FUNDAMENTAL RESEARCH

Accuracy of Recording Edentulous Arch Relations Using an Optical Jaw-Tracking System: An In Vitro Study

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Purpose: To establish a recording method for edentulous arch relations and to perform quantitative accuracy evaluation in vitro. ***Materials and Methods:*** Edentulous maxilla and mandible models with complete dentures were mounted on an articulator simulating arch relations in protrusion (A), left and right laterotrusion (B and C, respectively), and small opening (D) positions, aided by a metal foil wax record. In the test group, a tracking system was used to record the 3D trajectories of targets from intercuspation to positions A, B, C, and D, and the average of these trajectories was used for rehabilitation of the digital arch relations of A, B, C, and D. In the control group, the six pairs of positioning cylinders were pasted on the axial model surfaces. The center points of the bottom surfaces of the cylinders in the A, B, C, and D positions were measured for rehabilitation of digital arch relations in the control group. With the maxilla as the common area, the arch relations in the test group were registered with the control group, the 3D deviations of the mandible were calculated, and displacements in the horizontal left/right, horizontal anterior/posterior, and vertical directions were analyzed. ***Results:*** Three-dimensional deviations of the mandible in the A, B, C, and D positions were 131 ± 39 μm, 133 ± 44 μm, 120 ± 51 μm, and 112 ± 52 μm, respectively. The mean absolute values of displacement in the mandible were less than 200 μm. ***Conclusion:*** By using the optical jaw-tracking system, the accuracy of arch-relation records as measured on an articulator was acceptable for clinical demand. Further investigations among patients are required to clinically verify the results of this study. *Int J Prosthodont 2022;35:302–310. doi: 10.11607/ijp.7126*

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With the widespread application of digital technology[1] and the increasing demand for complete dentures,[2] the development of CAD/CAM technologies for complete dentures is facing new challenges and opportunities.[3] The application of CAD/CAM for complete dentures can reduce the number of dental visits and dependence on the experience of clinicians, improving the efficiency and accuracy of complete dentures.[4]

Arch-relation records for traditional removable complete dentures are usually taken by means of maxillary and mandibular record blocks in the clinic.[5] An accurate arch relation record is a highly crucial step for the production of complete dentures. Currently, the arch-relation record method used in commercialized CAD/CAM complete denture systems Avadent,[6,7] Dentca,[6,7] and 3Shape[8] is aided by record blocks prepared by the dental practitioners and then by extraoral 3D surface scanning of the record blocks to indirectly record the arch relation. In addition, obtaining the arch-relation

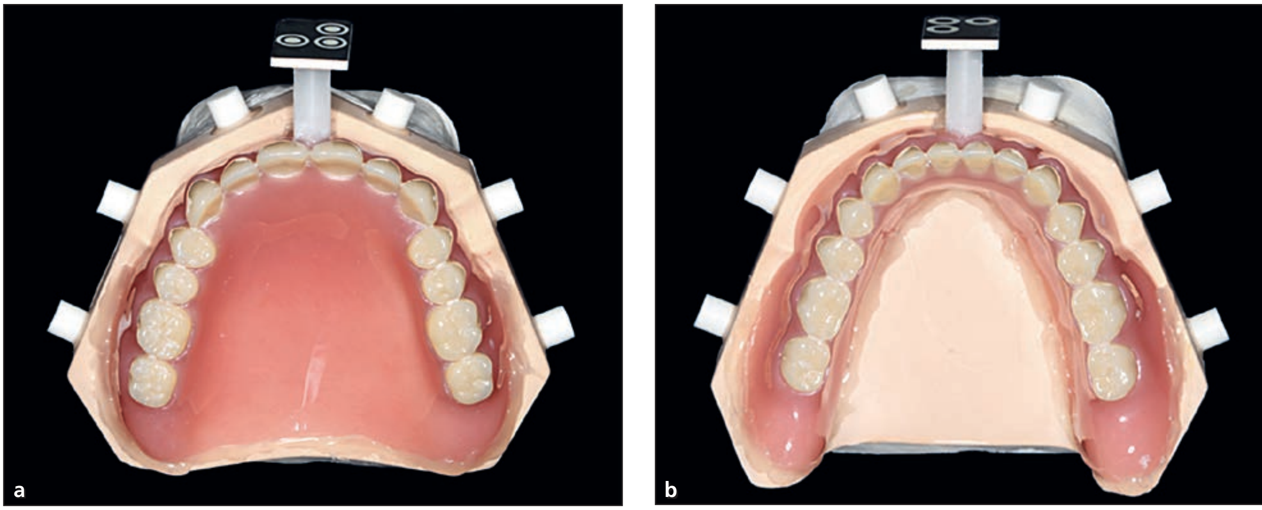


Fig 1 Standard gypsum models of *(a)* maxillary and *(b)* mandibular edentulous arches with supporting complete dentures.

record with intraoral scanners requires scratches on the occlusion rims to optimize scanning,[9] and the accuracy of this method needs to be improved for full-arch rehabilitation.[10,11] Li et al[12] developed a digital, direct recording of edentulous arch relations using a handheld scanner and specially designed headgear without requiring record blocks, but the headgear operations were very complex, and the accuracy of the recording method was relatively low. However, there remains no relevant research on the arch relations of edentulous patients based on 3D mandibular movement trajectories.

