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British Journal of Oral and Maxillofacial Surgery 60 (2022) 884–889

BRITISH Journal of Oral and Maxillofacial Surgery

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Study on the reconstruction of a four-dimensional movement model and the envelope surface of the condyle in normal adults

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Received 21 April 2021; accepted in revised form 19 August 2021
Available online 2 September 2021

Abstract

The objective of this study was to reconstruct the envelope surface of the condyle and the four-dimensional trajectory model in mandibular border movement in normal adults. Eleven healthy subjects were selected as volunteers. Cone-beam computed tomographic (CBCT) scanning was performed on the volunteers. The three-dimensional (3D) movement path of the mandible was recorded using a virtual articulator (PN-300), which was based on a 3D model of the mandible. We used Proplan CMF 3.0 (Materialise) software to perform this from the DICOM data generated by CBCT scans. The distance of condylar movement was measured in this model during volunteers' mouth opening, protrusion, and lateral excursions. The envelope surface of the condyle was reconstructed by merging a functional condylar surface at each recording moment during the movement of the whole border. In the mandibular digital models, the condyle moved downward firstly, and moved upward to the position of maximum mouth opening. The condyle moved forward and downward during protrusion. The working condyle rotated slightly and the non-working condyle moved forward, downward, and inward during lateral excursions. The mean (SD) movement distance of 11 subjects was 19.04 (4.37) mm during mouth opening (including downward and upward) and 9.75 (2.38) mm during protrusion. During lateral excursions the mean (SD) movement distance of the working condyle was 2.87 (1.13) mm, the mean (SD) movement distance of the non-working condyle was 10.85 (3.25) mm. The envelope surface of healthy volunteers showed a double-peak pattern. The envelope surface of the condyle and four-dimensional movement model can be reconstructed by merging the trajectory of the mandible recorded from the novel virtual articulator PN300 and a 3D image of the mandible.

Keywords: Digital technology; Four-dimensional movement; Envelope surface of condyle; Temporomandibular joint

Introduction

The mandible and temporomandibular joint (TMJ) compose a complex system that performs several physical functions including chewing, swallowing, and the pronunciation of speech. Temporomandibular disease (TMD) is one of the most common diseases resulting from the complex anatomy of the temporomandibular joint and long-term exercise load. In addition to the subjective report of pain or clicking in the TMJ region, abnormal jaw movement is also an important symptom to indicate the degree of temporomandibular joint disease. Studying mandibular movement has a profound impact on the aetiology, diagnosis, and subsequent treatment of TMJ diseases.[1–3]

Researchers have been trying to find a method to assess the motion of the condyle to fully understand TMJ movement. Mechanical articulators and facebow devices have been used to simulate the border movements and pathways

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https://doi.org/10.1016/j.bjoms.2021.08.006
0266-4356/

of the mandible, which is helpful in the fabrication of prostheses for dental restorations, or the diagnosis of temporomandibular joint (TMJ) diseases.[4–6] Several recording systems for mandibular movement have been developed to assess condylar motion, such as ARCUSdigma II (KaVo),[7] Axioquick® Recorder (SAM Co,[8] Cadiax® Compact 2,[9] and Freecorder BlueFox (Planmeca).[10]

The results of this traditional research were shown as point curves on a two-dimensional (2D) plane such as the coronal, vertical, or axial planes. These systems can only record the trajectory of mandibular movement on a 2D plane without obtaining the three-dimensional (3D) motion trajectory data of the mandible; so, additional steps are needed to obtain the 3D trajectory data, resulting in increased sources of error.

Some severe temporomandibular joint diseases involving a tumour or ankylosis require total joint replacement after temporomandibular resection. Several temporomandibular joint total replacement systems are available on the market such as TMJ Concepts and Zimmer Biomet, which are approved by The United States Food and Drug Administration (FDA).[11] There is no gold standard for the design of artificial temporomandibular joint fossa, and the ball and socket design is currently the most widely used. Motion-induced knee joint replacement systems consider the movement data of the knee joint during the design process.[12] A larger range of movement was made by changing the interaction curve between the joint and fossa. Few researchers have applied the data of mandibular movement to the design of an artificial temporomandibular joint replacement system.

