Clinical significance
Analysis of both condylar morphology and movement has potential clinical applications, such as (i) to evaluate the condylar position and movement under prosthodontic treatment, and (ii) to help determine subsequent treatments by assessing how patients’ clinical symptoms of temporomandibular disorders are interrelated with the condylar movements associated with bone change.

Abstract
Purpose: The aim of this study was to develop a means of coordinating helical computed tomography (CT)-based morphological data in 3 dimensions (3-D) with that pertaining to jaw movement as recorded by a device that measures jaw movement in six-degrees-of-freedom (6-DOF), thus producing multi-point movement analysis of the condyle.

Methods: The study sample was two volunteers. One of the subjects had erosive bony changes in both condyles, while the other had healthy condyles. We employed a customized facebow, which enabled us to coordinate jaw movement data and morphological volume data from CT. Total uncertainty of the coordination was computed, according to International Organization for Standardization (ISO). In order to demonstrate the effects of multi-point analysis for complex condylar movement, we tried to visualize the trajectory of the working condyle in lateral excursion.

Results: The overall uncertainty at a condylar center chosen as an example to illustrate the method was 0.38 mm, 0.19 mm, and 0.50 mm in antero-posterior, latero-medial, and supero-inferior directions, respectively, in terms of 95% coverage as defined by the ISO.

Conclusion: We developed facebow-based X-ray markers with high clinical operability, which could correlate the helical CT’s coordinate system with our 6-DOF jaw movement measuring system for precise analysis of 3-D condylar movements. In motion analysis of rotational condyle, even a small amount of measurement error cannot necessarily be neglected. Then, a multi-point approach such as that realized by our system presents the best option.

Key words: condylar movement, condylar morphology, temporomandibular disorder, helical computed tomography scan, jaw movement measurement

Introduction
Kinematic studies of the condyle involve X-ray cinematography, video-fluorography, and dynamic magnetic resonance imaging (MRI) scanning techniques, while analyses of the condylar position in the glenoid fossa have thus far been carried out by means of CT, MRI, and conventional tomography. While the use of X-rays exposes subjects to a certain amount of radiation, it provides us with images that are far superior, in both resolution and contrast, to those obtainable by MRI.

Dynam-ic MRI scanning uses echo planar imaging to clearly detect disc-deformations, but the data it provides regarding movement are unfortunately limited to only two dimensions. Systems that measure jaw movement in six-degrees-of-freedom (6-DOF) are employed extensively to study condylar movement. These studies differ with respect to the choice of distinct, anatomically- or kinematically-determined condylar reference points, where the former make use of arbitrary condylar reference points and the latter include a computer-aided hinge-
axis point and the kinematic axis point. This has led to a lack of consistency, when setting reference points. With respect to osteoarthritic/osteoarthrotic condyles or mandibular deviation, however, it is extremely difficult to determine a reproducible reference point for jaw movement recording, since the temporomandibular joint (TMJ) tends to exhibit extreme positional deviation of the condyle and/or condyle/fossa remodeling. So, each method has its obvious advantages and disadvantages.

However, in a move that circumvents the negative aspects of all of these approaches, Krebs et al. employed a system combining 6-DOF jaw movement recording with MRI TMJ-imaging, achieving a clear visualization of the movement of the entire condyle relative to the fossa. Such a complex approach to condylar movement analysis also has potential clinical applications, such as (i) to evaluate the condylar position and movement under splint treatment, and (ii) to help determine subsequent treatments by analyzing how the clinical symptoms of temporomandibular disorders are interrelated with the condylar movements associated with bone change. However, for these to be achieved, it is essential that the systems employed in jaw movement recording and imaging be fully coordinated. This coordination was accomplished by Krebs, using contrast medium-filled polyvinylchloride spheres, and by Tanaka using steel wires. From measurements of the markers' exact positions, they could coordinate jaw movement and morphological data. However, from a clinical standpoint, the use of such reference markers often requires additional and time-consuming measurements of jaw movement, and can even impair the operability and overall accuracy of the measurement itself.

