Three-dimensional Display System of Individual Mandibular Movement

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Chapter Overview. It is expected to develop an intelligible diagnostic system of temporomandibular disorders (TMD) for both medical doctors and patients. This study proposes a display system that visualizes motion of the human mandible. The system integrates two engineering methods. One is an optical motion capture technique for measuring the mandibular movements. The other is an individual modeling method based on the X-ray CT data. It is important to know exact mandibular movements for the proper diagnosis. This paper discusses experimental verification of the total performance of the system using a device of hinge movement. The verification clearly shows that precision of the model has a great effect on accuracy of the movements. The total performance of the system is achieved within an accuracy of 0.2mm at the hinge of the device. The system provides not only three-dimensional visual information of the mandibular movements as animations but also quantitative information of position, velocity and acceleration at an arbitral point of the model. The system will be useful for informed consent in medical treatments of TMD.

Introduction

It is very important to understand a motion of a mandibular condyle individually for proper diagnosis and treatment of temporomandibular disorders (TMD). Recently, some optical devices to record mandibular movements have been proposed. The non-contacting measuring devices have an advantage of permitting a masticatory movement of a patient under almost natural conditions.

There are some reports to evaluate mandibular movements using Gnatho-hexagraph (JM-1000, Ono-sokki Co.) [1][2]. Gnatho-hexagraph is an opto-electronic system with six degrees of freedom. This device consists of a facebow and a headframe with three LEDs on each frame. Two CCD cameras take time-series pictures of the positions of the LEDs, and the motions of the facebow and the headframe are calculated. Latest version of the system enables to display the movement with several three-dimensional mandibular models prepared in advance [3]. However the system has several problems although the visualization is useful for clinic. One of the problems is that the shape of the prepared mandibular model is different from that of the subject in the motion capturing. The geometrical difference of the mandibular shape causes an incorrect visualization such that a condyle and a mandibular fossa overlap even if motion-capturing data are fully accurate. The other problem is that the headframe possibly causes inaccuracy of motion capture because they are not directly fixed the skull.

In order to compute exact mandibular motions, it is essential to obtain geometrical relationship between motion-capturing devices and anatomical structures. For this purpose, the X-ray CT image of a patient with the devices is most appropriate solution. The original research of the authors aimed to indicate the mandibular movement using a cephalometric radiograph or laminated layer image obtained from X-ray CT data [4]. In the successive studies, we developed a display system of individual mandibular movement using patient-specific finite element models [5][6]. In the recent past, another research group reported a similar system with the same concept with us [7]. However, the quantitative accuracy of the system was not described in the paper as well as our previous studies. This study focuses on the improvement of the accuracy of the system.

Display System of Mandibular Movement

Overview of the System

The procedure of our display system of individual mandibular movement is shown in Fig. 1. There are several tasks to display mandibular movements. Firstly, optical markers are provided for motion capture of the human mandible. As the markers, we employ acrylic fluorescent balls that glow under UV-A lights often called “black lights.” A facebow equipped with the markers is designed to fit the human face as

