Repeatability comparison of conventional mounting technique using facebow and virtual mounting technique based on cone beam computed tomography

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Repeatability comparison of conventional mounting technique using facebow and virtual mounting technique based on cone beam computed tomography

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2020년 12월 김수진 올림

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ABSTRACT

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Su-Jin Kim, D.D.S.

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The introduction of digital technology in dentistry has led to the shifting of conventional methods to digital techniques. However, it is challenging to place a digitized dental model to a virtual articulator. To transfer the patient's location information to the virtual articulator, conventional mounting must be performed to the real patient using an anatomic facebow then scan it with a tabletop scanner and transfer it to the virtual articulator. But this process is complicated and inconvenient. Several techniques are available to resolve such problems, yet, they are not definite methods, and digitized dental models are often placed arbitrarily on a virtual articulator.

If cone beam computed tomography (CBCT)'s field of view is broad, the location information of the head and neck structures can be obtained. Therefore, this study presents the virtual mounting technique (VM) using virtual facebow based on CBCT and the

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conventional mounting technique (CM) using anatomic facebow and compare the repeatability precision of those two techniques. The null hypothesis of this study is there is no difference between the CBCT based VM and the anatomic facebow based CM.

The experimental group was divided into CM and VM group. A reference articulator was fabricated by scanning a semi-adjustable articulator (Hanau Modular Articulator System, Whip Mix Corp., Louisville, KY, USA) using an industrial scanner (C500, Solutionix, Seoul, Korea). For the CM group, the conventional mounting was performed using an anatomic facebow (Indirect Spring Bow, Waterpick, Buffalo, NY, USA), the articulator was scanned with an industrial scanner and located to the same position as the reference articulator. For the VM group, the CBCT (ASAHI Alphard 3030® Belmont Takara., Kyoto, Japan) image was converted to skull standard tessellation language (STL) format on cad software (Exocad cad software, ExocadGmbH, Darmstadt, Germany), then the skull was placed to the reference articulator by using a virtual facebow scanned with an industrial scanner. For both CM and VM, each of the representative model was placed on the reference articulator by using superimposed medium (CM-mounted cast, VM-skull), target points were set for #11, 16, 26 teeth in reverse engineering software (Geomagic Control X, OR3D Ltd., Chirk, UK), and the X, Y, Z coordinate values were obtained in the three-dimensional spatial coordinates.

To analyze the difference between CM and VM, comparative analysis was performed on the four aspects: average distance between the target points, standard deviation of target points for each axis, the spatial relationship between each technique for the X, Y, Z-axis of

tooth #11, and angle of the occlusal plane. A Kolmogorov-Smirnov test was performed to determine normality and paired t-test was conducted if variables followed a normal distribution, otherwise, a Wilcoxon signed-rank test was conducted.

The average distance between the predetermined target points was significantly greater in CM compared with the VM ($P<0.01$). Also, in CM, the standard deviation between the target points was more than VM ($P<0.05$). Especially, Z-axis (upward and downward) in CM showed a tendency for high standard deviation compared to other axes. In terms of tooth #11, VM was located more forward than CM ($P<0.01$), and there was a tendency of CM to be positioned higher than VM in one out of five repetitions (20%, $P<0.05$). The angle of the occlusal plane was significantly steeper in CM ($P<0.001$).

Based on the results of four analysis methods, VM shows higher precision than CM in terms of the average distance and the standard deviation. The cast mounted with VM positioned ahead of the cast mounted with CM. And the angle of the occlusal plane of CM tended to be steeper than VM. Further studies are required to verify the clinical usefulness.

Key words: CBCT virtual mounting, comparison of conventional mounting and virtual mounting, digital dentistry, direct digital method, virtual articulator, virtual facebow, virtual mounting technique

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Repeatability comparison of conventional mounting technique using facebow and virtual mounting technique based on cone beam computed tomography

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1. INTRODUCTION

One of the most important components in prosthodontic treatment is how precisely dentists can reproduce patient's oral environment. The maxillary model for fabricating a prosthesis should correspond to the movements of mandibular condyle, and mounted in the same position as the actual patient, while considering aesthetic factors, such as midline, anterior occlusal plane, etc[1, 2]. A facebow is an diagnostic instrument used for registration of the spatial position of maxilla against the cranial base to the articulator using anatomic reference points (GPT-9)[3]. It can reproduce anterior-posterior position of the cast against condyle that resembles the actual patient condition, and has ability to register horizontal relationships more accurately compared with the arbitrary mounting so that occlusal plane can be reproduced in articulator similar to the actual condition[4]. Facebow transfer is an essential procedure in prosthodontic treatment[5-7] but dentists who are not used to it often encounter difficulties in the actual clinical practice; they may not handle the instrument properly or make the patient uncomfortable while positioning the earplug into the external auditory meatus, and inevitably consume more time[8]. The standard transferring procedure cannot be applied in maxillofacial deformity[9], and, there has been constant controversy over its precision[10-12].

Recent advances in digital devices such as computer-aided design and computer-aided manufacturing (CAD/CAM), and intraoral scanner is causing many changes in the dentistry field[13, 14]. The method of manufacturing the computer-aided crown was first presented in the late 80s[15], in the following year, starting with the fabrication of the chairside crown using CAD/CAM system[16] most of the existing conventional technique is being replaced by digital technique. This has changed the workload, facilitated the retention of information on the final prosthesis and reproduction of the prosthesis. To place digitized dental model to virtual articulator, perform conventional mounting using anatomic facebow, scan it to tabletop scanner and transfer it to virtual dental space (Indirect digital method), or use intraoral scanner to implement total arch scanning, and then transfer it to virtual articulator by virtual facebow technique (Direct digital method) (Figure 1)[17, 18]. To use the indirect method, the mounting process on a mechanical articulator should be preceded, which is inconvenient and complicated. Various direct methods are available to compensate for these issues, such as utilizing standardized extraoral photograph[19], 3-dimensional (3D) optical scanner[20-23], digital axiography[24], switching to 3D face scan by continuous photographing [25], stereophotogrammetry[26], cone beam computed tomography (CBCT)[27-29], cephalometric image[30, 31] etc. However, so far, there is no definite method.

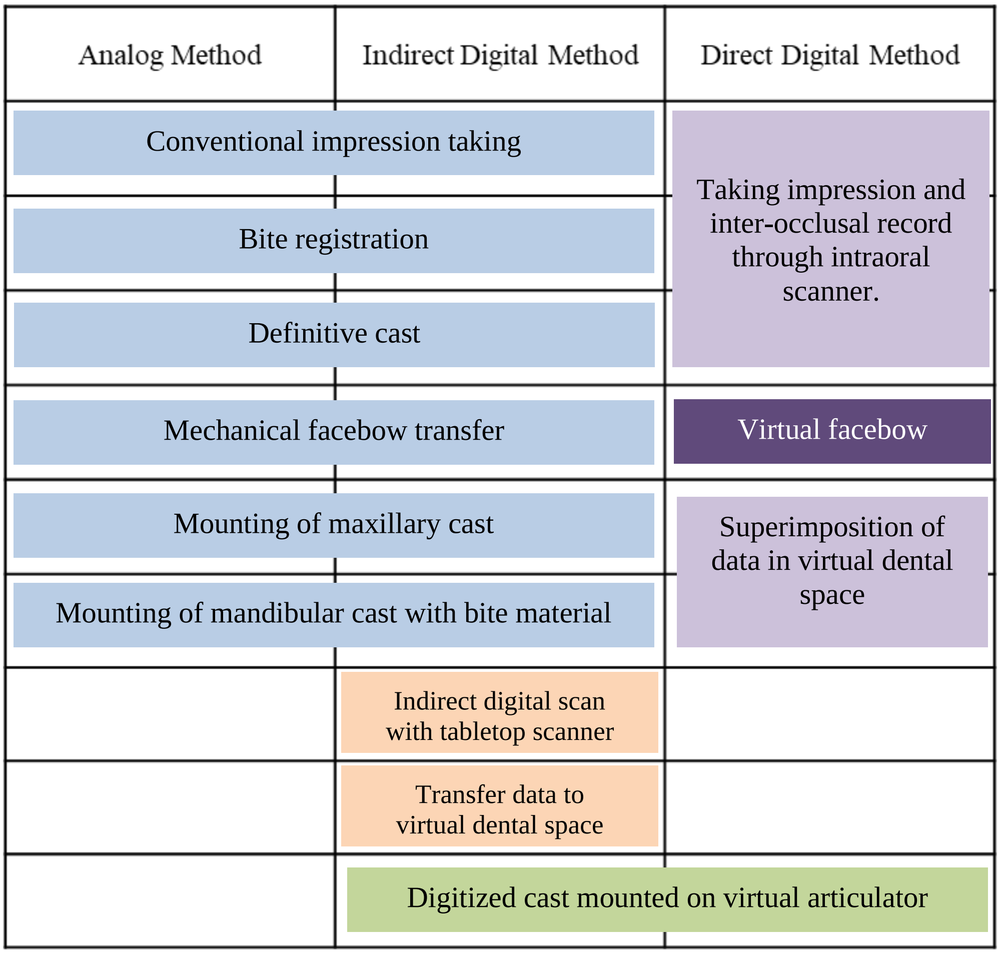

Figure 1. Schematic diagram for transferring patient information to articulator. There is no definite method for transferring the digitized dental model to virtual articulator in the process of direct digital method (dark violet).

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CBCT is a radiological tool for diagnosis and provides information on the position of maxilla against the cranial base, bilateral condyle, teeth, soft tissues, and their relationships. One drawback is that the patient is unavoidably exposed to radiation during CBCT imaging, however, it can be used as a medium for transferring the digitized dental model to the virtual articulator because it can identify the relationship between anatomical structures existing in the maxillofacial area in a single shot. Due to these features, a virtual patient was reproduced by overlapping CBCT images and stereophotogrammetric images obtained by an intraoral and facial scanner[32], a virtual facebow transfer technique using CBCT which set up the Bergstorm point as an arbitrary posterior reference point had presented[29].

If CBCT's field of view of is broad, the location information of head and neck anatomical structures can be obtained. Therefore, the purpose of this study is to present a digital facebow transfer technique based on CBCT and resolve any inconveniences occurring during the transfer of the existing digitized dental model onto virtual dental space. Also, the study aimed to evaluate the usefulness of the virtual mounting technique (VM) in real clinical practice by performing comparative analysis on the repeatability of the conventional mounting technique (CM) using anatomic facebow and virtual mounting technique using CBCT based virtual facebow along with the difference in the degree of an error. The null hypothesis of this study is there is no difference between the CBCT based VM and the anatomic facebow based CM.

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2. MATERIALS AND METHODS

Before explaining the flow of this study in detail, a simple schematic diagram is presented (Figure 2).

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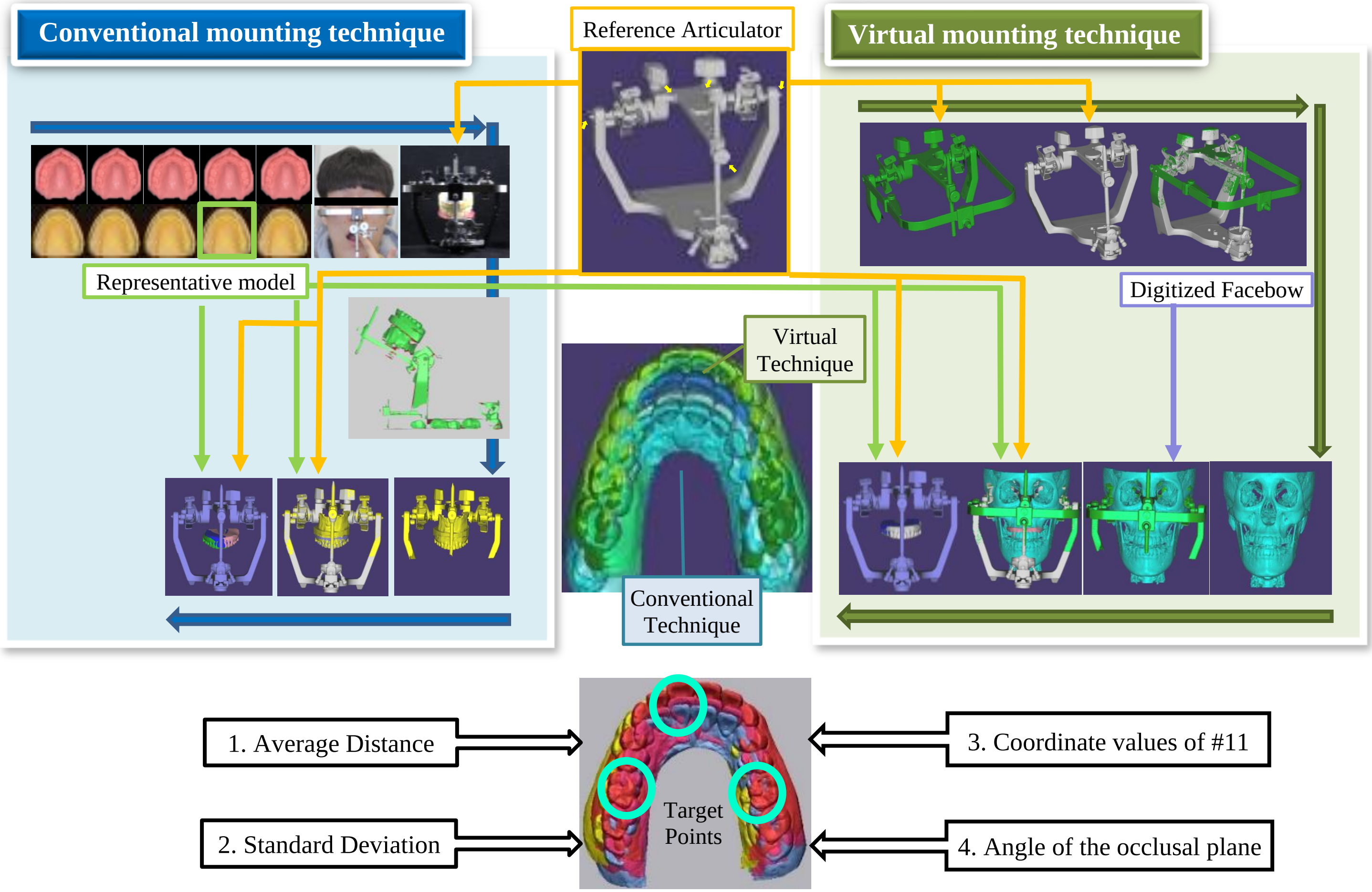

Figure 2. Schematic diagram of this study

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2.1. Selection of research subjects

The subject of the study was patients who were vulnerable and visited the Prosthodontic department of Yonsei University Dental hospital for one year after IRB registration (2-2019-0014). A total of 15 subjects were recruited based on precedent research involving human subjects, which performed a comparative analysis between conventional technique and virtual technique[33]. For patients agreeing to participate in the study, they were given an explanation of the purpose and method of the study, and written consent was prepared with the subject. The inclusion and exclusion criteria for selecting the subjects are as are listed on Table 1[34-36]. If a candidate met inclusion criteria, the person was selected as a subject of the study, and maxillary study impressions were taken five times with an alginate (Aroma fine plus normal set, GC, Tokyo, Japan). Then, five of the same model of facebow (Indirect Spring Bow, Waterpick, Buffalo, NY, USA) can be prepared, and one operator (K.S.J) performs facebow transfer five times without pause (Figure 3). The idea of repeating five times on 15 study subjects is based on the precedent research[26]. After that, CBCT (ASAHI Alphard 3030® Belmont Takara., Kyoto, Japan) was performed. P mode (exposure area of 15.4mm x 15.4mm, 0.3/voxel (mm), effective dose of 350.0±0.38 μSv,) was used for CBCT's field of view (FOV) to reproduce subject's anatomical structures including maxilla, infraorbital point, bilateral external acoustic pore (porion), and condylar components. The image is exported to digital imaging and communications in medicine (DICOM) file.

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Table 1. Inclusion and exclusion criteria for selection subjects

Inclusion criteria	Exclusion criteria
① Men and women over 19 years of age whose occlusion need to be analyzed before proceeding with prosthodontic treatment. ② Subjects with one or fewer metal prosthesis or a restoration in a quadrant that may cause scattering during CBCT imaging process. ③ Subjects with one or fewer missing tooth in a quadrant. ④ Subjects with four of fewer dental prosthesis ⑤ Subjects who signed the written consent.	① Subjects with history of temporomandibular joint disorder and jaw related surgery. ② Severe facial asymmetry or maxillofacial deformity. ③ Subjects with systemic disease who are unable to receive routine dental treatment. ④ Subjects devoid of mental capacity. ⑤ Pregnant women.

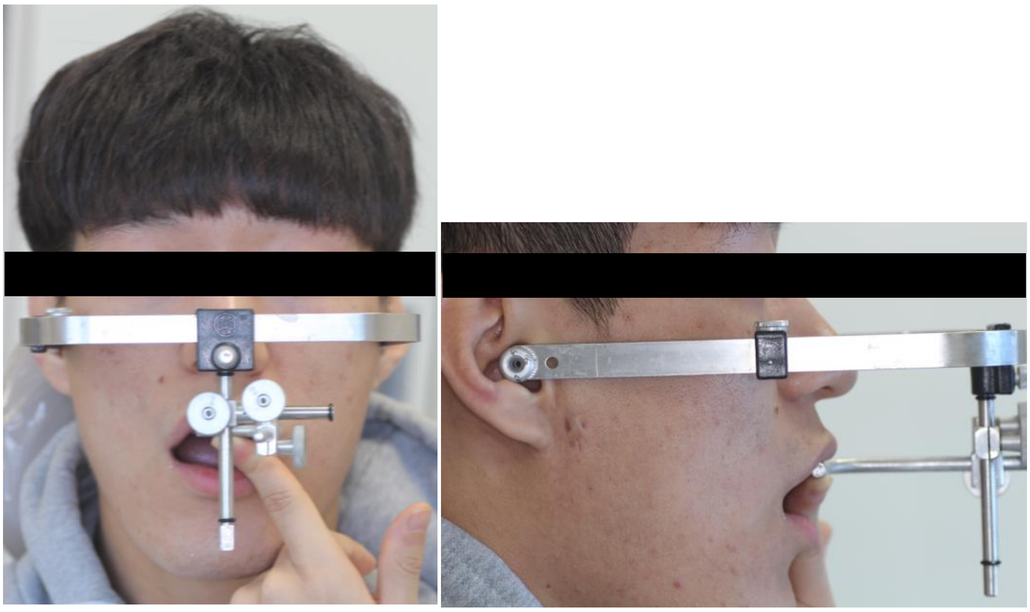

Figure 3. Facebow transfer for the conventional mounting. One operator repeats 5 times without pause using 5 identical facebows.

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2.2. Experimental design

2.2.1. Production of the Reference articulator library

Five cubic shaped resin markers (Z100, 3M ESPE, St Paul, MN, USA; size: 2mm x 2mm x 2mm) were attached on semi-adjustable articulator (Hanau Modular Articulator System, Whip Mix Corp., Louisville, KY, USA). The whole articulator was scanned with a high-resolution industrial scanner (C500, Solutionix, Seoul, Korea) that shows 10μm accuracy according to the manufacturer's manual. Calibration was performed on articulator according to the manufacturer's instructions and object holder was used to prevent unwanted movements of articulator during scanning. Also, powder spray (Dr. MAT 3D SCAN WHITE SPRAY PSCS-01, Dr. MAT, Istanbul, Turkey) was applied onto the articulator to prevent diffused reflection that can occur in articulator during the procedure. The overall quality of scanned data was checked, and it was converted into standard tessellation language (STL) format using software (ezSCAN 2017, solutionix, Seoul, Korea) to be used in CAD software (Exocad cad software, ExocadGmbH, Darmstadt, Germany) (Figure 4). The articulator STL file made as such is called a **"Reference articulator",** which will be used as a reference for all the superimpositions performed in this study.

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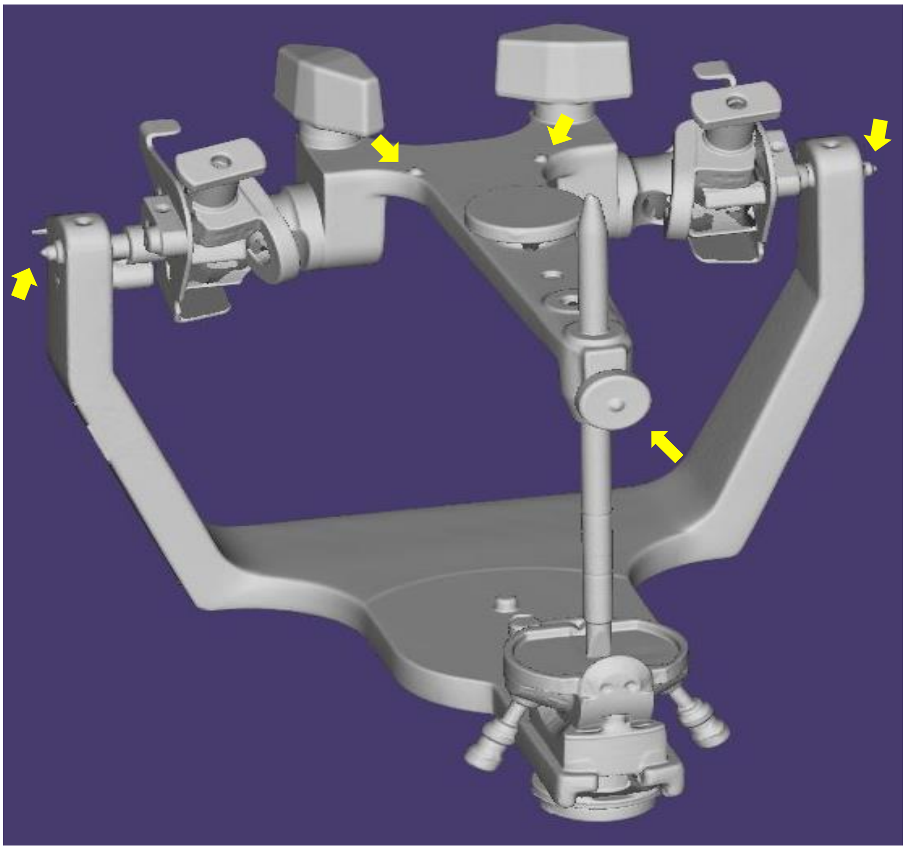

Figure 4. The Reference articulator. Resin markers were attached on the articulator to facilitate superimposition (Yellow arrows).

