Quantitative analysis of the TMJ movement with a new mandibular movement tracking and simulation system

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ABSTRACT

Purpose : The purpose of this study was to develop a system for the measurement and simulation of the TMJ movement and to analyze the mandibular movement quantitatively.

Materials and Methods : We devised patient-specific splints and a registration body for the TMJ movement tracking. The mandibular movements of the 12 subjects with facial deformity and 3 controls were obtained by using an optical tracking system and the patient-specific splints. The mandibular part was manually segmented from the CT volume data of a patient. Three-dimensional surface models of the maxilla and the mandible were constructed using the segmented data. The continuous movement of the mandible with respect to the maxilla could be simulated by applying the recorded positions sequentially. Trajectories of the selected reference points were calculated during simulation and analyzed.

Results : The selected points were the most superior point of bilateral condyle, lower incisor point, and pogonion. There were significant differences ($P<0.05$) between control group and pre-surgical group in the maximum displacement of left superior condyle, lower incisor, and pogonion in vertical direction. Differences in the maximum lengths of the right and the left condyle were 0.59 ± 0.30 mm in pre-surgical group and 2.69 ± 2.63 mm in control group, which showed a significant difference ($P<0.005$). The maximum of differences between lengths of the right and the left calculated during one cycle also showed a significant difference between two groups ($P<0.05$).

Conclusion : Significant differences in mandibular movements between the groups implies that facial deformity have an effect on the movement asymmetry of the mandible. (***Korean J Oral Maxillofac Radiol 2008; 38 : 203-8***)

KEY WORDS : Mandibular movement tracking and simulation; Optical tracking system; Patient-specific splints; Movement asymmetry of the mandible

Introduction

The temporomandibular joint (TMJ) is a complicated and frequently used joint of a human body. The condylar movement is considered to be one of the most important factors for the evaluation of TMJ. There have been many studies to analyze the condylar movement and to find out relationships between the movement and factors such as temporomandibular disorder or malocclusion.[1-3] Measuring the condylar movement precisely, however, has been considered to be a difficult task since the jaw movement is a complex combination of translation and rotation. Various techniques have been developed to record or analyze the condylar movement quantitatively and qualitatively.[4-8] Amongst them, MRI and arthrography are employed as primary methods for directly visualizing disk-condyle complex.[8] However, they have some disadvantages to be used in clinics because arthrography is an invasive method and involves a high radiation dose, and MRI requires the use of complex and costly equipment.[9] We have developed a new mandibular movement tracking and simulation system, which is a non-invasive method and can acquire condylar movement data quantitatively. The aim of this study was to develop a system for the measurement and simulation of the TMJ move-

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ment and to analyze the mandibular movement quantitatively.

Materials and Methods

The CT data were obtained from a total of 15 subjects (7 males and 8 females): 3 controls and 12 subjects having orthofacial deformities. All the subjects having orthofacial deformities were planned to have an orthognathic surgery to correct the deformities. The facial CT data were acquired by 10-slice helical CT (Siemens SOMATOM Sensation 10, Germany) under 120 kVp and 80 mAs with slice thickness of 0.75 mm.