Developments in digital technology over the past few decades have resulted in mechanical articulators that simulate mandibular movements being replaced and/or supplemented with virtual articulators in new technical systems.[13] A real-time, computerised, binocular, 3D trajectory tracking device has been designed to record functional mandibular border movements with accuracy of approximately ±0.1mm.[14,15] Combining the 3D trajectory of the mandibular movement obtained from this system with the 3D model of the mandible makes it possible to accurately, dynamically, and in real-time, measure the four-dimensional (4D) movement of the condyle.

The aim of the present article is to introduce a novel digital approach that portrays actual condylar 4D movements by merging cone-beam computed tomography (CBCT) data and the 3D trajectory of condyle produced by a 3D real-time, computerised, binocular tracking device, furthermore producing the envelope surface of a condylar functional surface.

Methods

This study was approved by the Bioethics Committee of Peking University School and Hospital of Stomatology, Beijing, China (No.PKUSSIRB-201947091). Written informed consent to publish these case details was obtained from participants.

There were five male and six female patients with a mean (SD) age 27.54 (2.62) years. The volunteers who participated in the research met the criteria for healthy volunteers: (1) no systemic diseases; (2) facial symmetry; (3) no maxillofacial trauma or history of surgery; (4) no history of orthodontic treatment; (5) no temporomandibular joint discomfort, noise, pain, limited mouth opening, or any TMJ treatment history; (6) no abnormal habits such as bruxism or clenching; (7) full dentition and a class I occlusal relationship.

Dental scan data and CBCT data preparation

Digital 3D images of the maxilla and mandible were acquired using CBCT (NewTom VG; voxel size = 0.3 mm, field of view (FOV) = 16 cm×16 cm). The segmentation and 3D reconstructions of the skull and jaws were performed using CBCT data in stereolithographic (STL) format from digital imaging and communications in medicine (DICOM) and image processing software Proplan CMF 3.0 (Materialise). Segmentation was performed for each tooth to produce all anatomical features needed for registration as accurately as possible. The dentition was scanned in maximum intercuspation using a structured-light 3D scanner (Rexcan CS2, Medit Co Ltd) to obtain the 3D spatial relations of each dental arch. A splint attached to incisor facial face was fabricated based on the 3D model of upper and lower dentition. And the splint designed above was printed using a 3D printer (SHINO I, nozzle diameter = 0.3 mm, thickness=0.1mm). (Fig. 1).

Real-time mandibular movement tracking process

Subject performed the physical mandibular movement wearing landmarks. The tracking processes were conducted sequentially in the following order: opening and closing movements; protrusion out to the edge-to-edge position; and lateral excursion movements to the left and right sides up to the canine-to-canine position. The movement trajectory of the target was measured at 120 HZ using the mandibular movement recording system PN-300, the core binocular vision device of the PN-300 system was two digital cameras. To track the mandibular movement trajectory, a detection

Fig. 1. Three dimensional print of the splint and landmark.

landmark target was fixed on the subject's dentition from outside the mouth. As soon as the mandible began to move, the camera began to capture images of the landmark target. These data were transmitted into PN-300 software to calculate the mandibular position information in real time.[16] The movement information data saved in a TXT file was opened in Geomagic Studio, 2012 software creating a point cloud of the maxillary dentition (Fig. 2a) and mandibular trajectory (Fig. 2b) transforming into STL format. The error in the real-time 3D, computerised, binocular, tracking system is 0.1mm based on experiments performed by Tian Zhao.[14]

Registration of mandible model and mandibular movement trajectory

The 3D trajectory STL data acquired from the tracking device was aligned with the mandibular CBCT STL data. The 3D model of the dentition served as the centre of registration. The maxillary dentition and mandibular trajectory data obtained from the PN-300 system was aligned with 3D model of the dentition using the maxillary canine cusp and the midpoint of the maxillary central incisor as the registration points (Fig. 2). The CBCT scan mandibular model was aligned with the 3D model of the dentition using the lowest point of the mandibular canine margin and the lowest point of the mandibular midsection as registration points. After this process of recording, the upper and lower jaw morphology, occlusion relation, and mandibular movement trajectory were converted into a digital model (Fig. 3).

