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Three-dimensional measurement and registration accuracy of a third-generation optical tracking system for navigational maxillary orthognathic surgery

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Objective. The purpose of this study was to evaluate the accuracy of an optical tracking system during reference point localization, measurement, and registration of skull models for navigational maxillary orthognathic surgery.

Study Design. Accuracy was first evaluated on the basis of the position recording discrepancy at a static point and at 2 points of fixed lengths. Ten reference points were measured on a skull model at 7 different locations, and their measurements were compared with predicted positions by using 4 registration methods. Finally, positional tracking of reference points for simulated maxillary surgery was performed and compared with laser scan data.

Results. The average linear measurement discrepancy was 0.28 mm, and the mean measurement discrepancy with the 5 registered cranial points was 1.53 mm. The average measurement discrepancy after maxillary surgery was 1.91 mm (for impaction) and 1.56 mm (for advancement). The registration discrepancy in jitter and point registration on the y-axis was significantly greater than on the other axes.

Conclusions. The optical tracking system seems clinically acceptable for precise tracking of the maxillary position during navigational orthognathic surgery, notwithstanding the chance of greater measurement error on the y-axis. (Oral Surg Oral Med Oral Pathol Oral Radiol 2019;128:213−219)

Bimaxillary orthognathic surgery is a corrective procedure that changes the spatial position of maxilla and mandible.[1,2] Accurate positioning of maxilla is a key factor in successful orthognathic surgery.[1-3] The purpose of this study was to evaluate the accuracy of a navigational tracking system for maxillary positioning in orthognathic surgery.

Confirmation of the maxillary position to quantify positional changes for maxillary orthognathic surgery has been described as challenging.[4] Measurement of the 3-dimensional (3D) translocation of the maxilla can be achieved by using various methods.[5-10] Recent developments in navigational or image-guided surgery have helped surgeons evaluate intraoperative and real-time results of maxillofacial, orthopedic, neurosurgical, and ear−nose−throat surgery.[11-14]

Electromagnetic tracking navigation systems have become popular because of the small sizes of the instruments and the ability to do real-time tracking. However, some limitations, such as adjacent metal- or electronic device-induced magnetic field distortion, result in inaccuracies. Optical tracking, generally regarded as an accurate and suitable method, is currently popular in computer-aided surgical applications.[11,15] Sensors or specific markers can be used to locate the 3D spatial position of an object by tracking the position of the sensor or marker with visible or infrared light; this requires line-of-sight and proper lighting.

Given the challenge of applying optical tracking in various fields of surgery,[16-18] its deployment in orthognathic surgical procedures has been limited. Because determining the maxillary segment position demands a high level of accuracy, error verification of the tracking system is essential for its clinical application in the field of orthognathic surgery.

We, therefore, wanted to introduce a third-generation stereoscopic optical tracking system to track the position of the maxilla and any positional changes during orthognathic surgery. This study aimed to evaluate the accuracy of this optical tracking system based on a series of reference points localized for the measurement and registration of the maxillary skull model, mimicking navigational maxillary orthognathic surgery.

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Statement of Clinical Relevance

The accuracy of third-generation stereoscopic optical tracking system based on reference points localized for the measurement and registration of the maxillary skull model can be used to track the position of the maxilla and any positional changes during navigational orthognathic surgery.

MATERIALS AND METHODS

A commercially available third-generation stereoscopic optical tracking system, MicronTracker (Hx40; Claron Technology Inc., Toronto, Canada), with its own indicator (950-MT-TOOL-CL01 Probe Body and Stem) was prepared (Figure 1A). Calibration refinement of the tracking camera was carried out with the R-Fine software application.

Three sets of experiments were performed under normal room lighting conditions without special lighting equipment after a lighting-related pilot experiment (details not shown). The tracking camera was set about 100 cm from the object point. The indicator was fixed tightly with a metallic stand holder to prevent any motion-related artifacts. The reference points were recorded in a 3D coordinate system by using a stereoscopic optical camera, as described in Figure 2. The x-axis of the coordinate system denotes the horizontal dimension, the y-axis the anteroposterior dimension, and the z-axis the vertical dimension, when facing the camera.

Measurement of the single-point position

Static 3D position recording was performed to address issues related to jitter, a momentary deviation caused by random optical or electrical noise.[19] We measured the 3D position of the indicator tip, which was fixed at a specific location on the table (Figure 1B). Results were compared, and the statistical significance of differences was calculated by using one-way analysis of variance (ANOVA) and in 3D distance by using Student's *t* test.

