Validity of a Novel Jerk-based Measurement Technique to Evaluate Instability of Condylar Movements due to Occlusal Interference or Joint Deformation

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Abstract To date, no method is available to quantify jerk at a local point of the human joint along a direction that depends on the 3D curvature of the articular surface. This paper proposes a new measurement technique of normalized jerk-cost (NJC) of a target point movement along a direction that is normal to the 3D curvature of the condyle of human temporomandibular joint (TMJ). This study aimed to investigate the reliability and effectiveness of NJC measurements at 9 condylar points. Five control subjects and 3 subjects with condylar asymmetry participated in this study. Each participant performed unilateral gum-chewing. In all control subjects, an artificial occlusal interference (OI) was inserted to the lower molar. The NJCs and intra-articular space of the TMJ on the working side were calculated with and without OI. In 3 control subjects and 3 test subjects, the experiment was repeated after an average interval of 2 months to evaluate reproducibility of the measurements. By means of dynamic stereometry, the NJCs of the 9 condylar point movements towards a direction normal to the condylar surface and intra-articular space were calculated and compared between control group with and without OI, between control group without OI and test group, and between group data measured in two separate sessions. Significantly greater NJC and joint space were observed after insertion of OI (P < 0.05). The NJC in test subjects was greater than that in the control group without OI (P < 0.05). In addition, these parameters measured at different sessions did not differ significantly. These findings suggest that measurement of the NJC and intra-articular space are effective and reliable to evaluate the instability of condylar movements due to OI or joint deformation.

Keywords: motor-dysfunction, mastication, normalized jerk-cost, temporomandibular joint, instability.


1. Introduction
To date, there is no method to quantify acceleration and jerk at a local point of the human joint on direction, which is specific to the 3D curvature of the bony surface. A partial differentiation procedure is needed to solve the orientation of local coordinate systems for measurement, with reference to the 3D curvature of the condylar surface. Thus, movement parameters should be converted to the inherent coordinate system. We hypothesize that very rapid acceleration/deceleration of movement (high jerk cost) may generate incongruences among the condyle, disk and fossae. Accordingly, it is very important to evaluate movement jerk of the condylar surface in multiple areas. Measurements of multiple point movements directed toward normal or tangential to the condylar curvature are the most effective method to understand stress field translation in the joint. In addition, there is no universally accepted index of temporomandibular joint (TMJ) stability or instability during articulation. In this paper, we propose a new jerk-based kinematic parameter to characterize the TMJ joint instability that is dependent on TMJ morphology in each individual [1, 2]. Quantifications of the irregularity in movement trajectory in terms of jerk have allowed not only valid discrimination between movements with and without motor dysfunctions, but also detection of the movements in the adaptive process [3]. Previous studies have claimed that the normalized jerk-cost (NJC) properly quantifies deviations from smooth and well-coordinated movements [3, 4]. Analysis of the TMJ space appears to be important in the study of joint loading [5]. Reconstruction and animation of the TMJ with real anatomic and kinematic data is currently the only method that allows quantification of articulating surfaces of a joint. A preliminarily paper [6] introduced part of accuracy of current measurements. However, total and individual component of systematic measurement errors, effectiveness and reproducibility of the measurements of both intra-articular space and NJC of condylar point movements in association with the morphology of joint surface are unknown. The present study aimed to validate the proposed NJC and intra-articular space measurements using dynamic stereometry. We examined possible measurement errors and the effectiveness to discriminate between joint articulations with and without artificial
occlusal interferences as well as between control subjects and subjects with joint deformity, and examined measurement reproducibility.

2. Methods

2.1 Subjects

Five adult female control subjects aged from 22 to 27 years (mean age, 23 years 2 months) and 3 adult subjects with condylar asymmetry (mean age, 25 years 8 months) participated in this study. All participants showed no clinical sign of jaw dysfunction and gave consent to participate in the experiment after receiving a full explanation of the aims and design of the study. The Ethics Committee of the Dental School approved the experiment.

2.2 Experiments

Each participant performed unilateral gum-chewing. All control subjects performed the chewing task with and without an artificial occlusal interference (OI) that was inserted to the lower molar on the contralateral side. In 3 control subjects and 3 test subjects, the experiment was repeated after an average interval of 2 months to evaluate reproducibility of the measurements. The OI was fabricated by piling up light curing composite resin on a plaster cast of the lingual cusp of the lower second molar, and was cemented to the lingual cusp of the lower second molar on the balancing side. Each subject performed deliberate unilateral chewing of gum on both sides. The six degrees of freedom (6DOF) mandibular movements were recorded. Subsequently, magnetic resonance (MR) imaging was performed in the control subjects, while cone beam computer tomographic (CBCT) imaging was performed in the test subjects.

