Target Registration Errors in Navigation-assisted Mandibular Surgery According to the Tracking Methods and the Type of Markers

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Research

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Abstract

Background:

This study was conducted to evaluate the accuracy of navigation process according to the type of tracking methods and registration markers. The target registration errors (TREs) were measured at seven anatomical landmarks of the mandible for evaluation.

Methods:

Four different experiments were performed to obtain the TREs using two different tracking methods, the optical tracker (Polaris) and the electromagnetic (EM) tracker (Aurora), and two different types of registration markers, invasive and noninvasive markers. All comparisons of TREs were statistically analyzed using SPSS and Python-based statistical package (Pingouin).

Results:

The average TRE values obtained from the four different experiments were as follows: 1) 0.85 mm using invasive marker and Aurora, 2) 1.06 mm using invasive marker and Polaris, 3) 1.43 mm using noninvasive marker and Aurora, and 4) 1.57 mm using noninvasive marker and Polaris. All comparisons among the type of markers and the seven anatomical landmarks revealed statistically significant differences, except for the type of tracking system. Although the comparison between the modality of the tracking system showed no significant differences, the EM-based approach consistently demonstrated better performances than the optical type in all comparisons.

Conclusions:

This study demonstrates that, irrespective of the tracking modality, the invasive marker is a better choice in terms of accuracy. When using the noninvasive marker, it is important to consider the increased TREs. In the present study, the noninvasive marker caused a maximum increment of TREs of approximately 0.81 mm compared with the invasive marker. Furthermore, EM-based tracking using an invasive marker may result in the best accuracy for the mandible.

Background

Computer-aided radiology and surgery (CARS) uses navigation surgical instruments or three-dimensional (3D)-printed surgical apparatuses based on preoperative simulation surgery and 3D skeletal analysis using maxillofacial computed tomography (CT).[1] Currently, CARS is being applied in clinical practice.

Computer-assisted navigation allows the surgery to be performed according to the preoperative treatment plan using preoperative imaging data during the surgery with real-time images to identify the major anatomical structures that are difficult to visualize.[2] Therefore, the popularity of this technique is increasing in the field of oral and maxillofacial surgery.

Although computer-assisted and image-guided surgeries that combine computer-generated images (e.g., CT images) and the actual anatomical environment of patients are widely used in craniofacial surgery, they have limited applications in mandibular surgery.[3] Although the mandible and the cranium are connected by the temporomandibular joint, they actually move independently. The soft tissue components of the mandible generate significant movements during surgeries that require opening and closing of the mouth. However, computer-assisted mandibular surgery can enhance the accuracy of the operation by identifying those locations of major anatomical structures that are difficult to visualize; therefore, it is necessary to investigate navigation errors.[4]

Navigation surgery is performed under the guidance of a position tracking system using navigation surgical instruments based on the preoperative imaging data of the patient. This surgery is performed by confirming the position of the surgical instruments and the anatomical landmarks at the surgical site by tracking the surgical tools during the operation.[5] However, even image- and computer-assisted surgeries, such as navigation surgery, are prone to errors, and a major cause of such errors could occur during the image registration process for coordinate matching between the CT images and the anatomical structures.

In navigation surgeries, it is essential to minimize errors, especially those that occur during the registration process. Therefore, this study was conducted to investigate the errors that occur during the registration process of mandibular navigation surgery and to evaluate the target registration errors (TREs) depending on the tracking method for mandibular movements and the type of markers used during the registration process.

Methods

Mandibular experimental model

Mandibles from six human cadavers (Skulls Unlimited International, Inc., Oklahoma City, OK, USA) were used as experimental models, and none of them had any mandibular defects. Clinically available markers were used for the navigation experiment. Screws were inserted in the mandibular model as invasive markers, and noninvasive markers were attached. Dual-top screws (Jeil Medical Corporation, Seoul, Republic of Korea) are generally placed at an approachable position for actual use as registration markers in clinical practice, and in the present study, they were used as invasive registration reference markers. The same number of screws (n = 5) were placed in each model. Five screws were placed as markers in the following manner: one screw 6 mm below the mandibular central incisor root apex, and two screws each on both sides of the alveolar region above the mental foramen and in the posterior region of the mandibular second molar.

In addition, five noninvasive markers, 1-mm-thick and made of gutta-percha (Meta Biomed Co. Ltd., Cheongju-si, Republic of Korea), were attached to the alveolar region of the mandibular central incisors, premolars, and molars. The noninvasive markers were attached at the top of the alveolar bone in the mandibular area that was anteriorly and posteriorly similar to that used for the invasive markers.

For measuring the TREs of the anatomical landmarks for recognition images of the areas used for measuring errors according to the superimposition method, small holes were made at seven mandibular landmarks (condylar head, condylar neck, coronoid process, sigmoid notch, posterior border, antilingula, and mandibular angle). These holes were filled using gutta-percha (Meta Biomed Co.) to mark the anatomical landmarks for error measurements (Fig. 1).