Mandibular movement kinesiographs are commonly used in the acquisition of articulator parameters,[13] the analysis of mandibular functional movement,[14] and the diagnosis of temporomandibular disorders.[15] Liu et al[16] applied cephalometric roentgenographs to study the movement trajectory of the mandible from an edentulous position without complete dentures to the largest open-mouth position with the complete denture, as well as the relation between the intercuspation and the trajectory, in order to determine a suitable intercuspation position for the edentulous patient. However, there has been no further study to determine the arch relations of edentulous patients based on the 3D trajectory of the mandible.

Under normal conditions, the human body is in a state of micromovement.[17] A head-mounted mandibular movement kinesiograph, such as an Arcus digma,[11] which is based on the principle of ultrasound, can directly record the 3D movement trajectory of the mandible. For the optical portion of a mandibular movement kinesiograph,[15,18–21] cameras are placed at a distance from the patient to record the trajectories of the maxilla and the mandible at the same time, as well as to calculate the mandibular motion trajectory relative to the maxillary motion trajectory (ie, the relative motion trajectory). The aim of this paper was to use the relative motion trajectory of an optical jaw-tracking system developed by the authors to record the arch relations of a standard edentulous gypsum model mounted on an articulator, including the protrusion (A), left and right laterotrusion (B and C, respectively), and small opening (D) positions. This paper preliminarily evaluates the quantitative accuracy of this novel method. The null hypothesis was that there would be no differences in the arch relation records obtained by using the optical jaw-tracking system and the Edge multiple degrees-of-freedom mechanical contact measurement system (Faro).

MATERIALS AND METHODS

Preparation

The authors prepared standard gypsum maxillary and mandibular edentulous arch models and supporting complete dentures (Fig 1), which were mounted on the non-Arcon articulator (Amann Girrbach)[22] with the Bennett angle set to 15 degrees (Fig 2). The A, B, C, and D positions were obtained using the metal foil wax record (Fig 3). The maxillary and mandibular tracing targets (Model RO4350B, Rogers Corporation) were bonded to the midlines of the maxillary and mandibular complete dentures. The optical jaw-tracking system can identify the centers of the maxillary and mandibular tracing targets in real time and output the 3D position information (in .txt format) of the circle center.

Positioning cylinders of the same size (base plane diameter of 6 mm) were designed and prepared using the Zenotec mini milling machine and software (Wieland Dental). Six pairs of positioning cylinders were adhered to the base axial surfaces of the arch models; therefore,

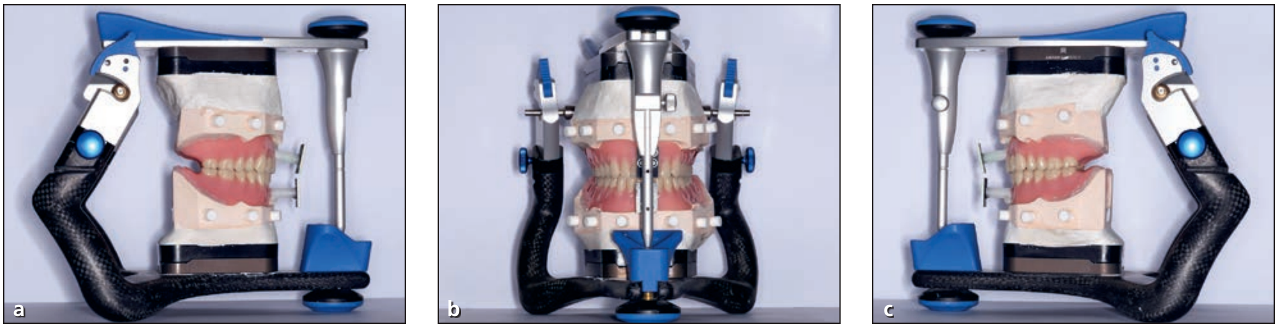


Fig 2 Models in place on the articulator. *(a)* Right, *(b)* frontal, and *(c)* left views.