2.3 Mandibular movement recording

The 6DOF mandibular movements were recorded using a video-based optoelectronic recording system (ProReflex, Qualisys, Inc, Sweden, Fig. 1a). The system allows recording of the 3D movements of stroboscopically illuminated retro-reflective markers that were fixed to the mandible and maxilla. The sampling frequency of the recording was set at 200 Hz. The movement recording system consisted of two digital cameras The camera setup allowed spatial resolution of ± 0.02 mm. Before measurement of movement, we calibrated the system with known distances between reflective markers on a wand and an L-shaped bar to establish the 3D coordinate system for the two cameras. Calibration was accepted if the standard deviation of the wand length was less than 0.1 mm. The mandibular movements were recorded using three hollow spherical plastic markers (external diameter, 7.6 mm; internal diameter, 7.1 mm; ProReflex, Qualisys, Inc, Sweden). In the control subjects, the maxillary movements were recorded using three organogel spheres that are visible on MR imaging (diameter 15 mm, gel marker, Alcare, Japan). The three markers for the maxilla were attached on a rigid triangular plane located near the TMJ and oriented parallel to the para-sagittal plane (Fig. 1d).

The line between the two upper markers was oriented parallel to the Frankfort horizontal plane. As for test subjects, the maxillary movements were recorded using three hollow spherical plastic markers located near the nose (Fig. 1b). The three markers constituted a frontal plane. The line between the upper two markers was the lateral axis of the maxillary coordinate system. The origin of the coordinate system was set at the center of the three markers (Fig. 1c). These lightweight markers were coated with silver chloride to reflect infrared light. The markers were attached to the maxilla and mandible via individually made frames connected to acrylic clutches that were adhered to the labial surfaces of the incisors.

2.4 Measurement errors

In order to determine overall accuracy of measuring intra-articular space, a dry skull (Fig. 2) was used to simulate the living condition. The phantom of joint space (“disk”) on both sides having equal thickness of 3.0 mm were fabricated using acrylic resin. Accuracy of 3D reconstruction using CBCT images was determined by comparing the length of condylar long axis for the condyle. Registration errors were examined using a gradient ruler as a mechanical joint simulator that imitates translator/rotatory jaw movements in three perpendicular anatomical planes.

2.5 MR and CT imaging

In control subjects, MRI focusing on unilateral TMJ was acquired using a superconductive type MRI scanner and a TMJ coil (Signa Horizon 1.5T, GE, USA) in T1-emphasized density conditions, with the mandible at the CO position. T1-weighted images of each individual TMJ and three organogel spheres attached to the maxilla were obtained in the para-coronal plane (PCP). The slice thickness was 0.5 mm, field of view (FOV) was 13 cm by 13 cm, and matrix size was 256 by 256 pixels. In the test subjects, a CBCT system (PSR 9000 N, Asahi Roentgen, Japan) was used to acquire the images of the condyle and fossae with slice thickness of 0.2 mm. The reference system consisted of three precision polyvinylchloride spheres (15 mm) arranged triangularly and positioned
near the TMJ (Fig. 1d).

2.6 Data analyses

Three-dimensional articular surfaces were reconstructed from the digitized images using a workstation (Fuel02 Work stationTM, Silicon Graphics, Inc., USA). The 3D objects were reconstructed by rendering and were exported as stereo-lithography files using image processing software (MR images by AnalyzeTM, Mayo Clinic and Foundation, Inc., USA; CBCT images by MimicsTM, Materialise, Belgium). MR images were reformatted parallel to the PCP. Voxel size was 0.5 mm × 0.5 mm × 0.5 mm. From each subject, 120 coronal MR images were obtained. Next, an experienced investigator traced the cortical bone of the fossa and condyle and the three markers on the maxilla. Each sagittal and coronal slice was segmented manually. Then, these curves (X curve and Y curve described in Fig. 3) were fitted by spline functions. CBCT images of 3D articular surfaces were reformatted in parallel to the PCP. Voxel size was 0.2 mm × 0.2 mm × 0.2 mm. The software program allowed identification of boundaries of the region of interest using lower and upper threshold gray values.

2.7 Mandibular movement data analyses

Because vibration of the markers cause high frequency noise, the time series data for each of the marker movement were fitted with the 30th order Fourier series (Mathematica v4.0, Wolfram Research, U.S.A.) The root mean square error of the fit was less than 0.001 mm. According to the vertical component of the mandibular marker, the data for the chewing sequence were divided into a single chewing cycle and three masticatory phases; namely, opening, closing and intercuspatation. The movement data for each subject were imported to each individual’s TMJ model reconstructed on the workstation.