TRE measurement and navigation tracking using Polaris optical tracker, Aurora electromagnetic tracker, and 3D Slicer medical image software

Navigation testing was performed using Polaris optical tracking system, Aurora EM tracker, and 3D Slicer to achieve higher reliability of the experiment. In the present study, the TRE in the mandibular anatomical landmarks was measured by two different tracking methods using two different types of markers. For the registration reference marker, five screws were used as invasive markers, whereas gutta-percha points attached to the alveolar bone of the mandible were used as noninvasive markers.

The TRE corresponding to each of the five registration markers was measured using the following two types of experimental equipment in the navigation surgery: Polaris optical tracker (Northern Digital Inc., Waterloo, Canada) and Aurora electromagnetic (EM) tracker (Northern Digital Inc.).

Polaris optical tracking system

Polaris tracker, an optical tracker installed in the surgical navigation equipment, was used for the tracking system that can retrieve spatial coordinate values of the mandibular model. The registration process of surgical navigation was performed according to the relative positional change in the Polaris probe with respect to the reference frame (RF) attached to the mentum of the mandibular model (Fig. 2).

The placement of the RF was based on the fact that the RF continuously tracks the actual position and the movement of patients and that the mandible exhibits relatively significant movement. The RF was set up on the mentum at the center of the mandible to avoid damage to the teeth in clinical use (Fig. 3). In addition, the optical sensor attached to the RF and the navigation probe was always directed toward the position sensor, ensuring there was no other object in the middle blocking the path.

Aurora electromagnetic tracking system

The Aurora tracker, based on the EM tracking method and installed in the surgical navigation equipment, was used as the tracking system that can retrieve spatial coordinate values of the mandibular model. The process of navigation registration was based on the relative positional change in the Aurora probe with respect to the tracking reference (TR) attached to the mentum of the mandibular model (Fig. 4). The TR was set up on the mentum of the center of the mandible, similar to the Polaris optical tracking system. The EM generator was placed at the bottom of the very center of the mandible to avoid influence from the left and right sides (Fig. 5).

Registration and transformation algorithm in the 3D Slicer medical image software

The 3D Slicer (open source medical software) was used for reproducing the surgical navigation registration experiment and the TRE measurements. This navigation software supports multipurpose visualization, and it is based on the open source software platform for medical image computing connected to the image-guided therapy (IGT) equipment through an open IGT link. The open IGT link uses the TCP/IP network communication protocol for connection to the two types of trackers (Polaris and Aurora) used in the present study.

The mandibular CT data in DICOM format were imported into the Slicer program. After rendering to 3D format, the data were registered using the markers attached to the mandibular models. The Polaris optical tracker and the Aurora EM tracker were tested on the basis of the registration error using the 3D Slicer software with realization of the navigation surgical method.

In the 3D Slicer program, the 3D Slicer-IGT module was used for landmark registration. The 3D Slicer-IGT module calculates the transformation between point pairs of registration markers based on the “vtkLandmarkTransform” technique. This module has the following three types of transformations: 1) rigid transformation with only translational and rotational transformations, 2) similarity transformation with translational, rotational, and size transformations, and 3) warping transformation using spline interpolation. In the present study, registration was performed using the rigid transformation type, which cannot control the size of models that are targeted for registration.

TRE measurement

After completing the registration process of matching the actual mandibular model coordinates and the CT image coordinates in the 3D Slicer, the target points were marked on the condyle, ascending ramus, coronoid process, sigmoid notch, posterior border, antilingula, and mandibular angle within the Slicer to display the anatomical landmarks for TRE measurements. The TREs were measured at all target points using a probe. For all six mandibular models, the measurements at the anatomical landmarks were repeated three times for each model, and this method was repeated for the four different experimental conditions. The unit of measure was 0.001 mm. The TRE was calculated with the 3D distance error of each anatomical landmark between the actual mandibular model coordinates and the CT image coordinates (Fig. 6).

Statistical analysis

Two different experimental equipment and two types of registration markers were used in the present study to derive TREs for the seven anatomical landmarks. In the experiment, the mean errors of TREs were compared for the seven anatomical landmarks and the four experimental conditions.

Variance between sample groups for the different conditions was tested by Levene's homogeneity of variance test. If the homogeneity of variance was satisfied, the analysis of variance (ANOVA) and Scheffe's post hoc test were used; otherwise, the nonparametric Kruskal–Wallis test and the Games-Howell post hoc test were used. For ANOVA and Scheffe's post hoc test, the Statistical Package for the Social Sciences 23.0 software (SPSS Inc., Chicago, IL, USA) was used to assess the statistical significance. For the Kruskal–Wallis test and the Games-Howell post hoc test, Pingouin (Python3 open source statistical package) was used to test the statistical significance. Values of $p < 0.05$ were considered to be statistically significant.

Results

Regarding the TREs measured according to the registration markers of the surgical navigation process, there were fewer errors in the experiment with invasive markers irrespective of the type of tracking devices. When the Polaris optical tracker was used, the mean error from all measured areas was ≤ 1.3 mm with invasive registration markers and ≤ 2.1 mm with noninvasive registration markers. When the Aurora EM tracker was used, the mean error from all measured areas was ≤ 1.0 mm with invasive registration markers and ≤ 1.7 mm with noninvasive registration markers (Table 1).