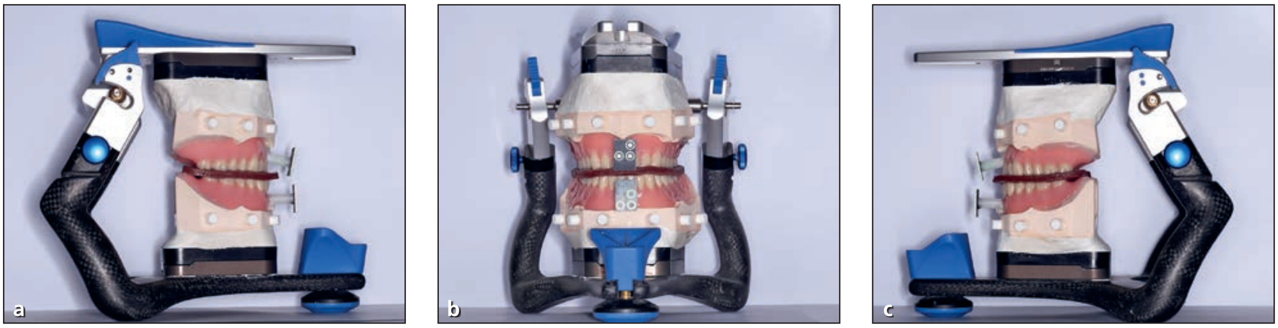


Fig 3 The protrusion, left and right laterotrusion, and small opening positions were obtained using the metal foil wax record. *(a)* Right, *(b)* frontal, and *(c)* left views in protrusion.

each arch had six positional cylinders that were arranged as evenly as possible. According to dental notation from the Fédération Dentaire Internationale (FDI), the 12 positional cylinders in the models were numbered as 11–13, 21–23, 31–33, and 41–43; and the six center-point pairs were defined as 11–41, 12–42, 13–43, 21–31, 22–32, and 23–33.

Control Group Data Acquisition

The articulator was fixed on the surface of a marble measuring platform (Fig 4a) using a glue gun. The maxillary and mandibular models were placed in position A by using the metal foil wax record placed on the occlusal surfaces between the complete dentures. Using a 3-mm zirconia probe of the Faro Edge system, the coordinates of the center points of the positional cylinders' bottom surfaces could be measured (Figs 4b and 4c). The average coordinate values were obtained from three measurements of the bottom center points of the 12 positional cylinders in position A (Fig 4d).

The maxillary and mandibular arch models were scanned with the model 3D scanner (SmartOptics Activity 880, Sensortechnik) and exported in standard tessellation language (STL) format (U and L data, respectively). U and L were imported into Imageware version 13.1 software (Siemens), and the center points of the bottom surfaces of the six positioning cylinders in U and L (Figs 5a and 5b) were calculated.

The center points of the positioning cylinders in U and L data were aligned with the average coordinate values of the cylinders in position A according to the reference point system alignment[23] in Geomagic Studio 2013 software (3D Systems). The arch relation in position A was rehabilitated (Fig 5c). The methods for rehabilitation of the arch relations in positions B, C, and D were the same.

Test Group Data Acquisition

The optical arch-tracking system[19] included two industrial cameras (DMK 33GP1300, Imaging Source) that can identify and record the centers of the maxillary and mandibular tracing target points in real time, one projection module (model DLP300, Texas Instruments) that can obtain high-speed grating 3D point clouds, and the supporting software.

The optical jaw-tracking system and the articulator with the complete dentures fixed to the models were placed on the marble platform (Fig 6a). The complete dentures, the labial and buccal surfaces of which were evenly sprayed with an oral opacifier (Yeti Dental), were scanned for trajectory from the intercuspation position

