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ORIGINAL ARTICLE

Digital Determination and Recording of Edentulous Maxillomandibular Relationship Using a Jaw Movement Tracking System

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Abstract

Purpose: To establish a direct digital method for determining and recording edentulous maxillomandibular relationship using a custom-made jaw movement tracking system and evaluate its accuracy.

Materials and methods: A novel jaw tracking system was used to record the trajectory of habitual opening-closing jaw movement, and mandibular rest position (MRP) in 10 edentulous patients. 3D surface scanning was performed on the conventional maxillomandibular impressions and facial structures of patients in MRP. The multisource data were registered using a custom-made recording tool. A plane parallel to the ala-tragus and horizontal lines was constructed 2 mm above the MRP, and its vertical position was used to determine the vertical relationship. The intersections of the trajectory passing through the plane were located, and their density distributions were analyzed. The coordinates of highest density, which presented the highest repeatability of jaw movement, were used to construct the digital maxillomandibular relationship (test group). The maxillomandibular relationship of the new complete dentures with artificial teeth in the intercuspal position was defined as the control group. The displacements of the anterior reference point and 3D deviations of the entire mandibular arch were measured and compared between the test and control groups using a Wilcoxon signed-ranks test and a one-sample t-test, respectively.

Results: With reference to the centric relationship position, the maximum displacements of the anterior reference points were in the horizontal anteroposterior direction for both groups, and there were no significant differences. Compared to the control group, the 3D deviations of the entire mandibular arch in the test group were significant (95% confidence interval: 0.76 mm to 1.35 mm, $p < 0.001$).

Conclusions: By analyzing the individual trajectory features obtained by the in-house developed jaw tracking system, a digital method for determining and recording edentulous maxillomandibular relationships was established; however, the accuracy needs to be further improved.

KEYWORDS
3D Construction, 3D surface scanning, jaw movement trajectory

The computer-aided design and computer-aided manufacturing (CAD-CAM) of digital complete dentures has developed rapidly in recent years. Various CAD-CAM systems for complete dentures, such as the commercial systems AvaDent,[1,2] Dentca,[1,2] Ceramill FDS,[1,2] Baltic denture,[1,2] and Vita VIONIC,[1] and research reports of Wieland [3] and Whole You Nexteeth[3] have emerged, which have improved the accuracy and efficiency of clinical procedures. However, the

CAD-CAM technology of the above-mentioned systems is mostly applied in the dental laboratory[4–6] and includes 3D surface scanning of conventional maxillomandibular impressions with their relationships, 3D virtual tooth arrangement, 3D design of dental bases, and additive or subtractive manufacturing of dental bases. Although there have been many investigations[7–9] on digital impression-making in edentulous patients using an intraoral 3D scanner, direct digital techniques for recording maxillomandibular relationships in edentulous patients are lacking.

As a key procedure in producing complete dentures, the maxillomandibular relationship of edentulous patients is commonly determined and recorded using record bases and wax occlusal rims. The procedure is time-consuming, and relies heavily on the clinical experience of dentists.[10] In addition, due to the presence of movable tissues and the absence of obvious features in edentulous patients, it is difficult to obtain a direct digital recording of the maxillomandibular relationship using an intraoral scanner. Therefore, the determination and recording of the maxillomandibular relationship of CAD-CAM complete denture systems are still primarily based on conventional clinical procedures.[11–13] Recently, there has been an increasing interest in jaw movement tracking in patients. Lee et al[14] proposed a target-tracking method for increasing the vertical dimension of occlusion based on the measured jaw movement trajectory of a patient with extremely worn dentition, but without considering the horizontal relationship. Han et al[15] analyzed the restoration space of an edentulous patient using a jaw movement tracking technique, in which the target material was attached to the existing old maxillary denture; however, the accuracy of the tracking method was not evaluated. For edentulous patients without old dentures, the direct digital method for determining and recording the maxillomandibular relationship remains a persistent problem.

This study aimed to establish a direct digital method to determine and record maxillomandibular relationships in edentulous patients without old dentures by analyzing the individual physiological features of habitual opening-closing jaw movements and mandibular rest position (MRP)[16] recorded using an in-house developed (PN–300) jaw movement tracking system. With reference to the centric relationship position, compared to a well-established maxillomandibular relationship of complete dentures with artificial teeth in the intercuspal position, the accuracy of this digital method was evaluated. The null hypothesis was that there is no difference between the PN–300 system and the well-established analogical method in recording the maxillomandibular relationship.

MATERIALS AND METHODS

The study was approved by the Bioethics Committee of Peking University School of Stomatology, Beijing, China (PKUSSIRB–201838120a), and was registered with the Chinese Clinical Trial Registry (ChiCTR1900022564). The procedures and risks involved in participation in this study were discussed with the volunteers and written informed consent was obtained from all participants. Ten patients (6 males and 4 females, aged 70.8 ±9.3 years) were enrolled in this study. Patients were eligible for inclusion if they were aged 55 to 85 years, were completely edentulous, had recovered for at least 3 months after extraction, and were able to understand and cooperate with the requirements of the study. Patients were excluded if they had temporomandibular joint disorders, mental illness, highly resorbed ridges, flabby residual ridges, pharynx sensitivity, uncontrolled mucosal diseases, or systemic diseases.