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2.2.2. Conventional mounting procedure

The process for collecting the CM data is as follows/

① Five study models for each study subject were fabricated by mixing type III improved dental stone (MG Hi-Koseton, Maryushi Gypsum Co.Ltd. Osaka, Japan) according to manufacturer's mixing ratio (plaster 100g/water 24cc) and by pouring it into the obtained alginate impressions. Since there is a total of 15 subjects, a total of 75 study models were prepared. One model with the least defects was selected and was converted into STL format with a tabletop scanner (Identica Blue, Medit Co., Seoul, Korea). This is called the "**Representative model**" for each subject.

② Mounting was performed on real Reference articulator by using five facebows that recorded the relationship of maxilla against the subject's cranial base. The study models fabricated in step ① were mounted by mixing type II dental plaster (Silky Gemma, SAMWOO CO., LTD, Seoul, Korea) according to the manufacturer's mixing ratio (plaster 100g/water 40cc). As there were 15 subjects, the mounting was performed a total of 75 times, five times each for a subject. At this time, the articulator was limited to only one real articulator which fabricated the Reference articulator in 2.3.1 (Figure 5).

③ 75 maxillary study models fabricated in ② mounted on an articulator were scanned with an industrial scanner C500 while replacing the mounting plate (Figure 6). Before scanning, powder spray was applied to the surface of articulator to

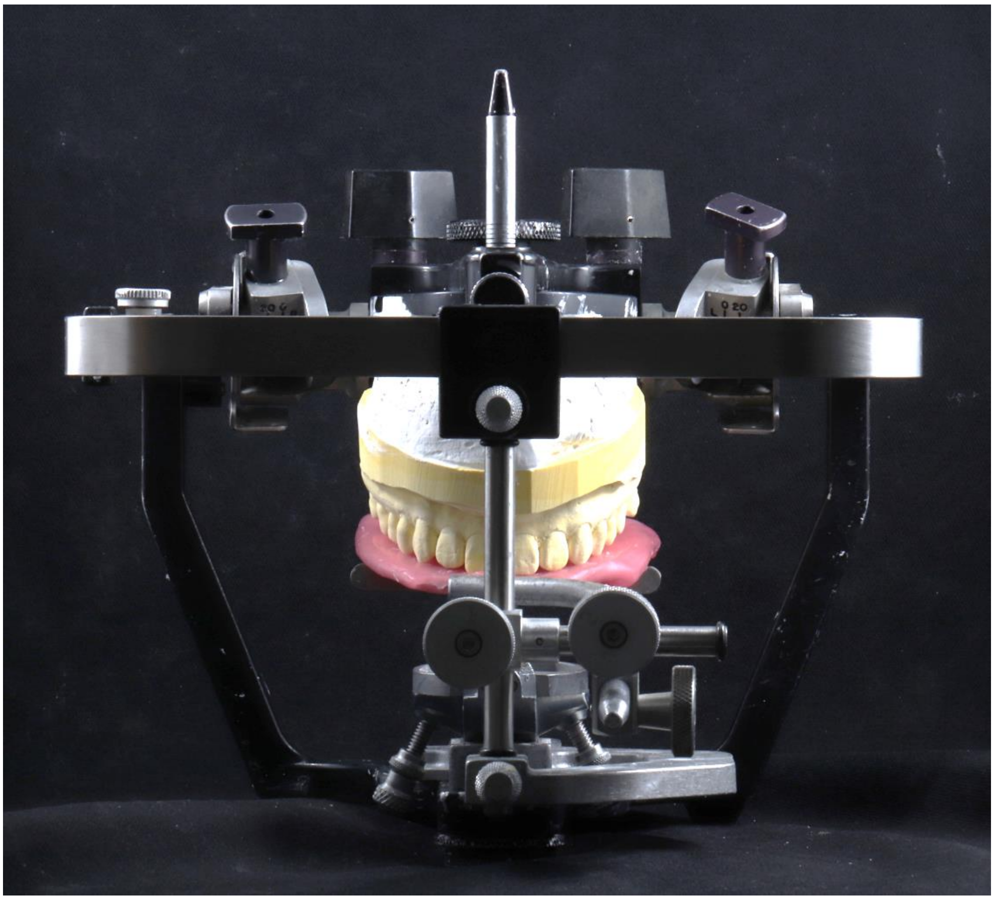

Figure 4. Conventional mounting on the Reference articulator using a mechanical facebow

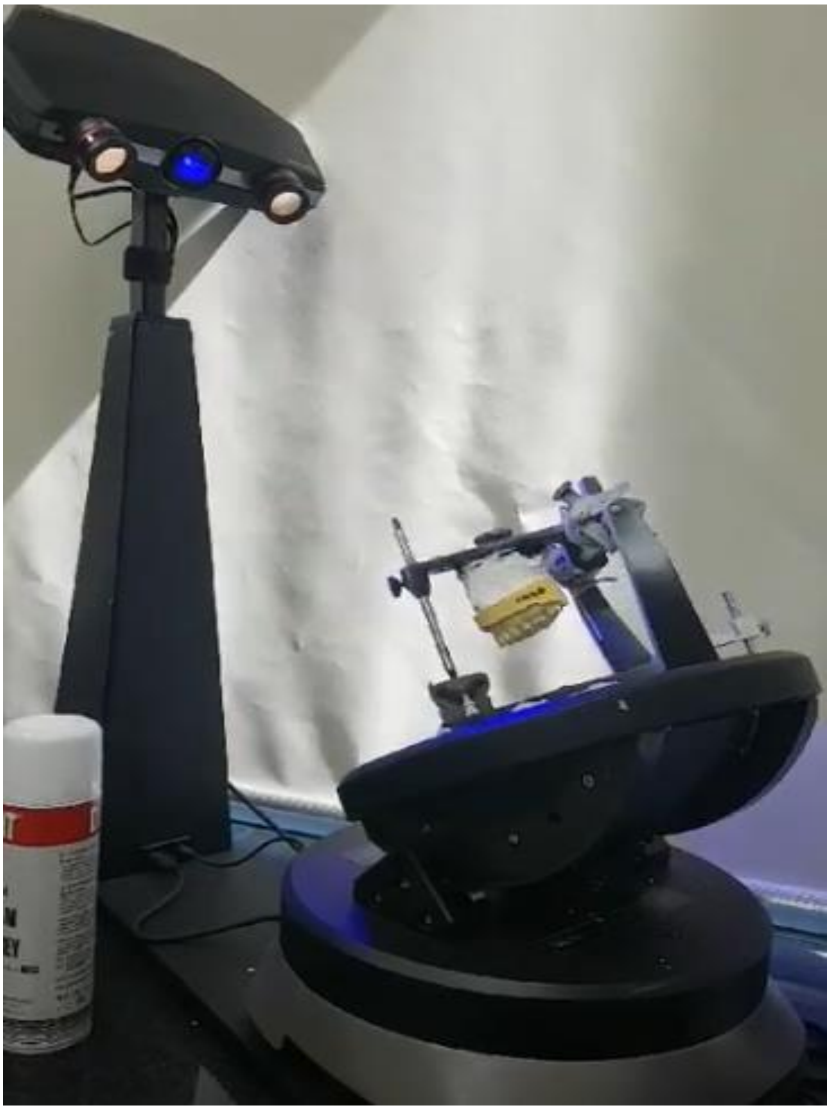

Figure 5. Scanning of conventional mounting models using the industrial scanner. Powder spray was applied to the surface of articulator to prevent diffused reflection that may occur during scanning.

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prevent diffused reflection that may occur during scanning. The file was converted into STL format with software ezSCAN 2017 to be used in Exocad software (Figure 7). These 75 STL files are called the **"Conventional mounting model**". Since Conventional mounting model will be superimposed on the Reference articulator file in the future, an attention was focused on scanning the upper part of articulator where the model is attached (Figure 8A).

④ The STL file of the Reference articulator and Conventional mounting model were imported to Exocad cad software and Conventional mounting model was superimposed over the Reference articulator file through a best-fit algorithm using a resin marker attached to the articulator (Figure 8B). If the Representative model fabricated in ① is superimposed over the maxilla of Conventional mounting model (Figure 8C), the Representative model having location information mounted on Reference articulator can be obtained (Figure 8D). This procedure was repeated five times and the data of the conventional mounting technique was prepared (Figure 8E, 8F).

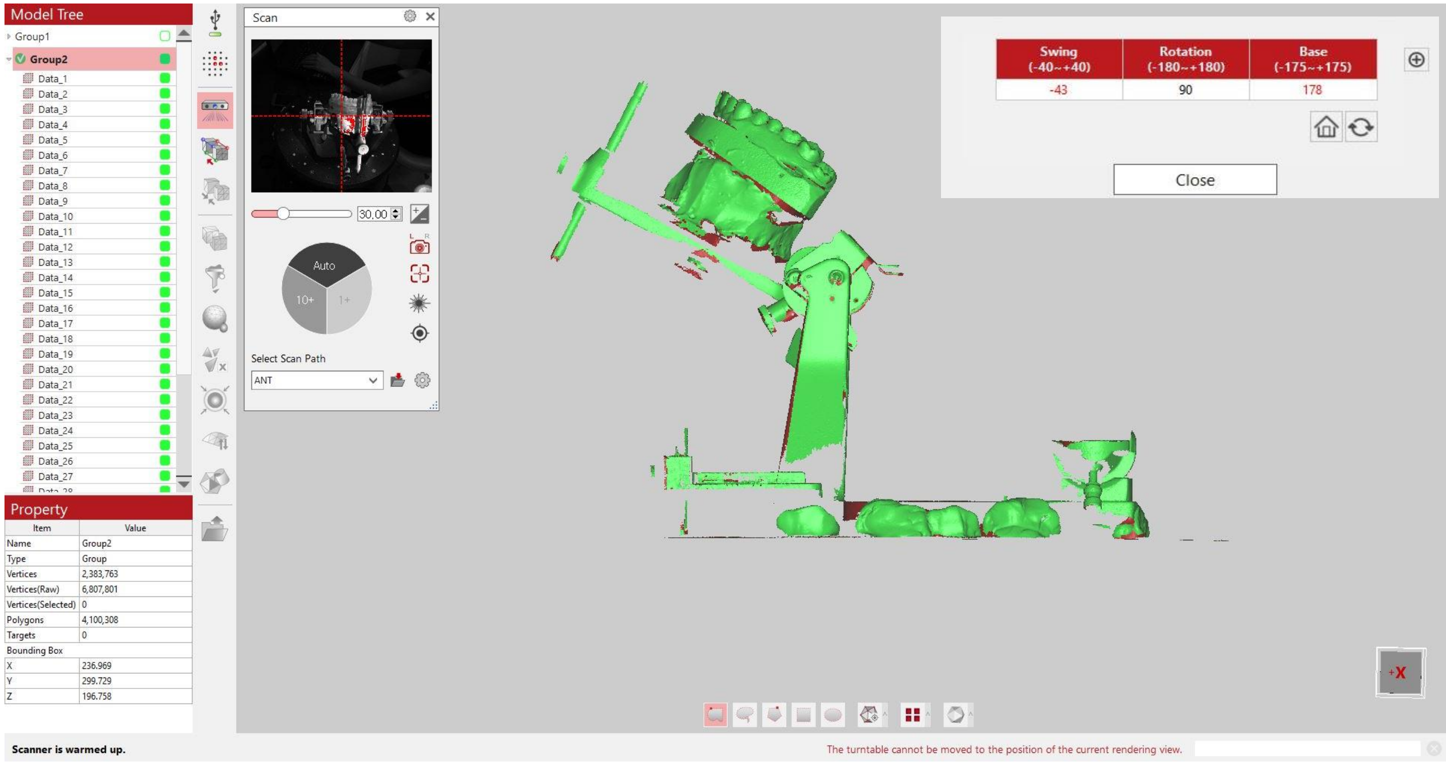

Figure 6. Scanning process using ezSCAN 2017, a software dedicated to scanning

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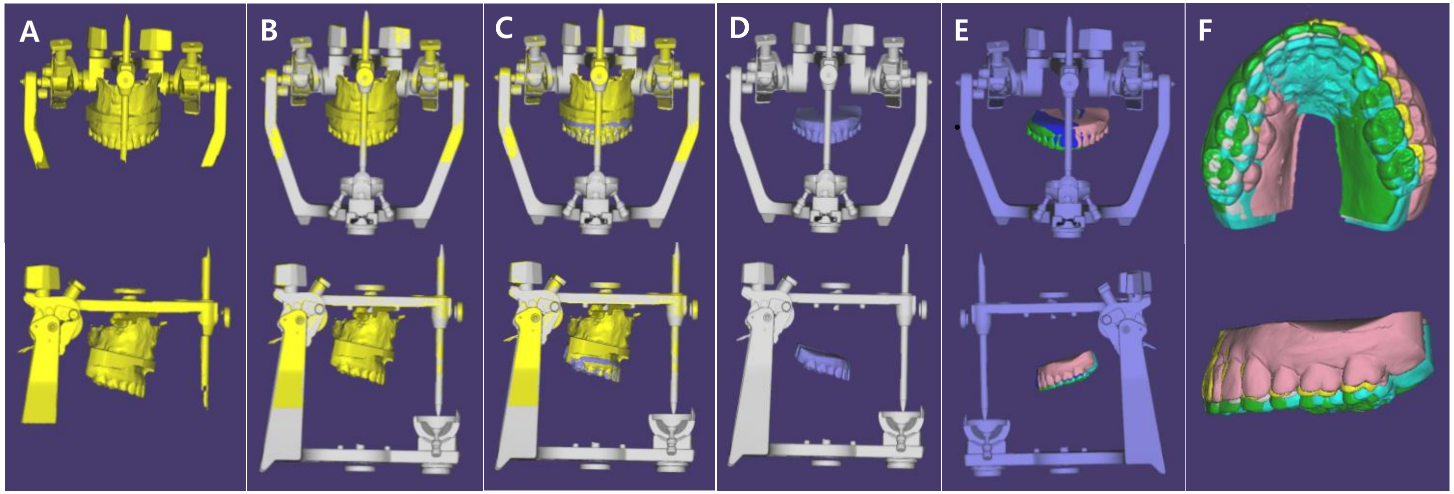

Figure 7. The process for collecting the CM data. A. Scanned Conventional mounting model. B. Superimposition of scanned conventional mounting model(yellow) to the Reference articulator(Grey) C. Superimposition of the subject’s representative model(violet) D. Mounted Representative model on the Reference articulator. E. Five identical Representative models mounted on the Reference articulator. F. Aligned STL files with the current locational information.

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2.2.3. Virtual mounting procedure

The process for collecting VM data is as follows.

① Attach the facebow to the real Reference articulator and scan the upper part of the articulator and facebow with an industrial scanner. This scan file is called "**Digitized facebow**". Import the Reference articulator and Digitized facebow file to Exocad software and superimpose the Digitized facebow over the Reference articulator using resin markers. Since all of the Conventional mounting models prepared earlier are aligned with the locational information of the Reference articulator file, the Digitized facebow is superimposed to the Reference articulator so that the locational information of the Reference articulator does not change (Figure 9).

② Import the DICOM file of CBCT on Exocad software and convert it into a 3D model through the DICOM viewer and export it to the STL file. At that time, complete the morphology of the skull by controlling the surface threshold so that one can identify both the external acoustic meatus and minimize the artifacts due to dental restorations (Figure 10A).

③ Align the skull file into Digitized facebow where the locational information is aved in the Reference articulator. As the CM procedure, place both external acoustic meatus of the skull to the earplug portion of the virtual facebow in virtual dental space. By taking the anatomic structure such as orbit, dental midline, sagittal suture, spine as a reference, midline of the virtual facebow was adjusted. After that the

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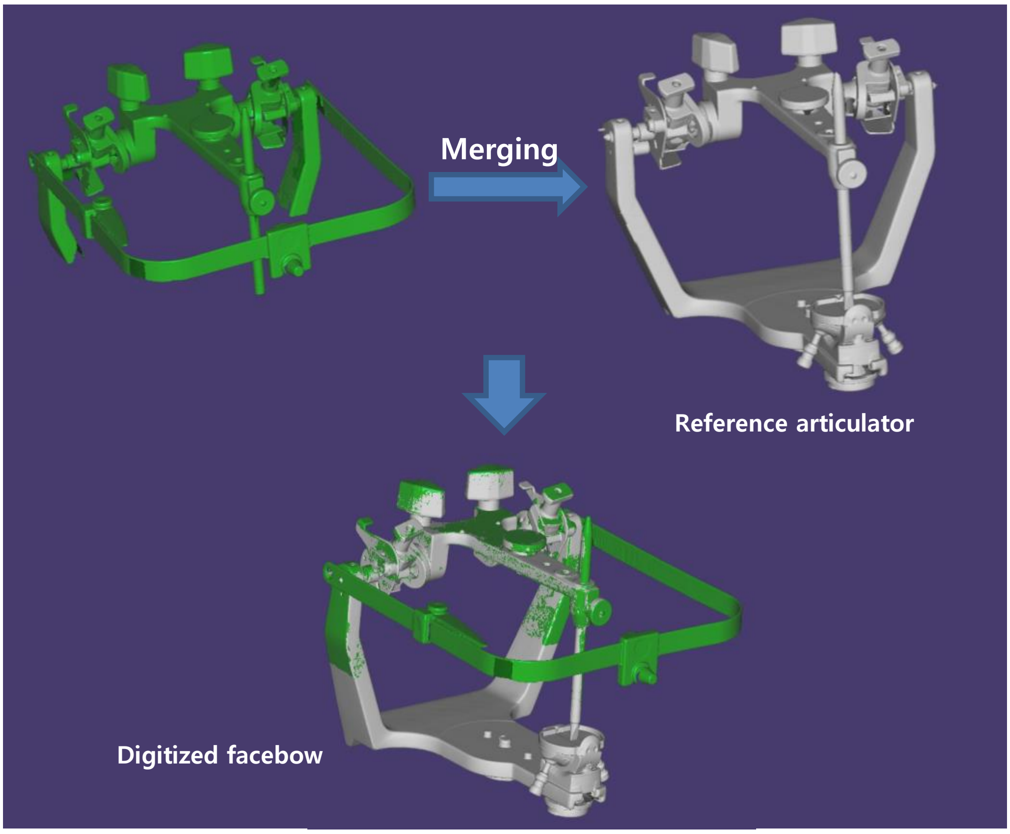

Figure 8. Digitized facebow for the virtual mounting technique. Scan the reference articulator and facebow complex, and place it to the Reference articulator file. The digitized facebow was aligned with the Reference articulator (Digitized facebow, Green).

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orbitale pointer of the virtual facebow, the third reference point, was positioned at the same level as the right infraorbital notch of the skull (Figure 10B). This process is called **“Virtual facebow transfer”** that allows acquisition of the skull containing locational information mounted on a Reference articulator in STL format (Figure 10D). After completing this process, it can be confirmed that the condylar component of the articulator exists in the same position as the condylar head of the skull.

④ Position the Representative model fabricated in 2.3.2 to the skull file (Figure 10D). This process “**Virtual mounting**”, and prepare data of virtual mounting technique by repeating the virtual facebow transfer and virtual mounting process five times for each subject (Figure 10).