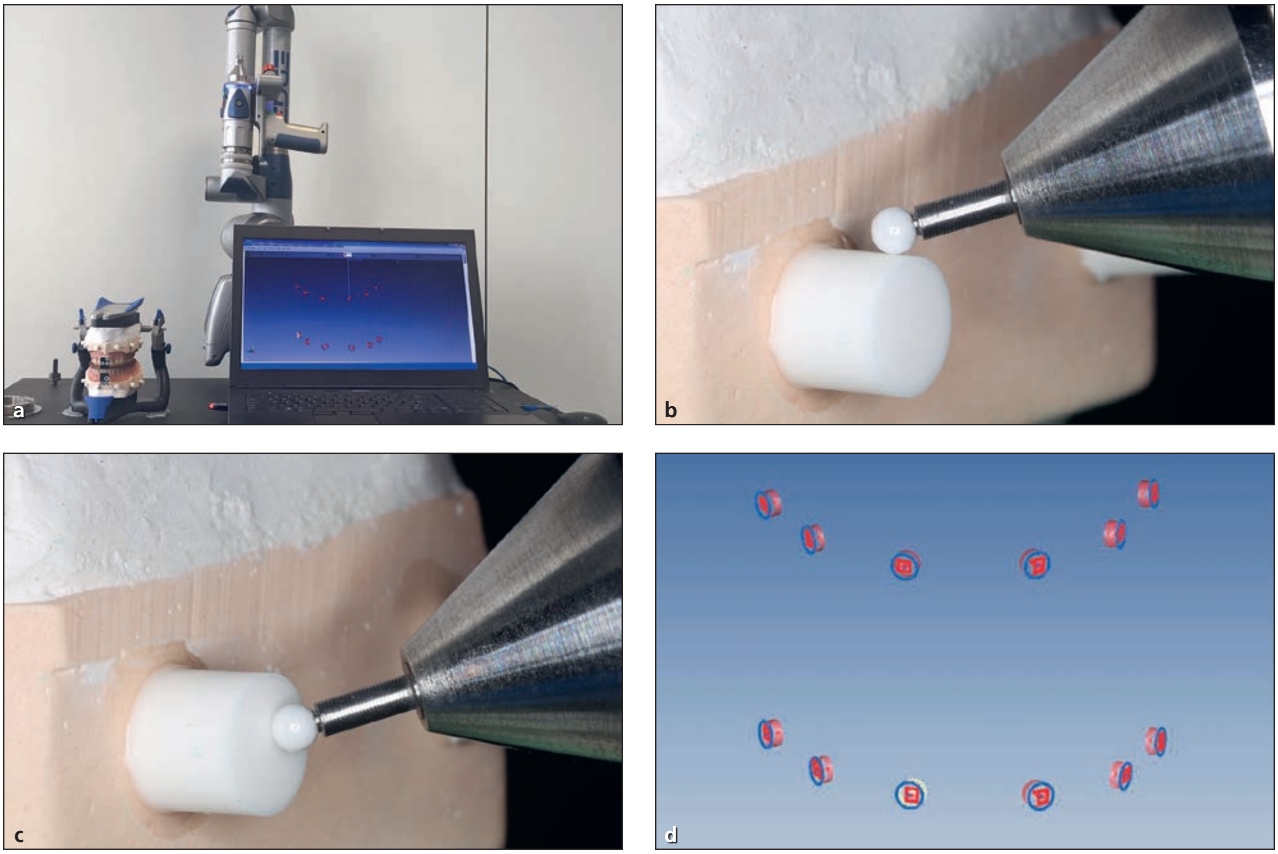


Fig 4 Measurement of protrusion position in the control group. *(a)* Measuring platform. *(b)* Side of positioning cylinder. *(c)* Bottom of positional cylinder. *(d)* Complete measurement with all positional cylinders.

using high-speed grating (Fig 6b) by lifting the maxillary section and then inserting a metal foil wax record of the protrusion position (Fig 6c); then the maxilla was located on the protrusive wax record steadily. The trajectories of the centers of the maxillary and mandibular target points were concurrently identified and recorded in real time by the optical jaw-tracking system (Fig 6b) until recognition was manually stopped.

The U and L data were registered with the labial and buccal 3D surface scans of the maxillary and mandibular dentures (Fig 7a) and then registered with the data of the high-speed grating 3D scan (Fig 7a) to obtain the initial moment in the intercuspation position of both U and L (Fig 7b). The 3D trajectory from intercuspation to position A was in the same coordinate system (Fig 7c). The data of the intercuspation positions of U and L, along with data for the maxillary and mandibular trajectories from intercuspation to position A (Fig 7c), were imported into the supporting software system of the optical jaw-tracking system; this software can calculate the relative motion trajectory and output the relation of the maxilla relative to the mandible at any one time. Therefore, the authors chose to output the last three relations of the maxillary and mandibular models, represented by the last three points in the relative motion trajectory when the maxillary section of the articulator was located on the protrusive wax record (Fig 8).

This method was repeated 10 times for the A position relation, and this method was also used for the B, C, and D position relations.

Accuracy Evaluation

3D deviations

Three-dimensional data of the maxilla and mandible in the test group and the control group were imported into Geomagic Studio 2013 using U data as the common area. U data in the test group were registered with U data in the control group, and L data in the test group were compared to L data in the control group using the “3D deviation” function in the software. A total of 25,965 points were present in the L data; using the 3D deviation analysis function, the software will automatically match the point in test group L and the nearest point in control group L in order. Thus, a total of 25,965 pairs of points were established, and their root mean square error (RMSE) was calculated.[24] The arch relations