The jaw tracking system was developed in-house (Fig 1). It has an accuracy of ±100 μm for trajectory tracking[17–19] and includes two industrial cameras (model DMK 33GP1300, Imaging Source, Germany) that can identify and record the circle centers of two-dimensional (2D) tracing targets (approximately 1 g) fixed on the maxilla and mandible in real time. The system also includes a projection module (model DLP300, Texas Instruments, TX) that can be used to perform 3D surface scanning in combination with the cameras. The 3D trajectory of the maxillomandibular movement was obtained using image feature extraction of the 2D targets. According to the actual motion of the maxillary and mandibular jaws, a trajectory subtraction algorithm based on the screw theory[17,20] was used to calculate the relative motion trajectory of the mandible relative to the maxilla.

An Activity 880 model 3D scanner (Smartoptics, Bochum, Germany) was used to perform 3D surface scanning of the conventional maxillomandibular impressions (Huge Dental Material Co., Ltd., Shanghai, China). Three-dimensional data of the maxillary and mandibular jaws were saved in standard tessellation language (STL) format. Individual 1.5-mm-thick trays with four spheres on the labial surface were designed using Geomagic Studio 2013 software (3D Systems Inc., Rock Hill, SC) and printed using a Lingtong 3D printer (Beijing Sinotech Co., Ltd., Beijing, China) (Fig 2). One end of a 1-mm-thick aluminum sheet was bonded to the trays using self-curing acrylic resin (Huge Dental Material Co., Ltd., Shanghai, China); the other end was bonded to the tracking targets using double-sided adhesive tape (Deli Group Co., Ltd., Ningbo, China). Based on the size of the oral fissure, the aluminum sheet was adjusted to avoid interference from the natural opening-closing movement. The custom-made recording tool, defined as a facial tray, included an individual maxillary tray and five spheres (diameter: 10 mm) that extended outside the mouth. The method used to create the facial tray was the same as that used to create the individual trays. After silicone impressions (Huge Dental Material Co., Ltd., Shanghai, China) were made (Fig 2), the maxillomandibular trays and facial tray carrying the elastic material that could stretch into the undercut portion were inserted into the mouth in such a fashion that they remained stable. Finally, 3D surface scanning of the trays was performed using a model 3D scanner (Fig 2).

Individual trays with tracing targets were inserted into the patient's mouth, and the patient was then asked to practice the habitual opening-closing jaw movement. During practice,

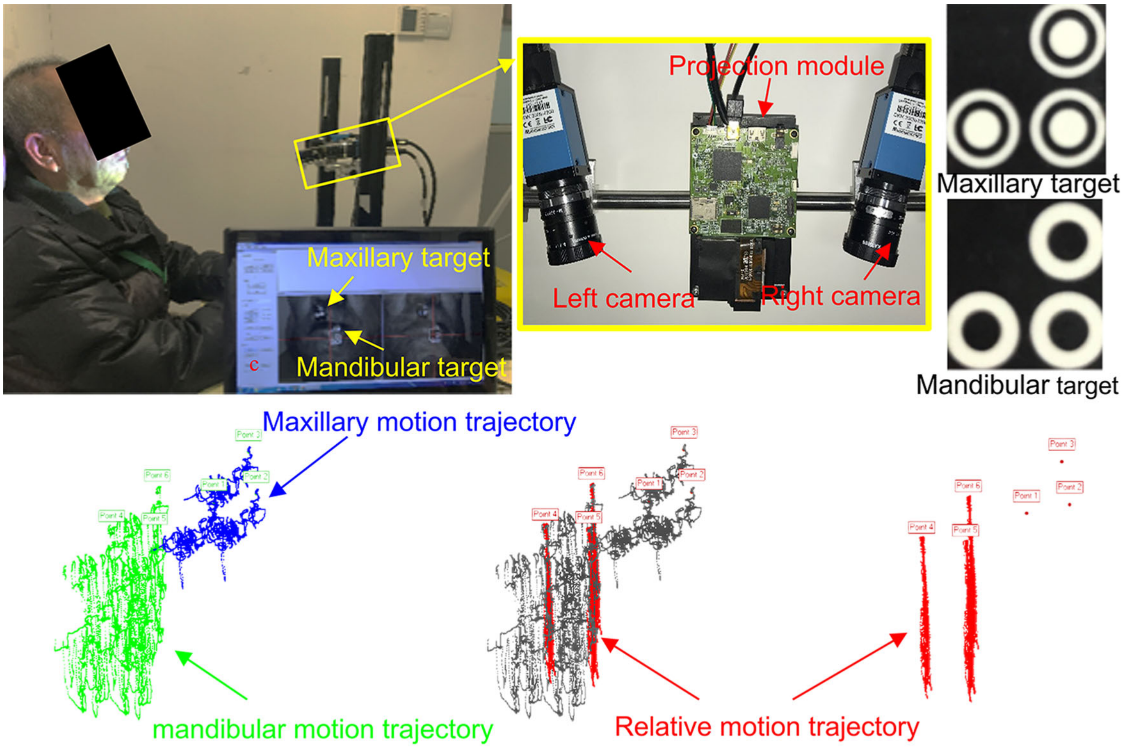

FIGURE 1 Construction of PN–300 system and recordings of movement trajectory.