Measurement of the straight-line distance of the condyle during mandibular border movement

The midpoint of condylar crest was chosen as the measurement point. Based on the digital model built above, the movement distances of the condyle were measured during opening, prostrusion, and lateral excursions movements (Fig. 4).

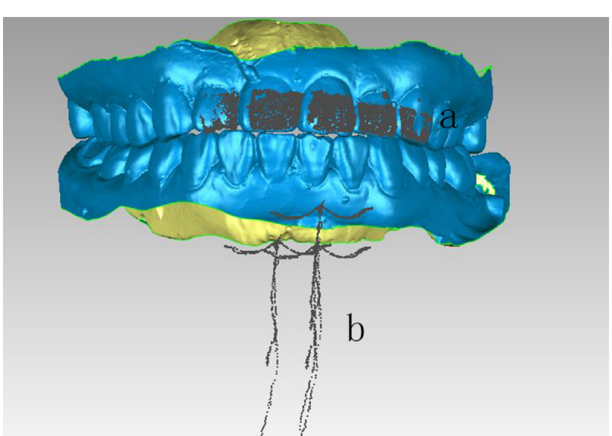

Fig. 2. Registration process between STL model of dentition and point cloud data recorded from PN 300 system. a: maxillary dentition point cloud recorded from PN300 system; b: mandibular trajectory point cloud recorded from PN300 system.

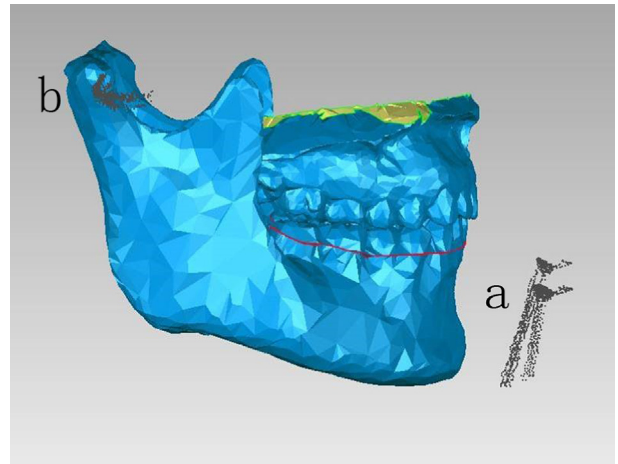

Fig. 3. Digital model of mandible and motion trajectory. a: three dimensional motion trajectory of mandible; b: three dimensional motion trajectory of condyle.

Reconstruction of the envelope surface of the condyle

Delineation of the functional surface of the condyle was done as follows. In the digital temporomandibular joint model, the most prominent points of the medial and lateral excursion of the condyles were connected through the top transverse crest. The functional surface was defined as the coverage of the transverse ridge 6 mm forward. The positions of the functional surfaces of the condyle at each moment when the condyle was moving were simulated and saved in the same 3D coordinated system. Condylar functional surface data was import into the Geomagic Studio, 2012 software in Polygon 3D file (PLY) format, and all positions of the functional surface at each moment were merged to construct the functional surface of the condyle. The merging process and results are shown in Fig. 5, which were related to the 3D motion range and the shape of the condyle.

Results

Reconstruction of the digital model and display of mandibular and condylar movement

Fig. 3 shows a 3D digital model based on CBCT images of the cranial region of the subject and the motion trajectory captured by the optical measurement device. The model could simulate mandibular movement in PN-300 software. The digital model of the mandible and temporomandibular joint can be displayed in chronological order.

Analysis of movement of condylar functional surface based on digital model

Fig. 4 shows the movement process of the condyle when the mandible was opening. The condyle moved downward firstly, and then upwards to the position of maximum mouth opening. The movement distance of the condyle during mouth opening was 14.7 mm (Fig. 4). The condyle moved