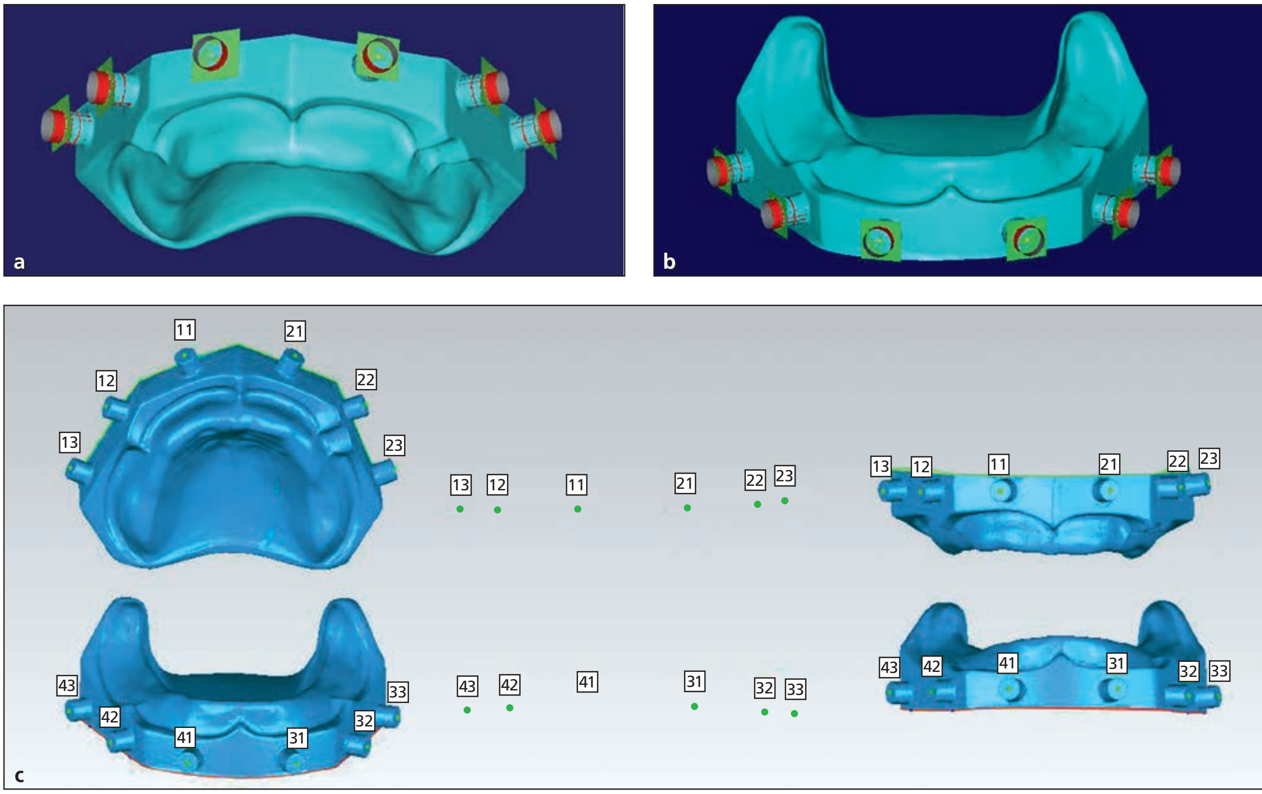


Fig 5 3D rehabilitation of control group using positional cylinders. Measurements of *(a)* the centers of the positioning cylinders in *(a)* U (maxillary) and *(b)* L (mandibular). *(c)* The U and L data were registered with the average coordinates of the protrusion position for arch relation rehabilitation.

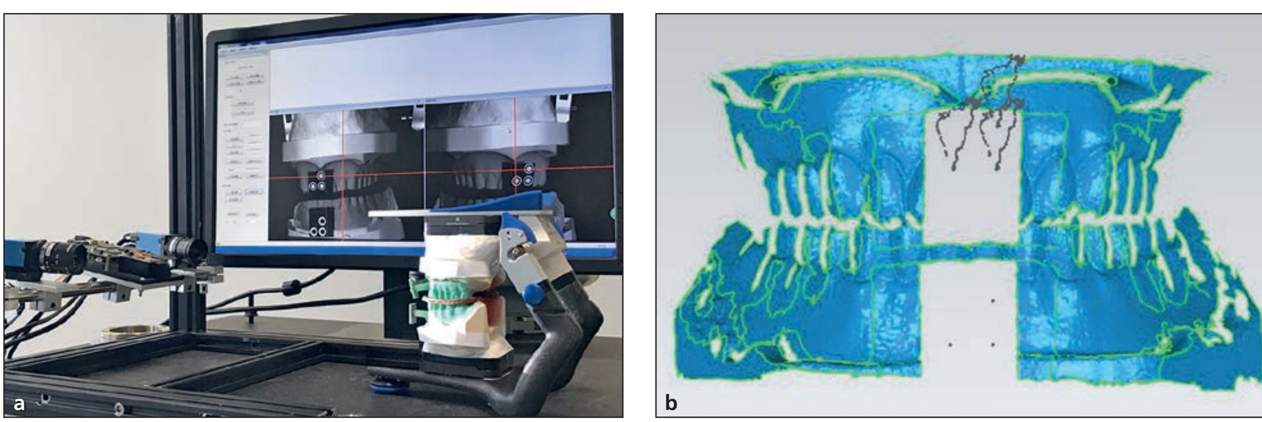


Fig 6 Measurement of relations in the protrusion position in the test group aided by the optical jaw-tracking system. *(a)* Measuring platform in test group. *(b)* Labial and buccal scanned data in the intercuspal position and the trajectory from the intercuspal position to the protrusive position of the maxillary and mandibular targets. *(c)* Metal foil wax record of protrusion.