The aims of this study were: (i) to develop facebow-based X-ray markers with high clinical operability; (ii) to devise the guidelines for their proper use, by correlating the helical CT's 3-D coordinate systems with our 6-DOF jaw movement measuring system, for precise analysis of 3-D condylar movements; and (iii) to compute the total uncertainty, as defined by International Organization for Standardization (ISO), regarding the position of a condylar center.

Materials and Methods

Subjects

With the approval of the ethical committee of Niigata University, two 24-year-old female volunteers with different features in condyles were selected in order to demonstrate the system performance. One of the subjects had erosive bony changes in both condyles, while the other had healthy condyles. After receiving a full explanation of the aims and design of the study, both the subjects gave their informed consent. Procedures commenced with an analysis of condylar movement during lateral excursions in order to ensure its operability.

CT scanning (Facebow-based X-ray markers)

We made a customized facebow that had three reference-point locators (Fig. 1A). The facebow and locator components were all constructed of either aluminum or acrylic resin, which effectively eliminated the possibility of artifacts disturbing the CT images. The 1-mm tips of each locator, which function as X-ray markers, were clearly discernable in the CT images. First, we attached the customized facebow to the maxillary clutch of a subject. Next, we placed the tips of each locator onto three cranium reference points (Fig. 1A)—the right and left reference points (P1 and P2), located 13 mm anterior to the tragus on the tragus-excanthion axis and the left subalare (P3). All points were marked on the skin by means of a 1-mm felt-tip pen before attaching the facebow. The locator tips completely coincided with skin markers (P1, P2, and P3) in a seated position. The subject wore a silicon bite-block (Exabite II, GC Co., Tokyo, Japan) in maximum intercuspation in order to prevent mandibular deviation due to postural change.

Finally, the subject’s head with the facebow was scanned by means of a helical CT (Xvigor Real, Toshiba Medical Co., Tokyo, Japan). During the scanning process, the subject, while wearing the bite-block, was placed in a supine position. Helical scans were taken trans-axially, parallel to Reid’s base line, starting at a few millimeters above it over a distance of 150 mm (120 kV, 100 mA, and 1 mm collimation).

Jaw movement measurement

We used a high-resolution, line-sensor-based photostereometric system (TRIMET, Tokyo Shizaisha Co., Tokyo, Japan) to measure jaw movements in 6-DOF (Fig. 1B). This recording was taken by measuring the 3-D position of light-emitting diode (LED) markers mounted on the maxilla and mandible at a rate of 100 Hz. Before recording the jaw
movement, the aforesaid positions of $P_1$, $P_2$, and $P_3$ relative to the maxillary LED markers were measured in a seated position by means of TRIMET’s measuring bow, as shown in Fig. 1C, in order to establish a cranial reference frame.

**CT image digitizing**

The scanned data were then transferred to a workstation (Xtension, Toshiba Medical Co.) and reconstructed into 3-D images (resolution: 0.47 mm) (In-tage3.1, K.G.T. Co., Tokyo, Japan: Fig. 1D). Frontal, sagittal, and horizontal images were all used to identify the medial and lateral poles of each condyle, which were defined as the points in the most lateral and medial sagittal images in the condyle. The condylar center ($P_c$) was defined as the point lying midway between these poles. The 3-D positions of each pole were digitized in three dimensions by manually placing a cross cursor onto the pole in the three images (digitizing resolution: 0.12 mm), where the cursor can be placed concurrently in the images. The three locator tips on the customized facebow were also digitized in the same manner.

**CT and TRIMET data-coordination method**

Three arbitrary reference positions: the right and left axis points ($P_1$ and $P_2$) and the left subalare ($P_3$) were used in both movement data and CT images, in order to construct the coordinated frames, denoted $\Sigma_{\text{TRIMET}} = o-xyz$ and $\Sigma_{\text{CT}} = O-XYZ$ (the frames of the TRIMET and CT, respectively) (Fig. 2).