All the seven mandibular anatomical landmarks exhibited significant differences in TREs under the four different experimental conditions. With respect to the four different experimental conditions, the results demonstrated significant differences for the seven different anatomical landmarks under three experimental conditions, excluding the one experimental condition using the Aurora EM tracker and invasive markers.

TREs according to mandibular anatomical landmarks

The ANOVA and Kruskal–Wallis ANOVA were used to determine whether the TREs obtained from one anatomical landmark exhibited differences under the four different experimental conditions. The tests were performed on all the target landmarks (seven anatomical landmarks), and based on the results, the same conclusion was reached for all the target landmarks that there were significant differences under at least one of the four experimental conditions ($p < 0.001$*; Table 1).

To analyze the results, the TREs obtained from each anatomical landmark were compared by pairwise comparisons using Scheffe's post hoc test and the Games-Howell post hoc test. Significant differences were observed between the experiment performed using the Polaris optical tracker with invasive markers and the experiment performed using the Polaris optical tracker with noninvasive markers for all the target landmarks ($p < 0.001$*; Table 2). Significant differences were also observed between the experiment performed using the Aurora EM tracker with invasive markers and the experiment performed using the Aurora EM tracker with noninvasive markers ($p < 0.001$*; Table 2). On the basis of these results, it was determined that significant differences in TREs were found when different types of markers were used in registration, irrespective of the tracker used.

When the mean differences in TREs obtained under each experimental condition were compared, the Aurora EM tracker with invasive markers exhibited the smallest mean error (approximately 0.85 mm) for all the target landmarks. The second smallest mean error (approximately 1.06 mm) was found for the Polaris optical tracker with invasive markers. Thus, the TREs were smaller for all the target landmarks when invasive markers were used compared with the use of noninvasive markers, irrespective of the tracker used.

Regarding the anatomical landmarks, the condyle exhibited the largest mean error among all anatomical landmarks. When the Aurora EM tracker was used with invasive markers, the ascending ramus displayed the smallest mean error of 0.73 mm, and when it was used with noninvasive markers, it still exhibited the smallest mean error of 1.25 mm. When the Polaris optical tracker was used with invasive markers, the mandibular angle displayed the smallest mean error of 0.92 mm, and when it was used with noninvasive markers, the antilingula, the posterior border, and the coronoid process exhibited the smallest mean error of 1.44 mm.

TREs according to the four different experiments consisting of two tracking devices and two marker types

The TREs were statistically analyzed under the four different experimental conditions, representing all possible conditions using two experimental equipment (Polaris optical tracker and Aurora EM tracker) and two types of registration markers (invasive and noninvasive). The ANOVA and the Kruskal–Wallis ANOVA were used for analyzing all experimental conditions to determine whether the TREs obtained under one experimental condition showed differences according to the anatomical landmarks. The results demonstrated that all experimental conditions, except one (using Aurora EM tracker with invasive registration marker), exhibited a significant difference in at least one of the seven anatomical landmarks. To identify this significant difference between the anatomical landmarks, Scheffe's post hoc test and the Games-Howell post hoc test were used for multiple comparisons (Table 2).

When the Polaris optical tracker was used, the TREs measured for the different anatomical landmarks exhibited significant differences for all landmarks, irrespective of the type of markers used ($p < 0.001$*). When invasive markers were used, the mean error was the smallest for the mandibular angle (0.92 mm) and the largest for the condyle (1.33 mm). When noninvasive markers were used, the mean error was again the largest for the condyle (2.14 mm). Among the TREs obtained for all anatomical landmarks using the Polaris optical tracker, the mean error of registration with invasive markers was 1.06 mm, which was approximately 0.5 mm lesser than that obtained with noninvasive markers (1.57 mm).

When the Aurora EM tracker was used, the TREs measured at different anatomical landmarks exhibited significant differences for all landmarks with noninvasive markers, but not with invasive markers. In other words, there were fewer errors in all anatomical landmarks when the registration was performed with invasive markers, similar to that observed with the Polaris optical tracker. When invasive markers were used, the mean error was the smallest for the ascending ramus (0.73 mm) and the largest for the condyle (0.98 mm). When noninvasive markers were used, the mean error was the smallest for the ascending ramus (1.25 mm) and the largest for the condyle (1.77 mm).

Discussion

Regarding the TREs at the different mandibular anatomical landmarks according to the types of registration marker used in the surgical navigation process, the smallest errors were found when the Aurora EM tracker was used with invasive markers. Based exclusively on the marker methods, the invasive markers (screws) used as registration markers exhibited smaller TREs than the noninvasive markers (gutta-percha points).

For navigation surgery, two methods are available for registering images and the physical body, viz., marker-based and marker-free registration.[6,7] The technique of placing screws as applied in the present study is an invasive method, which demonstrated fewer errors than using noninvasive markers with gutta-percha. Although it may be necessary to evaluate whether the gutta-percha used in the present study demonstrates sufficient functionality as a marker, noninvasive markers with gutta-percha can be an alternative marker method in mandibular surgery.