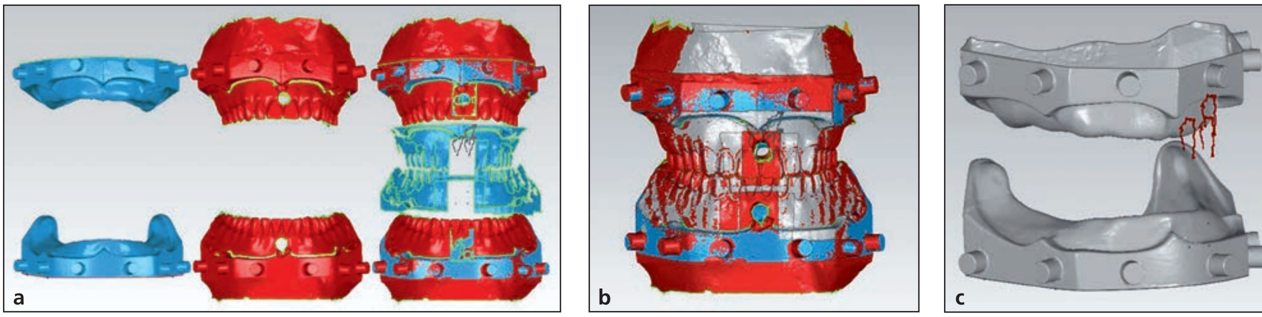
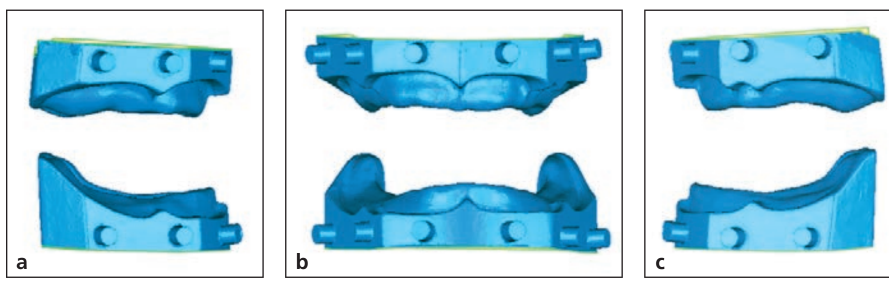


Fig 7 Registration of the data collected by the optical jaw-tracking system. *(a)* Data of U and L, the labial and buccal 3D surface scans of the dentures, and the high-speed grating 3D scan. *(b)* Registration of data in intercuspation position. *(c)* Data of U and L in the intercuspation position, along with trajectories from the intercuspation position to the protrusion jaw position.

Fig 8 Protrusion jaw position rehabilitated by supporting software of the optical jaw-tracking system in the test group. *(a)* Right, *(b)* front, and *(c)* left views.



in the test group, using the last three points in the relative motion trajectory of the maxilla, were compared to the arch relations in the control group by using the 3D deviation function in the Geomagic Studio software.

Displacement in arch positions

To further analyze the arch relations between the test and control groups in the horizontal left/right, anterior/posterior, and vertical directions, the features of a point, an axis, and a plane were used to establish the observation coordinate system (Fig 9). The coordinate origin O was the intersection of the incisal edge and the midline of the incisors; the left second premolar was point 1, the right second premolar was point 2, and the vector direction from point 1 to point 2 was the z-axis. The three-point plane comprising points O, 1, and 2 was defined as the XOZ plane. The x-axis was in the horizontal anterior/posterior direction, the y-axis was in the vertical up/down direction, and the z-axis was in the horizontal left/right direction. According to the measurement coordinate system, the distances between the six center-point pairs (11–41, 12–42, 13–43, 21–31, 22–32, and 23–33) were measured, and the distances were recorded in the horizontal left/right (z-axis), anterior/posterior (x-axis), and vertical (y-axis) directions. Calculating the average absolute value of the difference in distance between the two groups in the x-axis, y-axis, and z-axis directions allowed for quantitative evaluation of the differences in arch relations in positions A, B, C, and D between the test and control groups.