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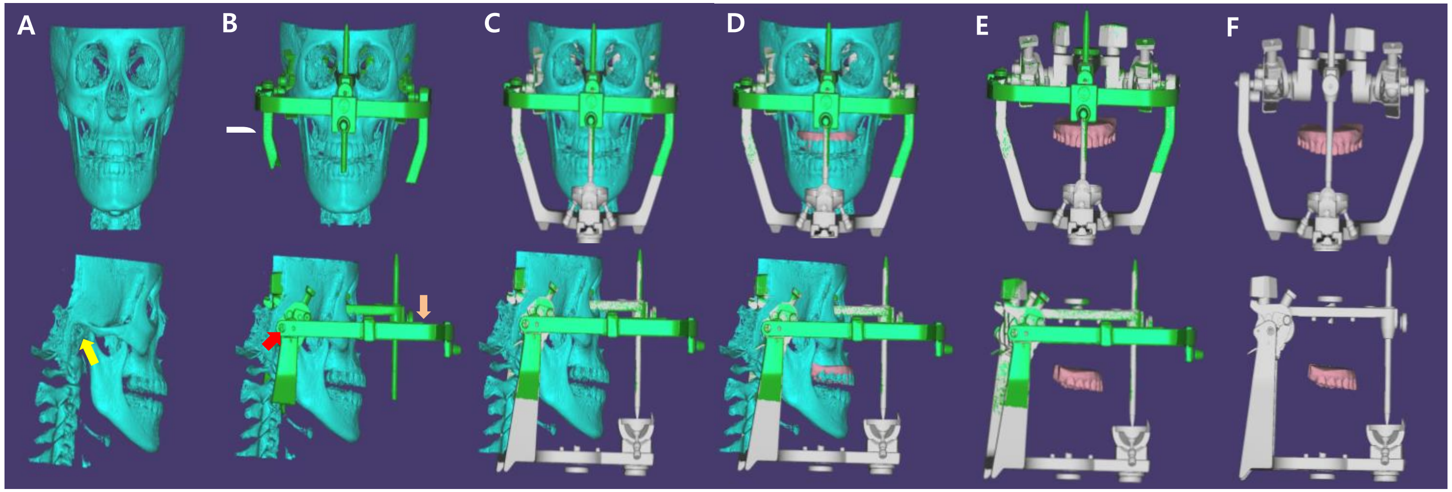

Figure 9. The process for collecting the VM data. A. Convert DICOM files to the skull STL file. Both external acoustic meatus (yellow arrow) should be clearly expressed. B. Place the skull to the Digitized facebow. Place the earplug part of facebow on both acoustic meatus of the skull (red arrow), and the orbitale pointer of facebow at the same level as the right infraorbitale of skull (orange arrow). And finally, match the dental, facial midline to the center of facebow. C. The skull is located in the Reference articulator. D, E, F. The Representative model (pink) is superimposed on the skull. The following process is the same as for the CM.

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2.2.4. Transfer to the coordinates system

Import the Representative models to reverse engineering software (Geomagic Control X, OR3D Ltd., Chirk, UK) to analyze Representative models placed via conventional mounting process (Figure 8F), and virtual mounting process (Figure 10H). Find coordinates of X, Y, Z-axis and the distance between coordinates on spatial coordinates by setting up the target points on the portion of teeth #11, 16, 26 (#11 mesial tip of incisal edge, #16 mesiobuccal cusp tip, #26 mesiobuccal cusp tip).

① Import the Representative models (Figure 8F,10H) that were repeatedly mounted (five times each for the same subject) to Geomagic Control X software (Figure 11A).

② Target mesial tip of incisal edge of tooth #11, most prominent portion of mesiobuccal cusp tip of teeth #16, #26. The same target points can be set because all five models are dentical, although their locations are different (Figure 11B).

③ Identify the coordinates within the three-dimensional space of the five target points established in each tooth and measured the distance between the points. Since the distance will be measured in pairs, there should be a total of ten distance data per a tooth (Figure 11C, 12).

④ Quantify the location information by applying the above process in teeth #11, 16, 26, and performing the CM as well as VM. The quantified coordinate values of the data were summarized in supplementary data (Supplementary table 1, 2).

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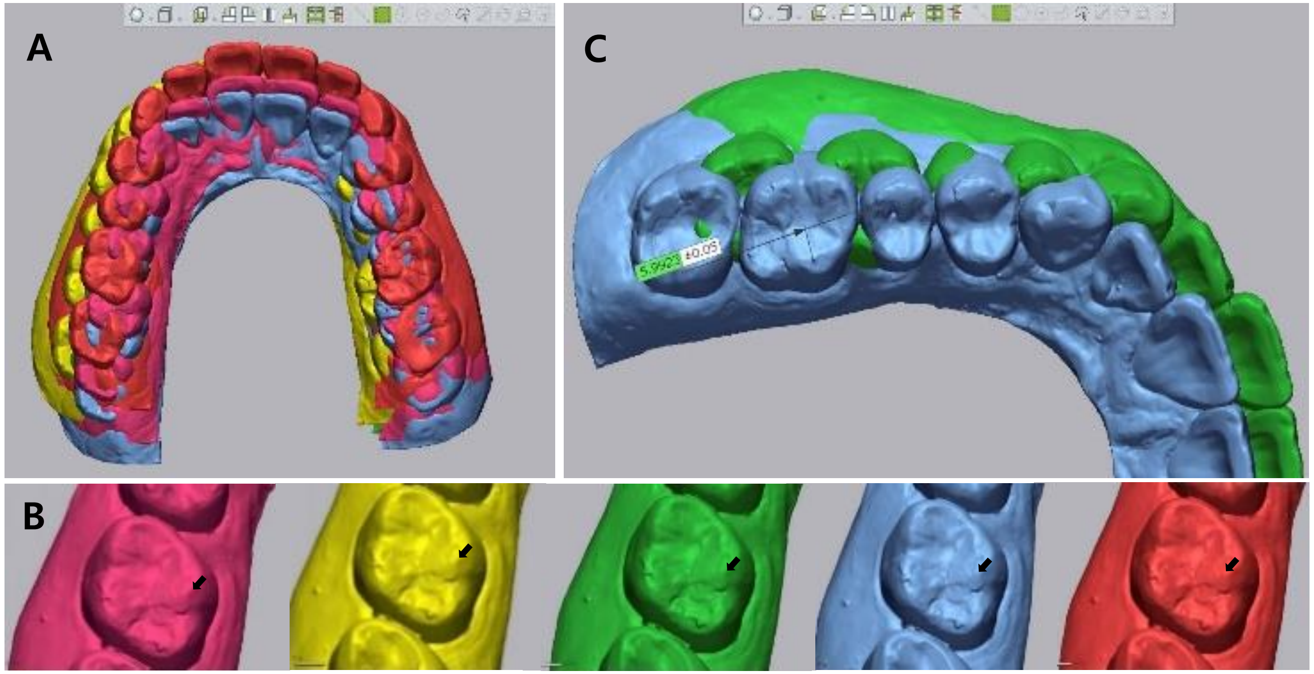

Figure 10. Selection of the target points. A. 5 identical representative models. B. Set the target points at #11, 16, 26. Since all five models are identical, the same target point with only different locational information can be selected. C. Calculate the distance between target points.

Figure 11. Finding coordinates of the target points and distance between the target points via Geomagic control X software.

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2.3. Data analysis

The data was analyzed in four ways. Firstly, the average distance between the five target points in the same tooth was estimated. Secondly, the standard deviation of X, Y, and Z coordinate of the same tooth was estimated. Thirdly, the significant difference analysis was performed for each coordinate value according to the order of trials at the target point of tooth #11. Lastly, the angle of the occlusal plane measured by linking the target point of the incisal edge of tooth #11 to the target point of the mesiobuccal cusp of tooth #16 was estimated.

2.3.1. Average distance between target points

The five target points selected in one tooth were paired up to obtain ten distance data by combination formula, and the average value was considered as the representative value. In 15 subjects, the average distance between target points for each tooth of each technique was calculated and summarized in Supplementary table 3.

2.3.2. Standard deviation of target points

The standard deviation was obtained for the X, Y and Z coordinates of the five target points for the each tooth and the results were summarized as Supplementary table 4, 5, 6.

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2.3.3. Spatial relationship between each technique

The difference between the X, Y, Z coordinates for the order of repetitions in tooth #11 was analyzed. Since the purpose was to identify the tendency of coordinates for each technique, significant differences between the order of trials was examined. Then, the coordinates value itself was used to analyze the two data according to the order in which the mounting was performed with each technique (Supplementary table 7). In other words, the difference between the X, Y, Z coordinates of the first CM and VM conducted in 15 subjects were analyzed, followed by an analysis of the coordinates between the second mounting models. The analysis took place a total of five times for each coordinate values because the analysis was performed five times per a subject.

2.3.4. Average angle of the occlusal plane

According to GPT-9, occlusal plane is defined as "The average plane established by the incisal and occlusal surfaces of the teeth. Generally, it is not a plane but represents the planar mean of the curvature of these surfaces[3]." In this study, when measuring the angle of the occlusal plane, only two variables including the incisal edge of tooth #11 and the mesiobuccal cusp tip of tooth #16 were used as in the cephalometric analysis to minimize errors caused by variables in the analysis[37, 38]. As shown in Figure 13, X-axis illustrates the lateral movements of the model. If the model moves to the right, the X coordinate value increases to the positive value, and if the model moves to the left, the X coordinate

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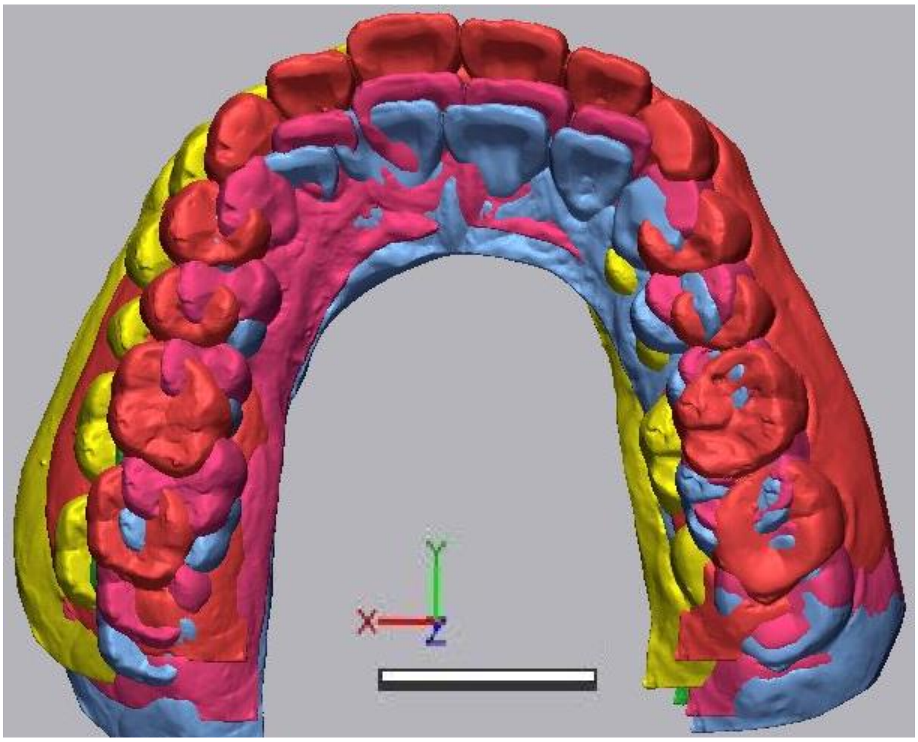

Figure 12. Mounted models in coordinate system. To find the angle of the occlusal plane, orthogonal projection was made on the YZ plane.

value increases to the negative value. Y-axis expresses the forward and backward movement of the model. If the model moves forward, the Y coordinate value increases to the positive value, and if the model moves backward, the Y coordinate value increases to the negative value. Z-axis expresses the upward and downward movement of the model. If the model moves upward, the Z coordinate value increases to the positive value, and if

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the model moves downward, the Z coordinate value increases to the negative value.

In this study, to find the angle of the occlusal plane, orthogonal projection of the target points of tooth #11 (mesial tip of incisal edge) and #16 (mesiobuccal cusp tip) on the YZ plane was obtained, and then the slope ($\Delta z/\Delta y$) created by the two points was calculated. Arctangent ($\theta = \tan^{-1}x$) was calculated to this value and the angle of a line formed by two points was obtained in radian. Finally, the angle that the occlusal plane forms with the Y-axis was attained by converting the value into degrees (Supplementary table 8). The angle formed by the horizontal plane of the reference articulator and Y-axis on virtual dental space was also considered. Dispersed five dots were marked on the top of Reference articulator, which denotes the horizontal reference plane, orthogonal projection of those dots were obtained on the YZ plane. The five dots were paired up to make ten pairs using combination formula and the slope of a line formed by the two dots was obtained. The mean value of the slope (degrees) was added (Supplementary table 9) to the angle formed by the occlusal plane and the Y-axis to obtain the angle of the occlusal plane against the horizontal plane (Angle of the occlusal plane). The slope is expressed as a negative value when the posterior part is facing upwards than the anterior part. For the convenience in interpreting the data, -1 was multiplied to all data to change their sign. Because each technique was repeated five times per subject, the average of the angle of the occlusal plane measured five times was used as a representative value for statistical analysis.

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2.4. Statistical analysis

A statistical software (SPSS v23.0, SPSS Inc, IL, USA) was used for comparative analysis of the two groups, CM and VM. The level of significance for all statistical analyses was set to be 0.05.

2.4.1. Average distance between target points

A statistical analysis was performed by setting the average of 10 distance data per tooth obtained through a combination formula in 15 subjects as representative values. The Kolmogorov-Smirnov test was performed to evaluate the normality of data. All of the data did not follow the normal distribution, the Wilcoxon signed-rank test was used to perform comparative analysis for CM and VM.

2.4.2. Standard deviation of target points

A statistical analysis was conducted for the standard deviation obtained from 15 subjects according to teeth and coordination. Kolmogorov-Smirnov test was performed to evaluate normality of data. Since X coordination in tooth #16 in the VM did not follow the normal distribution, Wilcoxon signed-rank test was performed exceptionally for X-axis of tooth #16, and paired t-test for the rest.

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2.4.3. Spatial relationship between each technique

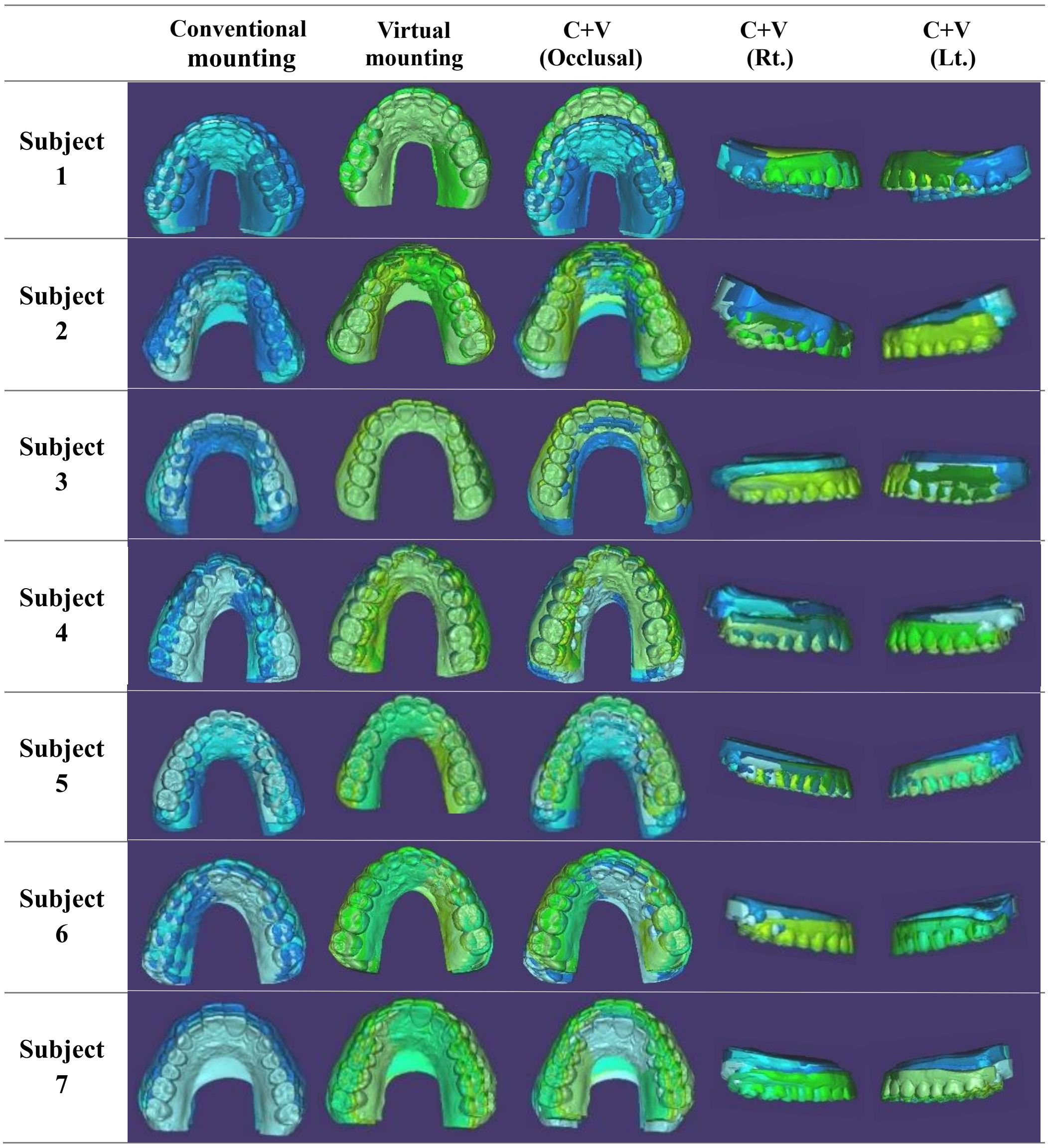
One-way RM-ANOVA was performed on each of the coordinates to find out whether there is a significant difference depending on the order of trials in tooth #11. Then, the difference between the X, Y, and Z coordinates of the CM and VM for the same number of trials was analyzed. The purpose was to identify the tendency of coordinates for each technique, therefore, instead of setting representative value, naïve data was used, and the two data was analyzed by mounting sequence. Kolmogorov-Smirnov test was performed to evaluate the normality of data. Wilcoxon signed-rank test was performed for Z coordinate of the second trial, X and Y coordinates of the third trial, X coordinates of the fourth trial, Y coordinates of the fifth trial that did not follow normality. A paired t-test was conducted for the rest of the data that followed normality.

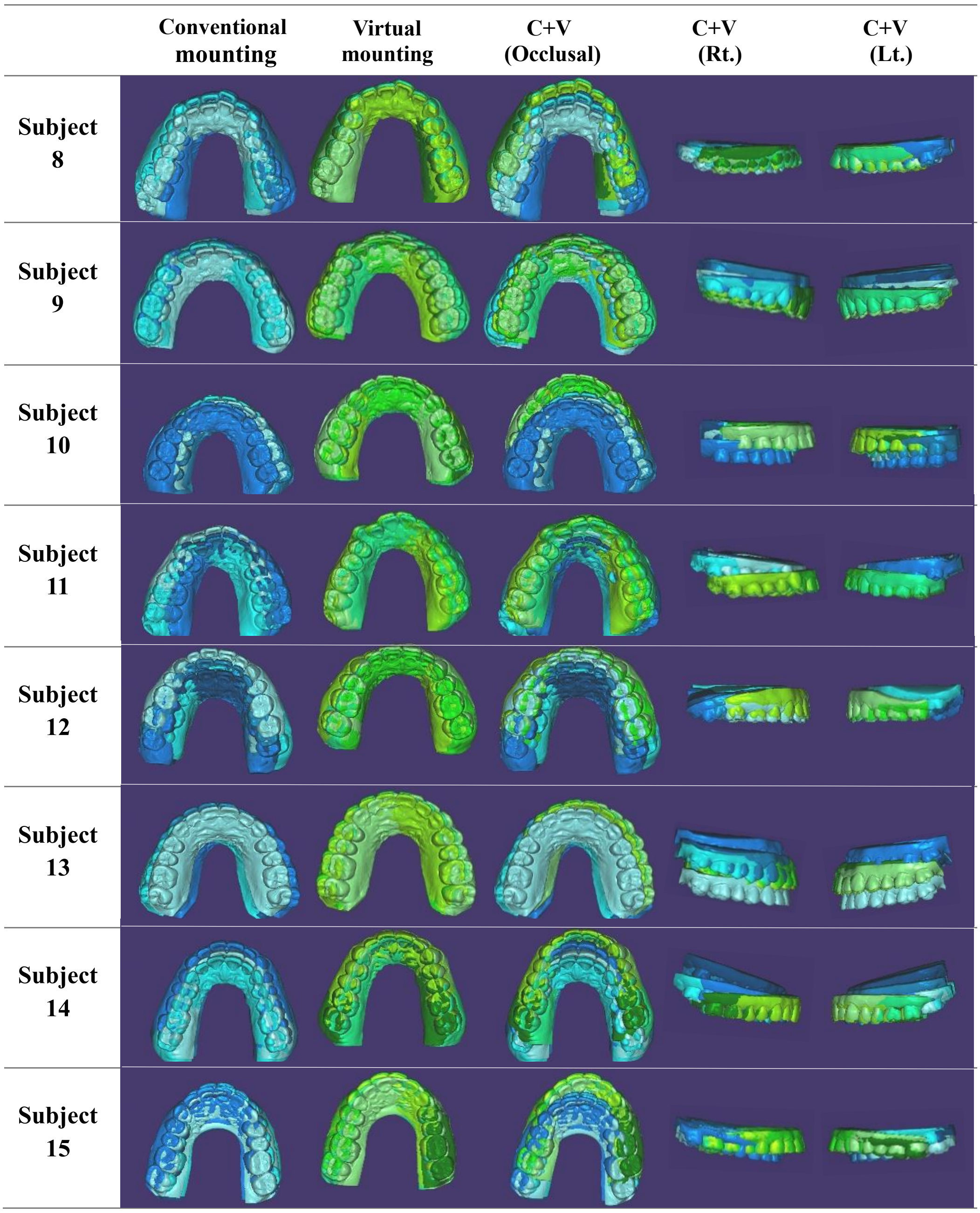
2.4.4. Average angle of the occlusal plane

A statistical analysis was performed by setting the average value of the angle of the occlusal plane measured five times per person in 15 subjects as representative value. According to the result of the Kolmogorov-Smirnov test, both the CM and VM followed the normality. Therefore, paired t-test was conducted.