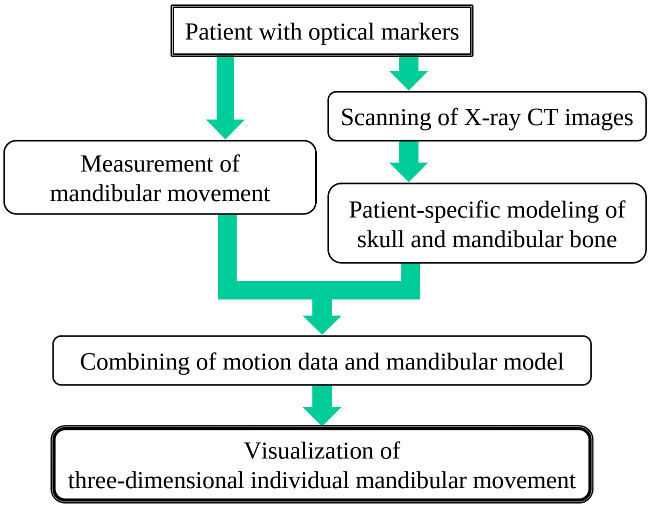
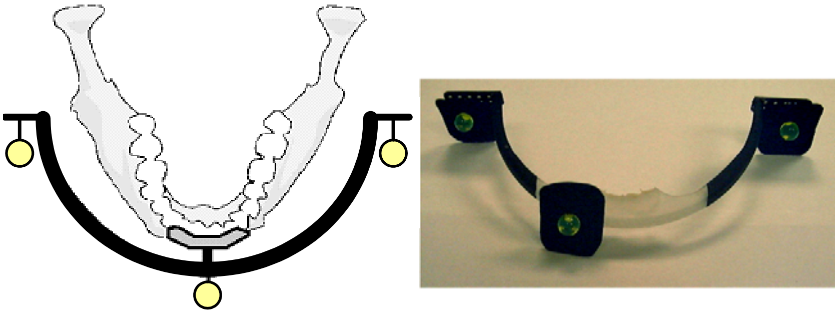


Fig. 1. Diagram of the three-dimensional display system.



(a) Attachment of the optical markers. (b) The facebow with the optical markers.

Fig. 2. Schematic diagram and fabrication of the facebow.

shown in Fig. 2. The facebows are attached to the labial surfaces of upper and lower incisors with cyanoacrylate adhesive. Three-dimensional mandibular movements are measured by two cameras.

Secondly, the patient with facebows is subjected to X-ray CT. Based on the CT images, individual models of a skull and a mandibular bone are generated.

Thirdly, coordinate transformation of the mandibular model is performed according to the three-dimensional motion data, and an animation of the mandibular movement is displayed. The following subsections describe details of these tasks.

Motion Capture

The two CCD cameras capture the motion of the optical markers attached to the facebows. Our current system is composed of two black-and-white CCD cameras (XC-7500, Sony Co., Japan) and two personal computers. The motion is recorded in the computers as time-series images with a sampling rate of 30Hz.

Motion data of the facebows are computed as the following procedures after the camera capturing. First, the positions of the markers are extracted as contours based on the brightness of each image. Next, best-fitting equation of a circle for each contour is solved by a least square method. Then, the direct linear transformation (DLT) method computes three-dimensional coordination of the markers. Finally, coordinate transform matrices of the skull and the mandible are computed using the coordinates of the three markers equipped to each facebow.

Patient-Specific Modeling

The patient-specific models are generated by our proposed modeling method [8][9]. Figure 3 shows patient-specific models of a skull and a mandible using the proposed method. To display the mandibular movement as an animation, we extract a surface polygon model from the finite element model. Since the finite element model is applicable to stress analyses, it is possible to build a new system that integrates stress and motion analyses in the future.

The geometrical relationship between optical markers and anatomical structures are also computed by use of the CT images. Three-dimensional coordinate transformations of the models are performed according to the matrices obtained by the motion capture. As the developed application software utilizes OpenGL, we can observe the motion from arbitral viewpoint with simple mouse operation.

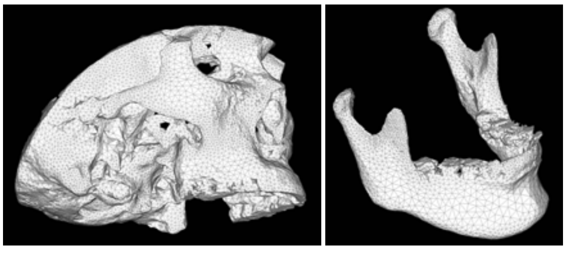


Fig. 3. Patient-specific models of a skull and a mandible.

Accuracy Evaluation

Evaluating the total performance of the system is essential to apply the system to medical diagnosis of TMD. Since the system combines the motion capture technique and three-dimensional models of bones, the verification in the state of motion is indispensable. In order to verify the performance of the system, we employ a mechanical device that performs opening-closing motions. The device consists of two acrylic square levers (20mm×20mm×100mm) that are connected each other with a rotation shaft (diameter=6mm.) The facebows are attached to the device. A dentomaxillofacial conebeam CT system (CB MercuRay, Hitachi Medical Co.) takes CT images of the device. This CT system outputs volume data of the device with a nominal voxel size of 0.377mm^3.