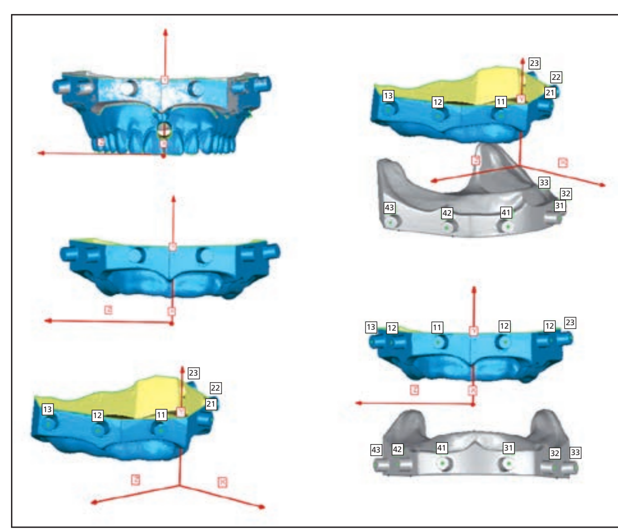


Fig 9 Establishment of the measurement coordinate system.

RESULTS

The mean and SD 3D deviation (RMSE) of the test group compared to the control group in positions A, B, C, and D were 131 ± 39 μm, 133 ± 44 μm, 120 ± 51 μm, and 112 ± 52 μm, respectively (Table 1). The arch relations in the test group, using the last three points in the relative motion trajectory, were analyzed using one-way analysis of variance (ANOVA) in SPSS version 20.0 statistical

Table 1 3D Deviation (Root Mean Square Error; µm) of Arch Relations Rehabilitated by Relative Motion Trajectory in the Maxilla and Statistical Analysis Compared to Control Group for Each Position

	A			B			C			D		
Measurements	1	2	3	1	2	3	1	2	3	1	2	3
1	54	57	136	73	176	147	73	54	125	96	106	111
2	134	122	149	190	179	217	66	174	217	182	147	134
3	160	118	112	96	115	76	127	146	152	50	171	66
4	133	195	158	75	164	47	190	79	160	54	52	77
5	59	68	75	121	128	84	60	123	89	78	99	67
6	160	83	176	98	89	186	173	164	132	185	206	79
7	116	136	181	195	156	101	36	187	93	43	64	70
8	155	160	164	173	131	76	89	107	61	183	144	185
9	156	124	136	130	147	170	206	77	66	176	118	191
10	165	149	147	166	152	159	191	106	102	59	85	94
Mean (SD)		131 (39)			133 (44)			120 (51)			112 (52)	
*P**		.443			.684			.996			.878	

A = protrusion; B = left laterotrusion; C = right laterotrusion; D = small-opening position.
*One-way ANOVA.

Table 2 Absolute Values (µm) of Differences in Distance Between Center Point Pairs in Each Position Between the Test and Control Groups

		13–43	12–42	11–41	21–31	22–32	23–33	Mean	SD
A	x	137	139	153	185	216	228	176	40
	y	88	86	138	127	66	118	104	28
	z	98	83	85	86	83	97	89	7
B	x	89	91	106	147	188	205	138	50
	y	110	82	122	107	75	113	102	19
	z	104	78	83	82	78	102	88	12
C	x	61	55	58	85	112	124	83	30
	y	125	97	91	55	99	171	106	39
	z	110	105	117	119	109	111	112	5
D	x	109	104	94	89	101	106	101	8
	y	103	86	104	80	91	146	102	24
	z	99	80	81	81	81	96	86	9

A = protrusion; B = left laterotrusion; C = right laterotrusion; D = small-opening position; x-axis = horizontal anterior/posterior direction; y-axis = vertical directions; z-axis = horizonal left/right direction.

software (IBM); there were no significant differences compared to the control group ($P = .443$ in position A; $P = .684$ in position B; $P = .996$ in position C; and $P = .878$ in position D).

The mean absolute value of displacements in the x-, z-, and y-axis directions compared to the control group was less than 200 µm for each position. The maximum error was 176 ± 40 µm in the x-axis direction in position A (Table 2).

DISCUSSION

The purpose of this study was to establish a recording method for arch relations in edentulous arch models and to perform a quantitative accuracy evaluation in vitro based on the self-developed optical jaw-tracking system. Compared to the control group, the 3D deviation of the arch relations in the test group was related to RMSE[24]—which reflects the 3D displacement of the entire mandibular model—and a smaller RMSE was reflective of higher accuracy. One-way ANOVA revealed that there was no significant difference in the position taken using the last three points in the relative motion trajectory. The commercial arch tracking systems SICAT,[25] Modjaw,[26,27] and Planmeca[27] can integrate the 3D maxillary and mandibular models with the arch movement trajectory in real time; however, there are no related studies on the arch relation record based on 3D movement trajectories.

Micromovement is present in the human body under normal conditions due to respiration and pulsation.[17] Therefore, an optical jaw-tracking system can record the trajectory of the maxilla and mandible simultaneously and can calculate the relative mandible/maxilla trajectory. However, in the present study, the standard edentulous maxillary model was in motion in the articulator, and the mandible was placed on the measuring marble platform, which was not fixed with slight movement. Therefore, to more accurately represent actual human jaw movement, the relative movement trajectory of the maxillary model relative to the mandibular model in the in vitro articulator was calculated.