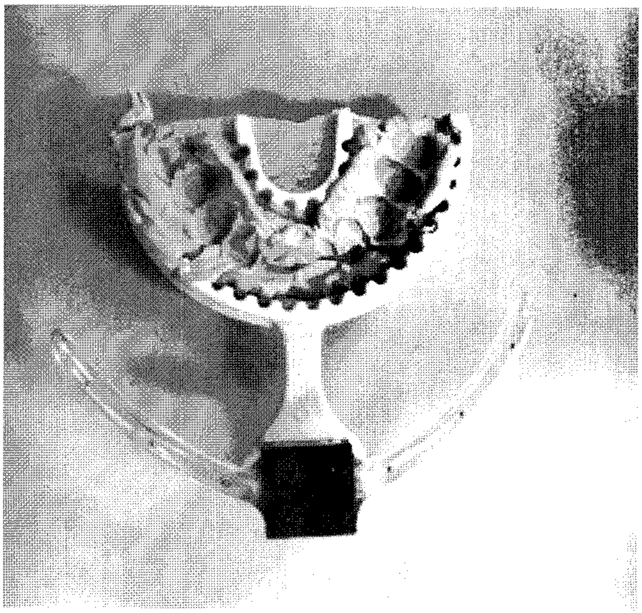

Fig. 1. A patient-specific splint with a registration body attached

We devised a patient-specific splint for image registration and mandibular movement tracking (Fig. 1). The splint could be mounted on the mandible teeth immediately using a dental impression material (Polyvinyl siloxane, PARKELL, NY, USA). Because only the bottom side of the splint was firmly attached to the patient's mandiblular teeth, the splint did not disturb the natural movement of the jaw during opening. A registration body was combined to the splint by LEGO blocks, which contained six iron spheres (1 mm diameter) and would be used for transferring the location of CT image in relation to the patient mandible (Fig. 1). The registration body was reusable, which could be attached to and detached from the patient's splint for repeated uses. When the subject underwent a dental CT scan, the corporate splint was mounted on the patient's teeth in a firm position.

After CT scanning, the CT data as DICOM files was downloaded onto the PC. The location of the six iron spheres which were on the registration body was identified in order in the 3-dimensional (3D) image (Fig. 2). The registration body was registered by point-to-point matching of six fiducial markers using affine transform. Once registration was completed, the transform (M_{reg}) was determined and used for calculating the position of the registration body that is the mandible in the CT coordinate system.

After registration, three-dimensional movements of the mandible and the maxilla were tracked by the optical tracking camera system (Polaris vicar, Northern Digital, Inc.). The reference tool was installed on a supporting frame mounted

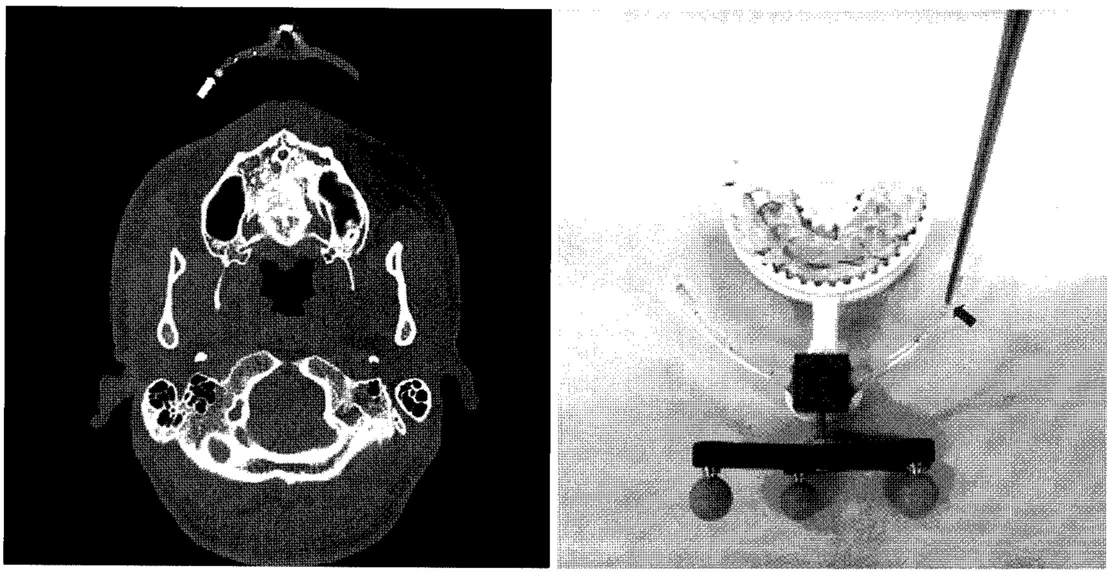

Fig. 2. Registration using a pointer tool and localization of the reference points in the CT data.

tightly on the forehead of the patient before starting the movement tracking. The mandible tracking tool was installed on a registration body (Fig. 3). When the movement tracking started, the splint mounted in the patient's mouth was in the same position as the CT scan, thus providing the synchronization between the CT images and the actual patient's jaw position. The position of the mandible tracking tool that is the mandible was tracked and recorded at 20 Hz in relation to the reference tool. After taking sufficient exercise of jaw opening movement, subjects were instructed to perform a voluntary maximum mouth opening movement for 30 times.