3. RESULT

The result of CM and VM are as follows (Figure 14).





C: conventional mounting, V: virtual mounting

Figure 14. Positional relationships between mounted models with CM and VM

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3.1. Average distance between target points

The mean distance between the two points measured in teeth #11, 16, and 26 was smaller in VM than CM, and these values were statistically significantly different between the two techniques in all the teeth #11, 16 and 26 (Table 2). Besides, the displacement between the maximum and minimum values was more in the CM than the VM (Figure 15). Suppose the mounting is repeated with each technique; the distance between the target points is closer in the VM than that of the CM, which signifies that the target points are present within the smaller radius. That is, the VM may have higher precision than the CM. The degree of errors that occurred in each mounting technique is shown in Figure 14. All the mounting cases performed using the CM had more errors within the group compared with the mounting cases performed with the VM. Among subjects in the CM, subject number 4 and 12 particularly showed more errors. In the case of subject number 9 and 13, the degree of error between the two techniques was comparable.

The Bland-Altman plot shows the range of deviations of the average distance of the target point in both CM and VM[39, 40] (Figure 16). The mean value of difference between average distance of teeth #11, 16, 26 are 2.58, 2.81, 2.77, respectively, and the data of the CM does not correspond with the data of the VM. The mean distance of the CM tends to be systemically larger than that of VM. Also, all three data showed an ascending diagonal graph, which signifies that there is a strong correlation between the mean value and measured difference value.

Table 2. Precision of the each technique (Average distance)

	Mean ± SD	
	Conventional mounting	Virtual mounting
#11	4.7239 ± 1.4461	2.1401 ± 0.5813
#16	5.1653 ± 1.5397	2.3521 ± 0.6044
#26	4.9636 ± 1.5543	2.1887 ± 0.5484

SD, standard deviation

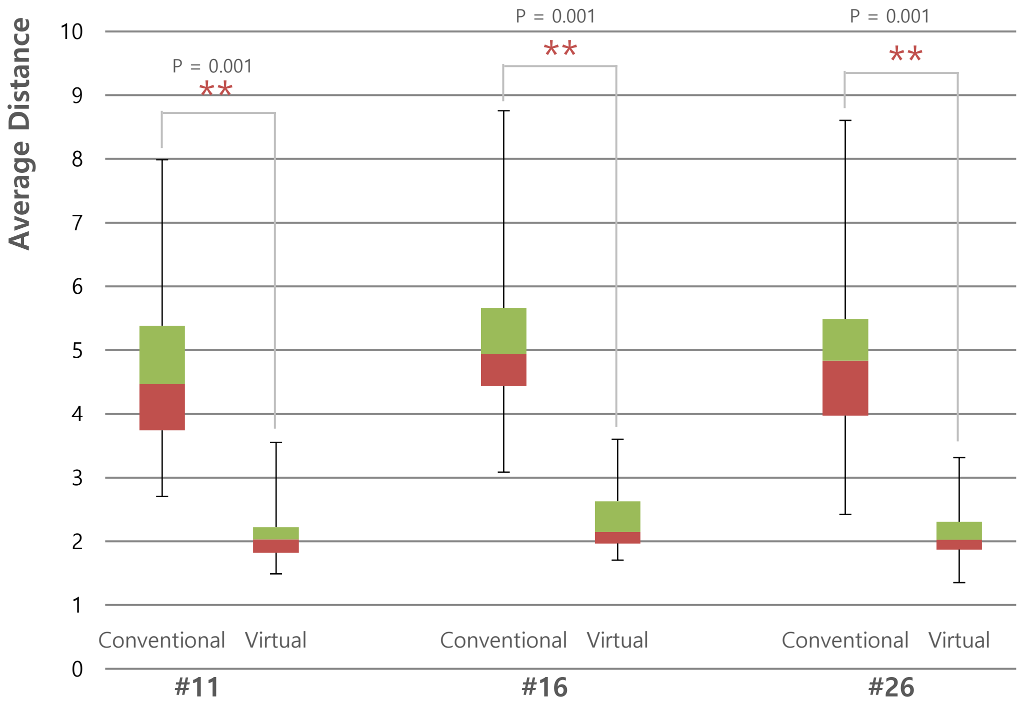

Figure 13. Box-plot table for the average distance of the target points. Comparison among groups is expressed as **P < 0.01, asterisks and horizontal bars indicate statistically significant differences among groups.

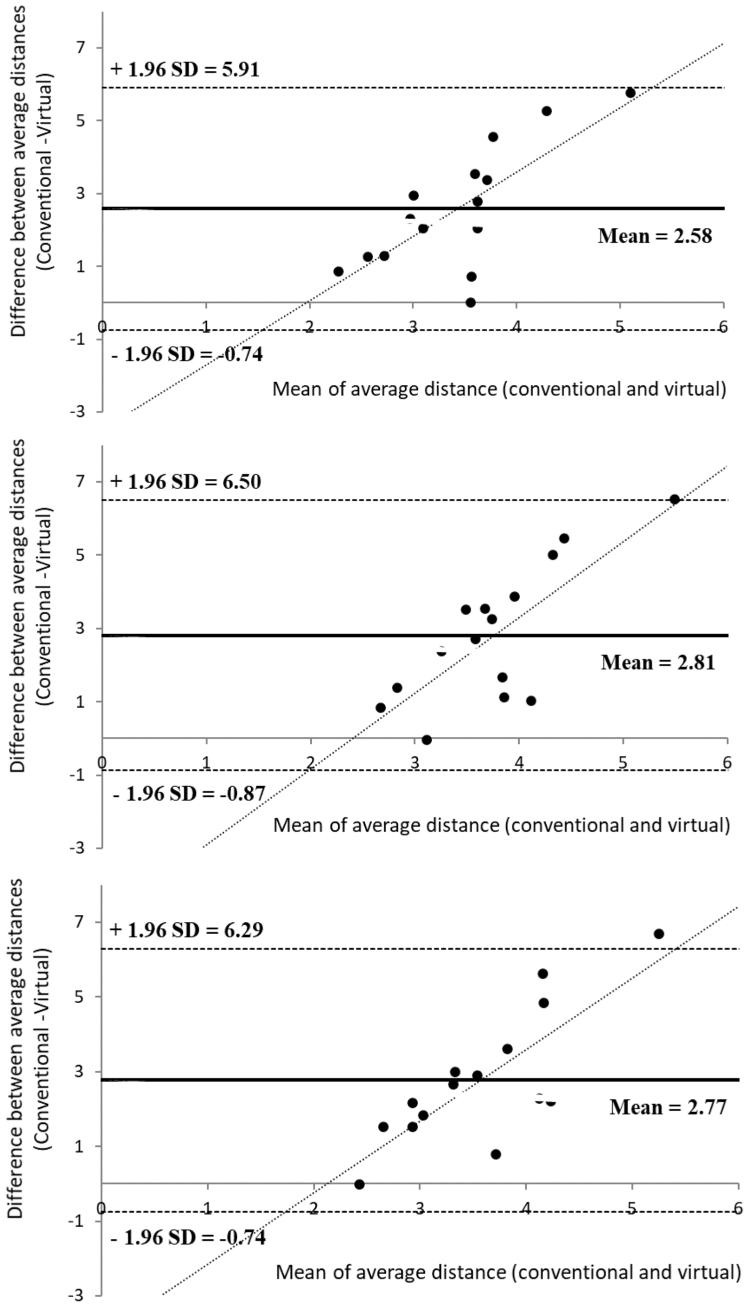

Figure 14. Bland-Altman plot for the average distance. SD, standard deviation

3.2. Standard deviation of target points

The standard deviation between the target points specified in teeth #11, 16, 26 showed greater values for the case of CM than the VM, all values showed statistically significant differences (Table 3, Figure 17). When each technique was repeated, each target point was more densely located for VM, implying that fewer spatial errors occur with the VM. In other words, along with the results of experiment number 1 (Average distance), it can be concluded that the VM has higher precision than the CM. In addition, while VM did not show tendency according to X, Y, Z-axis, the CM showed a huge displacement between the maximum and minimum values of the Z-axis standard deviation (Figure 17). This means that CM lacks upward and downward repeatability than anteroposterior and lateral errors.

Table 3. Precision of each technique (Standard deviation)

		Mean ± SD		
		SD of X Coordinate	SD of Y coordinate	SD of Z coordinate
#11	Conventional	1.5951 ± 0.6368	2.1568 ± 0.7458	2.0562 ± 1.3497
	Virtual	1.0690 ± 0.4705	0.7952 ± 0.2868	0.8021 ± 0.2695
#16	Conventional	1.8095 ± 0.6770	2.3042 ± 0.8684	2.1641 ± 1.6198
	Virtual	1.1170 ± 0.4517	0.9923 ± 0.3956	0.8085 ± 0.2760
#26	Conventional	1.8227 ± 0.7086	2.0559 ± 0.0815	2.1984 ± 1.5970
	Virtual	1.1225 ± 0.4536	0.8434 ± 0.3283	0.7420 ± 0.2275

SD, standard deviation

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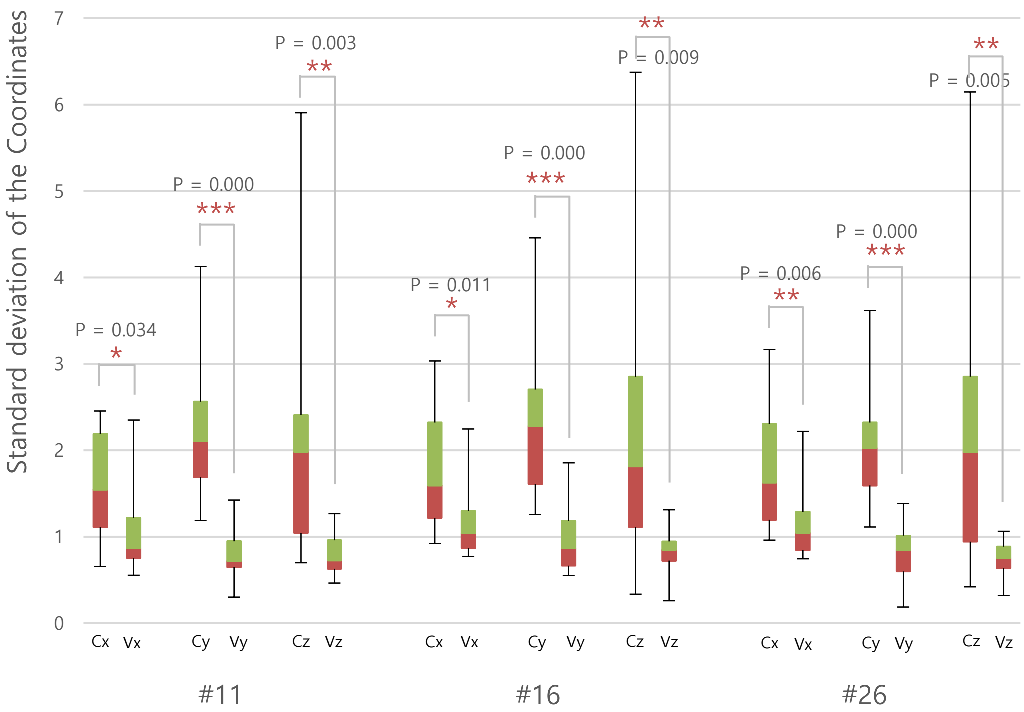

Figure 17. Box-plot table for the standard deviation. Comparison among groups is expressed as *P < 0.05, **P < 0.01, ***P < 0.001, asterisks and horizontal bars indicate statistically significant differences among groups. C, conventional mounting; V, virtual mounting

Bland-Altman plot depicts the range of deviations of the standard deviation of X, Y, Z-axis of the CM and VM (Figure 18-20). Since all X, Y, Z-axis of teeth #11, 16, 26 have positive mean values, the standard deviation of the CM is systemically big, and the data between the two groups does not coincide. However, the difference between the two measurements show a specific tendency to increase in a positive direction.

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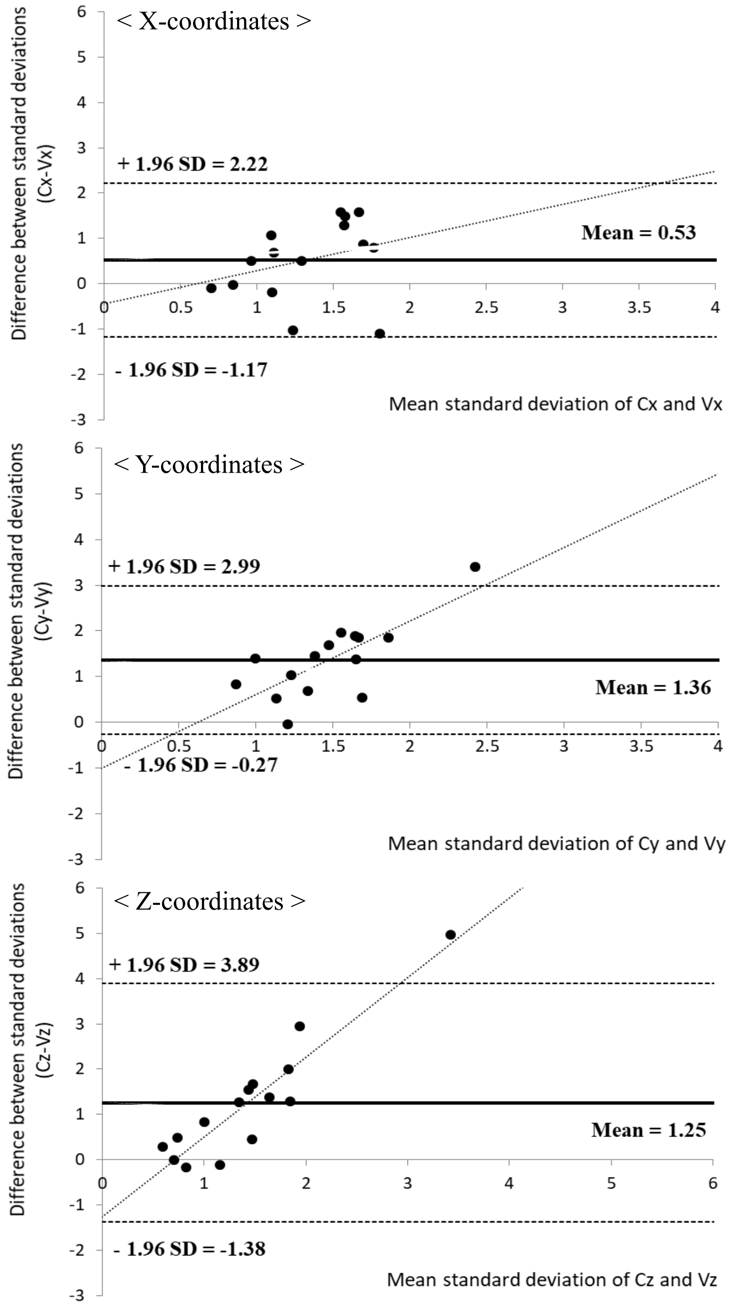

Figure 15. Bland-Altman plot for the standard deviation of #11. SD, standard deviation

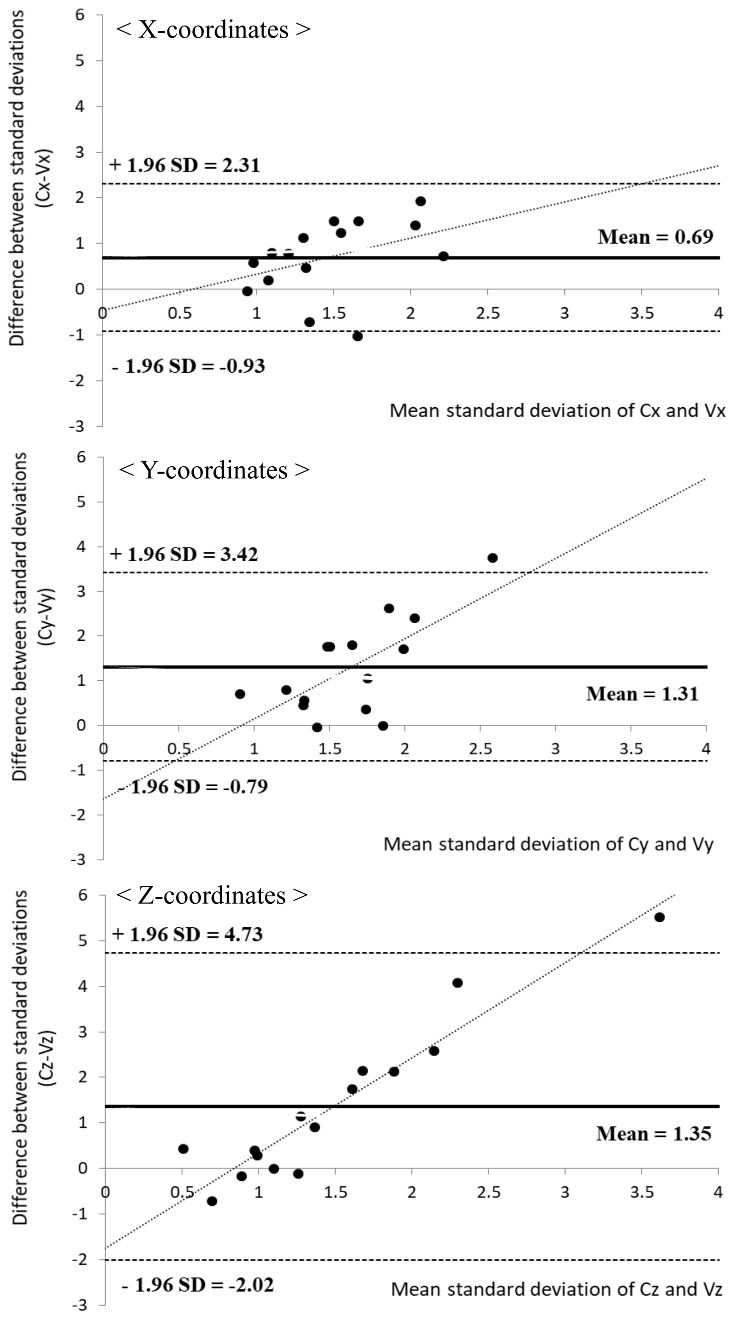

Figure 16. Bland-Altman plot for the standard deviation of #16. SD, standard deviation

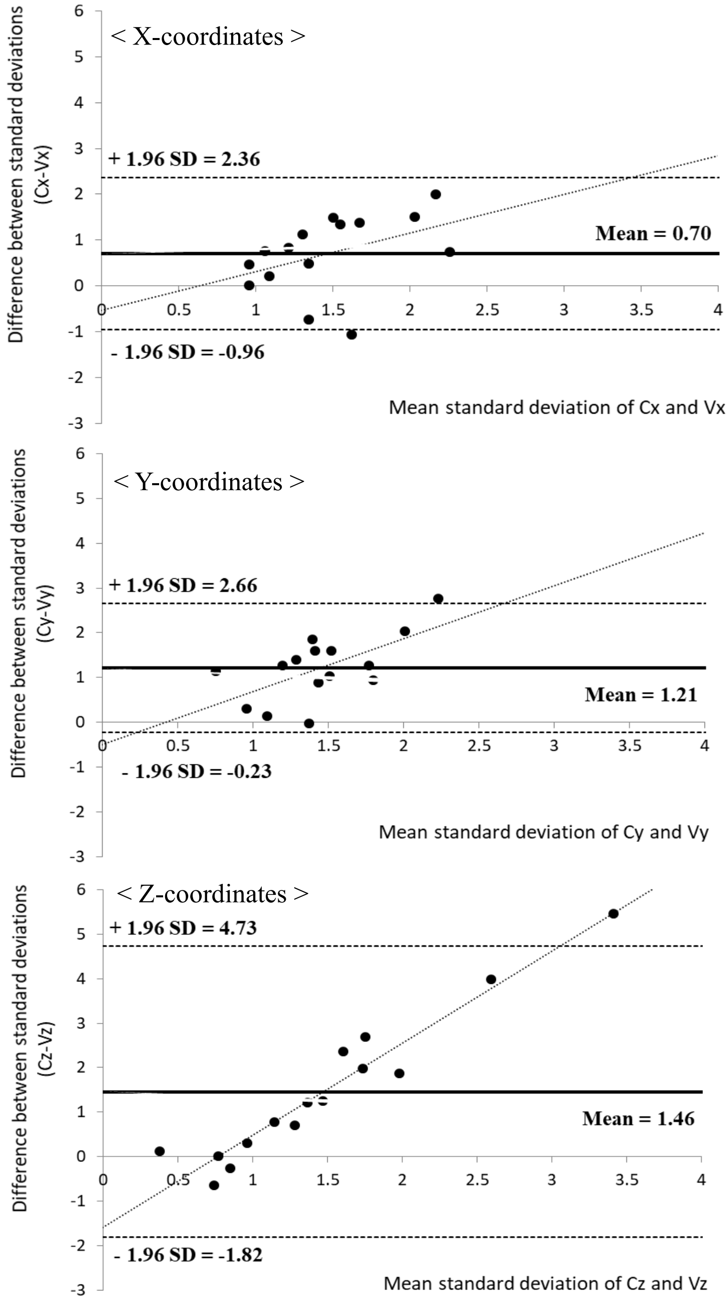

Figure 17. Bland-Altman plot for the standard deviation of #26. SD, standard deviation