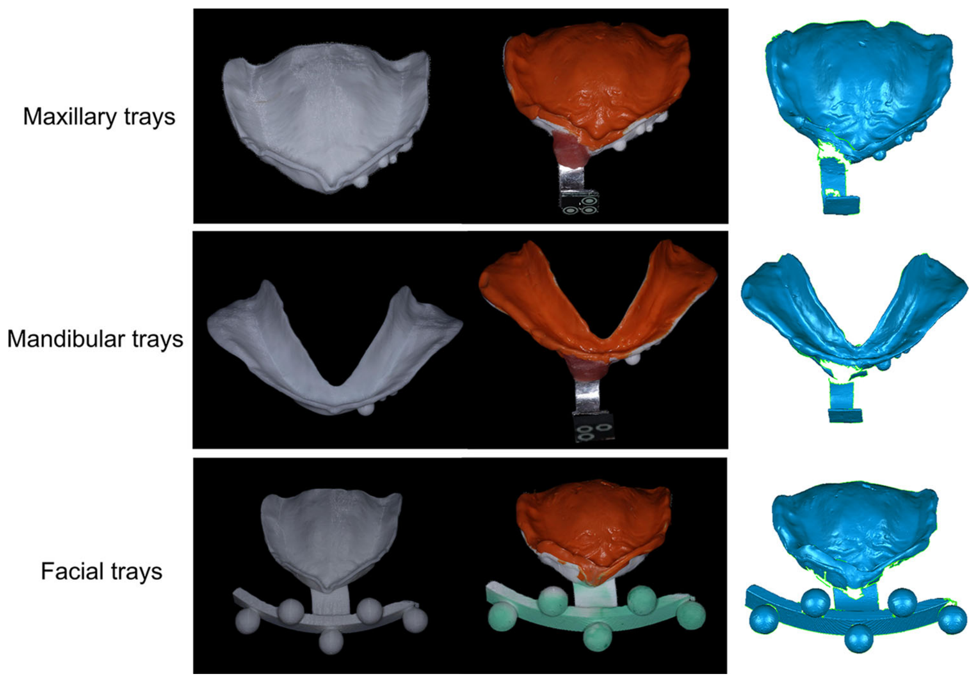

FIGURE 2 Maxillomandibular trays and facial trays. Left to right: 3D printing, impressions, 3D surface scanning.

necessary adjustments were made to the aluminum sheet to reduce interference from the lips and enhance the stability of the tray during jaw movements. The patient was asked to sit upright, look straight ahead, and relax. The MRP and 3D trajectory of the opening-closing movement were recorded using the PN–300 system, and the relative motion trajectory was calculated. The entire recording process took approximately 10 s. Individual trays with tracing targets were

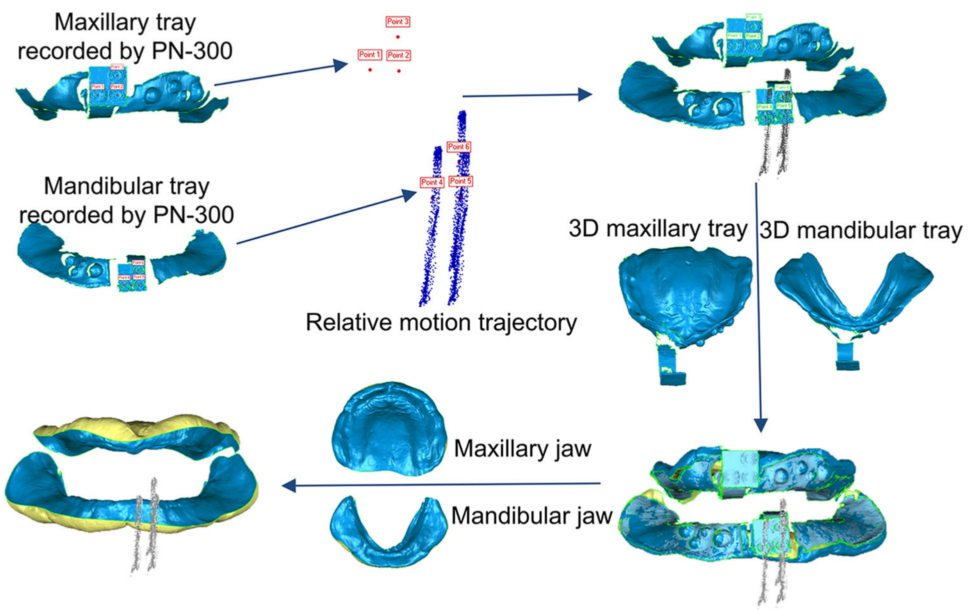

FIGURE 3 Procedures of registration of maxillary and mandibular jaws in the mandibular rest position with the relative motion trajectory.

then pulled away from the mouth and placed in front of the PN–300 system and a projection module was used to scan the labial and buccal surfaces of the trays. Simultaneously, the cameras started to record the circle centers of the tracing targets; therefore, the labial and buccal scans, along with the circle centers of the tracing targets, were in one coordinate system. Finally, the model 3D scanner was used to scan the cameo and intaglio surfaces of the individual trays, and the 3D data of the maxillary and mandibular trays were obtained in STL format.

The maxillary and mandibular jaws were registered into the MRP with the relative motion trajectory in Geomagic Studio 2013 software (Fig 3). First, the labial and buccal scans along with the circle centers of the tracing targets were registered to the MRP along with the relative motion trajectory using the reference point system (RPS) alignment.[21] The cameo and intaglio surface scans of the maxillomandibular trays were then registered to the above data based on the iterative closest point algorithm. Subsequently, 3D data of the maxillary and mandibular jaws were registered to that of the trays based on the common region of the edentulous residual ridge. In this way, the maxillomandibular relationship in the MRP along with a relative motion trajectory was identified.