The lengths between 2 static target points were measured (see Figure 1B). Four object points were marked in line at 10-mm intervals on a metal ruler (marked as arrowheads in Figure 1B). The locations of the 4 points in line were recorded 10 times. We calculated the lengths by subtracting the 3D position of 2 selected points, which were 10, 20, or 30 mm apart. The length between 2 selected points was compared with the referenced length set on the metal ruler, and their differences were statistically analyzed by using ANOVA.

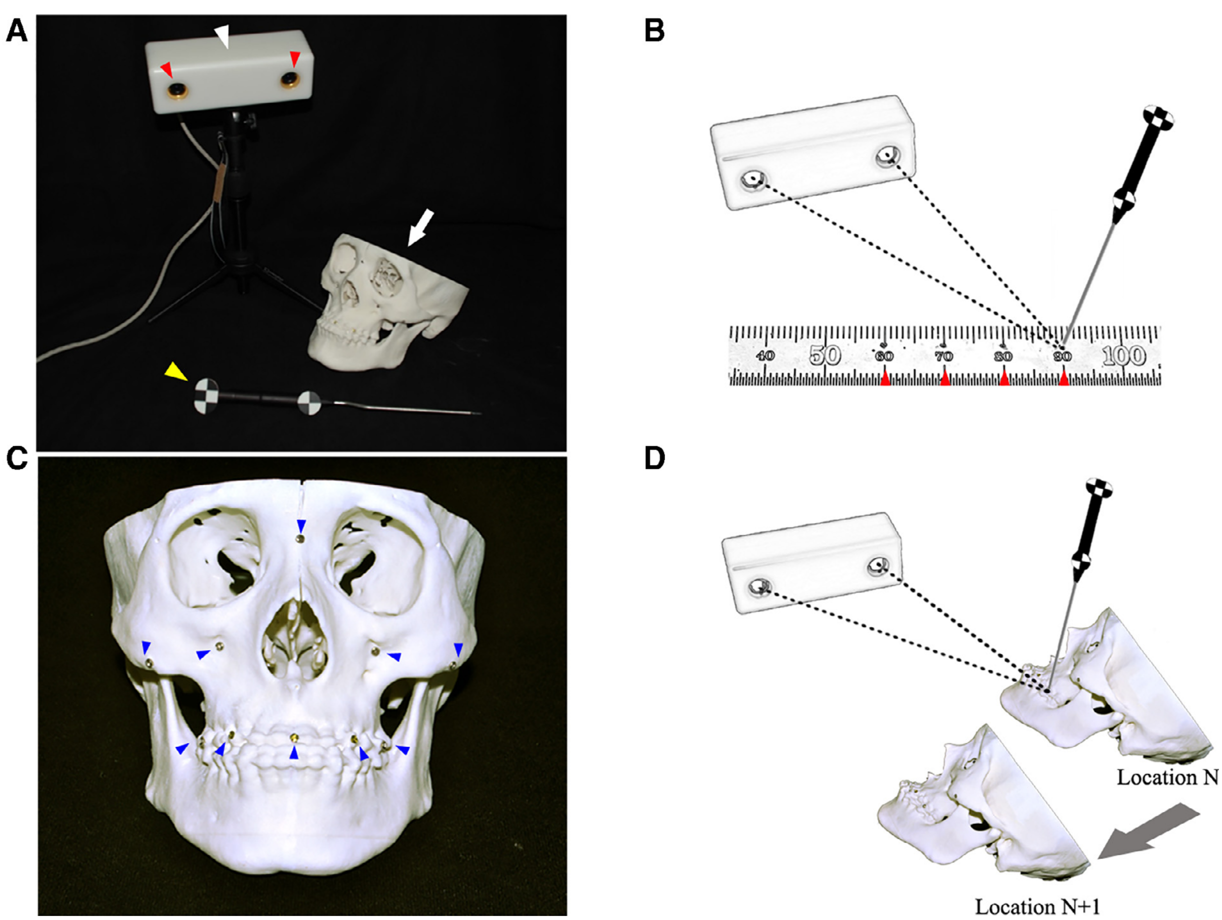

Fig. 1. The experimental design using an optical stereoscopic tracking system. **A,** MicronTracker (model Hx60; *indicated by white arrowhead*) as an optical tracking camera *(red arrowheads)*, its indicator *(yellow arrowhead)*, and the skull model *(arrow)*. **B,** The length measurement with 4 reference points *(indicated by arrowheads)* in a line at 10-mm intervals on a metal ruler. **C,** Five cranial *(indicated by arrowheads)* and 5 dental points *(indicated by arrows)* with mini-screws on a 3-dimensional (3D) printed skull model. **D,** The 3D positional measurement of reference points of the skull model at 7 different locations (from N to N+1).

