Effect of an exclusion range of jaw movement data from the intercuspal position on the estimation of the kinematic axis point

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1 Abstract

2 In patients who have lost natural occlusal contacts, the centric relation is usually estimated based on
3 several anatomical factors such as the temporomandibular joint and masticatory muscles except
4 dental arch. The clinical procedure to record the centric relation often depends on the clinician's
5 expertise and technique; an objective method to determine proper occlusal position is desirable. The
6 kinematic axis point (KAP) is kinematically estimated from sagittal movements and is an ideal
7 posterior reference point that is used in dental articulators for reproducing jaw movement. Occlusal
8 registration using the KAP may serve as a definite objective technique. The aim of this study is to
9 investigate the effect of the exclusion range of sagittal jaw movement data from the intercuspal
10 position (ICP) on the estimation of the KAP. The complete and incomplete sagittal border movement
11 data of dentate subjects were used to estimate the KAPs. The locations of the estimated KAPs were
12 compared. The results indicate that the incomplete sagittal border jaw movement data set does not
13 include data points inside a 7 mm distance from the ICP can be used for estimation of the KAP. In
14 conclusion, the sagittal border jaw movement data around the ICP is not indispensable in the valid
15 identification of the KAP.

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20 Introduction

21 The occlusal position at maximum intercuspation is determined by several anatomical factors
22 such as the dental arch, temporomandibular joint, and masticatory muscles [1]. In patients who have
23 lost natural occlusal contacts because of missing teeth, the centric relation is usually estimated based
24 on factors except dental arch [2]. As the clinical procedure to record centric relation, i.e., occlusal
25 registration often depends on the clinician's expertise and technique, an objective method to
26 determine proper occlusal position is desirable. Kohno studied the jaw movement of subjects with a
27 natural intercuspal position (ICP) and reported that the sagittal jaw movement pathway exhibits
28 convergence at the mandibular condyle head area. He named this point the kinematic axis point
29 (KAP) and the line that connects the KAPs on both sides the kinematic axis (KA) [3-5].
30 Mathematically, the KA separates the translational and rotational components of sagittal jaw
31 movement and enables the simple expression of jaw movement [3,4,6,7]. Because of this kinematic
32 property, the KAP is an ideal posterior reference point that is used in dental articulators to reproduce
33 jaw movement for the fabrication of prosthetic appliances. Since the KAP can be kinematically
34 estimated by computing jaw movement data, occlusal registration using the KAP as the posterior
35 reference point may serve as a definite objective technique with a theoretical background. To
36 confirm the usability of this technique, an accurate determination of the KAP is indispensable. In this

study, we studied sagittal border jaw movement of dentate subjects, and conducted a simulation study to investigate the effect of exclusion range of jaw movement data from the ICP on estimation of the KAP.

Materials and Methods

1. Subjects

Forty-five adult volunteers (23 men and 22 women; mean age, 26.6 ± 6.7 years) selected from among the faculties and students of Tokushima University Dental School participated in this research. All subjects underwent an examination with questionnaires and palpation of head and neck region according to the questionnaires and clinical protocol of the Temporomandibular Disorder Clinic, Tokushima University Hospital. All subjects had normal dentition and stable occlusal contacts at the ICP. None of the subjects had missing teeth except for the third molar and had received orthodontic treatment within the past year. No signs or symptoms of temporomandibular disorders including pain and dysfunction in the temporomandibular joint and/or the masticatory muscles were present in any of the subjects. This research was approved by the Research Ethics Committee of Tokushima University Hospital (No. 575). The informed consent was obtained from all participants prior to data collection.

