta et al. 2015b). In comparison with these studies using optical scanners, this study showed relatively improved results. This is thought to be due to differences in the performance of the scanner itself and the algorithm of the software.

3. Clinical considerations and future perspectives

Occlusion is a very important part of the prosthodontic field (Zarb 2005). A new prosthesis should be in harmony with the existing occlusion and the same occlusion must be maintained before and after the new prosthesis is tried in (Mehl, Blanz, and Hickel 2005). In general, the process of fabricating the prosthesis often involves only occlusion of the MICP condition, and thus, to deliver a suitable prosthesis, it must undergo processes to eliminate interference (Fang and Kuo 2008).

Meyer et al. first proposed the concept of the FGP in 1959. This technique attempted to record the occlusal path of the patient directly using the recording material placed in the patient's mouth (Meyer 1959). Since then, FGP techniques have been used in the area of fixed prostheses, with a variety of materials and techniques, and this technique has been applied in CAD/CAM area as well to establish optimal occlusion relationship such as group function. Some researchers have attempted to use FGP techniques in restorations using CAD/CAM techniques (Fang and Kuo 2009; Röhrle et al. 2009). When using the FGP technique and the conventional manufacturing method, the crown adjustment time was 5.4 minutes with the FGP technique, which was markedly less than for the conventional manufacturing method (12.6 minutes), when a single crown was delivered. Patient satisfaction was also much higher with restorations produced using the FGP technique (Lin et al. 2017).

However, the conventional FGP technique has a disadvantage in that it is complicated to produce, and the FGP record is limited in that it can be used only for the preparation of the prosthesis. The digital cumulative motion recording technique used in this study has the advantage that it can be used continuously by recording the patient's occlusion record and can be used to check whether the motion has remained unchanged after delivering the prosthesis.

The optical scanner used in this study is a low-resolution optical scanner with an 800 × 600 resolution scanner, with real-time recording of mandibular movement in mind. However, in future, if high-end computers can be easily accessed due to the development of computer equipment and graphic card, high-resolution optical scanners can be used and more accurate tracking of mandibular movement will be possible.

In addition, the target-tracking system used in this study can be used to record the patient's opening and closing motion, so that the patient's actual access pathway can be used to construct prostheses, such as occlusal splints, or those that require change in the vertical dimension.

Since the CBCT data can be superimposed, the actual motion path of the TMJ can be recorded as well. This can be used to set parameters at the time of manufacturing the prosthesis, or can be used for the diagnosis and treatment of TMJ disease patient.

In future clinical studies, it will be possible to evaluate accuracy in actual patients and to improve the utilization of the target-tracking system through evaluating the usefulness of this approach for prosthesis manufacturing.

V. CONCLUSIONS

Within the limitations of this study, the following conclusions were made. For the optical scanner and target-tracking system used in this study, the donut-shaped target with a diameter of 3 mm was the most stable in tracking, and the tracking stability was the highest when the target was arranged wide to the canine.

In addition, the digital method using the target-tracking system had better predictive value than the conventional technique using wax for the generation of cumulative motion data. Mandibular movements were highly reproducible, even if no additional mesh correction processes were used when the optical scanner recorded at 50 frames per second.

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Abstract (Korean)

광학스캐너와 타겟 추적 시스템을 이용한 디지털 치과 모델의 3차원 운동 추적 정확도 평가

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(지도교수 : 심준성)

본 연구는 광학스캐너와 전치부 순면에 부착된 타겟을 이용하여 상,하악 악궁운동의 추적 정확도를 평가하고 추적의 최적조건을 찾기 위한 *in vitro* 연구이다. 본 연구의 귀무가설은, 1. 타겟의 종류나 크기, 배열방식에 따른 추적안정성의 차이는 없다, 2. 왁스를 사용한 전통적인 누적경로 기록방식과 디지털로 누적경로를 기록하는 방식, 그리고 디지털 데이터에

존재하는 메쉬의 빈공간을 메우는 과정으로 생성된 데이터들 사이에 정확도의 차이가 없다 이다.

본 연구에서는 악궁운동의 추적을 위하여 구조광 3 차원 스캐너와 전치부 치아에 부착된 타겟 재료가 사용되었다. 3종류의 타겟과 3가지 방식의 타겟 배열에 따라 총 9 개의 그룹이 구성되었다. 구강 외 템플릿을 사용하여 타겟의 배열을 최대한 넓게 배열해 주어 얻은 추적안정성 데이터를 컨트롤 그룹 데이터로 하였다. 왁스를 사용하는 전통적 방식 누적경로 데이터를 얻었으며, 구조광 3 차원 스캐너와 타겟 트래킹 시스템을 이용한 디지털 방식의 전악 누적경로 데이터를 취득하였다. RMS 값과 +AVG, −AVG 값 및 공차 데이터를 역설계소프트웨어를 사용하여 계산하였다.

상악전치부 타겟 부위에서의 추적안정성은 3mm 직경의 도넛형태 타겟이 가장 높게 나타났다. 그 중에서도 Type III 배열이 가장 높은 안정성을 보였으며, 7.1um 정도의 안정성을 보여 7.4um 값을 나타낸 대조군과 유의한 차이를 보이지 않았다. 하악전치부 타겟 부위 및 상악, 하악 구치부의 추적포인트에서도 3mm 도넛타겟−Type III 배열의 조합이 가장 안정적 이었고, 대조군과 비교하여 유사한 결과를 나타내었다. 전통적 방식의 누적경로데이터는 170.3um 의 높은 RMS 값을 보였다. 50um 이하로 설정한 공차의 경우에서도 34.9% 정도만이 만족하는 것을 확인할 수 있었다.

디지털로 취득한 누적경로 데이터에서는 42.4um 정도의 RMS 값을 얻었다. 메쉬의 빈공간을 데이터 처리를 통해 1 회 채워준 경우에는 42.0um 의 값을 나타냈으며, 해당 과정을 1 회 더 시행한 경우에서는 41.8um 정도의 RMS 값을 나타내었다.

본 연구의 결과를 기초로 하여, 3mm 직경의 도넛 타겟이 가장 추적안정성이 높음을 확인하였으며, 타겟을 견치까지 배열한 Type III 배열에서 가장 추적안정성이 높은 것을 확인하였다. 또한, 전통적인 누적경로 취득 방식에 비하여, 광학스캐너와 타깃래킹시스템을 활용한 디지털 방식의 누적경로 취득 방식이 더욱 재현성이 높음을 알 수 있었다. 1 초에 50 프레임의 데이터를 취득하는 경우에는 알고리즘을 통하여 메쉬의 빈공간을 채우는 처리작업이 없어도 운동궤적을 안정적으로 취득할 수 있음을 알 수 있었다.

핵심되는 말: 광학스캐너; 타겟추적; 누적경로; 하악운동; 캐드캠; 교합기능운동로;