The 3D image of the face was registered to the data of the maxillary and mandibular jaws in MRP with the associated relative motion trajectory (Fig 4). Three-dimensional surface scanning of the face was performed using FaceScan 3D face scanner (3D-SHAPE GmbH, Erlangen, Germany) with the patient in the MRP. Subsequently, 3D surface scanning was repeated with a facial tray inserted into the mouth. The 3D data of the facial tray were then registered to the maxillary and mandibular jaws in the MRP with a relative motion trajectory based on the common region of the maxillary residual ridge. The 3D face with the facial tray inserted was then registered to the 3D data of the facial tray based on the common regions of the five spheres. Subsequently, the 3D face of patient in the MRP was registered to the data of the 3D face with the facial tray based on the common regions of the forehead and auricle. This resulted in a 3D face scan with both jaws in the MRP with a relative motion trajectory in one coordinate system.

First, individual facial features were identified. The midsagittal plane of the face was determined according to the center point of the eyebrows, tip of the nose, and the pogonion of the soft tissue. The intersections of the midsagittal plane and lines of the maxillomandibular residual ridge crests were defined as anterior reference point A and B, respectively. A horizontal line was established by connecting the points of the left and right outer canthus (Fig 5). Point A was defined as the origin (O) of the coordinate system, and the horizontal line towards the right was defined as the positive direction of the z-axis. The plane parallel to the ala-tragus line and horizontal line was defined as the XOZ plane. A rectangular coordinate system was established using Geomagic software (Fig 5). A horizontal plane parallel to the XOZ plane and 2 mm above the MRP was constructed and the vertical relationship was determined based on the vertical position of the horizontal plane (Fig 5).

The relative motion trajectory of anterior reference point B was calculated using the software supporting the PN–300 system (Fig 5). The intersection points of the relative motion trajectory of point B passing through the horizontal plane were calculated; these intersection points represented different horizontal relationships for the same vertical dimension. By analyzing the density distribution of all intersection points, the highest density point showing the highest repeatability of mandibular movement, was identified, and the horizontal relationship was determined (Fig 6A). The mandibular jaw in the MRP with three circle centers of the mandibular

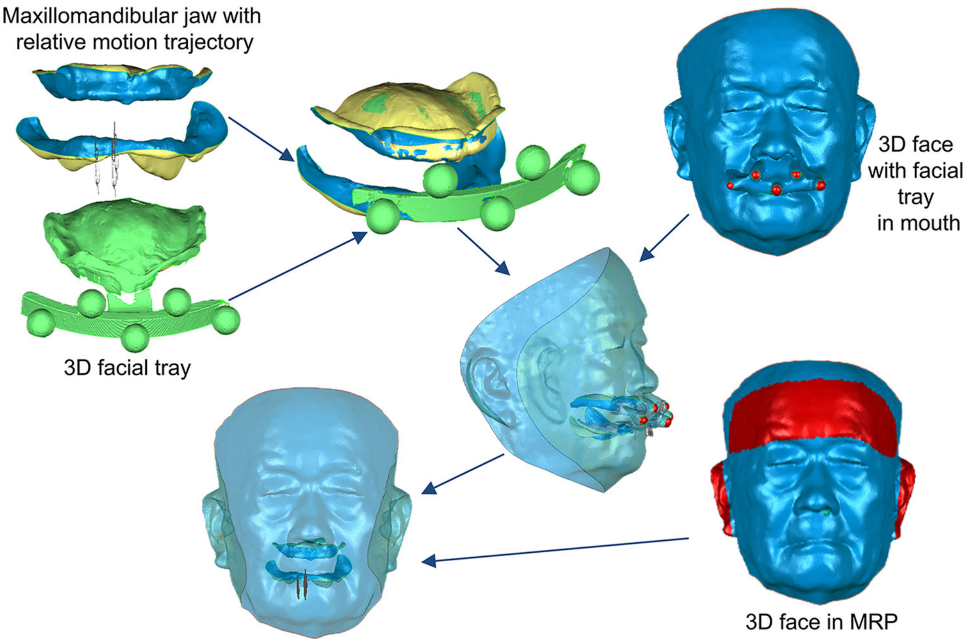

FIGURE 4 Procedures of registration of 3D face and maxillary and mandibular jaws in the mandibular rest position with the relative motion trajectory.