Frame $\Sigma_{\text{TRIMET}}$ was set in the following manner: (i) The origin ($O$) in $\Sigma_{\text{TRIMET}}$ was defined as the point located midway between $P_1$ and $P_2$; (ii) the
y-axis, as the line including P₁ and P₂; (iii) the x-axis, as the line included in the P₁P₂P₃ plane, passing through the origin, and perpendicular to the y-axis; and (iv) the z-axis, being the line perpendicular to both the x- and y-axes. Origin O of ΣCT was chosen as the corner point of the reconstructed 3-D data, and its X-, Y-, and Z-axes were set as per Fig. 2. To coordinate frames ΣTRIMET and ΣCT, we introduced an intermediate coordinate frame (ΣCT/TRIMET = oCT−xCT,yCT,zCT) for the CT image data, which was defined using P₁, P₂ and P₃ in the same manner as with ΣTRIMET. ΣCT-related unit vectors eₓ, eᵧ, and eȥ denote the direction of the xCT-, yCT-, and zCT-axes, respectively, while vector p CT denotes the position of oCT. The formula for coordinate transformation from ΣCT to ΣTRIMET can then be described as:

\[ \mathbf{p}_{\text{TRIMET}} = \left( e_{\text{x}}, e_{\text{y}}, e_{\text{z}} \right)^{-1}(\mathbf{p}_{\text{CT}} - \mathbf{p}_o) \]

where \( \mathbf{p}_{\text{TRIMET}} \) and \( \mathbf{p}_{\text{CT}} \) denote position vectors of an arbitrary point P with respect to ΣTRIMET and ΣCT, respectively.

**Uncertainty of coordinating CT and TRIMET frames of reference**

If cranial reference points P₁, P₂, and P₃ of CT images are assumed to coincide with actual reference points on the subject’s skin surface, uncertainty of coordinating CT and TRIMET frames of reference originates primarily from manual digitization error of these points in CT images and TRIMET measurement. Points P₁, P₂, and P₃ of CT images of the control subject were digitized 10 times in the manner mentioned previously by an experienced technician in order to verify reproducibility of the digitization. For the TRIMET measurement of the same subject, the positions of each locator tip were also measured 10 times indirectly by measuring the positions of P₁, P₂, and P₃ under the assumption that the locator tips completely coincided with P₁, P₂, and P₃. Such digitization and measurement yielded cranial coordinate frames (ΣCT/TRIMET(i): i = 1,2,...,10) and (ΣTRIMET(i): i = 1,2,...,10), respectively. Let \( e_{\text{x}}(i), e_{\text{y}}(i), e_{\text{z}}(i): i = 1,2,...,10 \) and \( \mathbf{p}(i): i = 1,2,...,10 \) denote direction vectors of the coordinate axes and position vector of the origin for each cranial frame, respectively. Roll, pitch, and yaw angles of each frame were computed as:

\[ R(i) = \tan^{-1}\left( \frac{-a_{\text{x}}(i)}{b_{\text{i}}(i)\cos Y(i)} \right) \]

\[ Y(i) = \tan^{-1}\left( \frac{a_{\text{y}}(i)}{a_{\text{z}}(i)} \right) \]

where \( a_{\text{x}}(i), a_{\text{y}}(i), a_{\text{z}}(i) \) and \( b_{\text{i}}(i) = (a_{\text{x}}(i), a_{\text{y}}(i), a_{\text{z}}(i))^{T} \) and \( e_{\text{x}}(i) = (b_{\text{x}}(i), b_{\text{y}}(i), b_{\text{z}}(i))^{T} \). We assessed the reproducibility of the cranial frames ΣTRIMET and ΣCT, by means of the standard deviations of \( \{R(i)\}, \{P(i)\}, \{Y(i)\} \), and \( \{p(i)\} \), as well as their maximum deviations from the averages.