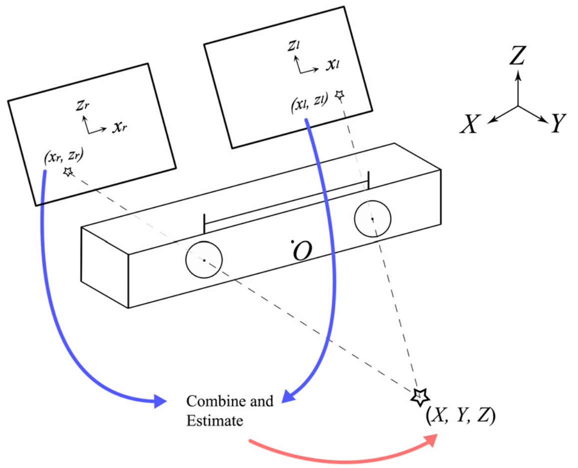

Fig. 2. The outline of measurements by the optical tracking system with 3-dimensional coordinates for the object point located at a point (x, y, z) and its projected image onto the charge-coupled device display of the stereoscopic tracking camera.

Prediction of point location by using registration

This experiment was performed to evaluate the accuracy of 3D point position measurement and prediction during movement of the skull model. Ten reference points were marked independently at the center of the titanium screw heads (Mini Screw, KLS Martin Co., Jacksonville, FL) on the 3D-printed skull model (calcium sulfate hemihydrate [VisiJet PXL]; ProJet CJP 660 Pro, 3D systems, Rock Hill, SC). Five reference points, assigned to the cranial group, were fixed on the craniomaxilla superior to the Le Fort I osteotomy line (blue arrowheads in Figure 1C). The 5 other points of the dental group were marked by the same metal screws in the maxillary teeth, including the first molars, canines, and central incisal tip (blue arrows in Figure 1C).

The positions of 5 cranial points and 5 dental points were recorded by the optical tracker at their original positions, and the measurements were repeated at 7 different locations on the experiment table by changing the position of the skull model (Figure 1D). At each location, the skull model was fixed to the table with straps to prevent any minor movement. Ten reference points were recorded 20 times in each experiment. The 3D positional data were recorded, and the registration conducted in 4 different ways by using the total least square method.

The first registration method was performed with whole reference points to obtain the predicted point locations by using Matlab software (Mathworks Inc., Natick, MA). The second registration was made with 5 cranial points, being registered to calculate the predicted positions of 5 dental points of the skull model. The measured and predicted dental positions were compared to obtain the difference between the referenced (actual) and predicted dental reference points.

The next registrations were performed with an individualized 3D coordinate system set with 3 cranial points of nasion and canine eminence. The third registration was performed with superimposition of 3 cranial points, and the discrepancies between the measured and predicted positions of the remaining 7 points were evaluated under an individualized coordinate system. The fourth registration was evaluated with the same individualized 3D coordinate system by registration at the cranial points to determine the prediction error of the dental points.

Point location prediction in simulated maxillary surgery

The maxillary segments of 4 phantom skulls with 10 reference screws after simulated Le Fort I osteotomy were moved in the vertical or horizontal dimensions and fixed with metal plate systems (Miniplate and Screw, KLS Martin Co., Jacksonville, FL). Two skull models underwent maxillary posterior impaction (3 mm at the tip of first molars), and anterior advancement (5 mm) was performed on the other 2 models. The skull models were scanned preoperatively and postoperatively with a laser scanner (Vivid 9i, Konica Minolta, Japan; resolution $\pm$ 50 μm) to record the reference point positions in 3D.

The positions of 5 cranial points and 5 dental points were recorded by the tracking system before and after maxillary surgery. The original and changed positions of the cranial and dental points were also measured by using the laser-scanned image data superimposition of the skull models (Rapidform 2006, INUS Technology, Inc., Seoul, Korea). The dental point positions were predicted by the registration of tracker-recorded cranial points, as described previously. Finally, the laser-scanned positions of dental points were compared with their predicted positions. All statistical comparisons of variance and mean values were made by using Statistical Package for the Social Sciences, version 21 (SPSS Inc., Chicago, IL).