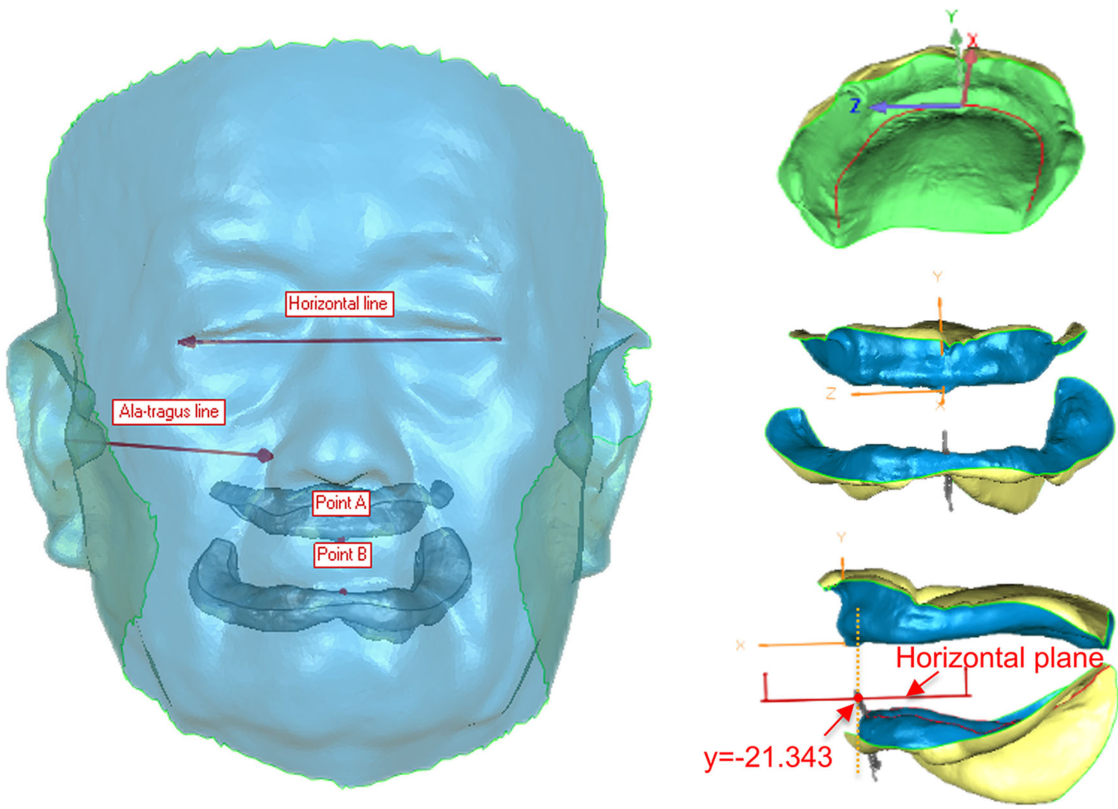

FIGURE 5 Recognition of features of the face, the establishment of the coordinate system, and determination of vertical relationship.

tracing targets was registered to the data of the three circle centers corresponding to the highest density point using RPS alignment, and the digital edentulous maxillomandibular relationship was recorded (Fig 6B).

Based on the reference of the centric relationship position recorded by the gothic arch tracer, the maxillomandibular relationship obtained using the PN–300 system (test group) was compared for the same patient with the well-established

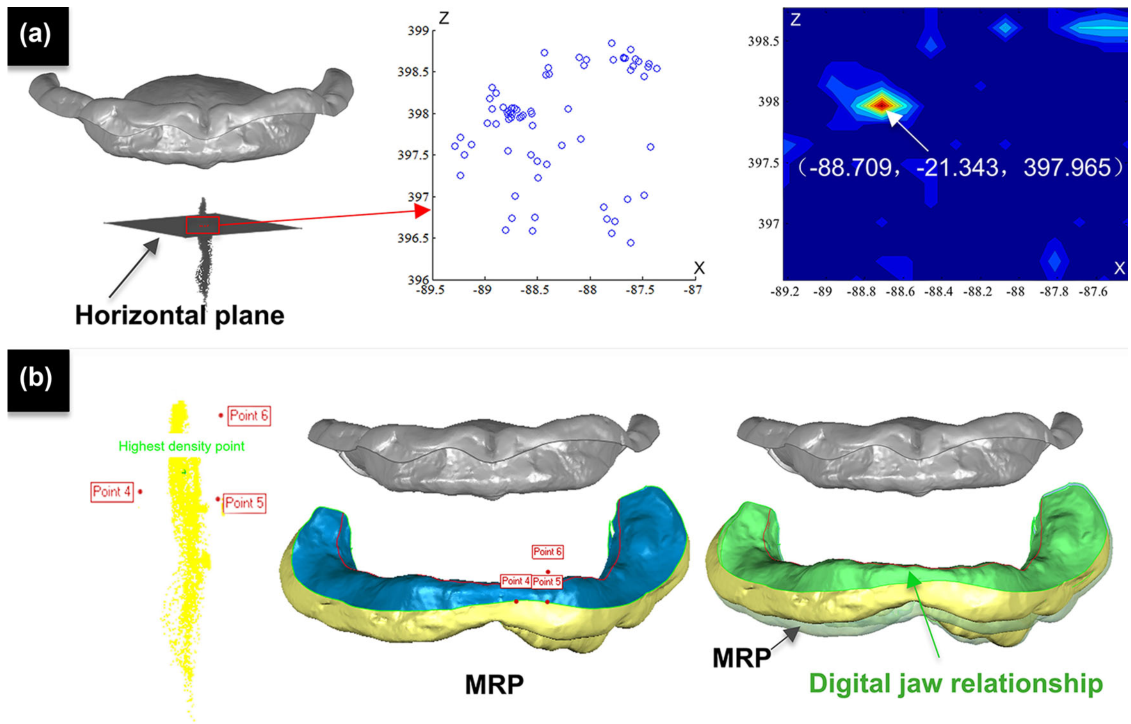

FIGURE 6 Determination of horizontal relationship. (a) intersection points and their density distributions of relative motion trajectory passing through the horizontal plane. (b) left to right: the highest density point with its corresponding three circle centers of mandibular tracing targets, mandibular rest position (MRP) with three circle centers of the mandibular tracing targets, construction of the digital maxillomandibular relationship.

maxillomandibular relationship of new complete dentures (control group) fabricated using a digital technique.[22,23] The vertical dimensions of the test and control groups were determined using the previously described method. After the new complete dentures were worn for at least 3 weeks, their maxillomandibular relationship, occlusion, lip support, and tooth arrangement were verified and confirmed by asking patients if they were satisfied with their complete dentures in terms of function and aesthetics. Extraoral 3D surface scanning of the cameo and intaglio surfaces of the complete dentures with artificial teeth in the intercuspal position was performed using a 3D scanner. Based on the morphology of the intaglio surfaces of the dentures, 3D data of the maxillary and mandibular jaws were recorded in the intercuspal position of the complete dentures.