**Positional error of the selected point**

Using these results, we estimated the positional error of a right condylar center (P₄) as an example to illustrate the method. The positional error of the origin and the rotation error about the origin of the axes were both considered in an error propagation model. The ISO total uncertainty of the position of P₄ was evaluated by the following procedure: (i) obtain the bias limit and the precision index for all error factors through experiments; (ii) compute the bias limit and the precision index due to all error factors; and (iii) compute the total uncertainty in terms of 95% coverage. The error factors are six independent parameters regarding the position and orientation of the cranial frame. This section deals with the uncertainty of the position of P₄ in terms of the precision index, assuming that the unknown bias limit was negligible. The total uncertainty of P₄’s each coordinate (x, y, or z) can be computed from the direct component \( U_{\text{A}} \) and the indirect component \( U_{\text{B}} \) as follows:

\[ U_x = t \sqrt{U_{\text{A},x}^2 + U_{\text{B},x}^2}, \]

\[ U_y = t \sqrt{U_{\text{A},y}^2 + U_{\text{B},y}^2}, \]

\[ U_z = t \sqrt{U_{\text{A},z}^2 + U_{\text{B},z}^2}, \]

where \( t \) denotes Student’s \( t \)-value. In the rest of this section, we shall describe the computation of x-coordinate component \( U_x \), and the other components, \( U_y \) and \( U_z \), can be computed in the same manner.

Component \( U_{\text{A},x} \), which originated from the positional error of the origin, can be computed as

\[ U_{\text{A},x} = \sqrt{\frac{\sigma_{\text{A},x}^2}{N_{\text{A}}} + \frac{\sigma_{\text{B},x}^2}{N_{\text{B}}}}, \]

where \( \sigma \) and \( N \) denote the standard deviation of each error factor and the number of trials, and
subscripts CT and TR represent the data of CT and TRIMET, respectively. The indirect component \( U_{\text{B,x}} \), which originated from the rotation error about the origin, can be computed from two different components \( S_{\text{B,x,CT}} \) and \( S_{\text{B,x,TR}} \) as follows:

\[
U_{\text{B,x}} = \sqrt{S_{\text{B,x,CT}}^2 + S_{\text{B,x,TR}}^2}
\]

Letting \( R, P, \) and \( Y \) denote roll, pitch, and yaw angles regarding the rotation, the position of \( P_\alpha \) can be described as a certain function of \( R, P, \) and \( Y \) as follows:

\[
p = (f_x, f_y, f_z)^T = f(R, P, Y|P_\alpha).
\]

Then, \( S_{\text{B,x}} \) can be represented as

\[
S_{\text{B,x,CT}} = \frac{1}{N_{\text{CT}}} \left( \frac{\partial f_x}{\partial R} \sigma_{R,\text{CT}} + \frac{\partial f_x}{\partial P} \sigma_{P,\text{CT}} + \frac{\partial f_x}{\partial Y} \sigma_{Y,\text{CT}} \right)^2,
\]

\[
S_{\text{B,x,TR}} = \frac{1}{N_{\text{TR}}} \left( \frac{\partial f_x}{\partial R} \sigma_{R,\text{TR}} + \frac{\partial f_x}{\partial P} \sigma_{P,\text{TR}} + \frac{\partial f_x}{\partial Y} \sigma_{Y,\text{TR}} \right)^2,
\]

where \( \sigma_{R}, \sigma_{P}, \) and \( \sigma_{Y} \) denote the standard deviation of roll, pitch, and yaw angles, respectively.