Marker-based registration uses reference markers that are clearly visible on CT images and easily identifiable for registration. In contrast, marker-free registration uses anatomical landmarks based on the anatomical structure of the patient or laser surface scanning for registration. To determine which method is more accurate, additional studies with varying surgical sites and methods are required. Using noninvasive markers in surgeries could be helpful for patients; therefore, further studies are necessary to assess marker methods optimized according to the patient and surgical characteristics and based on the additional studies on various noninvasive markers.

In the present study, TREs were derived and compared using optical and EM trackers, which are the tracking methods used in the surgical navigation system. The results demonstrated that using the Aurora EM tracker exhibited fewer errors than using the Polaris optical tracker. The Polaris optical tracker used in the present study was a Vicra version manufactured for use in maxillofacial surgery. According to the manufacturer's specifications, the volumetric accuracy of the tracker is 0.25 mm RMS with a 95% confidence interval of 0.5 mm RMS. In the Aurora EM tracking system, planar field generator and 6-degree of freedom sensors were used, and the experiment was conducted at cube volume. The tracker had positional and orientation accuracies of 0.48 mm RMS and 0.30°, respectively, with 95% confidence intervals of 0.88 mm RMS and 0.48°, respectively.

The optical tracking system has an approximately equal accuracy to that of the EM tracking system.[8] However, the biggest disadvantage of using an optical system is that all the trackers in all the cameras used require a direct line of sight for all targets. Hence, even a slight slope between the probe tip and the tracker could cause an error. Moreover, an optical tracking system may not be suitable for tracking needles or flexible objects.

For safe navigation surgery, tracking errors must be considered and reduced. Optical navigation systems could provide an accuracy of 0.1–0.4 mm for positional measurements, but the optical camera requires warming up for 15–30 min before the start of the surgery.[9] The trackable field size is approximately 100 × 100 × 100 cm. Errors may occur when the vector angle between a stereo optical camera, probe, and surgical instrument is ≥ 60°.[9] In the present study, the results may have been influenced by the position and angle of the probe and the size, angle, and length of the optical tracker. However, it was determined that such factors would have very little influence on the primary objective of the present study, which was to investigate the differences according to the type of registration markers and tracking methods.

Compared with optical navigation systems, EM navigation systems have a narrow measurement field, but they have the disadvantage of errors caused due to metallic instruments.[10] In this study, the Aurora EM tracker exhibited fewer errors, especially for the mandibular condylar head that showed the largest error with the optical tracking system, where the mean error was 1.3 mm with invasive markers and 2.1 mm with noninvasive markers. In contrast, the Aurora EM tracker with invasive markers exhibited a significant difference of 0.9 mm. A previous study that investigated errors in a plastic skull model using a conventional EM navigation system reported that positioning of the condyle error consisted of a positional error of 0.65 mm and a rotation error of 0.38°.[11]

Because several surgical instruments are made of metal, there is a need for additional studies on the errors caused due to metallic instruments used during surgery when using the EM method on the mandible. In addition to the errors caused by metallic surgical instruments, errors could occur during the registration of information about the surgical equipment. Technical errors may occur in the process of the tracking camera actively (emission detection diode) or passively tracking the dynamic RF attached to the patient and surgical instruments. When RFs are directly attached to the surgical instruments or probes that have been registered in the system program with the navigation system already calibrated, the calibration process is required and the position is subsequently tracked by the camera. Navigation errors may occur if the probe is bent, the information about the instrument is incorrect, or if an error occurred in the calibration process.

Errors in navigation surgery systems may occur due to various factors, including errors during the process of using a computer to superimpose digital images.[9] Technical measurement errors could occur in the proprietary software and hardware, such as a CT scan. There could also be imaging errors according to the software and imaging mode, such as the matrix size, slide thickness, and voxel size. Regarding registration errors, the process of registration after matching the coordinates of imaging data with the anatomical structures of a patient in the navigation system has the largest impact on errors in image-guided surgery. Accordingly, the present study aimed at reporting the registration errors with TREs according to the registration marker and the tracking methods.

Registration errors are those that are generated when the patient's imaging data are linked to the actual physical anatomical parts of the patient.[12] There are paired fiducial points, which are the points determined to represent the same area in the imaging data and the actual patient, and the error that occurs when finding such fiducial points is referred to as fiducial localization error. Furthermore, the error that occurs when the image and the physical body are superimposed during fiducial registration between the image and the patient is referred to as fiducial registration error, whereas the error representing the difference between the anatomical registration points and the actual coordinate values after image and body registration is referred to as TRE. This study investigated the TREs that could occur during navigation surgeries.

The application of the navigation system differs according to the surgery.[4,13] It is necessary to select markers with fewer errors and set their positions, as well as set the RFs that do not interfere with the surgery. The mandible is connected to the cranium by the temporomandibular joint, which is an independent structure as it is flexible and performs significant movements. In mandibular navigation surgery, the mandible remains in the open state or there is traction during surgery, which may cause deviation; therefore, it is important to use reference points on the mandible itself.[7] Accordingly, in the present study, markers on the mandible itself were used, and the RFs were located on the mandible. Furthermore, the RFs were placed on the mentum in the center of the mandible to prevent lateral error. Firm fixation and prevention of rotation are required for RFs. An optical tracker camera was used to fix the angle so that it could be recognized on the screen.