Using the 3D file in STL format derived from the design of the new complete dentures in the control group, white complete dentures were printed (Beijing Sinotech Co., Ltd., Beijing, China), and a gothic arch tracer was installed in the intercuspal position with a tracing stylus in the mandible and a tracing plate in the maxilla. After all contacts of the artificial teeth were removed, the vertical dimension maintained by the gothic arch tracer was the same as that of the trial complete dentures (Fig 7A). Without the influence of the dental cusps, the arrowhead was traced by protrusion, retrusion, and bilateral movements of patients without active intervention by the practitioner. The centric relationship position was recorded with the mandible at the tip of the arrowhead using silicone bite registration material (Huge Dental Material Co., Ltd. Shanghai, P.R. China) (Fig 7B). Subsequently, 3D surface scanning was performed to record of the centric relationship position. The 3D data of the maxillary and mandibular jaws were registered to the centric relationship position according to the morphology of the intaglio surfaces of the dentures (Fig 7C).

Based on the common region of the maxillary jaw, the 3D data of the maxillomandibular relationships in the test and control groups were registered to the 3D data of the centric relationship position in Geomagic Studio 2013 software. Displacements of the anterior reference point B in the test and control groups were measured relative to the centric relationship position (Fig 8A). The displacement value was considered positive if it was in the forward, right, or upward directions; in other directions, the displacement value was negative. Subsequently, a 3D deviation analysis was performed to measure the distance between the test and control groups over the entire mandibular arch. Color-coded mapping was generated (Fig 8B) and the root mean square (RMS) value was calculated according to the following formula:

$$\mathrm{RMS} = \frac{\sqrt{\sum_{i=1}^{n} \left(X_{1,i} - X_{2,i}\right)^2}}{\sqrt{n}}$$

where $X_{1,i}$ is the measurement point i in the test group, $X_{2,i}$ is the measurement point i in the control group, and n is

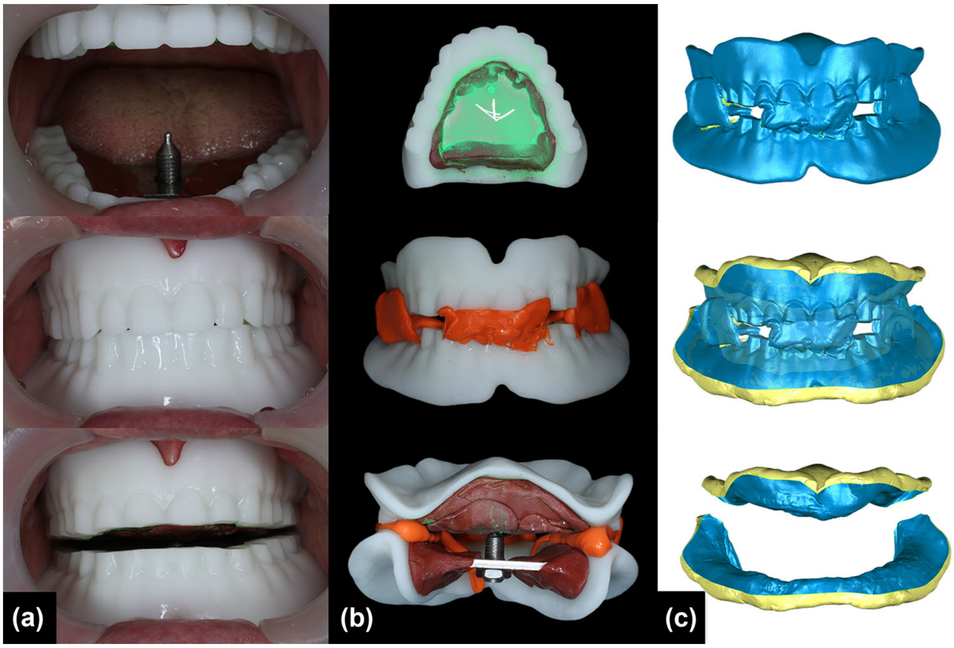

FIGURE 7 Acquirement and 3D construction of centric relationship position. (a) gothic arch tracer was installed in white complete dentures in the intercuspal position. (b) centric relation position record. (c) 3D surface scanning and 3D reconstruction of the centric relationship position.

the total number of measurement points. A low RMS value indicated a high accuracy of the 3D construction of the digital maxillomandibular relationship.

All statistical analyses were performed using SPSS 26 statistical software (IBM Inc., Armonk, NY). The Wilcoxon signed-ranks test was used to assess the displacements of the anterior reference points between the test and control groups in the anteroposterior, right-left, and vertical directions. Compared with the control group, the 3D deviations of the entire mandibular arch of the test group were in accordance with the normal distribution after the Shapiro-Wilk test, and one-sample t-test was used for comparing the RMS values of 3D deviations of test groups (test value was set to 0.3 mm, the tolerance range of the deviation which is the decrease amount of edentulous mucosal thickness under maximum occlusal force[24]). Statistical significance was set at $p < 0.05$.