### Results

#### Reproducibility

Table 1 summarizes the results of our efforts to reproduce coordinate frames \( \Sigma_{\text{TRIMET}} \) and \( \Sigma_{\text{CT/TRIMET}} \). The standard deviation of the origin position and the axis direction regarding \( \Sigma_{\text{TRIMET}} \) was less than or equal to 0.64 mm and 0.52 degrees, respectively. As regards CT digitizing, the standard deviation was less than or equal to 0.27 mm and 0.27 degrees, respectively. The position and orientation of \( \Sigma_{\text{TRIMET}} \) deviated from their corresponding averages by no more than 0.81 mm and 0.87 degrees, respectively. During CT digitizing, deviations were less than or equal to 0.60 mm and 0.48 degrees. The number of trials \( \langle N \rangle \) was 10, and Student’s \( t \)-value was 2.262. Values of \( \sigma_{R,\text{CT}}, \sigma_{P,\text{CT}}, \) and \( \sigma_{Y,\text{CT}} \) were 0.27 degrees, 0.16 degrees, and 0.06 degrees, respectively, while those of \( \sigma_{R,\text{TR}}, \sigma_{P,\text{TR}}, \) and \( \sigma_{Y,\text{TR}} \) were 0.39 degrees, 0.52 degrees, and 0.36 degrees, respectively. Then, total uncertainty \( U \) regarding the position of \( P_\alpha \) was computed from direct and indirect components \( U_\alpha \) and \( U_b \) in the manner mentioned in the previous section. The values of \( U_\alpha \) and \( U_b \) are listed in Table 2. Finally, the values of total uncertainty \( U \) were 0.38 mm, 0.19 mm, and 0.50 mm with respect to the \( x^*, y^*, \) and \( z^* \) components, respectively (Table 2).

### An application of our coordination method

Figure 3 shows onaxial and parasagittal CT images of the working-condyle passing through the condylar center, as well as the trajectories of several condylar points during lateral excursion. Figure 3A and B show data regarding subjects who either did and did not display changes in condylar bone, respectively. The stable working condyle’s lateral pole (Fig. 3A) was observed to move a greater distance medially, posteriorly, and superiorly, while its medial pole moved slightly in the medial direction, suggesting that the condyle rotated around the mediad pole. In the working condyle of the subject displaying changes to condylar bone (Fig. 3B), movement was principally in the lateroanterior direction in the entire condyle. The medial pole’s movement was similar to that of the lateral pole, suggesting that the rotation center was located far from the condyle.

### Discussion

Until this time, there were few workable methods of accurately coordinating TMJ morphology and jaw movement. Then, we developed the facebow system, and evaluated its total uncertainty. First of all, the coordination procedure of our method as a guideline for proper use of the system was summarized as follows: (i) to mark three cranial reference points, \( P_1, P_2, \) and \( P_3 \) on the skin; (ii) to mount the customized facebow on the maxilla (Fig. 1A) in order for the tips of the reference-point locators to...
coincide with $P_1$, $P_2$, and $P_3$ (Fig. 1A); (iii) to accomplish CT scanning of the subject's head with the customized facebow (Fig. 1D); (iv) to digitize the tips of the reference-point locators manually in the CT images for establishing the CT coordinate frame $\Sigma_{\text{CT}}$; (v) to mount LED markers on the mandible for jaw movement tracking after removing the customized facebow; (vi) to digitize mandibular points such as incisal point and arbitrary axis points $P_1$ and $P_2$ relative to the mandibular LED markers by means of TRIMET's measuring bow for preparing the analysis of jaw movement; (vii) to mount LED markers on the maxilla; (viii) to digitize $P_1$, $P_2$, and $P_3$ relative to the maxillary LED markers by means of the measuring bow for establishing the TRIMET coordinate frame $\Sigma_{\text{TRIMET}}$ (Fig. 1C); (ix) to measure jaw movements (Fig. 1B); and (x) to coordinate $\Sigma_{\text{TRIMET}}$ with $\Sigma_{\text{CT}}$.