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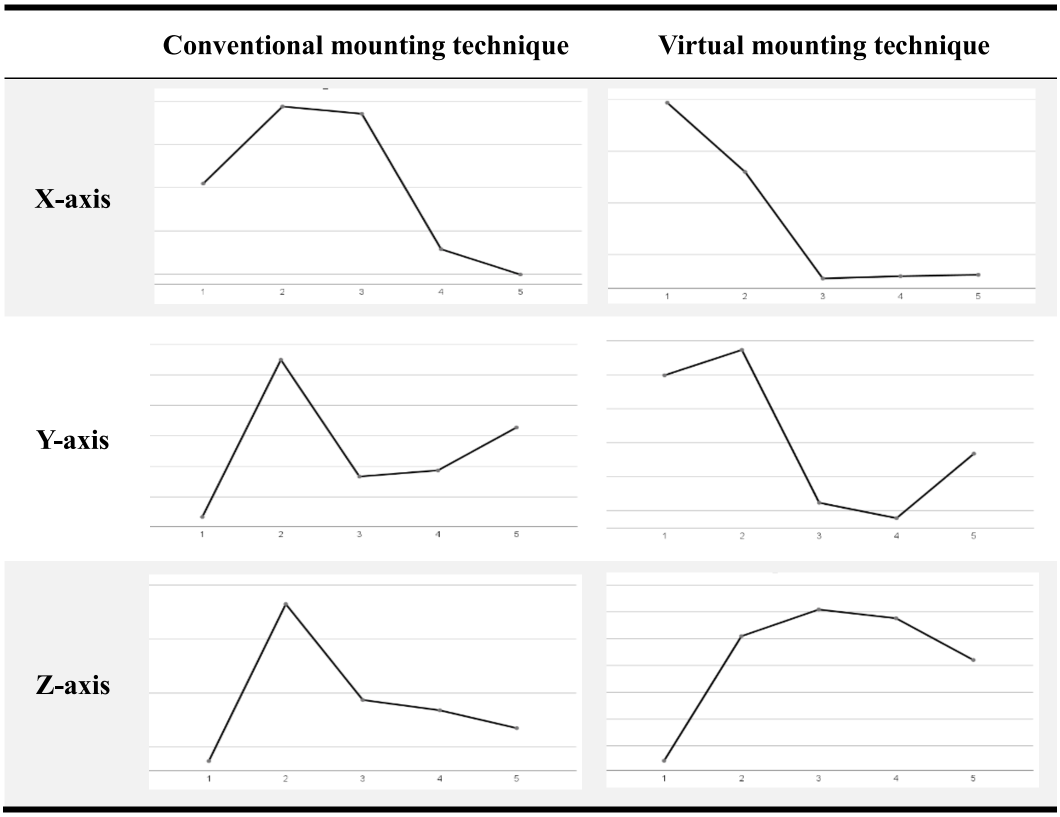
3.3. Spatial relationship between each technique

For both CM and VM, there was no significant difference by the order of repetitions (Figure 21). That is, repeating both techniques five times in a subject did not result in an increase or decrease of errors. Subsequently, a significant difference between each coordinate by order of repetitions in both the CM and VM was examined (Figure 22). In the case of the X coordinate, there was no significant difference between the CM and VM from the first to the fifth repetition. On the other hand, Y coordinate showed a significant difference in a positive direction in the case of VM from the first up to the fifth repetition. This finding can be interpreted that the dental cast is more anteriorly located in VM than CM. The results are shown in Figure 14. From the model's occlusal view, all 15 data are located ahead of CM in the case of VM. In the case of the Z coordinate, the coordinates of the CM were higher than the VM in the fifth repetitions only. In other words, in one out of the five-repeated experiments (20%), the cast is located more upwards in the CM compared with the VM.



X-axis of the graph, the order of repetitions; Y-axis of the graph, the coordinate value corresponding to X-axis

Figure 18. Result of one-way RM-ANOVA to analyze the significant difference between trials. There was no significant difference according to the order of trials in both the CM and VM.

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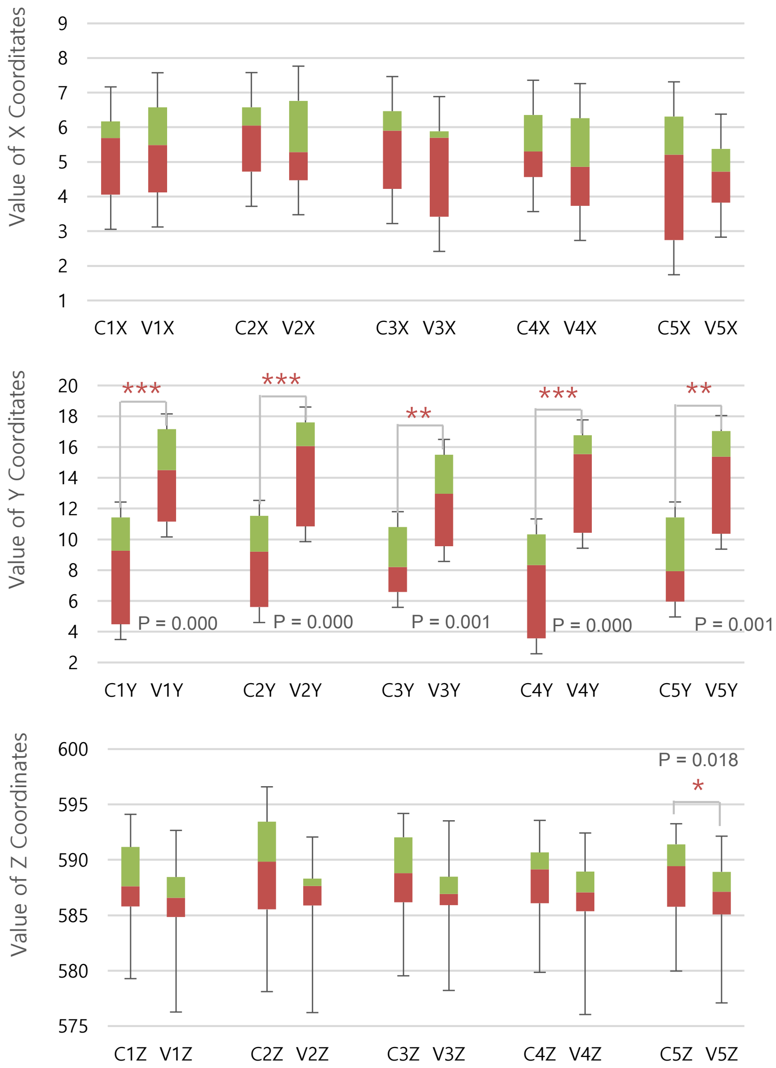

Figure 19. Box-plot table for the analysis of coordinate values according to the order of trials. Comparison among groups is expressed as *P < 0.05, **P < 0.01, ***P < 0.001, asterisks and horizontal bars indicate statistically significant differences among groups. C, conventional mounting technique; V, virtual mounting technique; X, Y, Z means each coordinates; the number of X-axis means the order of trials.

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3.4. Average angle of the occlusal plane

The mean angle of the occlusal plane measured by the CM was 8.14°, whereas it was 2.13° measured by the VM. The angle of the occlusal plane was statistically significantly steeper in the CM compared with that of the VM. Similarly, the maximum value for each group was greater in the CM compared to VM (Table 4, Figure 23).

Table 4. Precision of each technique (Angle of the occlusal plane)

	Mean ± SD	Maximum value
θc (degrees)	8.1383±7.8334	19.4249
θv (degrees)	2.1280 ±7.5637	14.4137

θ, angle of the occlusal plane; c, conventional technique; v, virtual technique

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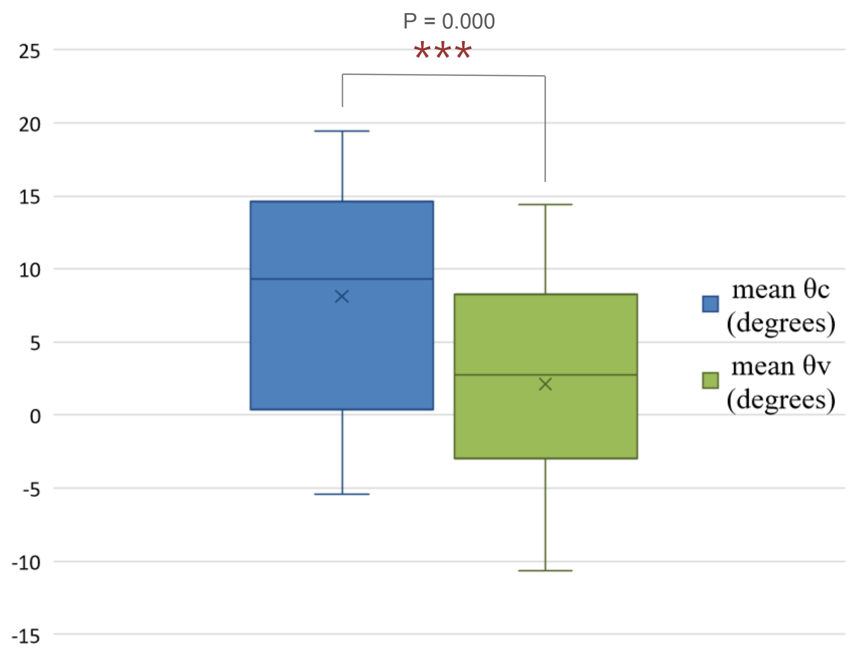

Figure 20. Box-plot table for the angle of the occlusal plane. Comparison among groups is expressed as ***$P < 0.001$, asterisks and horizontal bars indicate statistically significant differences among groups. θ, angle of occlusal plane; c, conventional mounting technique; v, virtual mounting technique.

Except for the subject number 6, all the mean angle of CM (θc) values were greater than mean angle of VM (θv), and subject number 6 also showed a minimum angle difference of less than 1 degree between the CM and VM. In the case of the subject numbers 3, 8, and 12, the angle formed by the occlusal plane and the horizontal plane was shown to be a

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negative value, but mean θc tended to be greater than mean θv. For the subject number 10, 11, and 15, the angle of the occlusal plane was shown to be positive for the CM, and negative for the VM. However, the tendency of the posterior part of the cast mounted with the CM being located upwards compared to the VM remained the same. This tendency is illustrated in Figure 14. As shown in the two columns on right displaying both CM and VM model, while there were individual differences by degree and quantity, the tendency of the occlusal plane heading downward for VM remained the same.

Bland-Altman plot depicts the range of deviation of the angle of the occlusal plane (Figure 24). Since Y-axis shows positive values in all except for one data, the angle of the occlusal plane measured by the CM is generally greater than the measured value of the VM; and the mean value was 6.05, showing a big difference between the two groups. Also, the upper limits of agreement (LOA) was 14.35, lower LOA was -2.24, and the 95% difference between the two techniques was 16.59° that fell within the range of big difference.

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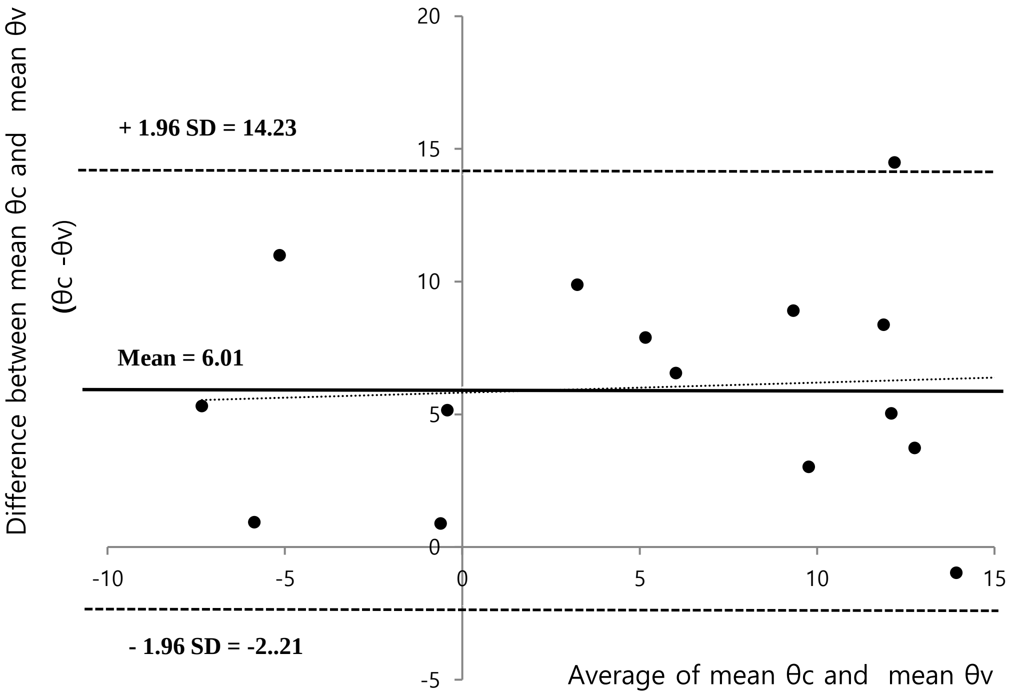

θ, Angle of occlusal plane; c, conventional mounting technique; v, virtual mounting technique

Figure 21. Bland-Altman plot for the angle of the occlusal plane. Since Y-axis shows positive values in all except for one data, the angle of the occlusal plane measured by CM is generally greater than VM.

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4. DISCUSSION

The introduction of digital technology in dentistry has led to the shifting of conventional methods to digital techniques. However, problems often occur while placing a digitized dental model to a virtual articulator. Since the indirect digital method is complicated and has complex procedures, several techniques were suggested to overcome this problem, yet no definite methods have been adopted so far.

Therefore, this study presents the CBCT based direct digital facebow transfer procedure. A comparative analysis was performed between CM and VM on the four aspects: the average distance between the target points, the standard deviation of target points for each axis, the positional relationship between each technique for the X, Y, Z-axis of tooth #11, and the angle of the occlusal plane (Figure 2). By the result, the null hypothesis of this study, there is no difference between the CBCT based VM and an anatomic facebow based CM is rejected. Also, it is confirmed that the VM has higher precision than the CM.

According to the International Organization for Standardization (ISO 5725-1), accuracy consists of trueness and precision. Trueness measures the closeness of agreement between the arithmetic mean and the true value, and precision measures the closeness of agreement between test results. The trueness was not measured, because this study was conducted on human body measuring the true values. Other in vivo study also measured the precision and not the trueness because they could not set the true value[41]. Another study insisted that their findings were "trueness", but in fact, they were measuring the spatial deviation

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between the two measurements[18]. Thus, additional studies are required to investigate the method of setting the true value for in vivo study.

When the FOV of CBCT is large, the accuracy is lower than that of the small FOV because the beam angulation becomes more severe in the superior and inferior volume areas and the contrast to noise ratio decreses[42]. Since the voxel size in the P mode of the CBCT used in this study had a specific voxel size (0.3/voxel (mm)), not adjustable, so it is difficult to assess the influence of this variable. The voxel size of CBCT has a great influence on the noise of the orthogonal slices. If the voxel size is small, the noise increases, but the spatial resolution is better[43]. In this study, the image was taken in P mode, which can reproduce all the anatomical structures necessary for the VM without violationg the ALARA principle. But the additional study will be needed to understand the relationship between all parameters related to the radiation dose and the accuracy of the reconstructed image during CBCT imaging.

Moreover, this study included a minimum number of subjects to prevent unnecessary exposure of subjects to radiation due to the CBCT procedure. Consequently, race, sex, age, craniomandibular relation, etc., were not considered.. Since the study recruited subjects with the least number of restorations, no missing teeth and TMJ disorder, the age of the subjects included in this study were mostly in their 20s to 30s.

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4.1. Average distance between target points

In an experiment that measured the difference in the mean distance among the target points between the CM and VM, the difference was significantly more in the CM compared to the VM. That is, even if one operator repeats the procedure five times without a pause, the error occurs more in the CM. The subject's strong resistance to facebow transfer procedure can affect the repeatability of the procedure. Especially, earplug insertion causes discomfort to the subject, which makes it difficult to place the facebow at correct position. On the other hand, the operator can manipulate the facebow as she intended in the VM, thereby produce fewer errors than the CM. Besides, in circumstances where both porions are not parallel due to facial asymmetry, or dental midline and facial midline does not coincide, errors are invisible with the naked eye if facebow transfer is directly performed to the patient. However, minute differences can be perceived when manipulating the skull on virtual dental space. Errors can be minimized even if facial midline and dental midline does not coincide, because there are still several anatomic points that can be used as references such as vomer bone, sagittal suture, spine, etc. The earplug and orbitale pointer, which determines the lateral and horizontal factors, are located on soft tissues. But in the skull, anatomic reference point is constant, so there will be fewer errors. Nevertheless, the initial orientation of external acoustic meatus is not parallel with the horizontal axis, and it can be affected by the subject’s skull size and CBCT's field of view during the CBCT imaging process. In other words, if the size of the subject’s skull is too big, it should be

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noted that it is the pathway of the external acoustic meatus that is reproduced on the skull and not the porions.

4.2. Standard deviation of target points

In the standard deviation measured by coordinates to determine the distribution of target points according to X, Y, Z-axes showed more compact target points of VM in all cases. Along with the results of test number 1 (Average distance), this results indicate that the VM has higher precision than the CM. In Figure 17, Z-axis of the CM showed big difference between the maximum and minimum standard deviation compared with other axes. Additionally, hardening expansion of dental plaster used in CM may have contributed to this difference as well. Despite the right mixing ratio and setting time, hardening expansion is affected by the surrounding envioronment such as moist and temperature. Cast mounting was carried out in a designated place. However, the weather, temperature, and surrounding environment at the time of mounting forms the factors of error.

4.3. Spatial relationship between each technique

There were no significant differences according to repeated trials in the X, Y, and Z-axes for the CM and VM in tooth #11. That is, repeating the mounting in a same subject does not increase or reduce errors. In a comparative analysis of the coordinates of each technique

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by the order of trials to pair up the CM and VM, the findings showed that the VM was always positioned ahead of the CM. This is because there was a positional difference between the porion of CBCT and that of soft tissue where the earplug of the facebow was inserted. There was a difference in degree for each subject, the porion on the CBCT located more posteriorly and upwardly than the porion on the soft tissue (Figure 25). If the porion on CBCT is located more posteriorly than the porion on soft tissue, the cast of VM is located more anteriorly.

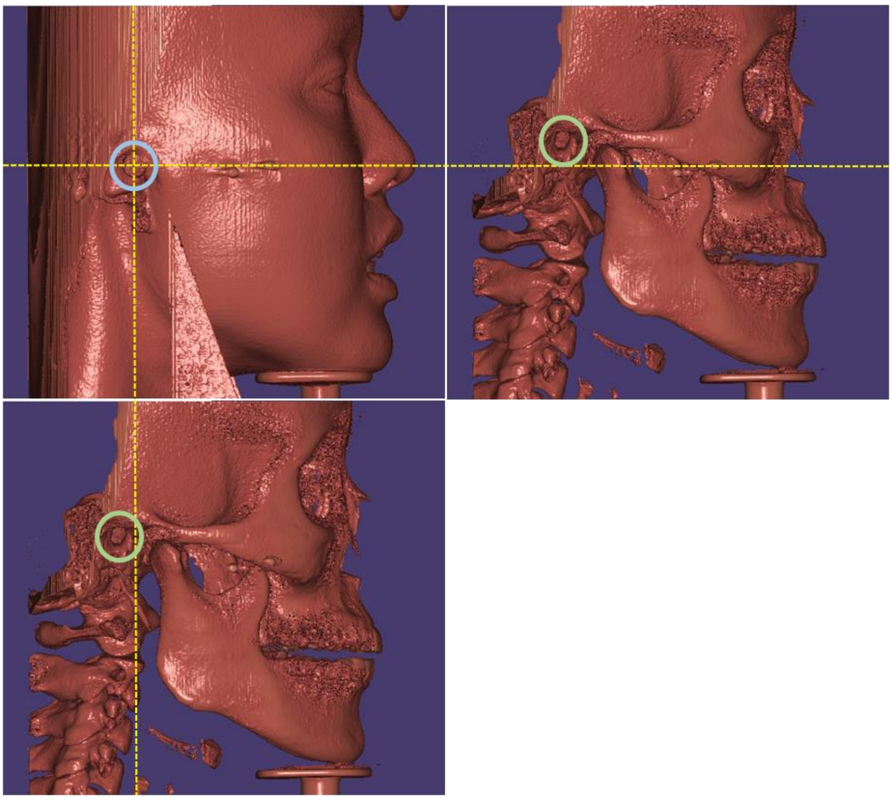

Figure 22. Positional difference of the porion on soft tissue and skull. The porion of the skull is located more posteriorly and upwardly to the porion of the soft tissue.

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The external acoustic meatus is a gentle S-shaped 2.5cm long canal consisting of two parts, i.e., inner two third bony part, and the outer one third cartilaginous part. When the canal is looked at from the horizontal view, the external part is protruded forward, and the inner part is protruded backward[44]. Due to the limitation of the CBCT's FOV, the external auditory canal is cut in external part on skull of VM, the effect of pathway of the auditory canal seems to be insignificant.

In actual clinical practice, the position of the anterior teeth when mounting on the articulator determines the anterior guidance and is determining the cusp height and cusp angle of the posterior teeth[45, 46]. Since it was impossible to set the true value for measuring the trueness of each technique, it would be a good attempt to try both techniques in making a simple prosthesis for patient.