However, in actual surgeries, continued real-time monitoring may be difficult because the head of the surgeon attempting to view the surgical site could block the RF recognition path, unlike the experimental environment used in the present study. Using a navigation system may initially consume a significant amount of time due to a learning curve, but this would eventually decrease. It is necessary to establish a registration method with the least amount of registration errors for the position and number of markers when positioning the RF as suitable for the mandible.

In the present study, the number of markers for superimposing teeth images was set to five. To address errors occurring during registration, at least three nonplanar markers are generally required. The markers used in registration should be placed widely around the anatomical structure in the surgical site and close to the surgical site to ensure high accuracy.[14] In actual surgeries, the use of markers for superimposition may be limited. The use of invasive markers and the positions of the markers should be decided by considering the surgical site and its anatomical structures. The head and neck areas have the characteristic of allowing the use of a bit splint, unlike registration in other surgical areas using mouth and teeth.[15] Noninvasive marker-based registration could be performed by attaching the markers on a template used in navigation surgery. An external RF that uses fiducial markers in denture-fixed acrylic template for mandibular navigation has been reported to demonstrate a registration accuracy that is similar to that of invasive markers placed on the bone but does not entail the invasive process of placing screws as markers. However, it has the disadvantage of fabricating the marker template before imaging and biting down on the template during the CT scan.

The navigation software 3D Slicer supports multipurpose visualization, and it is based on a free open source software platform for medical image computing that provides several high-end functions for this purpose.[16] In particular, it provides various applications for using medical images. The 3D Slicer is connected to IGTs through the Open IGT link, which uses the TCP/IP network communication protocol to enable real-time navigation function by sending and receiving data with various types of tracking systems in the operating room. Therefore, the Polaris optical and Aurora EM trackers could be used to realize the navigation surgery method. Regarding the experimental workflow, mandibular CT data in DICOM format could be imported into the Slicer program, and markers attached to the mandibular model could be used for registration after rendering to the 3D format.

Conclusions

When using a navigation system for the mandible, using invasive markers instead of noninvasive markers and an EM tracker instead of an optical tracker resulted in fewer TREs during the registration process. For all target landmarks, there were significant differences in pairwise comparisons using the Polaris optical tracker between the measurements obtained with invasive markers and those obtained with noninvasive markers ($p < 0.001$*). The same result was obtained in the case of the Aurora EM tracker ($p < 0.001$*). The noninvasive marker exhibited a maximum increment of TRE of approximately 0.81 mm on the condyle compared with the invasive marker. In contrast, no significant difference was observed in each pairwise comparison between the modalities of the tracking system, the optical and EM approaches. Therefore, irrespective of the tracking modality for the mandible, using invasive markers instead of noninvasive markers resulted in fewer TREs during the registration process.

List Of Abbreviations

Computer-Aided Radiology and Surgery (CARS), Three-dimensional (3D), Computed tomography (CT), Target registration errors (TREs), Electromagnetic (EM), Reference frame (RF), Tracking reference (TR), Image-guided therapy (IGT), Analysis of variance (ANOVA), Statistical Package for the Social Sciences (SPSS)

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

HGdesigned the experiments. Acquired, analyzed and interpreted the data. Wrote the manuscript.SH analyzed and interpreted the data.Suggested the main idea and drafted the manuscript. YD reviewed and revised the manuscript. Analyzed and interpreted the data. Finally approved the version to be published.HK designed the article and coordination. Analyzed and interpreted the data. Reviewed and revised the manuscript.All authors approved the final manuscript and agreed to be accountable for all aspects of the work.

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Tables

Due to technical limitations, table 1,2 is only available as a download in the Supplemental Files section.

Figures

Figure 1

A mandibular model for measuring target registration errors. Each model with five invasive markers, five noninvasive markers, and seven holes representing anatomical landmarks.

Figure 2

Experimental mandibular model with reference frames (RFs) attached for the Polaris optical tracking system.