2.8 Condylar movement analyses

In each TMJ model, nine reference points were set on the three-dimensional surface of the working side condyle with reference to the ten planes that intersect the condyle (Fig. 3). At each condylar point, normal direction along the three dimensional surface was determined as the z-axis of the localized coordinate system. The normal direction for each condylar point was that of the normal unit vector calculated by tangential vectors in anterior (Tx) and lateral (Ty) directions on the tangential plane that contains all the lines tangent to a specific point on a surface (Fig. 3). The Tex was directed toward the postero-anterior axis (x-axis) that was defined as the line intersecting PHP and PSP. The Ty was directed toward the long axis of the condyle that was defined as the line between medial and lateral poles. The Tx and Ty were calculated by three dimensional curvature (r = r(x, y), Tx = ∂r/∂x and Ty = ∂r/∂y). The NJCs were calculated for 9 condylar points (LAP, LTP, LPP, AP, TP, PP, MAP, MTP and MPP) during the closing phase of mastication. In addition, the intra-articular space (JS) was also calculated for the 9 condylar points during the intercuspal phase of chewing.

3. Results

3.1 Measurement errors

Measurement of the length of the reconstructed condylar axis from the CBCT images revealed mean (s.d.) error of 0.19 (0.09) mm. The rotations in physiological range around the mediolateral, vertical and antero-posterior axes resulted in mean (s.d.) registration errors of 0.54 (0.14), 0.67 (0.25) and 1.24 (0.38) degrees, respectively. The translations in physiological range along the mediolateral, vertical and antero-posterior axes resulted in mean (s.d.) registration errors of 0.16 (0.08), 0.13 (0.05) and 0.18 (0.06) mm, respectively. Using CBCT, the overall errors of measurement of JS (3.0 mm) on a dry skull at different position of the condyle revealed a mean (s.d.) of 0.71 (0.26) mm.

3.2 NJCs

For all 9 condylar point movements, no significant differences were observed between the NJCs measured in
the first experiment and those measured in the second experiment after an average interval of 2 months (all $P \geq 0.21$) (Fig. 4). In control subjects, all 9 condylar point movements measured with OI showed significantly greater NJCs than those measured without OI (all $P < 0.05$, Fig. 4 lower column). In the test subjects, all 9 condylar point movements showed significantly greater NJCs than those in control subjects without OI (all $P < 0.05$, Fig. 4 upper column).

3.3 Intra-articular space

The intra-articular spaces at all 9 condylar points did not
differ significantly between the first experiment and the second experiment after an average interval of 2 months (all $P \geq 0.32$). In control subjects, the intra-articular spaces during all 9 condylar points movements measured with OI were significantly greater than those measured without OI (all $P < 0.05$).

4. Discussion

Previous reports showed greater jaw elevator muscle activity resulting from occlusal interference on the balancing side. In addition, tooth contact on the balancing side has the potential to reduce joint loading on the ipsilateral side, and thus plays a protective role for the ipsilateral TMJ. Although balancing-side occlusal interference changes the jaw movement pattern [4] and is associated with TMJ disk dislocation, inter-subject variation of the data has hampered universal understanding of the relationship between occlusion and articular function or dysfunction of the human jaw. The present method allows measurement of condylar movement taking into account each individual’s temporomandibular joint morphology. For this specific measurement, multiple local coordinate systems were created with reference to the 3D shape of the temporomandibular joint surface, which was constructed with reasonable accuracy through 3D image reconstruction. Considering the mean peripheral JS during biting (3.6 mm), and the 3D condylar point movement path during the chewing cycle (8.2 mm), the present mean measurement errors of less than 1.0 mm (0.71 mm) are acceptable, as reported elsewhere [2, 5, 8]. Based on the results, 68% of the overall linear measurement errors using CBCT proved to be less than 0.88 mm. As for previous measurements of human TMJ articulation, the total measurement error using MRI recordings at 2-mm section thickness followed by 3D reconstruction procedures [1, 2, 5, 7, 8] was less than 1.0 mm [2, 8]. Our study followed their segmentation technique to ensure the reported accuracy. Currently developed MRI technique allows reduction of the section thickness to less than 1 mm. The thinner slice (0.5 mm) used in the present MRI recordings certainly improves image quality and accuracy of the model. Accordingly, it should be stated that total error of the present measurement is less than 1.0 mm.

5. Conclusion

The present study validates the measurements obtained by our proposed method, and strengthen the experimental results suggesting cause-effect relationships between motor function or dysfunction and morphology of the human TMJ.

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References


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