RESULTS

Point position measurement

The jitter size for a static target point was 0.013 $\pm$ 0.009 mm (mean $\pm$ standard deviation) in the x-axis, 0.050 $\pm$ 0.033 mm in the y-axis, and 0.056 $\pm$ 0.035 mm in 3D (Table I). The jitter size on the y-axis was significantly greater than on the x- or z-axis ($P < .001$).

The average discrepancy in length measurement was 0.276 $\pm$ 0.192 mm (Table II). The length estimation at 10, 20, and 30 mm showed discrepancies ranging from 0.213 mm (for 10 mm measurement) to 0.326 mm (for 20 mm measurement), the differences being statistically insignificant ($P = .419$) by ANOVA.

Table I. The discrepancy in repeated measurements of a static reference point to evaluate the level of optical tracker jitter

Coordinate	x	y	z	3D	P*
Discrepancy	0.013 ± 0.009	0.050 ± 0.033	0.015 ± 0.012	0.056 ± 0.035	<.001
Min	< 0.001	0.001	< 0.001	0.008	–
Max	0.036	0.139	0052	0.152	–

*One-way analysis of variance (ANOVA) for x-, y- and z-coordinates.N = 100; in mm; average ± standard deviation.

Table II. The optical tracker measurement discrepancy in the length between 2 object points

Length	Discrepancy	P*
10	0.213 ± 0.140	.419
20	0.326 ± 0.196	
30	0.290 ± 0.230	
total	0.276 ± 0.192	–

*One-way analysis of variance (ANOVA) for each length.N = 10; in mm; average ± standard deviation.

Point location prediction by using 4 registration methods

Every 2 data sets out of 7 were registered by 4 different methods (Tables III to V). The calculated discrepancy by the first registration method was 0.245 mm for the x-axis, 0.406 mm for the y-axis, and 0.595 mm in 3D space (see Table III). The y-axis discrepancy was significantly greater than that of other axis ($P < .001$). The cranial point group discrepancy was not significantly different from that of the dental point group ($P = .397$).

3D position difference of the cranial points by the second registration method was 0.278 ± 0.129 mm in 3D and ranged from 0.087 mm (x-axis) to 0.214 mm (y-axis) (see Table IV). The discrepancy on the y-axis was again significantly greater than those on other axes ($P < .001$). Moreover, the dental point discrepancy was significantly greater than that in the cranial point group ($P < .001$).

Evaluation of the third registration method for the individualized 3D coordinate system showed a discrepancy of 0.773 mm in 3D for 3 cranial reference points (see Table V). The discrepancy for the remaining 7 tracking points was 1.256 ± 0.683 mm in 3D and significantly greater than those of the 3 points ($P < .001$).

For the fourth registration, cranial 3D discrepancy was 0.960 ± 0.709 mm and that of the dental point group was 1.261 ± 0.679 mm. The dental point group discrepancies were significantly greater than those of the cranial point group ($P = .002$).

Point location prediction in simulated maxillary surgery

3D discrepancy between the predicted and measured dental point positions was 1.908 ± 0.953 mm for the maxillary posterior impaction but 1.563 ± 1.799 mm for the anterior advancement (Table VI). The y-axis discrepancies in both experiments exceeded those in other axes without statistical significance for the posterior impactions ($P = .476$) and anterior advancement ($P = .083$). There was no significant difference between the discrepancies of maxillary posterior impaction and anterior advancement ($P = .754$).

DISCUSSION

To achieve high accuracy during measurement in orthognathic maxillary surgery, we introduced a third-generation optical tracking system. The purpose of this study was to evaluate the measurement and registration accuracy of an optical tracking system through a series of experiments mimicking navigational maxillary orthognathic surgery.

Several factors inhibit accurate maxillary positioning,[4,5] including laboratory-related preoperative errors, such as impression-taking and wafer fabrication, as well as premature contacts during surgical positioning of maxilla. Maxillary positioning accuracy can also be affected by relaxed facial and masticatory muscles under general anesthesia, laxity or disease of the temporomandibular joint, and the surgeon's technical skills.