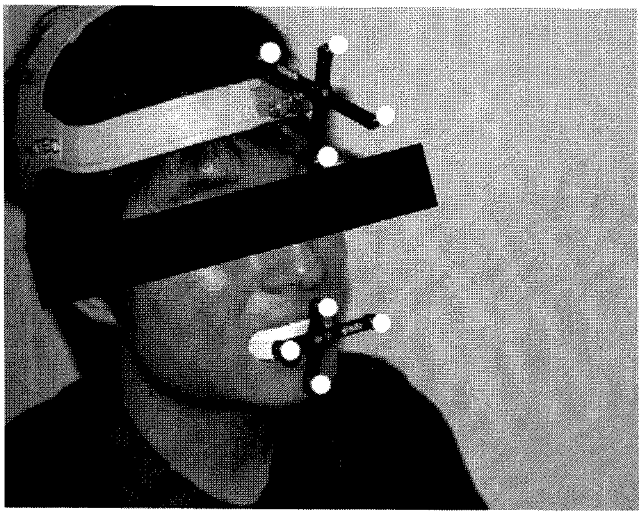

Fig. 3. Tracking with the patient-specific splint attached to the subject's teeth.

For 3D visualization and simulation of the TMJ movement, the 3D volumetric areas of the maxilla and the mandible were segmented using a semiautomatic thresholding technique from the CT images. From these, surface models of the maxilla and the mandible were constructed with a marching-cube algorithm. To simulate the mandible movement, the translation and rotation (T_{man_image}) was applied to the mandible model in relation to the maxilla model in 3D image space (Eq. 1). $T_{man\_physical}$ and T_{ref} mean positions of the mandible tracking tool and the reference tool respectively in physical space. T_{man_init} and T_{ref_init} are their initial positions of them respectively.

$$T_{man\_image} = M_{reg}(T^{-1}_{ref\_init} T_{ref})^{-1} T^{-1}_{man\_init} T_{man\_physical} \qquad (1)$$

The continuous movement of the mandible with respect to the maxilla could be simulated by applying the recorded positions sequentially (Fig. 4). By applying the same method, the sequential positions of any points on the mandible model could be calculated during the simulation. This was because the points on the mandible model were the same rigid body with the mandible. The points of interest could be selected by picking the

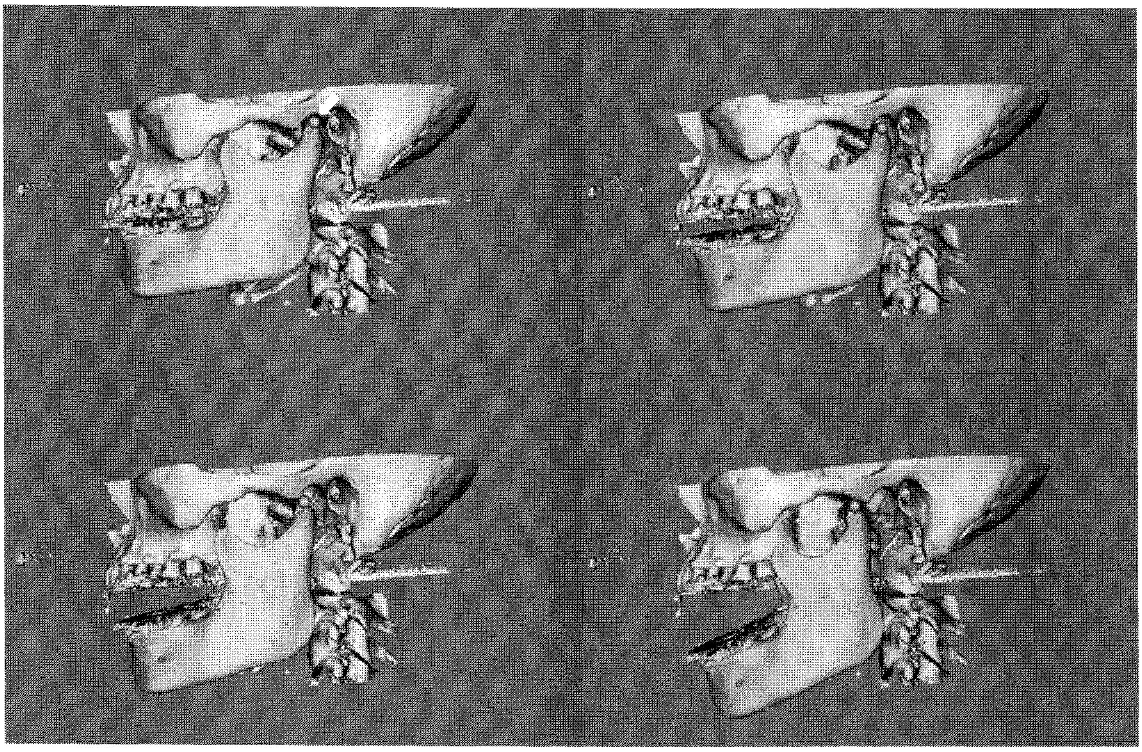

Fig. 4. Simulation of the mandibular movement with respect to the maxilla and the sequential positions of a point on the mandible model.

points on the surface model using a mouse before starting the simulation. Then, the sequential positions of points during simulation were calculated and recorded for future analysis.