By using the self-developed optical jaw-tracking system and mounting the standard edentulous gypsum model on the articulator, a novel method to record protrusion, left laterotrusion, right laterotrusion, and small opening jaw positions based on the 3D trajectory was found. Its average error was less than 200 μm, meeting the threshold for clinical trials in edentulous patients, as the error was smaller than the decreased amount (about 300 μm) of the edentulous mucosal thickness under maximum occlusal force.[28] The maximum error of jaw relation rehabilitated by an optical jaw-tracking system was 176 ± 40 μm in the horizontal anteroposterior direction (x-axis) in protrusion, and this result was consistent with that of Choi et al, who found the discrepancy in the horizontal anteroposterior direction was significantly greater than in the other directions by using a commercial optical tracking system for navigational maxillary orthognathic surgery.[29] The maxillomandibular relationships on an articulator, determined by metal foil wax records, were analyzed in terms of overall 3D deviations and displacements in three directions, while the occlusal contacts of the maxillomandibular artificial teeth of complete dentures were not involved in this study.

The supporting complete dentures used in this in vitro study can be replaced by the denture bases in the mouth of an edentulous patient to fix the tracking targets; however, the denture bases will not be as stable as the complete dentures in the articulator because of the mobility of the edentulous ridge mucosa.[28,30] Further edentulous patient arch-relation records with this method must be further designed and studied. Using the record of edentulous patient arch relations with mandibular 3D trajectories, suitable occlusal points in the trajectory for digital rehabilitation of arch relations in edentulous patients can be analyzed and located without the need for production or surface scanning of the record blocks.

CONCLUSIONS

Based on the presented self-developed optical jaw-tracking system, the average error of arch-relation record—including the protrusion, left and right laterotrusion, and small opening positions—in the articulator was less than 200 μm, thus meeting the demands for 3D recording of arch relations in edentulous patients. Further investigations assessing record of arch relations among patients are required to clinically verify the results of this study.

ACKNOWLEDGMENTS

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Literature Abstract

Immediately Loaded Implants Simultaneously Placed in Fresh Extraction and Healed Sites Supporting Four-Implant–Supported Fixed Mandibular Prostheses Using the All-on-4 Concept: A 5-year Prospective Study

The aim of this study was to evaluate the peri-implant marginal bone level for immediately loaded implants placed simultaneously in both fresh extraction sites (FES) and healed sites (HS) supporting a four-implant–supported mandibular fixed prosthesis (4-ISFMP) using the All-on-4 concept. A 5-year prospective study was conducted in 24 patients (96 implants) treated with a 4-ISFMP, including 55 implants inserted in FES and 41 implants in HS. At implant placement (baseline) and at the 1, 3, and 5-year follow-up examinations, the peri-implant marginal bone level was evaluated radiographically and compared between placement in FES vs HS. Marginal bone loss was calculated as the difference in the marginal bone level evaluated at the follow-up periods. Additionally, implant and prosthesis survival rates, as well as the presence of peri-implant mucositis (bleeding on probing + [BOP]) and peri-implantitis (BOP + > 2 mm MBL), were evaluated. Of the 24 patients, 22 with 88/96 implants (dropout rate: 8.3%) were continually followed for 5 years (survival rate: 100%). Radiographically measured marginal bone level differed significantly between FES and HS at implant placement (1.46 ± 0.80 mm vs 0.60 ± 0.70 mm; P < .001), at 1 year (–0.04 ± 0.14 mm vs –0.18 ± 0.20 mm; P = .002), and at 3 years (–0.26 ± 0.49 mm vs –0.58 ± 0.48 mm, P = .049), but not at 5 years (–0.90 ± 0.66 mm vs –1.00 ± 0.59 mm, P = .361). The marginal bone loss differed significantly (P < .001) between FES and HS between implant placement and the 1-year evaluation, but not for the 1- to 3-year (P > .99) or the 3- to 5-year period (P = .082). At the 5-year follow-up evaluation, no implant/prosthesis failed (100% survival), and peri-implant mucositis and peri-implantitis were noted in 41.2% and 11.7% of patients, respectively, and in 17.6% and 4.5% of implants. Implants placed in FES showed a prolonged peri-implant remodeling process but provided similar peri-implant marginal bone levels as implants placed in HS at the 5-year evaluation for immediately loaded 4-ISFMPs.

Krennmair S, Malek M, Forstner T, Krennmair G, Stimmelmayr M, Hunger S. *Clin Oral Implants Res* 2022;33(2):158-171. References: 60. Reprints: S Krennmair, krennmair@aon.at —*Steven Sadowsky, USA*