In Z-axis, the coordinates of the CM were located significantly higher than that of the VM in the fifth trial (20%). Here, factors such as discomfort from earplug insertion and plaster expansion during gypsum mounting must have affected the result. However, such a trend appeared only in one out of five trials, and thus considered insignificant.

4.4. Angle of the occlusal plane

The angle of the occlusal plane measured by the CM was statistically steeper than that of the VM. The average value of angle of the occlusal plane in the case of the CM was 8.13834±7.8334°, and 2.1280±7.5637° for VM, which was within the range of 1-9°[37, 47, 48],

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the adult mean value for Frankfort horizontal plane determined by previous studies. But both techniques seem to differ from previous study when considering the standard deviation of 7° or more. The mean angle of occlusal plane measured in 60 Koreans in another study was 9.75 ± 3.41°[49], and showed a difference with our study, too. In that study, there was no significant difference between angles of the occlusal plane when they compared the left to right. Also, they found no significant gender difference. Therefore, this study considered the characteristics of the subject as a factor of an error. The occlusal plane is affected by the skeletal class of the subject. However, the skeletal class of the 15 subjects was not considered, and 7 out of 15 subjects even had an orthodontic treatment history. Because the angle of the occlusal plane has individual variations, the number of subjects recruited for this study was too small to draw a specific conclusion with the result obtained from this study..

The angle of the occlusal plane for CM was stiffer than the VM. This can be explained by the difference in position of porion on soft tissue and skull as result of experiment 3 (Figure 25). Since the porion, the posterior reference point of facebow, is located more downward on the soft tissue, the angle of occlusal plane of the CM is stiffer.

A study that compared the angles of the occlusal plane between the CM and VM via Stereophotogrammetry[26] also showed a stiffer occlusal plane angle in CM. However, that study had set Frankfort horizontal plane as a horizontal reference plane during the CM, and Natural head position (NHP) as a horizontal reference plane during the VM. Consequently, differences in angles between those horizontal reference planes can also occur, and it is

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uncertain to take such a finding as a reference.

This study presents a CBCT based VM performed on virtual dental space, and the CM using an anatomic facebow. Also, it conducted a comparative analysis of the difference between the locational relationships of the two techniques and evaluated the repeatability of each technique. The VM showed higher precision in the aspect of average distance and standard deviation between the target points compared with the CM. Also, in tooth #11, definitive cast situated ahead of the CM.

According to previous study, the true hinge axis exists in the lower part of the condyle[50]. To compare the condylar position in both techniques, the skull was superimposed on the CM model (Figure 26). As a result, the condylar component of the articulator and the condyle of the skull after mounting were consistent with both the VM and the CM, and the VM tend to be positioned more downward than CM. In order to determine which of the two technique has higher trueness, an additional study is needed to compare and analyze the two techniques in actual clinical practice.

In the process of superimposing CBCT and dental cast, it is difficult to apply the VM suggested in this study for patients with multiple missing teeth or edentulous patients. Further research is required for these cases. In dentulous patients, the CBCT based VM can be used as an excellent tool to establish total digital dentistry with JMA system using ultrasound impulse to reproduce mandibular movements or jaw tracking system using optic technology.

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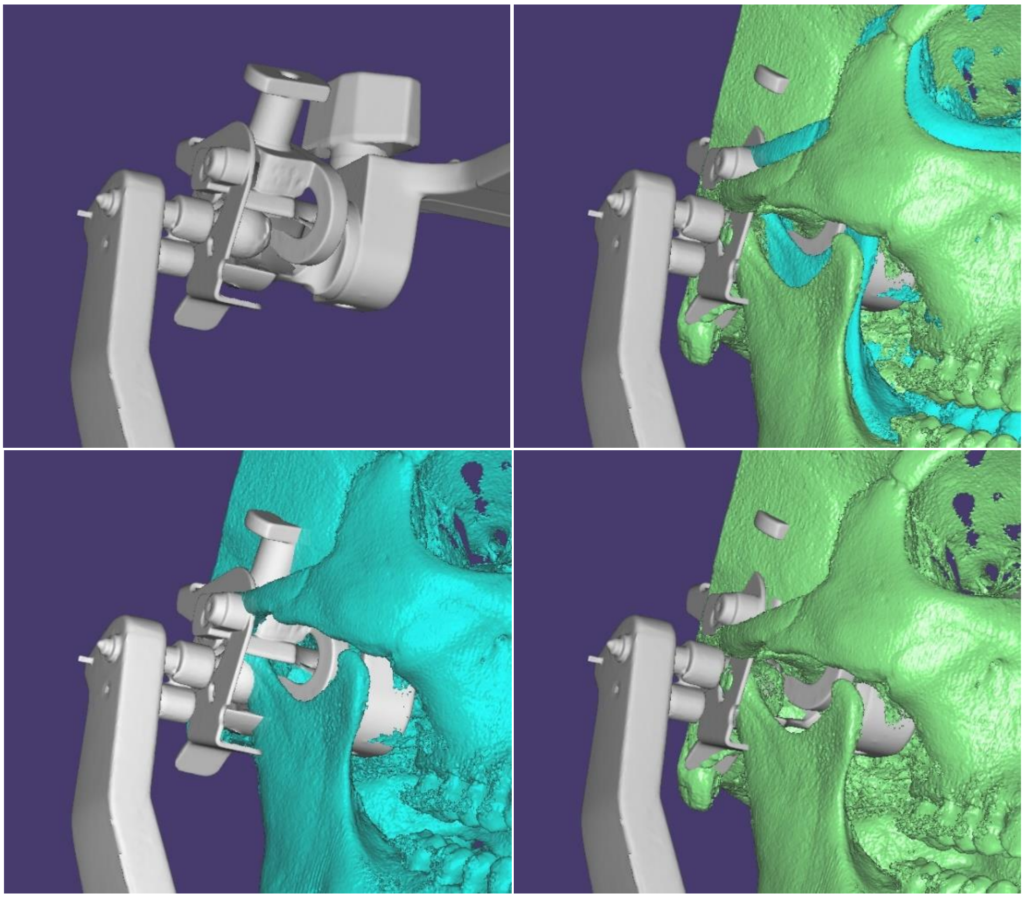

Figure 23. Condylar component of the articulator and condylar location of the CM and VM. Blue, skull of CM; Green, skull of VM

5. CONCLUSION

1. The VM shows higher precision in the aspect of average distance between the coordinates than the CM.

2. The VM shows higher precision in the aspect of standard deviation between the coordinates than the CM.

3. For the VM, there was not much difference in the degree of error in the X, Y, Z-axis direction between each trial. Whereas in the CM, the error in the Z-axis direction, i.e., the error in the upward and downward, was the largest.

4. The cast mounted with the VM positioned ahead of the cast mounted with the CM. Also, CM cast tends to be positioned higher than the cast of the VM (20%).

5. When the cast is mounted with CM, the angle of the occlusal plane tended to be steeper than that of VM.

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SUPPLEMENTARY DATA

Supplementary table 1. Naïve data - coordinates of conventional mounting

Subject No.	Order of Repetitions	#11			#16			#26		
		x	y	z	x	y	z	x	y	z
1	1	1.7104	1.34	585.2681	20.2684	-22.1807	589.8628	-17.0479	-19.1161	590.5655
	2	2.9852	2.2881	584.1472	21.802	-20.895	589.4702	-15.3881	-18.5254	588.1935
	3	2.8432	-0.7462	584.4546	20.7751	-24.5127	590.5597	-16.4404	-20.6268	589.2072
	4	-2.9666	2.1246	586.3671	15.3353	-21.4031	592.2965	-21.8934	-17.9546	591.311
	5	0.0667	3.4499	586.5818	18.9616	-19.6747	592.0104	-18.3056	-17.3901	590.5109
2	1	1.527	10.7433	579.2816	20.6051	-21.675	588.2198	-20.3338	-21.5014	586.7239
	2	4.8214	13.4005	578.1086	24.264	-18.7273	587.0594	-16.6012	-19.4107	584.0547
	3	1.0247	8.3787	579.535	20.9131	-23.7224	588.3372	-19.9838	-24.5046	586.2573
	4	1.7764	8.3393	579.8455	21.3393	-23.7822	589.3235	-19.5684	-24.0381	588.3625
	5	1.3616	7.9297	579.9649	20.5693	-24.5622	588.3025	-20.3981	-24.2243	587.6122
3	1	6.1582	4.9126	591.2545	23.0331	-20.7375	589.547	-22.5572	-17.6235	588.0381
	2	4.6815	9.3873	594.5491	23.149	-14.8935	590.8669	-22.6198	-14.7253	590.9231
	3	8.1705	10.3241	594.0894	26.2575	-14.2789	591.0394	-19.5412	-13.366	590.3058
	4	4.7233	7.2603	590.0572	22.4804	-17.5347	588.1362	-23.1586	-16.4125	587.5294
	5	5.2143	12.1193	589.438	23.3188	-12.2937	586.7906	-22.4307	-11.574	586.1705
4	1	5.8202	15.3797	591.6124	24.3742	-14.5915	598.0585	-19.9126	-17.7615	597.9047
	2	6.47	11.6125	593.7813	26.3545	-17.9991	597.2184	-17.8818	-23.0842	596.9295
	3	5.9061	9.9658	594.188	26.0248	-19.457	597.3773	-18.1008	-24.731	597.56
	4	5.1423	13.6079	592.065	24.3746	-16.174	597.6584	-20.0681	-20.0235	597.9598
	5	1.1065	9.0712	593.2595	19.8938	-21.0296	597.3513	-24.4299	-24.4629	597.3851
	1	3.4836	9.2698	586.312	24.9703	-18.9446	593.1911	-21.3381	-18.8967	590.9265

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5	2	7.5079	5.934	587.7987	29.5473	-21.6208	595.2148	-16.7232	-22.5839	592.9017
	3	6.4996	11.2731	581.6717	28.7765	-16.4832	588.1838	-17.5436	-17.396	587.6584
	4	5.3056	7.2111	585.1056	27.1563	-20.6388	591.9766	-18.9258	-21.2832	589.6375
	5	7.1131	11.0214	582.9213	29.0592	-16.7762	589.8831	-17.1892	-17.4743	588.3542
6	1	6.6678	10.1602	586.442	27.0235	-16.5453	592.0376	-21.8952	-14.143	590.6306
	2	6.054	9.1981	584.8027	25.9293	-17.5746	590.9606	-23.0017	-14.7498	588.877
	3	7.5587	8.1592	584.9859	27.5637	-18.4773	591.3123	-21.3222	-15.8166	589.3813
	4	6.788	10.4731	585.7979	27.4547	-15.433	592.8502	-21.4127	-14.3772	590.51
	5	4.8776	12.7148	584.9714	25.5245	-13.7291	589.9465	-23.4503	-12.0932	589.3718
7	1	5.686	12.3615	587.6111	29.0575	-15.5641	591.8115	-23.6314	-17.022	587.897
	2	6.4459	17.8886	590.7034	29.3365	-10.5488	593.5077	-23.3526	-10.9769	589.3588
	3	6.1201	14.9791	592.0922	30.4781	-12.022	596.6113	-22.2665	-15.2794	594.1757
	4	7.2642	14.904	593.5647	29.6178	-14.0833	596.9197	-23.2844	-13.3343	594.6607
	5	5.406	14.9696	591.44	27.7685	-13.3578	597.4974	-24.993	-13.5122	593.6773
8	1	4.4131	12.9498	586.9499	24.3847	-15.8783	582.9653	-21.8453	-19.8687	582.0854
	2	4.2609	11.4545	585.9567	24.2898	-17.5834	584.4594	-21.8923	-21.5159	580.8391
	3	4.1975	7.6167	587.3652	21.4833	-22.9681	583.6647	-24.9841	-22.5915	582.5349
	4	5.3446	12.1158	584.9882	25.736	-16.6048	582.239	-20.6632	-21.0888	580.9869
	5	5.5936	7.6851	583.1362	24.8027	-21.82	581.3737	-21.6974	-24.724	581.7274
9	1	6.1753	10.0438	591.059	25.4641	-11.7935	596.027	-23.7565	-15.0768	591.695
	2	6.6893	11.7122	590.3781	26.4262	-9.5923	595.7223	-22.7003	-13.852	592.4411
	3	6.4316	12.0183	588.269	27.0493	-9.1116	590.5222	-22.1931	-14.3539	590.8066
	4	6.5889	9.1489	587.0955	26.3431	-12.3021	591.6585	-22.7546	-16.6578	587.4806
	5	9.2333	10.9474	586.5624	28.5514	-11.2262	589.7493	-20.771	-13.931	586.2343
10	1	7.9874	-5.9247	584.3834	25.3906	-21.6453	583.811	-13.6669	-24.3817	583.4937
	2	1.895	-5.7358	589.8515	18.9272	-21.6016	590.6978	-20.0147	-23.8445	588.5161
	3	3.0475	-4.2998	587.8209	21.9324	-20.5686	592.3745	-18.5027	-22.7955	587.7844
	4	5.1131	-1.7199	589.99	20.4866	-20.037	587.8973	-16.8709	-19.7122	589.5984

	5	4.1242	-5.508	591.7745	22.1921	-17.7049	591.2438	-17.0125	-24.5275	591.3124
11	1	4.0703	6.657	592.9933	27.8962	-17.5681	593.1816	-24.6755	-23.9959	591.2065
	2	7.855	6.7308	593.0864	31.9386	-17.0508	591.8939	-20.5299	-24.2075	591.0601
	3	5.2415	8.1975	591.9824	29.4233	-15.4979	592.8591	-23.0021	-22.9354	591.8055
	4	1.1907	8.5265	592.7513	23.9779	-16.5585	592.2623	-28.7989	-20.78	590.6041
	5	5.806	11.842	591.3746	30.3867	-11.6176	591.3676	-22.0672	-19.6234	591.3971
12	1	5.7459	-3.3492	590.647	23.6004	-21.7671	588.5982	-22.6669	-18.8253	588.2768
	2	4.7565	6.3646	585.0916	23.6027	-11.2689	585.3027	-22.7084	-10.59	582.1874
	3	5.0075	-3.7218	589.0207	22.8953	-22.2699	589.3446	-23.2755	-19.343	587.1899
	4	6.1279	1.292	587.2994	24.4483	-16.9314	587.7795	-21.8003	-14.7147	584.5009
	5	0.3302	-0.9513	590.3802	18.9537	-18.932	590.1117	-27.4305	-17.5615	588.8005
13	1	10.4638	5.2973	580.0813	25.0905	-25.8569	586.4413	-16.9928	-27.2576	589.4273
	2	5.8148	4.6681	596.5938	20.247	-26.3668	603.8687	-21.7855	-27.6882	606.1904
	3	10.6122	7.2212	589.9442	26.1357	-23.2163	597.4916	-15.8271	-26.0321	599.7418
	4	11.0165	3.931	589.1316	27.2799	-26.0207	597.1762	-14.5616	-29.2481	601.2838
	5	9.9069	4.373	590.2405	25.8311	-25.5475	598.9362	-16.0989	-29.0294	600.7643
14	1	4.0403	12.1093	594.1094	27.4654	-11.589	602.0187	-20.8133	-10.2569	592.3279
	2	7.1714	11.3195	596.1979	30.8092	-11.4056	606.0938	-17.7073	-10.9327	597.5823
	3	6.225	14.6841	588.7863	29.9236	-8.9779	596.1238	-18.4233	-7.8737	586.7692
	4	5.9093	10.1864	589.7852	28.9692	-14.2669	596.5927	-19.3763	-11.7179	587.4524
	5	6.8187	7.6155	588.755	29.8638	-16.3593	597.0909	-18.4526	-14.2658	587.7283
15	1	4.3357	4.0699	590.0557	22.3861	-20.1816	593.3503	-19.7382	-23.4804	590.5156
	2	6.2255	5.2567	588.8212	23.9673	-18.9797	592.81	-18.251	-21.7457	592.3304
	3	4.2454	5.9503	592.3437	20.8631	-19.341	594.3467	-21.4188	-20.1233	593.7775
	4	4.411	3.2017	591.2676	21.4557	-21.5065	595.8773	-20.7688	-23.2836	594.258
	5	5.0148	7.5449	591.8329	22.2482	-17.2938	594.2537	-19.9392	-19.2437	593.7995

Supplementary table 2. Naïve data – coordinates of virtual mounting

Subject No.	Order of Repetitions	#11			#16			#26		
		x	y	z	x	y	z	x	y	z
1	1	2.8611	14.7741	587.9949	20.5663	-9.1815	589.1989	-16.6099	-8.1608	588.4579
	2	1.165	16.1205	588.2723	18.726	-7.9103	590.3941	-18.4313	-6.6131	589.3481
	3	2.7115	13.8259	587.1978	19.9344	-10.6113	589.0161.	-17.2483	-8.6555	587.7126
	4	0.7437	15.2014	588.5252	18.9949	-8.4184	590.9927	-18.242	-8.0785	589.8206
	5	1.9868	15.6604	588.1052	19.9882	-8.3796	589.3938	-17.2457	-7.3245	588.613
2	1	3.0286	15.568	576.266	22.3258	-17.4665	581.2682	-18.6448	-17.2934	578.9493
	2	0.1446	16.5292	576.2157	19.445	-16.4315	580.7159	-21.5001	-16.3703	578.8734
	3	1.8779	16.1698	578.212	21.7843	-16.4725	582.0548	-19.0498	-17.2443	580.1874
	4	2.0794	16.6715	576.0414	21.3392	-16.2027	580.8032	-19.4389	-16.3224	579.8628
	5	1.8206	17.2813	577.0875	21.1323	-15.8327	579.3741	-19.5607	-15.8992	577.8314
3	1	6.4436	13.0757	588.3946	23.7693	-11.9506	585.6844	-21.9354	-9.6319	584.8671
	2	8.2233	15.093	588.1695	25.5709	-9.9547	585.0348	-20.149	-7.8632	584.3286
	3	7.3819	13.4973	588.576	24.7488	-11.7299	585.22	-21.0037	-9.2511	584.1521
	4	7.0884	12.623	586.5795	24.9283	-12.1049	583.6241	-20.8096	-11.0062	582.9564
	5	6.3297	13.4825	589.0939	24.1251	-11.4522	585.9924	-21.5176	-9.8987	584.7305
4	1	7.9869	16.9227	586.0261	27.2613	-13.0376	588.0121	-17.0439	-17.1891	587.4221
	2	7.2988	17.3815	587.402	25.1779	-13.5516	588.5295	-19.2753	-15.5863	587.9793
	3	5.7679	15.9663	586.9348	23.7569	-14.8456	588.2874	-20.6494	-17.013	588.4296
	4	7.9587	15.9641	585.8848	26.8859	-14.4388	586.5228	-17.4346	-17.9143	586.36
	5	4.9532	17.5012	588.8803	23.0747	-13.4489	589.4199	-21.2911	-15.7665	589.1768
5	1	4.8177	17.0521	580.1771	26.4437	-11.2979	585.9768	-19.8005	-11.4379	583.1299
	2	4.5388	17.9177	580.9418	26.9401	-9.8933	586.2901	-19.277	-11.1959	584.7372
	3	5.5142	17.6618	583.0452	27.3285	-10.7044	587.4915	-18.9385	-11.1545	585.4228
	4	5.6732	16.0835	582.1924	27.5646	-12.3044	586.6581	-18.5598	-12.6465	584.6339
	5	4.4431	15.7198	580.5497	25.7065	-12.9752	586.1041	-20.4566	-12.4813	584.2786

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6	1	8.2617	9.7893	584.3655	27.0161	-16.6029	592.037	-21.8455	-14.1485	590.6295
	2	8.7739	9.6446	585.5703	25.8143	-17.5644	590.9478	-23.0683	-14.7992	588.8892
	3	6.5307	9.3445	586.064	27.6118	-18.5394	591.3278	-21.3222	-15.8166	589.3813
	4	6.0744	9.0865	584.8301	27.4547	-15.433	592.8502	-21.4127	-14.3772	590.51
	5	8.2593	9.756	584.6374	25.5161	-13.7828	589.9416	-23.3842	-12.0393	589.3584
7	1	5.6351	20.4533	587.0933	28.8083	-7.8677	588.302	-23.954	-8.6506	584.5223
	2	5.1162	20.8818	588.4581	27.5616	-8.1016	589.4565	-25.2224	-7.4018	585.2328
	3	2.1641	19.6144	588.3663	24.8923	-9.1297	588.441	-27.9213	-8.8209	585.3202
	4	6.9437	17.6849	587.6008	29.2756	-11.4187	587.4192	-23.535	-10.4727	584.4354
	5	4.7162	18.0445	588.696	27.3584	-10.6455	588.0436	-25.3214	-10.5473	584.9702
8	1	5.4838	17.838	585.3101	25.9295	-10.4018	580.586	-20.4379	-15.3101	578.7899
	2	7.1435	18.3267	588.3475	27.549	-9.9019	582.5602	-18.8894	-14.5907	580.4328
	3	5.2771	18.4014	586.2206	25.3766	-9.8886	579.9045	-20.9853	-14.462	579.4915
	4	5.6969	17.8162	587.7831	25.8552	-10.6689	583.0134	-20.5116	-14.9498	581.2211
	5	5.5638	19.2257	586.185	26.0255	-9.1435	581.1868	-20.5306	-13.8077	579.2355
9	1	5.5201	14.2758	583.8799	25.0178	-7.9091	586.8351	-26.6656	-7.4655	583.1929
	2	6.3878	12.1554	584.3997	26.1587	-9.6364	587.5553	-25.5088	-10.0282	583.6755
	3	4.166	13.405	582.4732	23.7594	-8.5868	585.2891	-27.9589	-8.3453	582.1067
	4	0.3483	14.391	583.7759	20.3981	-7.0827	586.6002	-31.2561	-8.1089	583.4102
	5	5.1957	11.6659	583.5278	24.2805	-10.7574	586.4762	-27.462	-9.3853	584.1177
10	1	6.7053	6.529	589.8192	24.3956	-8.577	588.7211	-14.5574	-12.2465	587.0787
	2	6.2793	5.4238	589.8259	23.7072	-10.0345	588.9439	-15.2911	-13.1152	587.4274
	3	5.5395	6.0043	590.8394	23.0741	-9.368	590.4919	-15.8522	-12.5669	587.7353
	4	4.8563	4.6628	591.8199	22.2849	-10.7792	590.525	-16.7393	-13.7235	589.6926
	5	4.8433	6.0239	590.7003	22.2695	-9.4569	589.4424	-16.9029	-12.5628	588.578
11	1	5.0537	17.8049	586.5838	28.3744	-6.227	581.1126	-24.357	-11.5233	579.8447
	2	4.9856	16.5939	586.1882	28.6734	-7.356	581.7326	-23.9541	-13.1443	579.3139
	3	5.4757	16.9501	586.3549	29.7583	-6.5326	581.806	-22.7193	-13.3019	579.0687
	4	4.7955	18.1348	586.6705	27.9399	-6.0232	581.4864	-24.5997	-11.0797	579.7228
	5	3.1927	16.8696	585.5352	26.7362	-7.3518	581.2821	-25.9719	-12.7168	579.6417