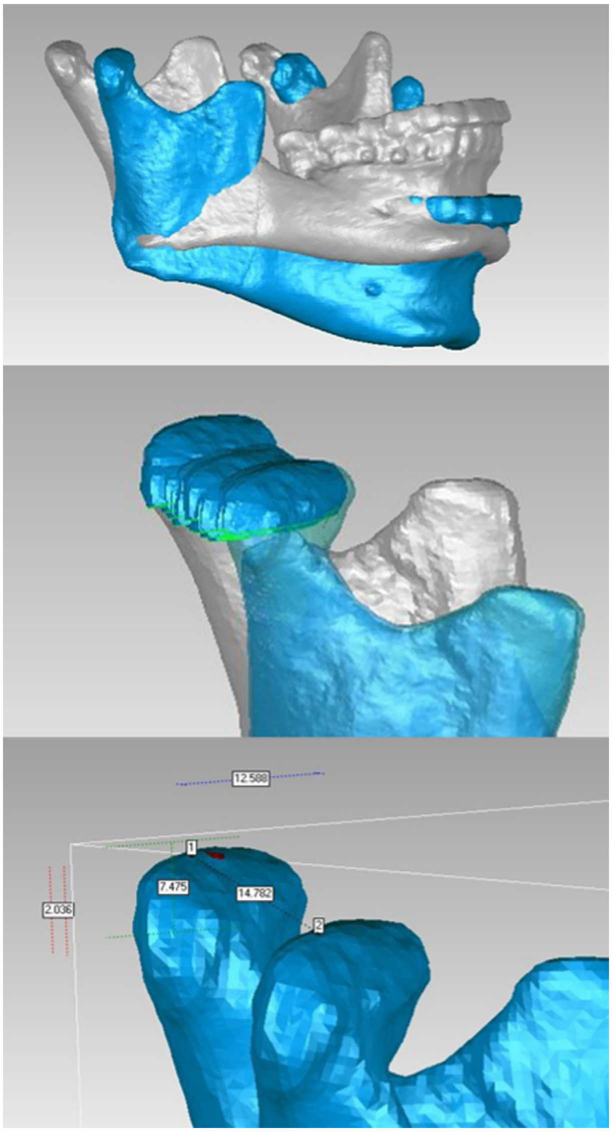

Fig. 4. Motion trajectory of condyle in mouth opening process. Condylar functional surface moved downward and inward firstly, and then moved upward near the maximum mouth opening. The movement distance of condyle was 14.78mm.

forward and downward during protrusion, and the movement distance of the condyle was 9.09 mm. The working condyle rotated slightly, and the non-working condyle moved forward, downward, and inward during lateral excursions, when the movement distances were 10.07 mm and 4.95 mm, respectively.

The mean (SD) of movement distance of 11 subjects was 19.04 (4.37) mm during mouth opening and 9.75 (2.38) mm during protrusion. During lateral excursions the mean (SD) movement distance of the working condyle was 2.87 (1.13) mm and the mean (SD) movement distance of the non-working condyle was 10.85 (3.25) mm.

Reconstruction of the envelope surface of the condyle

Fig. 5 shows the envelope surface of the condylar functional surface and the surface merging process during mouth opening. The envelope surface presents a two-peak model.

Discussion

Several kinds of devices and methods have been developed to record and analyse the movement trajectory of the mandible over the last years.[17–22] Several mandibular movement recording systems have been made to assess condylar motion. But the condylar trajectory recorded from these systems are presented in a two-dimensional image.

In this research, the authors developed a method that can analyse condylar movement in four dimensions by creating a patient-specific, real-time model from data obtained using CBCT and an optical 3D movement recording system. Morphological and quantitative analyses of the movement of the condyle were synchronously recorded by an innovative tracking system.

Compared to traditional methods, this innovative recording method can acquire more data on condylar movement. In traditional methods, one point is usually chosen as a reference to measure the condylar motion trajectory. While in a real situation, the displacement on different parts of the