The opening-closing motion was performed by moving a lever while fixing the other one. The motion was recorded with a sampling rate of 30Hz. The verification showed that the total performance of the system is achieved within an accuracy of 0.5mm at the shaft. The calculated position of the shaft contained slight periodical fluctuation. We examined the cause of the fluctuation of the shaft expecting that the error of the computational position of the shaft causes the periodical fluctuation. We measured the actual size of the device and adopted the rectified voxel size: 0.373mm^3. The geometrical model was generated according to the rectified size. Recalculated position of the shaft is shown in Fig. 4. The total error of the position decreases to 0.1mm in z direction and 0.3mm in y direction. That is, calibration of the CT device is a key element to obtain the exact motion of the mandibular condyles. Although there remains larger errors in y direction compared to z direction, the total accuracy of the system satisfies the requirement on a practical level.

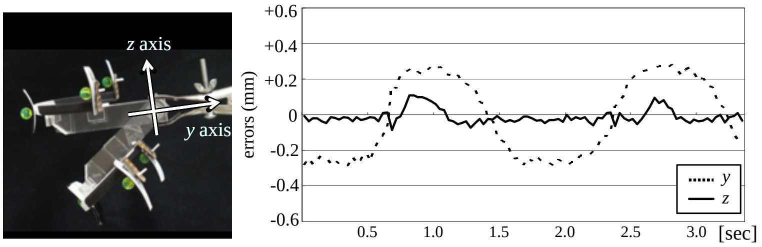


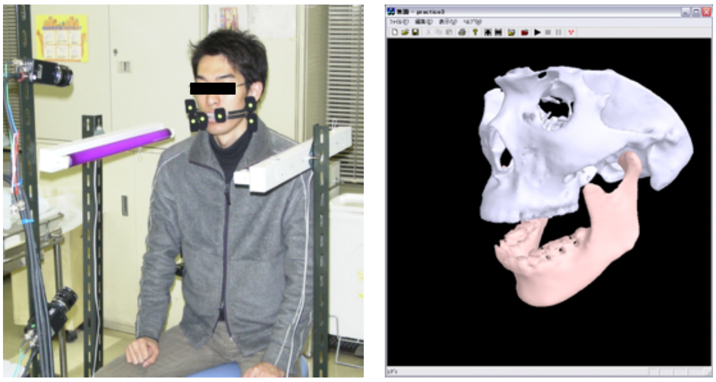
Fig. 4. Fluctuation in the position of the shaft (revised model.)

Application to Human Mandibular Movements

For confirmation of the effectiveness in the clinical field, the system was applied to a human subject who was a volunteer of a male adult, aged 22 years. He has no clinical history of TMD, but a slight single click sound on opening at the left-side condyle. The following fundamental mandibular movements were investigated: voluntary border movements in the sagittal plane, lateral excursion movements, and actual mastication of a chewing gum. The movements for about 3-sec period were recorded with a sampling rate of 30Hz. Figure 5(a) shows the state of capturing mandibular movements. The measurements of the mandibular movements are performed in an ordinary consulting room. Figure 5(b) shows the snapshot of the developed system.

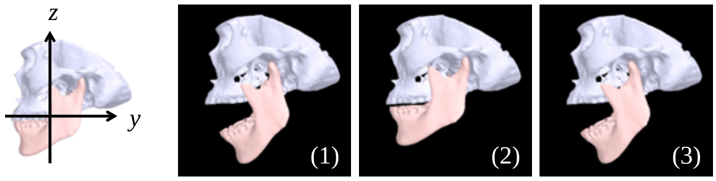
The proposed system utilizes the patient-specific model that reflects exact shapes of the skull and the mandibular bone of the patient. This enables to provide not only three-dimensional visual information of the mandibular movements as animations but also quantitative information at an arbitral point of the model. Figure 6 shows trajectories of left and right condyles in the border movement of the subject. The right condyle shows almost same trajectory in each opening and closing motion. On the contrary, the position of the left condyle indicates slight different trajectory in each movement. The difference of the motion was clearly observed in the animation of the mandible.