When measuring the points of interest on the mandible, the same coordinate system was used for all the subjects. The origin of the system was defined as the right porion. The x-axis extended from the origin to the left porion. The x-y plane was set as the Frankfort horizontal plane, containing both the left and right porion and the left orbitale. The y-axis was perpendicular to the x-axis and from posterior to anterior. The z-axis was defined according to the right-handed coordinate system, thus along inferior-superior direction.

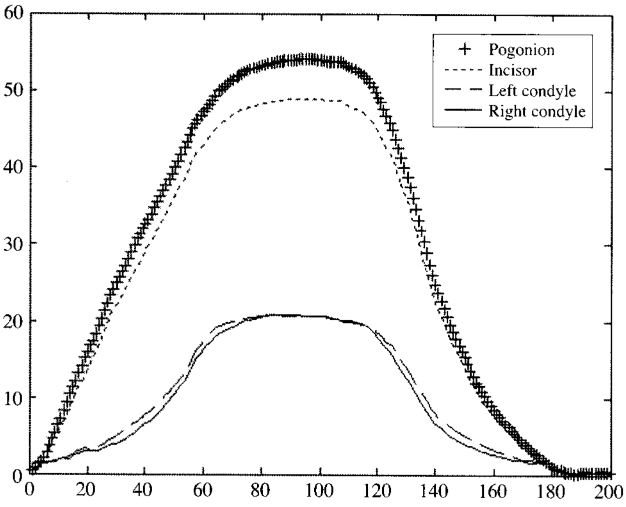

Fig. 5. Three-dimensional linear lengths of the points from its initial position during a single cycle of opening and closing.

The original data consisting of multiple cycles were segmented into every single cycle. Each single cycle was composed of sequential displacements of a point during a single mouth opening and closing movement. To represent the pure translation (x, y, z) from the initial position, the displacement of a starting point (x_0, y_0, z_0) was subtracted from the original data. Three-dimensional linear length of the point from its initial position was also calculated by Eq. (2) (Fig. 5). For each subject, five cycles was selected and used for statistical analysis.

$$\sqrt{(x-x_0)^2+(y-y_0)^2+(z-z_0)^2} \qquad (2)$$

x, y, z: displacements in each direction

x_0, y_0, z_0: initial displacements in each direction

Results

The selected points for analysis were the most superior point of bilateral condyle, lower incisor point, and pogonion. Measurement results for lower central incisor, pogonion and both condylar paths during opening and closing are shown in Table 1. Especially in vertical direction (in z-direction), the maxima of path lengths showed significant differences ($P<0.05$) between control group and pre-surgical group except the right

Table 1. Mean values and SD for maximum of each cycle for selected points in absolute values

	Control group	Pre-surgical group	P-value
Left condyle point			
Linear length	18.80±2.72	16.12±7.16	NS
Displacement in horizontal direction	1.61±1.13	1.46±0.41	NS
Displacement in antero-posterior direction	18.70±2.70	16.15±7.11	NS
Displacement in vertical direction	3.29±1.12	4.85±1.86	0.0027**
Right condyle point			
Linear length	18.80±2.74	14.82±5.67	0.0227*
Displacement in horizontal direction	1.58±1.14	1.42±0.42	NS
Displacement in antero-posterior direction	18.41±2.81	14.79±5.70	0.0197*
Displacement in vertical direction	4.53±1.33	4.32±1.87	NS
Incisor point			
Linear length	43.30±4.20	37.30±12.90	NS
Displacement in horizontal direction	3.47±1.53	4.08±2.91	NS
Displacement in antero-posterior direction	11.24±3.03	15.70±8.66	NS
Displacement in vertical direction	41.68±3.75	34.47±10.64	0.0121*
Pogonion point			
Linear length	45.06±4.93	41.53±15.19	NS
Displacement in horizontal direction	3.43±1.86	4.04±2.85	NS
Displacement in antero-posterior direction	26.43±3.94	30.14±14.06	NS
Displacement in vertical direction	36.36±3.93	29.53±8.30	0.0028**

All measurements are in mm. NS: non-significant, *: $P<0.05$, **: $P<0.005$

Table 2. Mean values and SD for differences between the right and the left condylar maximum linear length

	Control group	Pre-surgical group	P-value
Difference between the maximum lengths of the right and the left condyle path in one cycle	0.59 ± 0.30	2.69 ± 2.63	0.0014**
Maximum of differences between lengths calculated during one cycle	3.07 ± 1.65	4.76 ± 3.07	0.0438*

All measurements are in mm. NS: non-significant, *: $P<0.05$, **: $P<0.005$

condylar path.