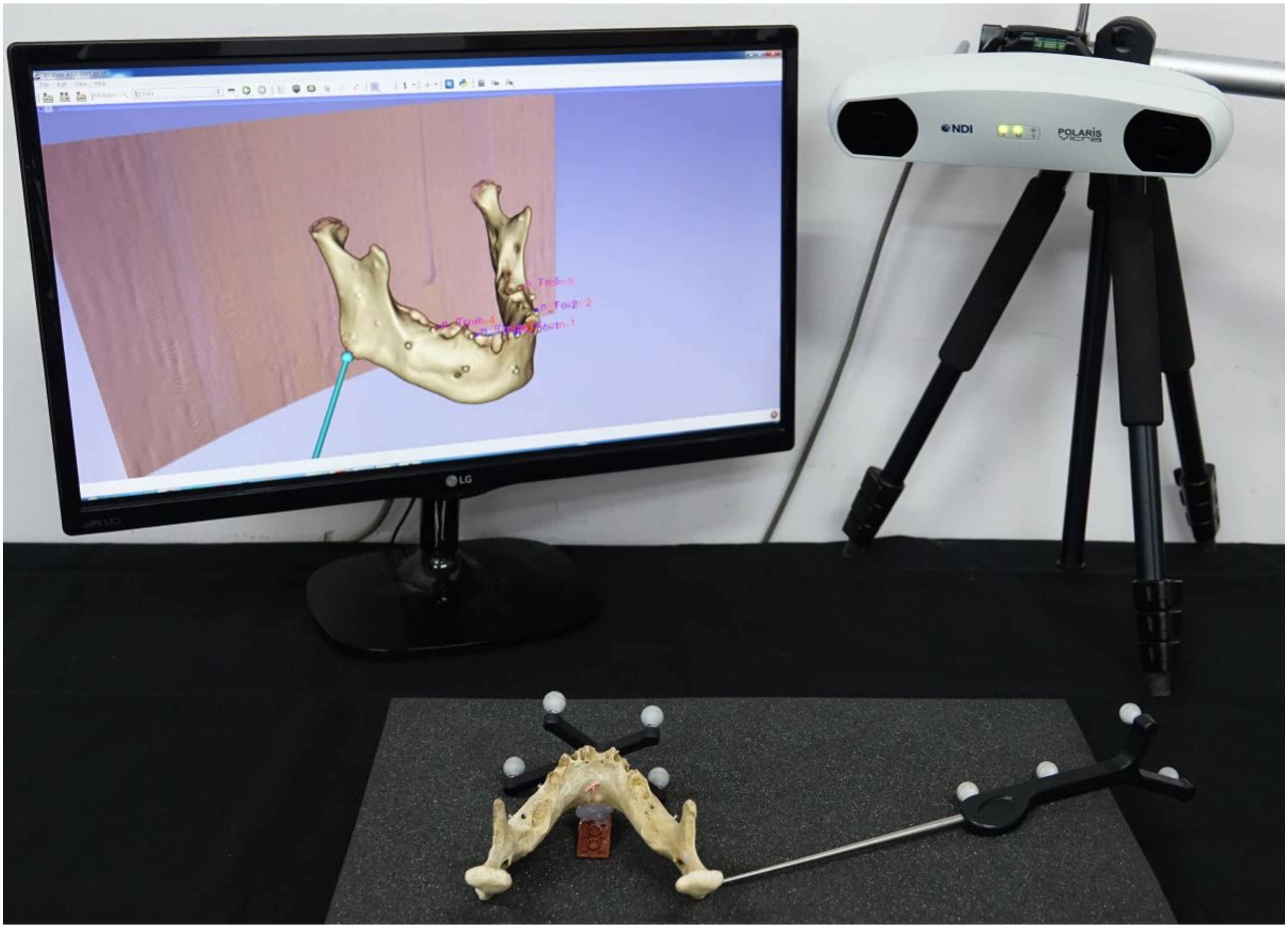

Figure 3

Registration and coordinate tracking process using Polaris optical tracker and the experimental mandibular model with reference frames attached.