2. Jaw movement recording

A custom-made six degree-of-freedom jaw tracking device using a magnetic sensor system (Fig. 1) [8,9] was used to record the jaw movement. This device uses a pair of miniature triaxial coils connected to the maxillary and mandibular dentitions. Each sensor unit is a 21 mm cube weighing 7.0 g. The calibration study revealed the measurement errors of this device were better than 48 μm for translation and 0.035 $^\circ$ for rotation [8, 9]. An acrylic splint attached to the labial surface of the dentition was used to mount the sensor unit. The primary sensor unit (Fig. 1a) generates triaxial magnetic fields and is placed in the anterior area of the nose. The secondary sensor unit (Fig. 1b) is placed in the left lateral area of the buccal region and detects magnetic field changes. These sensor units were initially placed 100 mm apart from each other, i.e., the ICP of the jaw movement recording (Fig. 1).

Each subject was asked to sit upright in a dental chair without the head supported and to start jaw movements from the ICP. Each participant performed three sagittal border jaw movements that were measured separately with a sampling rate of 100 Hz. To analyze and display jaw movement data, we employed the upper jaw coordinate system (O_u - x_u y_u z_u) [10] as the reference coordinate system, as shown in Fig. 2. The origin of this system is located at the centroid of the triangle defined by an incisal point (IN, central point of the medial edge of the maxillary incisor) and the left and right first molar points (L6 and R6, central fossa point of the maxillary first molar). The positive x_u -,

y_u -, and z_u -axes point in the subject's anterior, left, and superior directions, respectively. The positive rotation directions are defined by the right-hand rule.

3. Estimation algorithm for the KAP

As shown in Fig. 2, the intercondylar axis (ICA) is initially determined based on the Bonwill triangle with a side length of 110 mm and a Balkwill angle of 20° , and 13 distinct points P_m ($m: 1 \dots 13$) are arranged at 10-mm intervals on the ICA. P_2 and P_{12} are included in the Bonwill triangle as the right and left condylar points, respectively. A two-dimensional (2D) projection of the sagittal border jaw movement pathway of P_m in a particular sagittal plane V_m that passes through P_m is used to determine the KAP. V_m is perpendicular to the ICA (Fig. 2). The least squares circle in V_m that fits the set of the 2D projection sagittal border jaw movement pathway is found. The circumference of the circle is divided into n arcs of 0.2 mm using dotted rays that start at its center, and then the maximum radial thicknesses rth_i ($i = 1 \dots n$) of the jaw movement data between two adjacent dotted rays is calculated (Fig. 3). The sum $\sum_{i=1}^n rth_i^2$ of the squares of the radial thickness (rth_i) is employed as a geometric parameter to determine the KAP. The KAP in V_m (KAP_m) is obtained as a point minimizing the value of this geometric parameter. As shown in Fig. 4, the searching procedure is started from 5×5 grid points spaced 10 mm apart, the center of which is set to P_m . The point (MP_m) minimizing the value of the geometric parameter is chosen from among these 25 points, and then the

same grid analysis is performed for 25 new points spaced 5 mm apart, representing half of the initial grid interval, and the center is set to MP_m . This searching procedure is repeated nine times (grid interval = 0.039 mm), and finally, the last MP_m value is selected as the KAP_m . Additionally, its quadratic mean radial thickness $\sqrt{\frac{1}{n} \sum_{i=1}^n rth_i^2}$ is calculated. Using 3D linear regression, we determined KA such that the sum $\sum_{m=1}^{m=13} d_m^2$ of the squares of the perpendicular distances (d_m) between the KAP_m and the line is minimized, and its quadratic mean perpendicular distance $\sqrt{\frac{1}{13} \sum_{m=1}^{m=13} d_m^2}$ is calculated. We decided KAP_2 and KAP_{12} were the right and left condylar points, respectively. We used all of the KAP_m for the following analysis. This searching procedure was performed automatically using a custom application that was created in Microsoft Visual C++ 2008.

4. Estimation of the kinematic axis point from the excluded sagittal border movement data (exc_KAP)

A complete and an incomplete (excluded) sagittal border movement data set were used to estimate the KAPs. The complete data set, including all of the recorded data, ranges from the ICP to the maximum protrusion position (Pr) and then to the maximum opening position (MO) through the anterior border movement pathway, and then from the MO to the ICP through the posterior border movement pathway (Fig. 5A). The excluded data set, on the other hand, does not include the data

points in the exclusion range of a 15 mm distance from the ICP. The data exclusion range was changed each 1 mm (Fig. 5B).