12	1	3.4269	8.3278	586.4499	21.8655	-9.645	585.5177	-24.4258	-8.0424	583.459
	2	5.2854	7.8284	587.493	24.1791	-9.6967	587.006	-22.1681	-9.1564	583.6285
	3	3.4267	6.5449	585.7848	21.9693	-11.2435	585.5772	-24.2303	-10.1533	582.5431
	4	4.0912	7.7604	587.0719	22.6017	-10.1651	586.8167	-23.6474	-8.5175	583.2355
	5	4.1755	6.9665	586.5758	22.7902	-10.8355	585.8425	-23.606	-9.6412	583.4244
13	1	7.266	9.7706	588.5129	23.6415	-20.8947	593.16	-18.2738	-24.7478	596.3731
	2	4.4121	8.8236	587.6308	20.3712	-21.9707	591.8859	-21.4146	-25.2204	596.038
	3	6.3631	9.0907	587.9067	22.3924	-21.5951	593.0141	-19.4465	-24.9292	596.4626
	4	6.4505	8.7811	589.5793	21.8839	-22.2478	594.2503	-20.0094	-24.8993	597.6304
	5	7.6846	8.5969	587.1259	23.4951	-22.1621	592.6693	-18.4391	-25.1145	595.9459
14	1	5.0629	19.2358	588.6362	28.9638	-5.2488	590.5138	-19.7586	-2.6263	583.9501
	2	5.4327	19.8942	588.1583	28.8018	-4.9741	590.4121	-19.8323	-1.6586	583.7642
	3	5.4653	19.1023	589.1308	28.6669	-6.0628	590.7658	-19.9073	-1.9798	583.8586
	4	4.5617	18.0988	589.3571	27.3765	-7.527	591.038	-21.2461	-2.791	584.7512
	5	3.76	19.7252	588.9634	27.8105	-4.7273	590.8895	-21.0443	-2.4156	585.092
15	1	3.2747	14.5624	592.658	21.4512	-9.7365	591.5232	-20.6455	-12.9297	590.3452
	2	1.6177	14.4879	592.0629	19.4318	-10.0392	590.8146	-22.7431	-12.6811	589.6466
	3	2.9421	14.7669	593.5195	20.2822	-10.0692	592.8698	-21.7221	-11.7203	588.27
	4	3.3764	16.7045	592.4259	21.3904	-7.6156	591.1533	-20.7323	-10.5841	589.5833
	5	3.8962	15.9944	592.1402	21.7832	-8.4601	591.4619	-20.363	-11.1592	589.2821

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Supplementary table 3. Distance between target points with each mounting technique

Subject No.	Pair	#11		#16		#26	
		C(mm)	V(mm)	C(mm)	V(mm)	C(mm)	V(mm)
1	1&2	1.9444	2.1833	2.0393	2.536	2.9546	2.5506
	1&3	2.5094	1.2478	2.4861	1.5738	2.1205	1.099
	1&4	4.868	2.2248	5.5554	2.5039	5.0383	2.1277
	1&5	2.9798	1.2498	3.5497	1.0076	2.1363	1.0619
	2&3	3.0532	2.9684	3.9152	3.2641	2.5594	2.8716
	2&4	6.3545	1.0424	7.0756	0.8299	7.2362	1.5513
	2&5	3.9743	0.9566	4.0013	1.6775	3.895	1.566
	3&4	6.7567	2.7438	6.502	3.0981	6.4267	2.4008
	3&5	5.4627	2.1711	5.3665	2.2641	3.9566	1.607
	4&5	3.3172	1.3906	4.0273	1.8827	3.719	1.7377
	Average	4.12202	1.81786	4.45184	2.06377	4.00426	1.85736
2	1&2	4.392	3.0404	4.8397	3.1105	5.0427	3.0017
	1&3	2.4306	2.3395	2.0737	1.3784	3.0594	1.3036
	1&4	2.4818	1.4728	2.4894	1.6694	3.1154	1.5517
	1&5	2.9001	2.2516	2.8885	2.7716	2.8648	2.0081
	2&3	6.4551	2.6681	6.1491	2.6957	6.4994	2.9146
	2&4	6.1566	1.9479	6.2635	1.91	6.9839	2.2868
	2&5	6.734	2.0334	7.0173	2.2375	7.0883	2.2514
	3&4	0.8143	2.237	1.0761	1.3555	2.1959	1.052
	3&5	0.7071	1.5822	0.9081	2.8321	1.4444	2.7606
	4&5	0.5952	1.2382	1.4979	1.4906	1.134	2.0786
	Average	3.36668	2.08111	3.52033	2.14513	3.94282	2.12091
3	1&2	5.7496	2.6995	5.9923	2.7661	4.0898	2.571
	1&3	6.432	1.0445	7.3714	1.1062	5.689	1.2347
	1&4	3.0007	1.9787	3.5431	2.3689	1.4447	2.609
	1&5	7.4918	0.8171	8.8869	0.6855	6.3326	0.5142
	2&3	3.6417	1.8492	3.1734	1.9651	3.4214	1.6395

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	2&4	4.9702	3.1492	3.8574	2.6507	3.8281	3.4926
	2&5	5.8199	2.6522	4.8378	2.2913	5.7056	2.4856
	3&4	6.1261	2.1992	5.7702	1.6491	5.4841	2.1326
	3&5	5.7963	1.1729	5.5344	1.0309	5.3537	1.009
	4&5	4.9228	2.7635	5.4755	2.5846	5.0781	2.208
	Average	5.39511	2.0326	5.44424	1.90984	4.64271	1.98962
4	1&2	4.3952	1.6054	4.0298	2.2073	5.7798	2.8033
	1&3	5.9959	2.5815	5.1828	3.9529	7.2094	3.7478
	1&4	1.9502	0.9693	1.6322	2.0791	2.268	1.3441
	1&5	8.0454	4.2053	7.8755	4.436	8.0983	4.8106
	2&3	1.7875	2.1365	1.5031	1.9371	1.777	2.0313
	2&4	2.9479	2.1786	2.7285	2.7805	3.8999	3.3809
	2&5	5.958	2.7751	7.1374	2.2862	6.7072	2.3516
	3&4	4.2843	2.4293	3.6852	3.6153	5.1177	3.9282
	3&5	4.9697	2.6086	6.3295	1.9233	6.3372	1.5886
	4&5	6.1884	4.5131	6.6143	4.8886	6.25	5.2364
	Average	4.65225	2.60027	4.67183	3.01063	5.34445	3.12228
5	1&2	5.4344	1.1882	5.6751	1.5224	6.2285	1.7076
	1&3	5.8857	3.0137	6.7542	1.8519	5.2279	2.4659
	1&4	3.0022	2.394	3.0206	1.6533	3.6299	2.2939
	1&5	5.2668	1.4333	5.689	1.8366	5.0847	1.6848
	2&3	8.1892	2.3326	8.7421	1.5007	7.4215	0.7658
	2&4	3.7059	2.493	4.1433	2.5176	4.147	1.6215
	2&5	7.0588	2.2347	7.2205	3.3249	6.856	1.8038
	3&4	5.4513	1.801	5.8549	1.8194	4.5758	1.7297
	3&5	1.4146	3.3386	1.7474	3.1164	0.7847	2.3182
	4&5	4.7494	2.0842	4.7878	2.0516	4.3784	1.9368
	Average	5.01583	2.23133	5.36349	2.11948	4.83344	1.8328
6	1&2	1.9974	2.0609	1.8484	1.8856	1.3172	2.2242
	1&3	2.6301	2.542	2.1332	2.1466	2.4656	2.1481
	1&4	0.7261	0.6877	1.4434	1.4907	2.3439	0.5039

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	1&5	3.4487	3.5785	3.8145	3.8202	0.274	2.9038
	2&3	1.8377	1.8596	1.9	2.08	2.3164	2.08
	2&4	1.7761	1.8138	3.2379	3.2944	2.8543	2.355
	2&5	3.712	3.7092	3.9975	3.9245	1.0712	2.8172
	3&4	2.5705	2.5848	3.4125	3.4629	1.3406	1.8314
	3&5	5.286	5.3143	5.345	5.3795	2.2788	4.3036
	4&5	3.059	3.0956	3.8808	3.8654	2.2933	3.2678
	Average	2.70436	1.85553	3.10132	3.13498	2.42264	2.4435
7	1&2	6.3787	1.5217	5.3016	1.7152	6.2255	1.9166
	1&3	5.2077	3.791	6.1321	4.1167	6.6574	4.0503
	1&4	6.6633	3.1038	5.3479	3.6888	7.7114	1.8716
	1&5	4.6412	3.0357	6.2337	3.1441	6.8981	2.3807
	2&3	3.2403	3.2139	3.6202	3.0353	6.5494	3.0505
	2&4	4.2148	3.7808	4.9207	4.2534	5.8028	3.5935
	2&5	3.185	2.8752	5.1252	2.917	5.2696	3.158
	3&4	1.8662	5.2108	2.2548	5.0494	2.2483	4.7697
	3&5	0.9672	3.0143	3.1483	2.9218	3.2872	3.1404
	4&5	2.8234	2.5081	2.0688	2.1594	1.9794	1.8662
	Average	3.91878	3.20553	4.41533	3.30011	5.26291	2.97975
8	1&2	1.8016	3.4956	2.269	2.602	2.0661	2.3695
	1&3	5.3536	1.0905	7.6924	1.0166	4.1794	1.2292
	1&4	2.3262	2.4823	1.6974	2.4431	2.023	2.4589
	1&5	6.6072	1.6423	6.1653	1.3977	4.8708	1.5698
	2&3	4.0885	2.8307	6.124	3.4311	3.6867	2.3012
	2&4	1.5968	1.6346	2.8247	1.9138	1.3096	1.839
	2&5	4.8928	2.8249	5.2662	2.1869	3.3345	2.1772
	3&4	5.2161	1.7206	7.7852	3.2408	4.8296	1.8585
	3&5	4.454	0.8734	4.1934	1.6188	4.0003	0.8369
	4&5	4.8087	2.135	5.3682	2.3859	3.8513	2.2907
	Average	4.11455	2.07299	4.93858	2.22367	3.41513	1.89309
	1&2	1.8739	2.3493	2.4215	2.1917	1.7811	2.8528

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9	1&3	3.4276	2.1379	6.3252	2.1054	1.9381	1.9043
	1&4	4.0843	5.1742	4.485	4.6989	4.6114	4.6405
	1&5	5.5124	2.6535	7.0188	2.964	6.3281	2.2748
	2&3	2.1466	3.1952	5.2593	3.4632	1.7834	3.3611
	2&4	4.1661	6.4702	4.8851	6.3732	5.6993	6.0652
	2&5	4.6493	1.556	6.547	2.439	6.5002	2.1033
	3&4	3.1041	4.1526	3.4596	3.9089	4.0848	3.5534
	3&5	3.4509	2.2797	2.7065	2.5283	4.807	2.3179
	4&5	3.2421	5.5665	3.1112	5.3471	3.5949	4.0651
	Average	3.56573	3.55351	4.62192	3.60197	4.11283	3.31384
10	1&2	8.1886	1.1845	9.4449	1.6272	8.1122	1.1894
	1&3	6.2337	1.6356	6.5828	2.3469	6.6567	1.4867
	1&4	7.5747	3.3022	9.0002	3.5439	8.327	3.7114
	1&5	8.3503	2.121	9.2979	2.4114	8.5057	2.8017
	2&3	2.7411	1.3826	3.5668	1.8003	1.9804	0.8428
	2&4	5.1481	2.5652	5.1129	2.2533	5.3039	2.7565
	2&5	2.9529	1.7852	3.593	1.6276	4.1592	2.0559
	3&4	3.9531	1.7966	4.4211	1.6172	3.9319	2.4404
	3&5	4.272	0.7102	4.7348	1.3254	4.2033	1.3469
	4&5	4.3026	1.7625	3.0897	1.709	5.1132	1.6175
	Average	5.37171	1.82456	5.88441	2.02622	5.62935	2.02492
11	1&2	3.7865	1.2759	4.274	1.3224	4.1535	1.7527
	1&3	2.1832	0.9804	2.5927	1.5778	2.0697	2.5393
	1&4	3.4417	0.4278	4.1493	0.6083	5.2638	0.5201
	1&5	5.7024	2.3319	6.7009	1.9944	5.0949	2.0183
	2&3	3.1938	0.6284	3.1096	1.364	2.8785	1.2688
	2&4	6.9101	1.6258	7.9843	1.5411	8.9628	2.2015
	2&5	5.7666	1.928	5.6749	1.9889	4.8467	2.0885
	3&4	4.1362	1.4021	5.5797	1.9153	6.3002	2.9836
	3&5	3.7378	2.4271	4.2673	3.1747	3.4656	3.3541
	4&5	5.8471	2.3364	8.1415	1.8044	6.8763	2.1377

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	Average	4.47054	1.53638	5.24742	1.72913	4.9912	2.08646
12	1&2	11.2338	2.189	11.0033	2.7514	10.2422	2.5233
	1&3	1.8245	1.903	1.1433	1.603	1.349	2.3094
	1&4	5.7352	1.0725	4.9773	1.5811	5.6485	0.939
	1&5	5.9288	1.5587	5.6498	1.5421	4.9562	1.7971
	2&3	10.8275	2.832	11.7414	3.0524	10.0976	2.5347
	2&4	5.6997	1.2681	6.238	1.6563	4.8155	1.6586
	2&5	10.0541	1.6781	10.1716	2.14	10.7067	1.5311
	3&4	5.4181	1.891	5.776	1.7604	5.5523	1.8696
	3&5	5.6036	1.1679	5.2217	0.9543	4.7992	1.1953
	4&5	6.9381	0.94	6.2954	1.1975	7.6349	1.1402
	Average	6.92634	1.65003	6.82178	1.82385	6.58021	1.74983
13	1&2	17.166	3.1336	18.0952	3.671	17.4401	3.1938
	1&3	10.0499	1.2825	11.4094	1.4395	10.4522	1.1901
	1&4	9.1695	1.6677	10.9571	2.4715	12.2658	2.1485
	1&5	10.2163	1.8645	12.5206	1.367	11.5094	0.5867
	2&3	8.5878	1.9885	9.2342	2.3451	8.9348	2.0344
	2&4	9.1261	2.8202	9.7145	2.8206	8.8709	2.1479
	2&5	7.5628	3.3189	7.4956	3.2263	7.9737	2.9789
	3&4	3.4131	1.7033	3.0453	1.4875	3.7845	1.2966
	3&5	2.9491	1.6123	2.7594	1.287	3.1786	1.1473
	4&5	1.6298	2.7524	2.3282	2.2589	1.6374	2.3129
	Average	7.98704	2.21439	8.75595	2.23744	8.60474	1.90371
14	1&2	3.8457	0.8937	5.2745	0.3347	6.1411	0.9881
	1&3	6.3038	0.6514	6.9	0.9024	6.5031	0.6696
	1&4	5.0882	1.4366	6.2349	2.8256	5.2886	1.6975
	1&5	7.5222	1.4298	7.2658	1.3203	6.5422	1.7324
	2&3	8.1944	1.2546	10.2994	1.1526	11.2603	0.343
	2&4	6.6332	2.328	10.0917	2.99	10.2965	2.0628
	2&5	8.3211	1.864	10.3192	1.1275	10.4291	1.9506
	3&4	4.6181	1.3692	5.3949	1.9705	4.019	1.802

	3&5	7.0936	1.8232	7.4448	1.5913	6.4637	1.7332
	4&5	2.9151	1.8555	2.3295	2.8371	2.7242	0.5458
	Average	6.05354	1.4906	7.15547	1.7052	6.96678	1.3525
15	1&2	2.5503	1.7621	2.0583	2.1614	2.918	2.2248
	1&3	2.963	0.9458	2.0048	1.814	4.9734	2.6321
	1&4	1.4927	2.157	3.0011	2.1538	3.8867	2.4678
	1&5	3.9617	1.6447	3.029	1.3203	5.3642	2.0844
	2&3	4.1	1.9883	3.4826	2.2244	3.842	1.9649
	2&4	3.6743	2.8527	4.7012	3.1344	3.5242	2.9059
	2&5	3.9714	2.7326	2.8074	2.9055	3.3568	2.8485
	3&4	2.9564	2.2669	2.7173	3.1928	3.262	1.9987
	3&5	1.8426	2.0783	2.4736	2.6123	1.7214	1.785
	4&5	4.4212	0.9253	4.5839	0.9812	4.1496	0.7468
	Average	3.19336	1.93537	3.08592	2.25001	3.69983	2.16589

The number written in the pair column means the order of trial.

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Supplementary table 4. Standard deviation of each coordinates for #11

Subject	Cx(mm)	Vx(mm)	Cy(mm)	Vy(mm)	Cz(mm)	Vz(mm)
1	2.210066	0.93116	1.39294	0.87948	0.980414	0.50069
2	1.544389	1.0409	2.318215	0.63298	0.742219	0.90445
3	1.457772	0.76899	2.79142	0.93172	2.328236	0.94846
4	2.166371	1.36709	2.590722	0.74577	1.105329	1.21349
5	1.625976	0.56428	2.340377	0.96149	2.48396	1.20013
6	1.00021	1.19577	1.699389	0.30099	0.699291	0.70296
7	0.723325	1.75226	1.956665	1.42386	2.208107	0.67095
8	0.656215	0.74823	2.533205	0.57295	1.694005	1.25402
9	1.250357	2.36013	1.186667	1.23088	1.981585	0.71117
10	2.321245	0.83703	1.749811	0.71286	2.820813	0.83132
11	2.454289	0.87884	2.105245	0.66215	0.735753	0.45073
12	2.337536	0.76085	4.12688	0.71706	2.31699	0.648
13	2.132615	1.25992	1.286471	0.45902	5.904661	0.94236
14	1.218226	0.71317	2.591073	0.70367	3.417433	0.46718
15	0.827929	0.85617	1.68337	0.99279	1.424566	0.58557

C, conventional mounting technique; V, virtual mounting technique

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Supplementary table 5. Standard deviation of each coordinates for #16

Subject	Cx(mm)	Vx(mm)	Cy(mm)	Vy(mm)	Cz(mm)	Vz(mm)
1	2.241631	0.76116	1.610891	1.05948	1.131465	0.85386
2	1.55481	1.08543	2.361391	0.60652	0.803304	0.977837
3	1.492335	0.70429	3.267595	0.86503	1.815925	0.912991
4	2.577589	1.84975	2.55643	0.74946	0.334703	1.053832
5	1.868275	0.74266	2.279219	1.2306	2.753088	0.608793
6	0.921409	0.95988	1.855612	1.85457	1.097809	1.100375
7	0.98525	1.70711	1.921892	1.55948	2.477339	0.74055
8	1.591128	0.82255	3.208689	0.58406	1.201988	1.311593
9	1.146425	2.16659	1.390512	1.44214	2.946649	0.820021
10	2.400035	0.92078	1.610838	0.82019	3.43643	0.847908
11	3.033066	1.10076	2.384834	0.62549	0.728815	0.29334
12	2.165355	0.92656	4.457238	0.70475	1.850047	0.707047
13	2.726862	1.33358	1.256883	0.55204	6.372811	0.857255
14	1.265226	0.69222	2.848114	1.13423	4.342858	0.259422
15	1.172638	0.98189	1.552912	1.09591	1.168933	0.782221

C, conventional mounting technique; V, virtual mounting technique

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Supplementary table 6. Standard deviation of each coordinates for #26