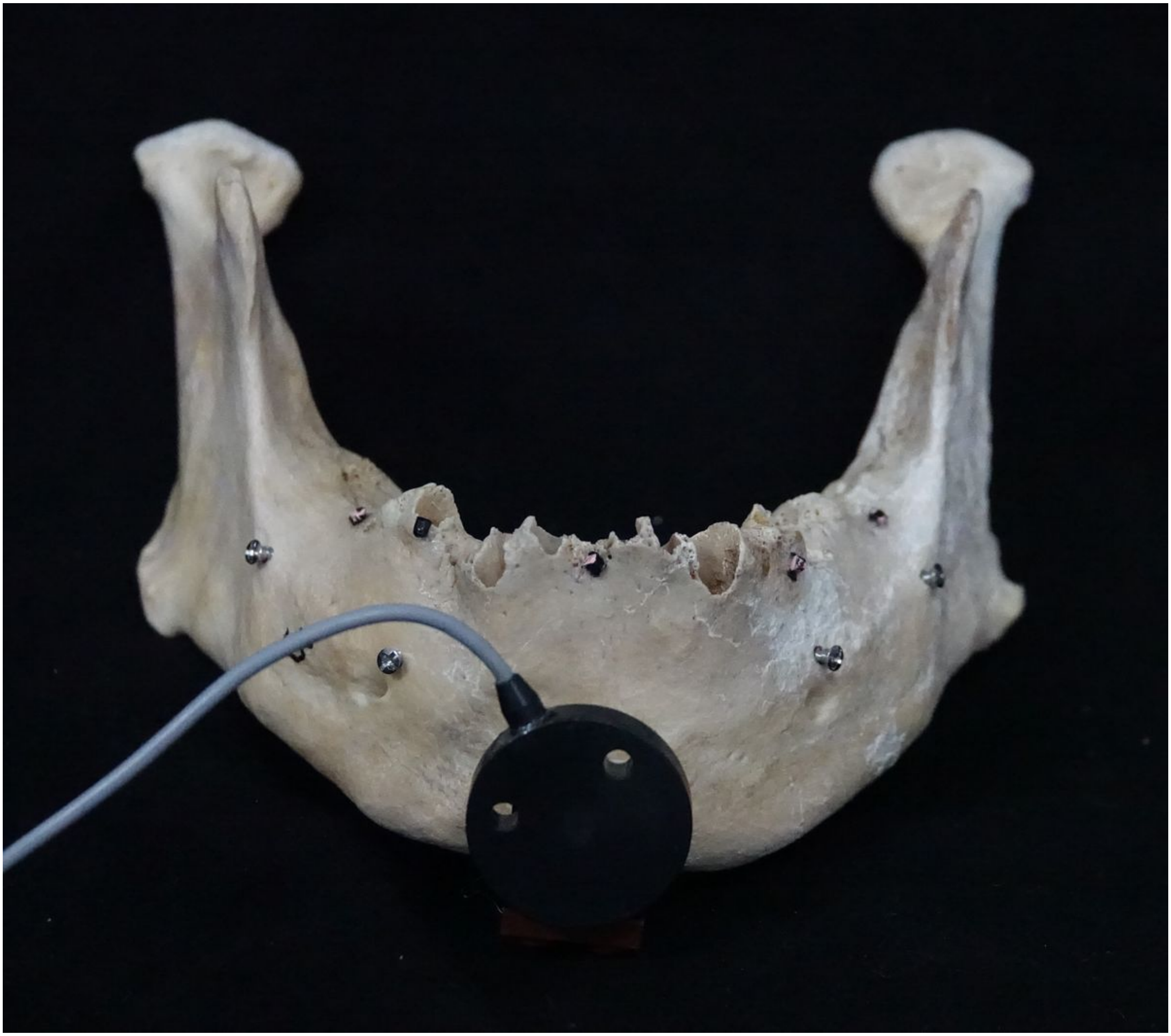

Figure 4

Experimental mandibular model with tracking reference attached for the Aurora electromagnetic tracking system.