RESULTS

Figure 8A and Table 1 show the displacements of the anterior reference points of the maxillomandibular relationships obtained using the PN–300 system and complete dentures in the three directions. Compared with the reference of centric relationship position, the maximum displacement of anterior reference positions of the maxillomandibular relationships was 2.34 mm in test group and 2.42 mm in control groups in the anteroposterior directions from the same patients. To avoid the offsets of positive and negative numbers, the absolute values of data were calculated; and the mean of the displacements of anterior reference points for test and control groups in the horizontal right-left (0.78 mm and 0.61 mm, respectively) and vertical directions (0.74 mm and 0.85 mm, respectively) were smaller than those in horizontal anteroposterior direction (1.15 mm and 0.98 mm, respectively) and the situation similar for the median calculated by absolute values. In addition, the mean and median of the displacements of the anterior reference positions in the anteroposterior directions in the test group were slightly larger than those in the control group; group differences were not significant in the anteroposterior, right-left and vertical directions.

The 3D deviations of the entire mandibular arch for the test and control groups are shown in Figure 8B and Table 2. The color-coded mapping showed that the 3D deviations of the mandibular jaw in the posterior arch were larger than those in the anterior arch (Fig 8B), and the minimum RMS values of the 3D deviations of the entire mandibular arch (Table 2) was 0.55 mm which is larger than the test value of 0.3 mm; therefore, the differences between the test and control groups were significant (95% confidence interval: 0.76 mm to 1.35 mm, $p < 0.001$).

DISCUSSION

In this study, the individual features of the trajectory of jaw movement based on a custom-made PN–300 jaw movement tracking system were analyzed and a jaw position that showed the highest repeatability of mandibular movement was established. Although the procedure appeared complicated, it could be performed automatically using software and was less dependent on operator experience. In terms of the centric relationship position, which is the clinically repeatable reference position,[16] the displacements of the anterior

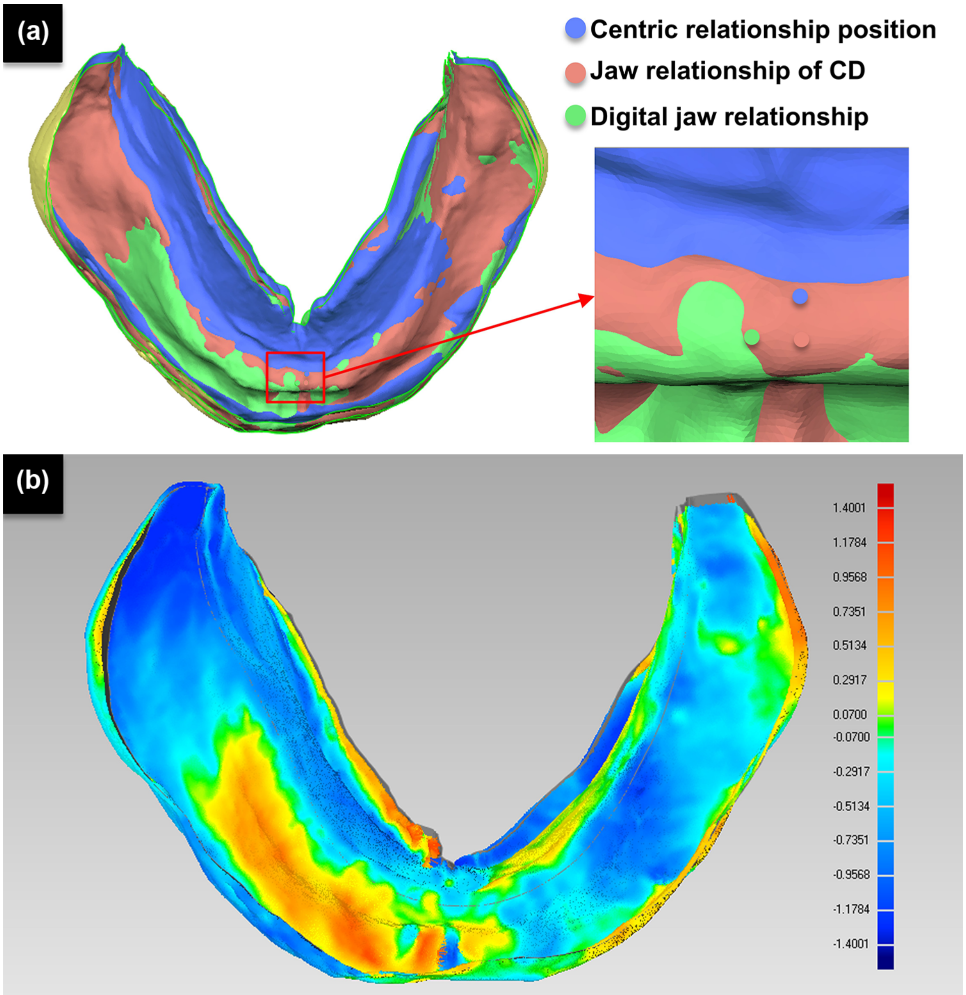

FIGURE 8 Evaluation of position of the mandibular jaw in digital maxillomandibular relationship. (a) displacements of anterior reference points in three relationships. (b) 3D deviations of the entire mandibular arch of test versus control groups. CD, complete denture.

reference points of maxillomandibular relationships obtained by PN–300 system and complete dentures were evaluated, and the maximum displacement was in the anteroposterior direction (2.34 mm and 2.42 mm, respectively) for both groups. The reason may be that during biting, the variation in anteroposterior direction was larger than that in right-left and vertical directions.[25] Although the inter-group difference between the displacements of the anterior reference point in three directions was not significant, the 95% confidence interval of RMS values of 3D deviations of the entire mandibular arch was ranged from 0.76 mm to 1.35 mm and showed a significant difference. Therefore, the null hypothesis was rejected.