Table III. Discrepancies between skull models with 10 reference points by the total least square method for the first registration method

	x	y	z	3D	P*	P†
Cranial points	0.276 ± 0.107	0.399 ± 0.104	0.285 ± 0.063	0.650 ± 0.091	<.001	.397
Dental points	0.204 ± 0.099	0.412 ± 0.099	0.173 ± 0.042	0.539 ± 0.098		
Total	0.245 ± 0.212	0.406 ± 0.293	0.229 ± 0.169	0.595 ± 0.285	–	–

*One-way analysis of variance (ANOVA) for x-, y- and z-coordinates.
†Student's *t* test for 3D discrepancies between cranial and dental point groups.
In mm; average ± standard deviation

Table IV. Positional discrepancies in dental points after registration with 5 cranial points by total least square method for the second registration method

	x	y	z	3D	P*	P†
Cranial points	0.087 ± 0.108	0.214 ± 0.136	0.108 ± 0.091	0.278 ± 0.129	<.001	<.001
Dental points	0.877 ± 0.494	0.892 ± 0.486	0.574 ± 0.393	1.534 ± 0.643	.048	

*One-way analysis of variance (ANOVA) for x-, y- and z-coordinates of cranial and dental point groups.
†Student's *t* test for 3D discrepancies between cranial and dental point groups.
In mm; average ± standard deviation.

Table V. The positional discrepancies between predicted and measured dental points after the third and fourth registration using the individualized coordinate system

		x	y	z	3D	P*	P†
Third registration	Three points on the axes	< 0.001	0.162 ± 0.291	0.610 ± 0.740	0.773 ± 0.656	<.001	<.001
	Seven tracking points	0.477 ± 0.373	0.361 ± 0.262	1.006 ± 0.683	1.256 ± 0.683	.073	
Fourth registration	Cranial points	0.220 ± 0.407	0.268 ± 0.319	0.734 ± 0.707	0.960 ± 0.709	<.001	.002
	Dental points	0.448 ± 0.316	0.335 ± 0.224	1.040 ± 0.707	1.261 ± 0.679	<.001	

*One-way ANOVA for x-, y- and z-coordinates.
†Student's *t* test for 3D discrepancies between three and seven points or cranial and dental groups.
In mm; average ± standard deviation.

Table VI. Discrepancies between the tracker-recorded and laser-scanned positions of 5 dental points during the maxillary simulation surgeries

Movement type	N	x	y	z	3D	P*	P†
Posterior impaction	2	0.887 ± 0.551	1.137 ± 1.211	0.670 ± 0.612	1.908 ± 0.953	0.476	0.754
Anterior advancement	2	0.518 ± 0.801	1.389 ± 1.527	0.498 ± 0.516	1.563 ± 1.799	0.083	

*One-way analysis of variance (ANOVA) for x-, y- and z-coordinates.
†Student's *t* test for 3D discrepancies between posterior impaction and anterior advancement.
In mm; average ± standard deviation

A computer-assisted navigation system aids in image-guided orthognathic surgery by guiding the surgical device using registered images and thus minimizing inadvertent access to deep structures.[20,21] The navigation systems in orthognathic surgery also helps the surgeon appreciate the 3D position of the bony segment in the operation room in real time and, thus, determine whether the surgery is going as planned.

However, several barriers remain to the system's successful clinical application in orthognathic surgery, such as the need for special equipment and software, the complicated and time-consuming handling process, and the required high level of accuracy. In addition, the application of navigational technology to maxillary orthognathic surgery involves the introduction of an invasive cranial or orbital reference frame, application of a restraint to immobilize the head, and errors in tracking to the multiple and/or approach-limited reference points at teeth and bone under soft tissue coverage.[20] In particular, the soft tissue envelope invites inaccurate localization and measurement of the navigation system, although this study, which was confined to positional recording and registration, did not intend to consider it. Further work on the practical application of our results to a clinical setting will be pursued soon.

Optical tracking systems can be classified by their mode of function.[22] First-generation optical trackers utilized infrared light emitting diodes at targets that could be observed by infrared light sensors. Because they needed a bulky power source at the target, they were not easy to use clinically. Second-generation sensors emit infrared light from a ring surrounding each infrared camera lens and use balls or disks coated with retro-reflective material as targets. These are currently in wide use for navigational surgery, although they cause some errors in sensing round targets.[15]

In this study, we introduced a third-generation optical system to track maxillary positional changes during orthognathic surgery. These trackers offer some advantages over earlier systems in that they are fully passive and use visible light to identify targets. Unlike magnetic tracking devices, they do not present interference of metal in the operating area. However, they were sensitive to intense operation room illumination and its reflection to detector, resulting in detection error (details not shown here). Because this limitation could be overcome by reducing operation illuminance, we performed our experiments under normal room lighting conditions.