Using the estimation algorithm mentioned above, the reference KAP_m (ref_ KAP_m) and KA (ref_KA) were estimated from three complete sagittal border movement data sets. In the same manner, the exclusion KAP_m (exc_ KAP_m) and KA (exc_KA) were estimated from three excluded sagittal border movement data sets for each exclusion range. The mean positional deviations (antero-posterior (dx), supero-inferior (dz), and Euclidean distance (d)) between the exc_ KAP_m and the ref_ KAP_m of 45 subjects were calculated for each exclusion range (Fig. 6).

5. Statistical analysis

Paired *t*-test was used to compare the values of the radial thicknesses of the pathways of the ref_ KAP_2 (right condylar point) and those of the ref_ KAP_{12} (left condylar point). To evaluate effect of the data exclusion range on the validity of the KAP estimation, a segmented linear regression analysis with two segments was used to determine the relationship between the 2D position deviation of the exc_KAP from the ref_KAP and the range of the exclusion area and two regression slopes were compared by means of a one-way analysis of covariance (ANCOVA) to analyze the effect of the range of data exclusion on the position of exc_KAP. The level of significance was $P < 0.05$ (two-tailed).

Results

1. Estimation algorithm for the KAP

The pathways of axis points (P_2 , P_7 , and P_{12} for the ICA and KAP_2 , KAP_7 , and KAP_{12} for KA) are illustrated in Fig. 7. As a result of analyzing the complete sagittal border movement data of 45 subjects, the estimated ref_KAP_m ($m: 1 \dots 13$) pathway showed a narrow, belt-shaped range and the average of the quadratic mean radial thickness of the right (ref_KAP_2) and left (ref_KAP_{12}) condylar points pathway (mean $\pm$ SD; $n=45$) were 0.96 ± 0.31 mm and 0.89 ± 0.40 mm, respectively. There were no significant differences between the radial thickness of the right and left condylar points (Paired t -test, $p=0.20$). Furthermore, the ref_KAP_m was located mostly on the ref_KA , and the average of the quadratic mean perpendicular distance from the ref_KAP_m to the ref_KA (mean $\pm$ SD; $n=45$) was 0.36 ± 0.24 mm (Fig. 7).

2. Estimation of exc_KAP from the excluded sagittal border movement data

Fig. 8 shows the relationship between the data exclusion range and the mean positional deviation between the exc_KAP_m and the ref_KAP_m ($m: 1 \dots 13$). The antero-posterior (dx) and supero-inferior (dz) mean positional deviations of the exc_KAP_m from the ref_KAP_m (mean $\pm$ SD; $n=13$) were 0.02 ± 0.02 mm and -0.02 ± 0.05 mm with a 1-mm data exclusion range, 0.18 ± 0.10 mm

and -0.26 ± 0.30 mm with a 7-mm data exclusion range, and 1.18 ± 0.26 mm and -1.64 ± 0.23 mm with a 13-mm data exclusion range, respectively. In addition, the mean Euclidean distances (d) between ref_KAP_m and exp_KAP_m (mean $\pm$ SD; n=13) were 0.12 ± 0.02 mm with a 1-mm data exclusion range, 0.47 ± 0.13 mm with a 7-mm data exclusion range, and 2.12 ± 0.25 mm with a 13-mm data exclusion range. The exc_KAP position gradually deviated in the antero-inferior direction from the ref_KAP. There were two linear relationships in the data until the exclusion range of 13 mm and a segmented linear regression analysis detected the breakpoints (BP) of 8.51 mm for dx, 7.64 mm for dz, and 8.36 mm for d, respectively. Slopes below the BP were 0.0290 for dx, -0.0373 for dz, and 0.0649 for d, respectively and those above the BP were 0.2121 for dx, -0.2571 for dz, and 0.3355 for d, respectively. To test for differences in slopes among the regression lines below and above the BP, we conducted a one-way ANCOVA with exclusion range as a covariate and the exc_KAP position deviation as the dependent variable. The slopes below and above the BP were significantly different ($p < 0.05$) in all position deviations (dx, dz, and d). In other word, there was a significant change in the position deviation rates below and above the BP. The effect of the exclusion range on the exc_KAP position deviation below the BP was smaller than that above the BP.