The error in the determination and recording of digital maxillomandibular relationships arose from the following three aspects. First, the recording error of the PN–300 system is determined. The recording accuracy for the edentulous maxillomandibular relationship of the system was evaluated in the laboratory, and its accuracy was approximately 200 μm, which meets the maxillomandibular relationship record requirements for edentulous patients.[26] The error in the anteroposterior direction was the largest, which may be associated with the use of 2D targets. The 2D targets can be replaced by 3D dispersed targets to improve the system. Second, the better the stability of the maxillomandibular trays in the mouth during movement, the more accurate the trajectory recorded, although it was unavoidable that trays in an edentulous mouth would be mobile. Finally, there is a source of error associated with 3D reconstruction. It is not yet possible for the PN–300 system to verify different periods during opening and closing, and trajectory extraction cannot be used to calculate the frequency of the opening-closing movement. However, Naeije et al[27] studied the stability of the opening-closing movement cycle and found that the movement parameters vary significantly according to the magnitude of the movement frequency. If the closed state alone, without an opening trajectory at a specific frequency, is independently analyzed for 3D reconstruction of the maxillomandibular relationships of an edentulous jaw, the accuracy of the digital maxillomandibular relationship record may be further improved.

The advantage of using the jaw movement tracking system is that it can be used to distinguish whether the patient

TABLE 1 Displacements of the anterior reference points of maxillomandibular relationships obtained by PN–300 system and complete dentures in the horizontal anteroposterior, horizontal right-left, and vertical directions, compared with the reference of centric relationship position (unit: mm)

	AP		LR		VD	
	PN–300	CD	PN–300	CD	PN–300	CD
1	1.45	1.29	1.40	0.00	–0.05	0.05
2	1.81	1.09	0.15	–0.97	0.63	0.02
3	0.37	1.45	0.00	–0.49	–0.02	0.41
4	–0.29	0.08	0.92	0.64	–1.25	–2.26
5	1.89	–0.02	–0.06	0.23	–0.37	–0.28
6	1.12	0.08	–0.76	–1.29	–1.58	–1.46
7	2.34	2.42	0.31	–0.43	0.19	0.18
8	0.31	–0.59	–0.02	–0.36	–0.70	–0.83
9	0.44	0.96	–3.53	–1.53	–2.42	–2.71
10	1.49	1.81	0.63	0.11	0.16	0.27
Mean*	1.15	0.98	0.78	0.61	0.74	0.85
SD*	0.76	0.80	1.07	0.51	0.79	0.97
Median*	1.29	1.03	0.47	0.46	0.50	0.35
Minimum	–0.29	–0.59	–3.53	–1.53	–2.42	–2.71
Median	1.29	1.03	0.08	–0.40	–0.21	–0.13
Maximum	2.34	2.42	1.4	0.64	0.63	0.40
95% CI	0.49 to 1.70	0.18 to 1.53	–1.06 to 0.87	–0.90 to 0.09	–1.22 to 0.14	–1.46 to 0.14
P^a	0.58		0.11		0.58	

AP, horizontal anteroposterior direction; LR, horizontal right-left direction; VD, vertical direction; CD, complete denture; CI, confidence interval.
*Calculating the absolute value of data.
[a]Wilcoxon signed-ranks test.

TABLE 2 Statistics analysis of 3D deviations of the entire mandibular arch in the test group compared with control group using one-sample *t*-test (N = 10)

	Mean ± Standard deviation (mm)	Minimum (mm)	Median (mm)	Maximum (mm)	95% CI (mm)	*p*
RMS	1.05 ± 0.41	0.55	0.97	1.74	0.76 to 1.35	<0.001

RMS, root mean square; CI, confidence interval.

protruded the mandible. Under normal circumstances, the MRP should be located within the range of the trajectory of the opening-closing movement, that is, within the muscular contraction path. If the movement trajectory was in front of the MRP, it indicated that the patient's mandible was protrusive, and the opening-closing trajectory was not accurate for 3D reconstruction of the maxillomandibular relationship. In such cases, measures were taken to guide the patient to the appropriate position, for instance, asking patients to swallow several times when closing the jaw or repeat the opening-closing movement to deprogram the muscles. In addition, the phonetic and functional movement trajectory can be recorded to assist in the accurate determination of the vertical dimension,[28] and the movement trajectory of condyles can also be analyzed to locate the articular position of the mandible if cone beam computed tomography is used.

However, there are some limitations to the determination and recording of digital maxillomandibular relationships using the PN–300 system. The 3D deviations of the entire mandibular arch, especially the posterior arch of the digital maxillomandibular relationship, need to be further reduced, and jaw movements were analyzed without considering the state of the maxillofacial muscles. To record the movement trajectory of the mandible, combining the position of the condyle in the glenoid fossa or muscle tension may produce a better record of the position of the mandible in its physiological state. In addition, owing to the error arising from the above three aspects, the digital method for the determination and recording of maxillomandibular relationships is not currently suitable for clinical application. Further research is required to improve the accuracy of this method.

CONCLUSIONS

By combining the techniques of recording jaw movement trajectory, 3D surface scanning, and 3D reconstructions, it is feasible to determine and record the edentulous digital maxillomandibular relationship with the mandibular jaw in the physiological position of highest repeatability of mandibular movement. The articular position of the mandible still requires further study, and the digital maxillomandibular relationship determined and recorded by the in-house developed jaw tracking system is not clinically applicable at present because its accuracy needs to be further improved.

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CONFLICT OF INTEREST

The authors do not have any conflicts of interest in regards to the current study.

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