Figure 7 shows the changes in velocity and acceleration of condyles in the border movement. The velocity and the acceleration are calcu-

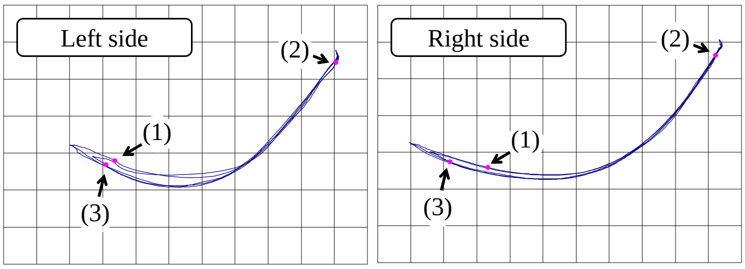


(a) (b)

Fig. 5. Measurement of mandibular movements of a human subject (a), and visualization using the proposed system (b).



(a) Snapshots of animation



(b) Positions of condyles in time sequence (unit of length: 2mm)

Fig. 6. Computed results of positions of condyles in border movement.

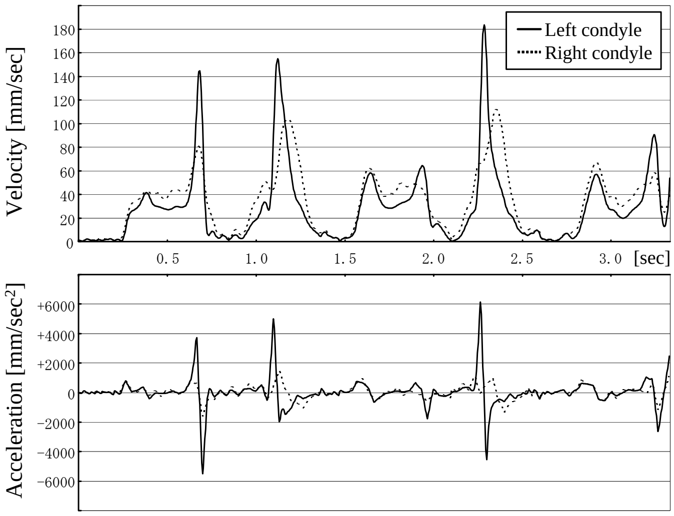
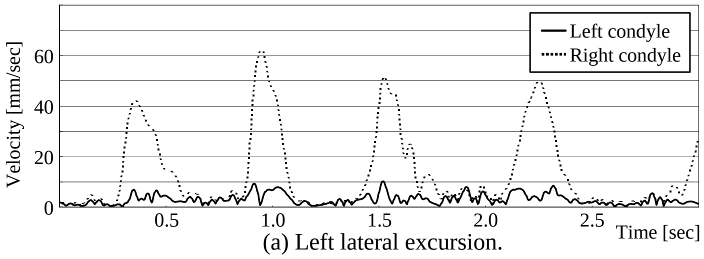
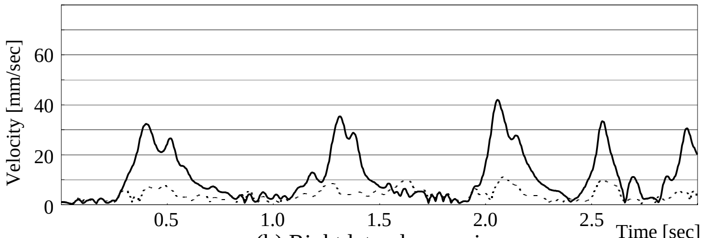


Fig. 7. Changes in velocity and acceleration of condyles in border movement.

lated as following processes. First, a three-dimensional interpolation of the positions of condyles is computed using a cubic spline. Then, the velocity and the acceleration in time-series are calculated. The changes in the velocity and the acceleration of the left side condyle are quite larger than those of the right one. Figure 8 also shows changes in ve-



(a) Left lateral excursion.