Discussion

In describing mandibular movements several kinematic reference points, or axes, are being used

[11]. The hinge axis is widely used as the condylar axis for reproduce of jaw movements in a mechanical articulator because of its easy identification and reproducible [6,11,12]. However, the movement paths of the hinge axis depends upon the rotatory component of mandibular movements and are representative of those of the subject's condyle during only the terminal hinge movements [6,11]. While, KA separates the translational and rotational components of the various sagittal movements [3,4,6,7], it can be an ideal condylar reference axis. If it would be possible that KA coincides with the ICA of the mechanical articulator, the various types of jaw movements in the sagittal plane can be reproduced in the articulator and thus the design of dental prosthesis is improved. Beneficially, KA is mathematically estimated from jaw movement data without the necessity of the use of the face bow. Furthermore, the results of this study have the advantage of high applicability in the development of a sophisticated virtual articulator. The final goal of this study was to develop clinical techniques of determining KA of a patient with loss of occlusal support and transferring their KA to an articulator. The concept of the KA was originally found by Kohno [3] from the investigation of sagittal jaw movements in ten subjects with normal dentition and stable occlusal contacts at the ICP, without signs or symptoms of temporomandibular disorders. In this research, all subjects were therefore selected using the same selection criteria for inclusion as those of Kohno's study [3] and the possibility of determining the KAP and the KA from the incomplete jaw movement data without data points in and around the ICP were examined.

Several techniques and parameters such as vertical width of the condylar pathway [3,4,5,13], vertical deviation of the curve fitting the pathway [14], area enclosed the pathway [15,16], space volume dictated by the pathway[17], and consistency of the pathways [6,7] have been applied for estimations of KA and/or KAP from mandibular movement. In this research, the least squares circle fitting the sagittal border movement pathway was constructed, and then the radial thickness of the jaw movement pathway around this circle was evaluated. As shown in Fig. 7, the ref_KAP_m exhibited a convergence pathway the same as that reported in previous studies [3-5]. The overall average of the quadratic mean perpendicular distance between the ref_KAP_m and ref_KA of 45 subjects was 0.36 mm. The KAP_m estimated in this study had the kinematic characteristic that the KAP must theoretically be located mostly on the KA [15]. The overall averages of the quadratic mean radial thicknesses of the right and left condylar point of 45 subjects were 0.96 mm and 0.89 mm, respectively. These values were almost the same as the vertical width of the KAP pathway reported by Kohno [3-5]. The above results prove that our estimation algorithm for KA may be considered valid.

A simulation analysis of data exclusion in the range of a 15 mm distance from the ICP exhibited a gradual deviation of exc_KAP_m from ref_KAP_m in the antero-inferior direction. In a data exclusion area below the BP, the exc_KAP_m was located close to the ref_KAP_m, and was within 1 mm of deviation, as Kohno [3] and Nishi [18] reported that the KAP can be distributed around a 1 mm area.

It could be said that if the exclusion area is below the BP, the sagittal border movement can be validly used for an estimation of the KAP. This finding indicates that the incomplete jaw movement data set without the data points in the range of a 7 mm distance from the ICP can be used for the estimation of the KAP. As a result of this study, the possibility of determining the KA of patients with loss of occlusal support was suggested.