Differences between the maximum lengths of the right and the left condyle path in one cycle and maximum of differences between lengths of the right and the left during one cycle were calculated for each group (Table 2). The difference between the maximum lengths in pre-surgical group was higher than that of control group, which showed a significant difference ($P<0.005$). There was, also, a significant difference in the maximum of differences between lengths for two groups ($P<0.05$).

Discussion

There have been several studies on measurement and simulation of the TMJ movement with computer-aided system. Hayash et al.[5] measured the mandibular movement using a photo stereo-metric technology and analyzed the dental occlusion. Okamoto et al.[10] used an optoelectronic tracking device to measure the mandibular movement and visualized occlusion contact area. In these systems, however, the movement of the mandible could not be observed dynamically, only the analysis of occlusion was possible. Enciso et al.[11] presented a system which fully visualized the movement of the mandible with surface models generated from CT data. Although they visualized the movement of three-dimensional model, it was not possible to track the trajectory of a point of interest on the mandible. Therefore, it didn't provide the quantitative analysis of the mandibular movement. Zhang et al.[12] has also developed a virtual dynamic system for analyzing mandibular movement and occlusal contact. They tracked the trajectories of points on the mandible, however, no quantitative analysis was performed. Koseki et al.[7] developed a movement tracking and visualization system of their own using an optical tracking technique, however, the device was just a prototype for the experiment and too bulky to be used in clinics routinely. In this study, we have developed a new mandibular movement tracking and simulation system, which made it possible to analyze the TMJ movement quantitatively.

Optical tracking devices have been widely used for computer-aided surgery in medical filed. In this paper, an optical tracking system was applied to track and record the mandibular movement relative to the maxilla by measuring the position of multiple frames. It was also possible to simulate and visualize the jaw movement of patients using the movement data. Our system could measure the trajectories of designated points based on the simulation of the TMJ movement.

The patient-specific splint was light weight and of little size, which was different from other systems.[7,13] The splint was firmly attached using a dental impression material. Therefore, it allowed the patients to move the upper teeth back to the initial intercuspal position after they performed the maximum opening movement. It also improved the reliability and accuracy when the mandibular movements were recorded during multiple cycles. The splint could be used repeatedly and there was no harm to the surface of the teeth in attaching the frame. In the registration body, metal ball markers were used as registration points instead of anatomical points, which minimized the inter-subject registration error. Yoshito et al.[14] used an optical tracking system for jaw tracking and attached specially manufactured jigs for infrared reflecting markers to the patient's teeth using a dental resin. Anatomically characteristic points on the teeth were used for the registration between patient and CT data.

In our system, it was not difficult to fabricate the splint since it was based on a ready-made bite tray and a dental impression material used frequently in dental clinics. It took about 10 minutes to fabricate the patient-specific splint and to acquire the jaw movement data respectively. The same registration body was used repeatedly for all subjects. It could be attached to and detached from the splint easily by using LEGO blocks.

We compared the mandibular movement between control group and pre-surgical group by measuring the movement of several reference points. In most cases, deviations of data in pre-surgical group were relatively higher than those of control group and there were significant differences in the maxima of path lengths between two groups in z-direction except the right condylar path.

The difference between the maximum lengths of the right and the left condyle path in pre-surgical group was higher than that of control group. There was also a significant difference between control and pre-surgical group in the maximum of differences between lengths of the right and the left. These mean that the pre-surgical group shows the more asymmetrical movement of the mandible than the control group. These results imply that the morphological deformation in the mandible or the maxilla might affect the jaw movement. Some researchers have tried to find out the relationship between mandibular movement and facial morphology, but the exact relationship is still not clear.[3,15]

The developed mandibular movement tracking and simulation system is a non-invasive method and can acquire condylar movement data quantitatively. The results imply that the facial deformity may affect the mandibular movement asymmetry. Further researches based on both morphological parameters and mandibular movements of subjects are needed to discover the relationship between the facial morphology and the mandibular movement.

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