(b) Right lateral excursion.

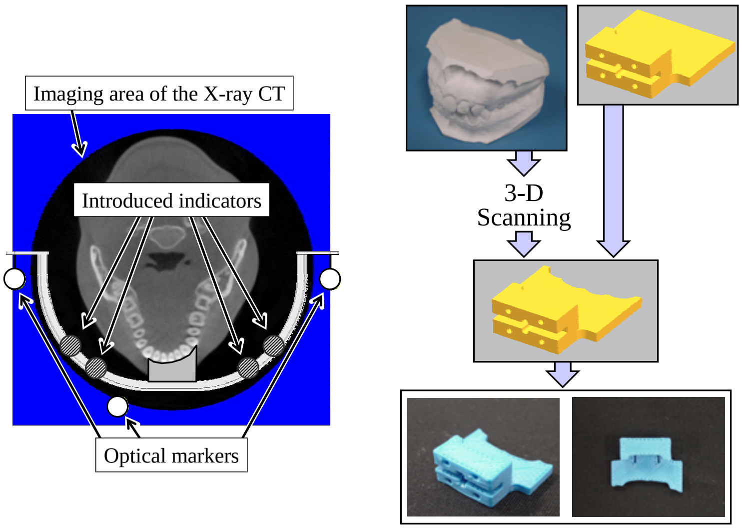
Fig. 8. Changes in velocity of condyles in the lateral excursion.

locity in the lateral excursion movements. The subject was asked to move his mandible to each side in the same way, however there is a significant difference in the velocities of condyles. That is, the motion analysis method of the system enables to detect slight symptoms of TMD.

Discussions

The current facebow demonstrated effectiveness for measuring mandibular movements as mentioned above. However the facebow is not applicable to another person because that has been designed for a specified person. It is desirable that the facebow satisfies the following requirements.

1. The optical markers should be located at the positions adjacent to the mandibular condyles in order to measure the motion of mandibular joints with a high accuracy.
2. The device should be made with non-metallic parts to suppress metal artifacts in CT images.
3. Attachment of the device to a patient should be easy for rapid diagnoses.
4. The device should be applicable to any patients for diverse and high-quality medical care services.



(a) The new facebow with indicators. (b) Modeling process of the brace.

Fig. 9. Proposal of the new facebow.

Taking into consideration of these requirements, we design a new facebow. First, the new facebow is divided in two parts; an arch with the optical markers and a brace for connection to the surface of the teeth. The arch of the new facebow is designed to be larger than the current one because the current facebow is too small to apply to various patients. Since it is difficult to fit the large arch in the scan area of the CT, we introduce multiple indicators as illustrated in Fig. 9(a). The indicators are utilized to extrapolate the positions of the optical markers that are out of imaging area. The extrapolation method enables to use high-resolution CT images without decreasing CT image quality to fit the whole arch in the image.

A three-dimensional scanning data of dental casts (plaster model) of a patient is obtained by a contact type digitizer. The data is converted to a CAD data of the brace, and then the patient-specific brace is fabricated using a rapid prototyping as shown in Fig. 9(b). This modeling process reduces not only the cost of the facebow but also operations of medical doctors to attach the facebows to patients. Besides, the brace is applicable not only to a patient with a normal bite but also to one with an oberbite. The brace is attached to the surface of premolars if a patient has an overbite. The performance of the display system using the new facebow will be confirmed in our further study.

Conclusions

This paper described the display system of mandibular movement using a patient-specific model was proposed. We examined accuracy of the system using the device with the opening-closing mechanism. The examination revealed that the total error of the system decreases to 0.3mm by rectification of the CT image. The system was applied to a human subject, and showed the ability to detect slight symptoms of TMD. The system will be useful for informed consent of patients as well as the adequate medical treatments of TMD.

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