In this research, all subjects had natural dentition and stable occlusal contacts at the ICP. Therefore, it is questionable whether the same results would be obtained with the jaw movement of complete and/or partially edentulous patients who have lost their original ICP. As an earlier study on the jaw movement of completely edentulous patients by the multi-flash method [19] reported that the condylar point movement exhibited a convergence pathway the same as that found in subjects with normal occlusion, we believe that a valid estimation of the KAP is possible, even in edentulous patients. Before the clinical application of this technique, further studies to identify the most suitable jaw movements for KAP detection and effective instruction methods for jaw movement recording, and to determine occlusal vertical dimension kinematically will be required. It is also necessary for developing the virtual articulator to apply the results of this study in an efficient and effective manner. Definitely, experimental trials of KAP detection in patients who have lost their natural occlusal contacts would also be indispensable.

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219

220 Conflict of interest

221 The author confirms that there is no conflict of interest in relation to this work.

222

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227 Ethical approval

228 This research was approved by the Research Ethics Committee of Tokushima University
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Fig. 1. A six degree-of-freedom jaw tracking device using a magnetic sensor system.

a: primary sensor unit b: secondary sensor unit

Fig. 2. Reference coordinate system and intercondylar axis determined based on the Bonwill triangle and the Balkwill angle.

Three orthogonal axes show the upper jaw coordinate system ($O_u-x_u y_u z_u$). The $x_u z_u$ and $x_u y_u$ planes are the sagittal (SAG) and horizontal (HOR) planes, respectively. The equilateral triangle $IN-P_2-P_{12}$ is the Bonwill triangle with a side length of 110 mm. $\angle \alpha$ is a Balkwill angle of 20° . Line P_2-P_{12} is the initial intercondylar axis (ICA) and P_m ($m = 1 \dots 13$) is a distinct point arranged at 10-mm intervals on the ICA, and P_2 and P_{12} are the right and left condylar points, respectively. V_m is the sagittal plane that passes through P_m and is perpendicular to the ICA.

Fig. 3. Radial thickness of the sagittal border movement pathway.

The least squares circle fitting the 2D projection of sagittal border movement data is found. The circumference is divided into n arcs of 0.2 mm using dotted rays that start at the center (C) of the least squares circle. The maximum radial thickness rh_i ($i = 1 \dots n$) of the jaw movement data between two adjacent dotted rays is calculated. The sum of the squares of rh_i is employed as a geometric parameter to search for the KAP.

Fig. 4. Searching procedures for the KAP.

The searching procedure for the KAP is started from 5×5 grid points spaced 10 mm apart, the center of which was set to P_m that is on the ICA. MP_m is the point minimizing the value of the geometric parameters, and is chosen from among the 25 points, and then the same grid analysis performed for 25 new points spaced 5 mm apart, the center of which is MP_m . This searching procedure is repeated nine times (grid interval = 0.39 mm), and finally, the last MP_m is selected as the KAP_m . The two perpendicular arrows show the subject's anterior (A) and superior (S) directions, respectively. The length of the arrow indicates 10 mm of jaw movement pathway.

Fig. 5. Complete and incomplete (excluded) sagittal border movement of the incisor point in the sagittal view.

A: The complete sagittal border movement. B: The excluded sagittal border movement.

Fig. 6. Deviation of the exc_KAP estimated from the incomplete sagittal border movement from the reference KAP (ref_KAP).

Antero-posterior (dx) and supero-inferior (dz) positional deviations and Euclidean distances (d) between exc_KAP (●) and ref_KAP (○) were calculated.

Fig. 7. Jaw movement pathways of the points on the ICA and the estimated KAP_m .

The estimated KAP_m demonstrated a narrow, belt-shaped range during the complete sagittal border movement, and was located mostly on the KA.

Fig. 8. Relationship between the data exclusion range and the antero-posterior (dx) and

supero-inferior (dz) positional deviations and Euclidean distance between exc_KAP and ref_KAP.

There were two linear relationships in the data with a sudden change in the slope. Data are plotted as the mean $\pm$ SD.

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