Subject	Cx(mm)	Vx(mm)	Cy(mm)	Vy(mm)	Cz(mm)	Vz(mm)
1	2.246858	0.76204	1.112213	0.80138	1.111982	0.81793
2	1.586507	1.10062	2.214741	0.615124	1.638771	0.927275
3	1.436077	0.68353	2.399139	1.138145	1.979313	0.756899
4	2.631497	1.885858	3.023672	0.990363	0.42013	1.062247
5	1.864425	0.743411	2.322762	0.723196	2.094456	0.841759
6	0.960196	0.958137	1.358535	1.38461	0.77364	0.771576
7	0.979272	1.713551	2.268616	1.333397	3.099446	0.403327
8	1.626708	0.801901	1.828128	0.563599	0.720192	0.980849
9	1.0893	2.157323	1.159483	1.028031	2.722594	0.751201
10	2.358225	0.985002	1.98704	0.58308	2.917493	1.048008
11	3.165723	1.173083	2.024389	0.996069	0.441337	0.31918
12	2.218095	0.884681	3.616017	0.846067	2.785817	0.423364
13	2.784798	1.280208	1.325475	0.186325	6.145281	0.673661
14	1.196102	0.72431	2.31899	0.46762	4.590952	0.598703
15	1.197142	0.983875	1.878922	0.993333	1.535132	0.754218

C, conventional mounting technique; V, virtual mounting technique

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Supplementary table 7. Coordinate values of #11 according to the number of trials

Order of Repetition	Subject	Cx	Vx	Cy	Vy	Cz	Vz
1	1	1.7104	2.8611	1.34	14.7741	585.2681	587.9949
	2	1.527	3.0286	10.7433	15.568	579.2816	576.266
	3	6.1582	6.4436	4.9126	13.0757	591.2545	588.3946
	4	5.8202	7.9869	15.3797	16.9227	591.6124	586.0261
	5	3.4836	4.8177	9.2698	17.0521	586.312	580.1771
	6	6.6678	8.2617	10.1602	9.7893	586.442	584.3655
	7	5.686	5.6351	12.3615	20.4533	587.6111	587.0933
	8	4.4131	5.4838	12.9498	17.838	586.9499	585.3101
	9	6.1753	5.5201	10.0438	14.2758	591.059	583.8799
	10	7.9874	6.7053	-5.9247	6.529	584.3834	589.8192
	11	4.0703	5.0537	6.657	17.8049	592.9933	586.5838
	12	5.7459	3.4269	-3.3492	8.3278	590.647	586.4499
	13	10.4638	7.266	5.2973	9.7706	580.0813	588.5129
	14	4.0403	5.0629	12.1093	19.2358	594.1094	588.6362
	15	4.3357	3.2747	4.0699	14.5624	590.0557	592.658
2	1	2.9852	1.165	2.2881	16.1205	584.1472	588.2723
	2	4.8214	0.1446	13.4005	16.5292	578.1086	576.2157
	3	4.6815	8.2233	9.3873	15.093	594.5491	588.1695
	4	6.47	7.2988	11.6125	17.3815	593.7813	587.402
	5	7.5079	4.5388	5.934	17.9177	587.7987	580.9418
	6	6.054	8.7739	9.1981	9.6446	584.8027	585.5703
	7	6.4459	5.1162	17.8886	20.8818	590.7034	588.4581
	8	4.2609	7.1435	11.4545	18.3267	585.9567	588.3475
	9	6.6893	6.3878	11.7122	12.1554	590.3781	584.3997
	10	1.895	6.2793	-5.7358	5.4238	589.8515	589.8259
	11	7.855	4.9856	6.7308	16.5939	593.0864	586.1882
	12	4.7565	5.2854	6.3646	7.8284	585.0916	587.493
	13	5.8148	4.4121	4.6681	8.8236	596.5938	587.6308
	14	7.1714	5.4327	11.3195	19.8942	596.1979	588.1583
	15	6.2255	1.6177	5.2567	14.4879	588.8212	592.0629
3	1	2.8432	2.7115	-0.7462	13.8259	584.4546	587.1978
	2	1.0247	1.8779	8.3787	16.1698	579.535	578.212
	3	8.1705	7.3819	10.3241	13.4973	594.0894	588.576
	4	5.9061	5.7679	9.9658	15.9663	594.188	586.9348
	5	6.4996	5.5142	11.2731	17.6618	581.6717	583.0452
	6	7.5587	6.5307	8.1592	9.3445	584.9859	586.064
	7	6.1201	2.1641	14.9791	19.6144	592.0922	588.3663
	8	4.1975	5.2771	7.6167	18.4014	587.3652	586.2206
	9	6.4316	4.166	12.0183	13.405	588.269	582.4732
	10	3.0475	5.5395	-4.2998	6.0043	587.8209	590.8394

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	11	5.2415	5.4757	8.1975	16.9501	591.9824	586.3549
	12	5.0075	3.4267	-3.7218	6.5449	589.0207	585.7848
	13	10.6122	6.3631	7.2212	9.0907	589.9442	587.9067
	14	6.225	5.4653	14.6841	19.1023	588.7863	589.1308
	15	4.2454	2.9421	5.9503	14.7669	592.3437	593.5195
4	1	-2.9666	0.7431	2.1246	15.2014	586.3671	588.5252
	2	1.7764	2.0794	8.3393	16.6715	579.8455	576.0414
	3	4.7233	7.0884	7.2603	12.623	590.0572	586.5795
	4	5.1423	7.9587	13.6079	15.9641	592.065	585.8848
	5	5.3056	5.6732	7.2111	16.0835	585.1056	582.1924
	6	6.788	6.0744	10.4731	9.0865	585.7979	584.8301
	7	7.2642	6.9437	14.904	17.6849	593.5647	587.6008
	8	5.3446	5.6969	12.1158	17.8162	584.9882	587.7831
	9	6.5889	0.3483	9.1489	14.391	587.0955	583.7759
	10	5.1131	4.8563	-1.7199	4.6628	589.99	591.8199
	11	1.1907	4.7955	8.5265	18.1348	592.7513	586.6705
	12	6.1279	4.0912	1.292	7.7604	587.2994	587.0719
	13	11.0165	6.4505	3.931	8.7811	589.1316	589.5793
	14	5.9093	4.5617	10.1864	18.0988	589.7852	589.3571
	15	4.411	3.3764	3.2017	16.7045	591.2676	592.4259
5	1	0.0667	1.9868	3.4499	15.6604	586.5818	588.1052
	2	1.3616	1.8206	7.9297	17.2813	579.9649	577.0875
	3	5.2143	6.3297	12.1193	13.4825	589.438	589.0939
	4	1.1065	4.9532	9.0712	17.5012	593.2595	588.8803
	5	7.1131	4.4431	11.0214	15.7198	582.9213	580.5497
	6	4.8776	8.2593	12.7148	9.756	584.9714	584.6374
	7	5.406	4.7162	14.9696	18.0445	591.44	588.696
	8	5.5936	5.5638	7.6851	19.2257	583.1362	586.185
	9	9.2333	5.1957	10.9474	11.6659	586.5624	583.5278
	10	4.1242	4.8433	-5.508	6.0239	591.7745	590.7003
	11	5.806	3.1927	11.842	16.8696	591.3746	585.5352
	12	0.3302	4.1755	-0.9513	6.9665	590.3802	586.5758
	13	9.9069	7.6846	4.373	8.5969	590.2405	587.1259
	14	6.8187	3.76	7.6155	19.7252	588.755	588.9634
	15	5.0148	3.8962	7.5449	15.9944	591.8329	592.1402

There is no unit because it is a coordinate value in space; C, conventional mounting technique; V, virtual mounting technique

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Supplementary table 8. Angle between Y-axis and the Reference articulator

	Y Coordinate	Z coordinate
1	16.7378	650.785
2	5.2679	650.4512
3	-8.3294	650.6381
4	-21.3623	650.2887
5	-35.704	650.1708

	Δz/Δy	θ (radian)	θ (degrees)	mean θc (degrees)
1&2	0.0291	0.0291	1.6670	**0.635894***
1&3	0.0059	0.0059	0.3358	
1&4	0.0130	0.0130	0.7463	
1&5	0.0117	0.0117	0.6710	
2&3	-0.0138	-0.0137	-0.7875	
2&4	0.0061	0.0061	0.3496	
2&5	0.0068	0.0068	0.3921	
3&4	0.0268	0.0268	1.5357	
3&5	0.0171	0.0171	0.9780	
4&5	0.0082	0.0082	0.4710	

(Left) Set 5 points randomly on the horizontal reference plane of the Reference articulator and project in orthogonally on the YZ plane. There is no unit because it is a coordinate value in space. **(Right)** Calculate the average value after calculating the angle of the Y-axis and the line formed by two points in 10 pairs by the combination formula. Add the marked average value(*) to the mean θ value in Supplementary Table 9.

Supplementary table 9. Angle of the occlusal plane

		Conventional					Virtual				
No.	Order of Repetitions	Δz/Δy	θ (radian)	θ (degrees)	SD θc (degrees)	mean θc (degrees)*	Δz/Δy	θ(radian)	θ (degrees)	SD θv (degrees)	mean θv (degrees)*
1	1	-0.1953	-0.1929	-11.053	1.32442	13.7854	-0.0503	-0.0502	-2.8772	1.3088	4.8780
	2	-0.2296	-0.2257	-12.931			-0.0883	-0.0881	-5.0458		
	3	-0.2569	-0.2514	-14.407			-0.0744	-0.0743	-4.2554		
	4	-0.252	-0.2469	-14.145			-0.1045	-0.1041	-5.9639		
	5	-0.2348	-0.2306	-13.211			-0.0536	-0.0536	-3.0683		
2	1	-0.2757	-0.269	-15.414	0.72895	16.0654	-0.1514	-0.1503	-8.6105	1.8777	7.6942
	2	-0.2786	-0.2717	-15.568			-0.1365	-0.1357	-7.7747		
	3	-0.2742	-0.2676	-15.334			-0.1177	-0.1172	-6.7142		
	4	-0.2951	-0.2869	-16.44			-0.1448	-0.1438	-8.2419		
	5	-0.2566	-0.2512	-14.392			-0.0691	-0.0689	-3.9501		
3	1	0.06657	0.06647	3.8085	1.95701	-5.3877	0.10829	0.10787	6.18071	0.5140	-6.324
	2	0.15165	0.1505	8.62324			0.12515	0.1245	7.13343		
	3	0.12397	0.12334	7.06682			0.13303	0.13225	7.57762		
	4	0.07748	0.07732	4.43016			0.11952	0.11895	6.81548		
	5	0.10844	0.10802	6.1891			0.12438	0.12375	7.09031		
4	1	-0.2151	-0.2118	-12.138	2.6041	9.300	-0.0663	-0.0662	-3.7925	1.1239	2.7548
	2	-0.1161	-0.1156	-6.6209			-0.0364	-0.0364	-2.0875		
	3	-0.1084	-0.108	-6.1865			-0.0439	-0.0439	-2.5136		
	4	-0.1878	-0.1856	-10.637			-0.021	-0.021	-1.2022		
	5	-0.1359	-0.1351	-7.7411			-0.0174	-0.0174	-0.9988		
5	1	-0.2438	-0.2391	-13.702	0.6847	14.6137	-0.2046	-0.2018	-11.562	1.2387	10.886
	2	-0.2691	-0.2629	-15.064			-0.1923	-0.19	-10.886		
	3	-0.2346	-0.2304	-13.204			-0.1567	-0.1555	-8.9084		
	4	-0.2467	-0.2419	-13.859			-0.1573	-0.156	-8.9399		
	5	-0.2504	-0.2454	-14.06			-0.1936	-0.1912	-10.955		
	1	-0.2095	-0.2065	-11.834			-0.2907	-0.2829	-16.208		

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6	2	-0.23	-0.2261	-12.953	1.7153	13.4421	-0.1976	-0.1951	-11.18	3.2458	14.414
	3	-0.2375	-0.2332	-13.361			-0.1888	-0.1866	-10.69		
	4	-0.2722	-0.2658	-15.228			-0.3271	-0.3161	-18.112		
	5	-0.1881	-0.186	-10.655			-0.2253	-0.2216	-12.699		
7	1	-0.1504	-0.1493	-8.554	2.5286	9.1078	-0.0427	-0.0427	-2.4438	1.5830	1.217
	2	-0.0986	-0.0983	-5.6319			-0.0344	-0.0344	-1.9729		
	3	-0.1674	-0.1658	-9.5014			-0.0026	-0.0026	-0.1489		
	4	-0.1157	-0.1152	-6.6021			0.00624	0.00624	0.35751		
	5	-0.2138	-0.2107	-12.07			0.02274	0.02274	1.30266		
8	1	0.13822	0.13735	7.86952	2.1353	-4.6854	0.16729	0.16575	9.4968	1.3868	-9.997
	2	0.05156	0.05152	2.95177			0.20502	0.20221	11.586		
	3	0.12099	0.12041	6.89877			0.22326	0.21966	12.5856		
	4	0.09572	0.09543	5.46782			0.16745	0.16591	9.50573		
	5	0.05974	0.05966	3.41853			0.17618	0.17439	9.99206		
9	1	-0.2275	-0.2237	-12.817	3.3633	11.2705	-0.1332	-0.1324	-7.5876	0.3614	8.2573
	2	-0.2508	-0.2458	-14.082			-0.1448	-0.1438	-8.2395		
	3	-0.1066	-0.1062	-6.0868			-0.128	-0.1274	-7.2966		
	4	-0.2127	-0.2096	-12.009			-0.1315	-0.1308	-7.4927		
	5	-0.1437	-0.1427	-8.1788			-0.1315	-0.1307	-7.4907		
10	1	0.03641	0.03639	2.08527	8.5926	2.1551	0.07269	0.07257	4.15769	1.4360	-2.996
	2	-0.0533	-0.0533	-3.0533			0.05706	0.05699	3.26557		
	3	-0.2799	-0.2729	-15.637			0.02261	0.0226	1.29498		
	4	0.11425	0.11376	6.51769			0.08386	0.08366	4.79336		
	5	0.04351	0.04348	2.49143			0.08126	0.08108	4.64539		
11	1	-0.0078	-0.0078	-0.4453	1.8548	0.3479	0.22766	0.22385	12.8256	1.1699	-10.64
	2	0.05014	0.0501	2.87062			0.18604	0.18394	10.5387		
	3	-0.037	-0.037	-2.1189			0.19371	0.19134	10.9631		
	4	0.01949	0.01949	1.11677			0.21459	0.21139	12.1115		
	5	0.0003	0.0003	0.0171			0.17559	0.17382	9.95919		
12	1	0.11124	0.11078	6.34746	3.2233	-0.1656	0.05187	0.05182	2.96911	0.9875	-1.045
	2	-0.012	-0.012	-0.6859			0.02779	0.02778	1.59177		

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	3	-0.0175	-0.0175	-1.0004			0.01167	0.01167	0.66864		
	4	-0.0263	-0.0263	-1.5091			0.01424	0.01424	0.81565		
	5	0.01493	0.01493	0.85552			0.04119	0.04117	2.35879		
13	1	-0.2041	-0.2014	-11.538	1.7782	14.6152	-0.1515	-0.1504	-8.6172	0.9066	9.5781
	2	-0.2344	-0.2303	-13.193			-0.1382	-0.1373	-7.8672		
	3	-0.248	-0.2431	-13.926			-0.1664	-0.1649	-9.4498		
	4	-0.2686	-0.2624	-15.034			-0.1505	-0.1494	-8.5609		
	5	-0.2906	-0.2828	-16.205			-0.1802	-0.1783	-10.216		
14	1	-0.3337	-0.3221	-18.456	2.9846	19.4249	-0.0767	-0.0765	-4.3851	0.6040	4.9434
	2	-0.4355	-0.4107	-23.531			-0.0906	-0.0904	-5.1785		
	3	-0.3101	-0.3007	-17.228			-0.065	-0.0649	-3.7173		
	4	-0.2784	-0.2715	-15.557			-0.0656	-0.0655	-3.7529		
	5	-0.3477	-0.3346	-19.172			-0.0788	-0.0786	-4.5038		
15	1	-0.1359	-0.135	-7.7364	2.5216	8.1849	0.0467	0.04667	2.67387	0.7318	-1.698
	2	-0.1646	-0.1631	-9.3459			0.05089	0.05085	2.91354		
	3	-0.0792	-0.079	-4.5282			0.02616	0.02615	1.49849		
	4	-0.1866	-0.1844	-10.568			0.05233	0.05228	2.99539		
	5	-0.0975	-0.0972	-5.5665			0.02774	0.02773	1.58882		

*, These are the value obtained by adding the angle formed by the Reference articulator and the Y-axis(Supplementary Table 8) to the measured mean θ value.; SD, Standard deviation; θ, angle of the occlusal plane.

`

ABSTRACT (KOREAN)

안궁 이전을 통한 전통적 모형 부착법과 콘빔형 전산화 단층 영상에 기반한 가상 모형 부착법의 반복 재현성 비교 평가

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치과 영역에 디지털 기술이 도입되면서 많은 부분들이 전통적인 방법에서 디지털 기법으로 대체되고 있으나 가상 모형을 가상 교합기로 위치시키는 과정에서 난관에 봉착하게 된다. 환자의 위치 정보를 가상 교합기로 옮기기 위해서는 실제 환자에서 안궁 이전을 시행하여 전통적인 방법으로 교합기에 모형을 부착한 뒤 이를 탁상형 스캐너로 스캔 하여 가상 교합기로 옮겨야 하는데 이러한 과정 자체가 번거롭고 복잡하다. 이러한 단점을 해소하고자 가상 모형을 가상 교합기로 옮기기 위한 많은 기법들이 소개되었으나 아직까지 명쾌한 방법은 채택되지 않았고, 주로 임의로 위치시키는 경우가 많은 실정이다.

이에 본 연구에서는 콘빔형 전산화 단층 영상의 관측 시야가 넓은 경우 두경부 해부학적 구조들 간의 위치정보를 얻을 수 있음에 착안하여 콘빔형 전산화 단층

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영상을 활용한 디지털화된 안궁 이전 기법을 소개하고, 콘빔형 전산화 단층 영상 기반의 가상 안궁을 이용한 가상 모형 부착법과 실물 안궁을 이용한 전통적인 모형 부착법의 정확도 (precision)를 비교하고자 한다. 본 연구의 귀무 가설은 “콘빔형 전산화 단층 영상 기반의 가상 모형 부착법과 실물 안궁을 이용한 전통적인 모형 부착법 간의 정확도 차이는 없다.” 이다.

실험군은 전통적인 모형 부착 그룹 (CM)과, 가상 모형 부착 그룹 (VM) 두 군으로 나뉜다. 두 군을 비교할 때 기준점으로 사용할 반조절성 교합기 (Hanau Modular Articulator System, Whip Mix Corp., Louisville, KY, USA)를 산업용 스캐너로 스캔하여 기준 교합기를 제작한다. CM은 실물 안궁을 이용하여 교합기에 모형을 부착 한 뒤 산업용 스캐너를 이용하여 교합기 전체를 스캔해 기준 교합기와 같은 위치로 정합시킨다. VM은 환자의 콘빔형 전산화 단층 영상 영상을 캐드 소프트웨어 (Exocad cad software, ExocadGmbH, Germany) 상에서 두개골 모형 (STL format)으로 변환하고 안궁을 교합기에 장착한 상태로 산업용 스캐너로 스캔한 가상 안궁을 이용해 두개골 모형을 기준 교합기에 위치시킨다. 두 그룹 모두 중첩의 매개체를 이용해 하나의 대표 모델을 기준 교합기상으로 위치시킨다. 그 뒤 역설계 소프트웨어 (Geomagic Control X, 3D Systems, South Carolina, USA) 상에서 #11, 16, 26 치아에 표적 지점을 설정하고, 3차원 공간좌표에서의 X, Y, Z 좌표값을 구한다.

CM과 VM간의 차이점을 분석하기 위해 표적 지점간의 평균 거리, 각 축별로 측정한 표준편차, #11 치아에서 X, Y, Z축에 대한 기법 별 위치관계, 교합 평면의

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각도라는 4가지 측면에서 비교분석 하였다. 정규성을 평가하기 위하여 Kolmogorov-Smirnov test를 수행하였고, 정규성을 따르는 경우 paired t-test, 그렇지 않은 경우 Wilcoxon signed rank test 수행하였다.

설정한 표적 지점간의 평균 거리는 전통적인 기법이 가상 기법에 비해 유의하게 큰 결과를 보였다 ($P<0.01$). 또한 좌표점들 사이의 표준편차도 전통적인 기법이 가상 기법에 비해 더 크게 측정되었다 ($P<0.05$). 전통적인 기법에서는 다른 축들에 비해서 Z축 (상하) 방향의 표준편차가 특히 높은 경향을 보였다. #11번 치아에서 가상 기법의 경우 전통적인 기법에 비해 더욱 전방으로 위치하였으며 ($P<0.01$) 5번의 반복 횟수 중 1번의 경우에서 (20%) 전통적인 기법이 가상 기법에 비해 더 상방으로 위치하는 경향을 보였다 ($P<0.05$). 교합 평면의 각도는 전통적인 기법이 더 유의하게 컸다 ($P<0.001$).

분석한 네 가지 방법으로 인해 본 연구의 귀무 가설은 기각되었으며 가상 기법이 전통적인 기법에 비해 더 높은 정확도 (precision)를 보이는 것으로 판명되었다. 향후 임상적인 유용성을 검증하기 위해 추가적인 연구가 필요할 것이다.

핵심 되는 말: 가상 교합기, 가상 마운팅 기법, 가상 페이스 보우, 고전적인 방법의 마운팅과 가상 마운팅의 비교, 디지털 치의학, 직접 디지털법, 콘빔형 전산화 단층 영상 기반의 가상 마운팅,