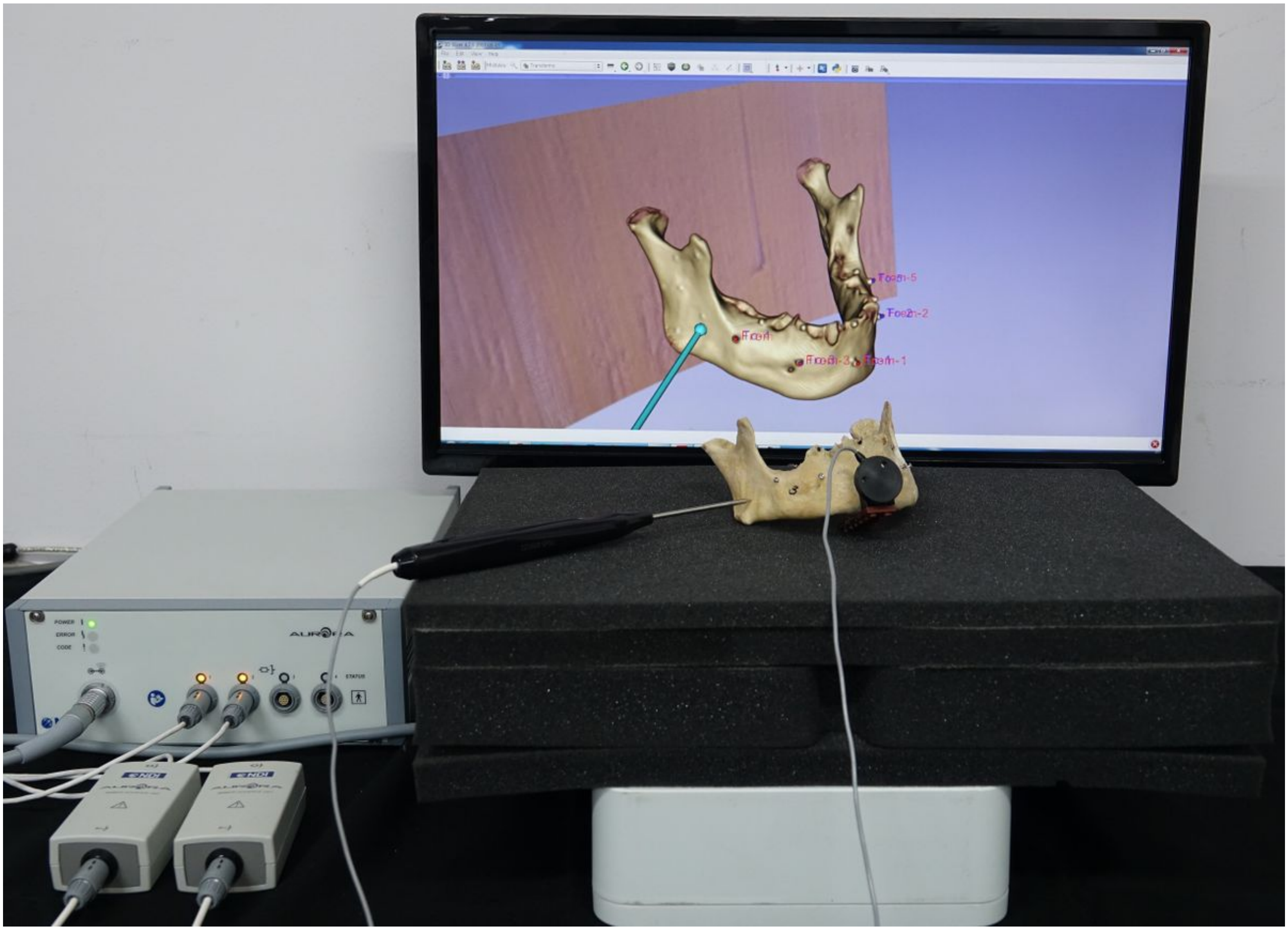

Figure 5

Registration and coordinate tracking process using Aurora electromagnetic tracker and the experimental mandibular model with tracking reference attached. The model is placed above the electromagnetic generator.

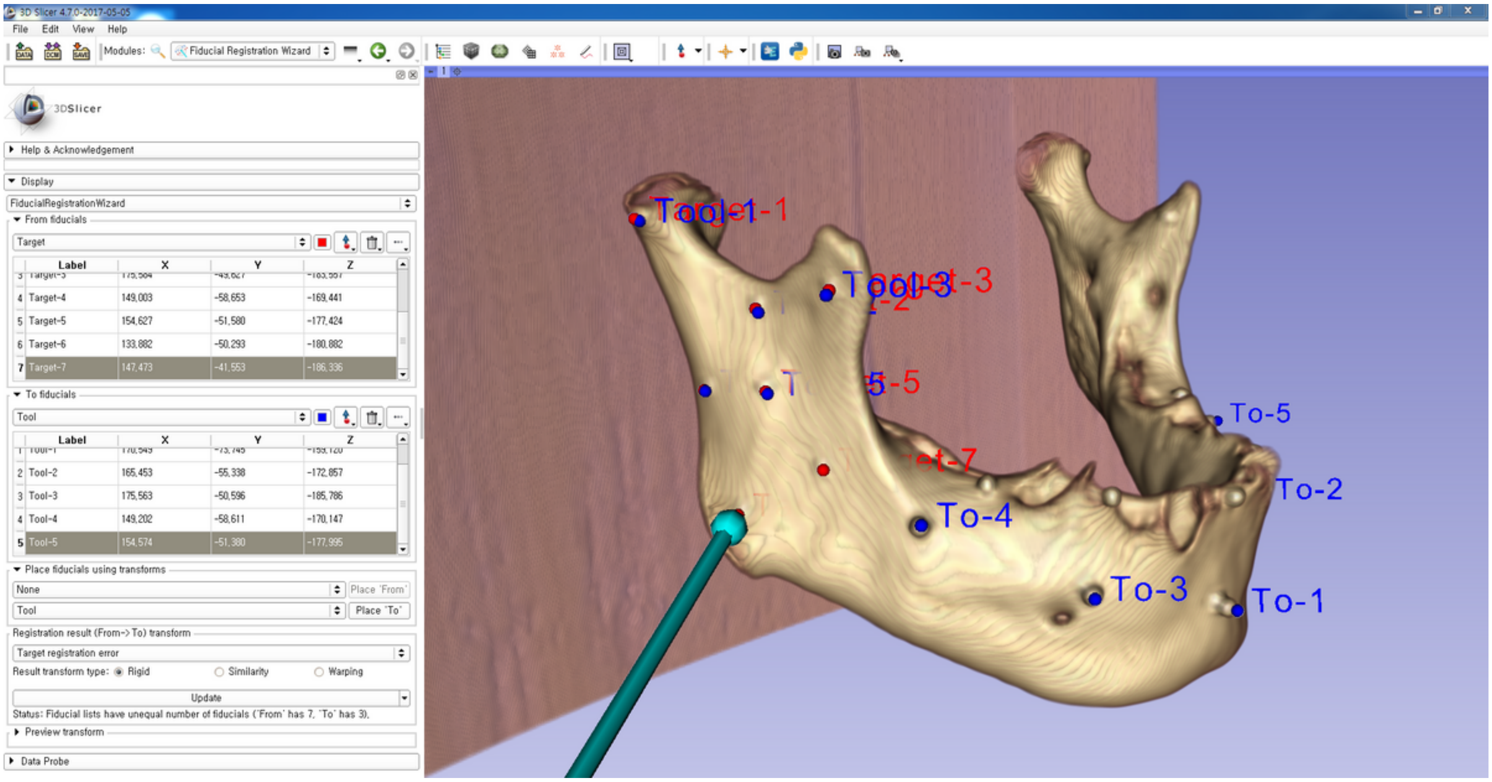

Figure 6

After the registration process between 3D-rendered computed tomography data and actual experimental mandibular model, the target registration error was measured by 3D Slicer, a medical image processing software. (Figure shows the example of measuring target registration error on mandibular angle.)

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.xlsx
- Table2.xlsx