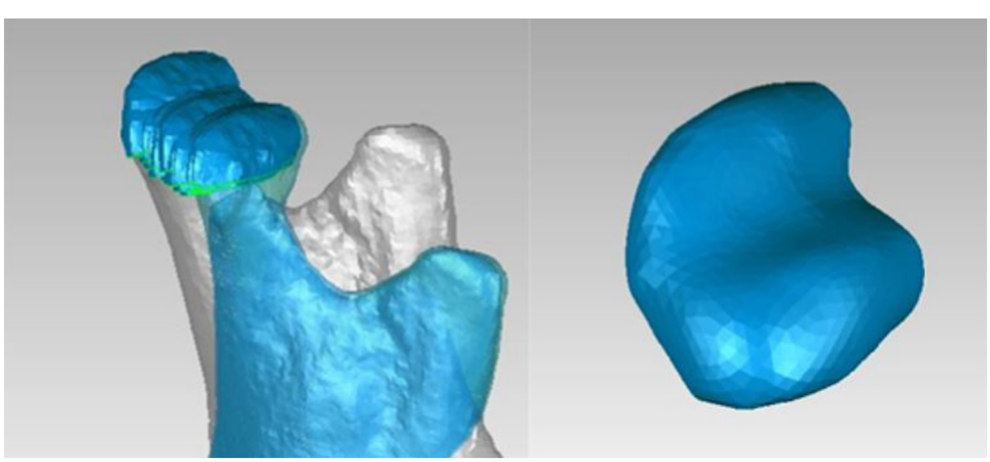

Fig. 5. Envelope surface of condylar functional surface and its merging process when the mandible was performing mouth opening movement.

condylar functional surface varies because the condylar surface movement consists of rotation and sliding movements. For example, in the process of lateral excursions movement, the traditional method showed a slight movement of one point, while in the results shown in this paper, the condyle rotated slightly.

The idea of the envelope surface of the condyle is proposed by us, to the best of our knowledge for the first time, in this article. To get the envelope surface of the condyle, several digital methods were used in this research. A 3D scanner was used to obtain the digital model of the maxillary and mandibular dentition and the occlusal relationship between them. Three-dimensional printing technology was used to produce the light-weight splint, which resulted in more physiological mandibular movement and less recording error. The 3D real-time, computerised, binocular, tracking system PN-300 with high precision was used to record the real-time movement of the mandible. All the digital methods mentioned in this article contributed to the reconstruction of the envelope of the condylar surface. The envelope surface of the condyle in normal adults showed as a 'two-peak' model. The two peaks in this model represented the starting and ending positions of the condyle during movement of the border, and a smooth movement pathway was recorded during the movement process, which was in line with traditional research results.

The 3D space formed by the envelope and its shape tracked physiological condylar activity, which can be applied in total temporomandibular joint replacement design. There are several alloplastic temporomandibular joint replacement systems emerging in market, but only four devices have been approved by regulatory bodies. Zimmer Biomet and TMJ Concepts were approved by the FDA,[11,23,24] OMX Solutions and OrthoTiN[25,26] have been approved by the Australian Register of Therapeutic Goods. At present, the research focus of total temporomandibular joint replacement systems is the surface materials above the glenoid fossa and condyle. Few research institutions have focused on the design of glenoid fossa morphology. There is only a simple ball and socket design in the present alloplastic temporomandibular joint replacement system. The rotation design of the fossa has its limitations because of the complex sliding and rotational movement of the TMJ. Motion-induced knee joint replacement system have considered the movement data of the knee joint during the design process, which has resulted in more accurate physiological knee movement. In our study, we simulated and reproduced the 3D motion range of the condyle, namely the envelope surface, which represents the spatial range of the three-dimensional motion of the condyle. We can apply the envelope surface to the design of the glenoid fossa, to guide the condylar process to carry out physiological movement in the fossa, making the total joint replacement system more in line with the design of human biology.

Conclusion

The personalised system we have built and described in this article can display real time movements of the temporomandibular joint, which are not visible to the naked eye. The envelope surface of the condyle and 4D movement model were reconstructed by merging the trajectory of the mandible recorded from the novel virtual articulator PN-300 and 3D images of the mandible. The envelope surface of healthy subjects showed a two-peak pattern.

This microscopic and detailed simulation method can be helpful for the diagnosis and treatment design of patients with TMJ diseases. The envelope surface of condylar movement recorded from normal adults will be applied in the design of an artificial joint replacement system with the help of 3D printing technology, resulting in a more physiological design of the artificial temporomandibular joint.

Conflict of interest

We have no conflicts of interest.

Ethics statement/confirmation of patients' permission

This study was approved by the Bioethics Committee of Peking University School and Hospital of Stomatology, Beijing, China (No.PKUSSIRB-201947091). Written informed consent to publish these case details was obtained from participants.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bjoms.2021.08.006.

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