Before discussing the features of our system, we would like to review two previous studies regarding the coordination of jaw-movement measurement and TMJ morphology. Tanaka employed an apparatus consisting of an acrylic board with several steel-wire markers mounted on it that enabled them to combine X-ray tomographically-reconstructed images of the TMJ with 6-DOF jaw movement data. They evaluated the overall accuracy of their system, in terms of either coordinate-transformation error or contour-interpolation error, through experiments involving a dried human skull. The former error was evaluated in terms of the distance between a condylar contour obtained from the coordinate transformation of its CT image and a reference contour directly measured by a dedicated system. So while translation-error was assessed, rotation-error was not. By superimposing a digitized CT/TMJ contour on the reference contour, Tanaka was able to calculate the latter's interpolation-error. The superimposition, however, was done on a trial-and-error basis, impairing the reliability of the quantitative assessment.

Krebs et al. employed two sets of three spherical reference markers with a contrast medium, to combine reconstructed TMJ-images of MRI and 6-
DOF jaw movement data. Inaccuracies in the MR system’s geometry were assessed by calculating the degree of error in the spheres’ localization, which was evaluated by comparing actual inter-sphere distances and their measured values obtained in reconstructed marker images. However, what should actually be evaluated is the error of coordinating maxillary LED target- and MR-frames. Additionally, they assessed the error in the repositioned monoblock, which was set in such a way as to repeatedly locate the reference spheres, relative to the maxilla. This error was evaluated in terms of the reproducibility of the position and orientation of maxillary LED targets attached to the bite-block, relative to mandibular LED targets secured to the lower dental arch.

As mentioned, the two earlier studies2,9 of as-yet-unverifiable accuracy attempted to analyze certain flaws detected in the coordination of jaw-geometry and -motion. We, of course, tried to evaluate the total uncertainty in our facebow-based coordination of jaw movement recording and CT data. Errors occurred in such coordination originate primarily from: (i) incorrect cranial reference-point measurements obtained by means of TRIMET which yielded erroneous data, when locating \( \Sigma_{TRIMET} \), to the extent of 0.64 mm and 0.52 degrees (Table 1); (ii) CT cranial reference-point measurement errors which yielded erroneous data, when locating \( \Sigma_{CT/\Sigma_{TRIMET}} \), to the extent of 0.27 mm and 0.27 degrees (Table 1); and (iii) the reproducibility of the intercuspation, immobilized by means of a silicon bite-block. Error component (iii) is actually negligible in comparison with the others, because the deformation of the impression material was certified equal to or less than 0.1%.12 The remaining error component (CT-imaging reproducibility) cannot be evaluated, because of the danger inherent in repeated exposure to X-rays. Previous studies using dried human skulls revealed that when the data were acquired with a 1 mm collimation, length measurements showed relative errors of less than 2%.13 In the aforementioned coordinate-error analysis, this feature was included in error component (ii), but it should also be factored into any geometrical error regarding the condyle and fossa. Finally, we would like to discuss the total uncertainty regarding the position of the condylar center (Pc). We measured the same maxillary reference points, P, Pc, and Pw, with respect to both \( \Sigma_{TRIMET} \) and \( \Sigma_{CT} \), in order to coordinate them. Errors occurring in both measurements can be considered random and uncorrelated because of their independence, enabling us to carry out the ISO total uncertainty analysis. Consequently, total uncertainty \( U \) regarding the position of \( P_c \) was 0.38 mm, 0.19 mm, and 0.50 mm with respect to the \( x^c, y^c, \) and \( z^c \)-components, respectively (Table 2). These errors were just less than 4.7% relative to the size of subject’s condyle, whose dimensions were 7.8 mm, 18.6 mm, and 13.1 mm with respect to the \( x^c, y^c, \) and \( z^c \)-components, respectively.

Even an error factor of such miniscule proportions cannot be neglected in kinematic analyses of this type, because its trajectory changes significantly, from point to point, particularly near the rotational center (Fig. 3A). This underlines the necessity of avoiding one-point kinematic analyses of the working condyle. Thus, a multi-point approach presents the best option, when using coordinated helical CT scanning- and TRIMET data. Any analyses of reproduced condylar movement relative to the fossa must also take into account the accuracy of TRIMET measurements,10 in which static overall accuracy for any condylar point was reported to lie within 0.34 mm.

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