In this study, we aimed to evaluate the accuracy of such an optical tracking system through a series of experiments. The first experiment was designed to evaluate 3D positional recording discrepancies for a static target reference point, which is generally ascribed to jitter, defined as a momentary deviation caused by random optical or electrical noise during image capture and analog-to-digital conversion.[19] Our experiment showed that the jitter distribution on the y-axis was greater than that on the x-axis and z-axis with statistical significance, being 0.05 mm in 3D as well as in root mean square error. Our data were about 3 times larger than the official data and were possibly obtained under ideal conditions. However, the jitter in this study, all less than 0.05 mm, was confirmed to be sufficiently small for clinical purposes.

The second experiment aimed to measure the linear length between 2 reference points ranging from 10 to 30 mm, their discrepancies being less than 0.4 mm. The length discrepancies may be related to errors in the handling and angulation of the indicator as well as the inherent jitter of the optical tracking system. Previous studies vary in their reported levels of accuracy in length measurement with a tracking system. One study, which reported a much lower level of accuracy than that in our study, used the Polaris (0.15−0.07 mm; Northern Digital, Waterloo, Canada) and Stryker systems (0.05 mm; Stryker, Freiburg, Germany).[16,18] However, other studies reported different levels of error, such as 0.4 mm for Polaris during length measurement,[15] 0.72 mm for Stryker, and 0.33 mm for BrainLab (Munich, Germany) in terms of single pointing error.[18] We may need a standard evaluation protocol for tracking and navigational systems in the future.

The third series of experiments was conducted mainly to compare the error level of point registration. We evaluated registration- and position-related errors in 4 different ways, the clinical setting inevitably limiting the number of registered reference points. We, therefore, may need to accept the level of error achieved by using these predicted dental points, which yielded less than 1.6 mm of discrepancy in 3D. Our results for the predicted dental point positions in an individualized coordinate system failed to present a marked improvement in accuracy compared with those in the original coordinate system. Similar registration-related errors in commercial systems, including Stealth Station and Vector Vision have been studied.[23] A direct comparison with our results is complicated by the different number of screws and reference points, but their errors ranged from 1.00 to 1.34 mm, quite close to ours.

The fourth experiment involved navigation of the maxillary surgery on skull phantom. We designed 2 types of maxillary translocations, that is, horizontal and vertical movements. These yielded a similar level of error, the anterior advancement showing 1.563 mm of measurement error for dental points in 3D and the posterior impaction being 1.908 mm. All our results indicated the feasibility of 3D optical tracking through 3D position recording and registration. Our search of the literature did not reveal a similar finding.

As described previously, a series of experiments consistently showed relatively accurate x-axis and z-axis errors, and the y-axis error was greater during 3D position measurement. The optical tracking equipment measures 3D position by using a stereoscopic optical system with a camera lens. The positional depth in the y-axis is estimated on the basis of the difference between the images projected onto the right and left lens (see Figure 2). The y-axis error may be associated with the structure of the stereoscopic camera. Depth resolution may decrease as the distance between the tracking system and object increases. As demonstrated by the formula (given in the supplementary manuscript) and Figure 2, the y-axis error is limited by the absolute value of Y. It is, therefore, recommended that the distance between the stereoscopic camera and the object be minimized to reduce y-axis error.

The error level of traditional measurements in orthognathic surgery is known to be about 1 to 2 mm at the incisor tip when using 2-dimensional cephalometry.[5,24] In this study, we evaluated the accuracy of an optical tracking system via a series of experiments involving position recording and registration on a skull phantom and in navigational maxillary surgery. The results showed that the level of error was small enough for clinical application, even with a greater level of anteroposterior or y-axis error. Optical tracking, therefore, seems clinically applicable and valuable for precise tracking of the maxillary position during orthognathic surgery. More work is necessary to overcome greater errors in the y-axis. As well, the distribution of registration points and choice of registration method merit careful consideration to reduce the magnitude of errors.

CONCLUSIONS

We hope that the simulated benchtop experiments in this study would lead to further research into the clinical application related to a 3D navigation system for orthognathic surgery, particularly focusing on operation time, patient positioning, and cost−benefit analyses.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.oooo.2019.01.008.

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